

Review of the PQ Application Note for Textile Industries

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Agenda

1. The Introduction and the mill configuration
2. Major Mil electrical Equipment
3. Methodology Adopted for PQ Survey
4. Various Observations and Analysis Of the PQ survey
5. A summary - Harmonic Generation and Mitigation

The Introduction and the mill configuration

Introduction

- This application note provides **information on the Power Quality (PQ) issues and their mitigation** relevant to the textile mills .
- **Energy conservation measures** which are driving the rise of PQ issues are also discussed.
- These issues are discussed widely , as **neglect of these** can pull down plant productivity.
- Poor PQ results in **equipment overheating, capacitor bank failures, erratic tripping of protection relays, mal operation and card failure of micro electronic equipment, bearing failures** of motors due to superimposed of negative torques .
- The textile mill AC motors operated through **VFD-s** , have added newer PQ issues by introducing **harmonics to the current and voltage waveforms** in addition to the conventional PQ problems of voltage dip and rise, and voltage / current unbalances .
- This application note is prepared after **undertaking power quality related measurements in nearly 20 odd textile / spinning mills** , with various configurations.
- The note provides (i) **the mill electrical configurations** (ii) **the technical specifications of the used equipment and their selection criteria**, (iv) the **PQ measurement methodologies**, (v) **analysis of the observations** as well as **guide lines** to the mill personnel to manage the PQ related problems

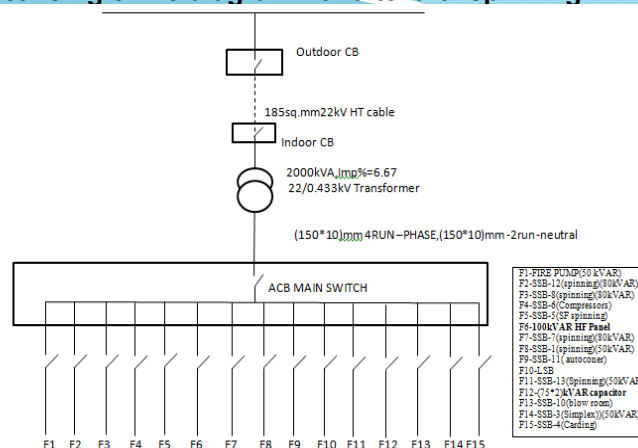
Introduction

- There is **significant awareness of the PQ issues** amongst the Tamil Nadu textile Industry personnel, after the implementation of the CEA regulations on Harmonics by TANGEDCO.
- Tamil Nadu is also a **major hub of textile activities in the country**; hence it is only appropriate that **Asia Power Quality Initiative (APQI)** had undertaken the project of preparing the PQ Application notes for textile industries based on the studies undertaken in mainly in Tamil Nadu industries and the **results of the studies are meant for open access for all the stack holders**.
- **Electrical energy** is used for driving the various motors of the textile machinery; **compressed air** is also used extensively. **Thermal energy** is used in the processing units. **Energy costs** are in the range **15 to 20 % of the production cost**. Efforts are being made to **reduce the Ukg (Units per kg)** cost of the products, **by modernization**.
- For modernization of these industries the mills are **adopting variable frequency drives** mainly for the spinning spindles requiring **significant speed changes**. For the other sections, the VFD-s are used to provide **controlled start of the equipment**. **Auto-coners** are also extensively using these features. In some mills the **compressors are also speed controlled** using VFD-s to **regulate the air pressure** within a very narrow band of variation.
- **The VFD-s introduce harmonic content** into the power system. As per the CEA regulations, these harmonics **needs to be within the mandated limit**. The harmonic currents are produced due to the on/off switching of the user loads (by the power electronic devices) which results in non-sinusoidal input currents.
- These currents, **then distort the supply voltage waveform** which is transmitted **throughout the grid**. All the consumers connected to the grid, **including those using only linear loads**, are also affected.

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5

Typical single line diagram for a textile spinning mill



- The mills of **500 kVA / 3000 spindles and above** go for HT supply (11 kV / 22kV) which is connected to the transformer at the **point of common coupling (PCC)**.
- The transformer **secondary supplies 415 V LT** to the power distribution board (PDB) through an **ACB**.
- The PDB feeds the SSB-s of **different load centres** like blow room, carding, spinning etc. as well as is connected to the **power factor correction (PFC) panel** -manually switched or switched through **APFC system**.
- Additional capacitor banks are mounted near the SSB-s also. The mill personnel try to **maintain nearly unity power factor at the PCC**.

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6

Major Mil electrical Equipment

Textile Mill – Major Electrical Equipment

- **A fairly deep knowledge of the involved electrical equipment considering the prevalent PQ issues** is necessary ; these are covered in Section # 5 of the Application Note .

- Major Electrical equipment requiring such in depth knowledge are as below . :

1. **Transformers**
2. **Motors**
3. **VFD-s**
4. **Components of the PFC and Harmonic mitigation as well as methods for the mitigation**

- The selection of energy efficient transformers and motors are also important in view of the additional losses due to poor PQ.

1.Transformers

- All new Distribution Transformers are to be as per revised standard -IS1180 (Part1): 2014 up to and including 2500 kVA with BEE efficiency levels of 3 star, 4 star and 5 star transformers. In addition **the following to be kept in mind** when feeding non-linear loads.
- Transformer losses -(i) **core loss or no load loss** – occurs whenever the transformer is ON irrespective of the load (ii) **coil or load loss**- as a function of the resistance of the winding materials and the square of the load current .
- The transformers feeding the non-linear loads dissipate **additional losses** due to **harmonic current and voltage waveforms**.
- Major increase in the **eddy current losses which vary with the square of the frequency**; hence for nonlinear loads, **transformers with minimum eddy losses** in total load loss are preferred.
- The transformer **for the VFD fed motors loads of the textile mills** shall be suitable for the **3- phase rectifier currents (6 pulse trapezoidal current waveforms)** produced by power converters. The magnitude of the n^{th} harmonic current is the fundamental current divided by n
- Voltage **drops are introduced due to commutation notches** of varying widths -approximately 0 to 30 deg wide
- Voltage **spikes with dv/dt of 150 % of V_{pk} / microsecond** are introduced
- The transformer **insulation material shall be suitable for the voltage waveforms** specified above

1.Transformers

- Transformers for non-linear loads require careful designs to take care of the **additional heating due to the increased RMS current rating as well as the high frequency harmonic currents** which **increases as the square of the frequency**.
- **Attenuation of line current Harmonics by Transformers :**
- i) **Attenuation**: Transformers provide, due to its predominantly inductive impedance, good attenuation of high frequency harmonics at the primary side
- ii) **Delta windings** : The delta windings do not allow the third harmonic currents to pass through them to the lines ; however the transformer itself will be required to handle the trapped 3rd harmonic currents and voltages
- (iii) **Harmonic Cancellation** : Large power requirements can be provided by transformer **with double secondary windings- Dd0 and Dy1** ; the currents in them having 30° phase shift **cancels the 5th and 7th harmonic currents** in the primary side if the two windings have balanced equal loads. With such transformer , the **lowest harmonic current frequencies are 11th and 13th** .

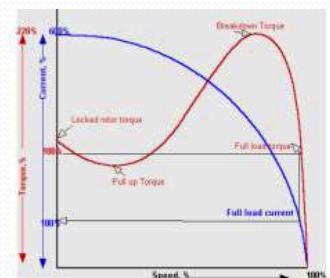
1.Transformers

iv) K- Rating of transformers

- **Transformers** , handling the full plant current, are the equipment of the plant **most affected by non-linear loads**; hence **they are the first to receive a harmonics capability rating system** by way of **K-Factor** .
- Other electrical equipment **are yet to receive** such a **harmonics capability rating system** .
- Underwriter's (UL) laboratory's '**K factor de-rating**' for handling **higher frequency harmonic currents**. K-Factor of 1.0 indicates a linear load (no harmonics). The **higher the K-Factor**, greater is the **additional thermal capacity requirement** for harmonic heating effects
- **The K-Factor equals $\sum (i_h)^2 h^2$** ; Standard K-factors are 1, 4, 9, 13, 20 ; these figures **indicate the multiples of the 50 Hz winding eddy current losses that the transformer can safely dissipate**.
- **Single phase transformer** used to feed the computer loads in office **use K- factors above 4** .

2. Induction Motors- Basics

- AC motors are used for various applications of the textile mill. They are speed controlled through VFD, to **enable soft-starts of the equipment, achieve variable speed operations and for energy saving applications like pumps and fans** .
- Unlike the Transformers , there are no PQ specific motor standards; however manufacturers are claiming that the motors are for operation with VFD-s providing PWM output voltage by having higher reactance.
- In the IM-s the magnetic fields of the stator and rotor currents which are rotating at N_s and $(1-s) \cdot N_s$ RPM-s , **interact due to the difference in their RPM-s**. This produces a developed torque which accelerates the rotor to its running speed of $N_R = (1-s) \cdot N_s$. **Here $s = (N_s - N_R) / N_s$, defined as slip. As the load torque increases the difference increases ; s_r , is the rated slip indicated on the nameplate and the maximum slip is s_{max} corresponding to about 250 % of the rated torque.**
 - The slip in the motor speed indicates losses and hence less slip for a load means a more efficient motor. The energy efficient motors achieve this by suitable design methods.



Important motor parameters (as shown in the characteristic):

Locked Rotor Torque is referred to as starting torque, when the rotor is held at rest with rated voltage and frequency applied.

Locked Rotor Current is the starting current taken from the supply line at rated voltage and frequency with the rotor at rest.

Pull Up Torque is the torque developed during acceleration from start.

Breakdown Torque is the maximum torque a motor can develop at rated voltage and speed

2. Induction Motors- Basics

Starting Current of an AC Motor on the incoming line is typically 600% of full-load current when rated voltage and frequency is applied. **Line Voltage (V_s)** is applied to the stator from the AC power supply.

Magnetizing Current (I_M) is responsible for producing magnetic lines of flux which magnetically link with the rotor circuit.

Working Current (I_W) flows in the rotor circuit and produces torque. This is a function of the load. An increase in load causes the rotor circuit to work harder increasing working current (I_W). A decrease in load decreases the work done by the rotor circuit, decreasing working current (I_W).

Stator Current (I_S) is the current that flows in the motor stator circuit and which is measured by a clamp-on ammeter. The **full-load ampere rating on the name plate** of a motor refers to **stator current** at rated voltage, frequency and load. Stator current is the **vector sum of working current (I_W) and magnetizing current (I_M)**. Typically magnetizing current (I_M) remains constant.

Change in working current I_W due to load and causes a corresponding change in stator current (I_S). I_W can be calculated from the measured I_S during any load and I_M which is measured under no load as per the equation $I_W = \sqrt{I_S^2 - I_M^2}$

Magnetizing current is typically about 30% of rated current and like flux (ϕ), is proportional to voltage to frequency ratio (explained in the slide for VFD controls); **I_M is approximately equal to the no-load reactive current**. **Stator current decreases** to its rated value from its **starting current** levels due to the **reduction in the magnetizing current**, as the rotor comes up to speed.

13

2. Induction Motors- Basics

Recent Induction Motors Standards : IS 12615 :2011 (updated in 2014) is for energy efficient induction motors; replaced the original IS 325 and BS 499; The equivalent IEC standard : 60034-30. This standard sets forth **four energy-efficiency classes for motors: IE1: standard efficiency ; IE2: high efficiency ; IE3: premium efficiency ; IE4: super premium efficiency**

Depending on their rated power, high-performance motors can improve operational efficiency by up to 3 – 5 % compared to standard motors.

$$\text{Energy savings (kWh per year)} = \text{Initial Electrical Load in kW} \times \text{hours per year} \left(\frac{\eta_{\text{new}} - \eta_{\text{old}}}{\eta_{\text{new}} \times \eta_{\text{old}}} \right)$$

% Motor Loading

$$= \frac{\text{Input power drawn by motor at existing load} \times \text{Name Plate full load efficiency} \times 100}{\text{Name Plate full load rating}}$$

Under-loading of motors: Under loading of motor results in lower efficiency and power factor (figure in next slide), hence in such cases downsizing of the motor (with an energy efficient motor) is recommended.

Operating the motor in Star mode: For motors which consistently operate at low loads, cost-effective method for higher efficiency is to operate in star mode which leads to a voltage reduction by a factor of ' $\sqrt{3}$ ' and capacity reduction to 1/3. The efficiency increases due to reduced no load losses.

Use of Soft Starter / VFD-s: Under DOL starting, AC Induction motor develops **more torque than that is required at full speed**. This **stress** is transferred to the **mechanical transmission**. Additionally, results in **large in-rush currents** – up to 6 times of the normal current. **The soft starters enables reduced starting currents and extended motor life as damage to windings and bearings is reduced.**

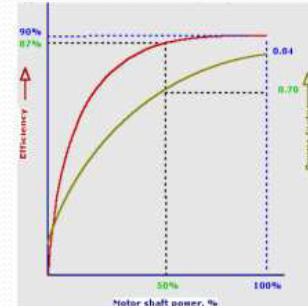
2. Power factor of AC Induction Motors

- Induction motors always operate at lagging power factor as its stator leads draws both the required load current and the reactive magnetizing current from the mains.
- The ratio of the working component of the current to the total stator current provide the power factor of operation of these motors. Since excitation power is required, induction motor loads cannot operate at unity power factor without compensation.
- The power factor gets poorer as the working current reduces (due to load reduction). The characteristic showing the deterioration of the power factor with reduction in load is as shown.
- **Power Factor Correction (PFC) for Motors**

Capacitors connected in parallel (shunted) with the motor are used to improve the power factor. PF capacitor improves the power factor at the point of installation by supplying the reactive magnetizing current. Hence PF improves at the supply side and not for the motor.

The size of capacitor required for a particular motor depends upon the no-load reactive kVAR drawn by the motor, which can be determined by the no-load testing of the motor. Generally, the correction by the capacitors are limited to 90 to 95 % of the no-load kVAR of the motor.

Higher rated capacitors could result in over-voltages and motor burn-outs.



- A plant with number of Induction motors provides power factor compensation capacitors normally at the incomer panel and also some times at the load centers.

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15

3. Basics of Variable Frequency drives for Textile Industries

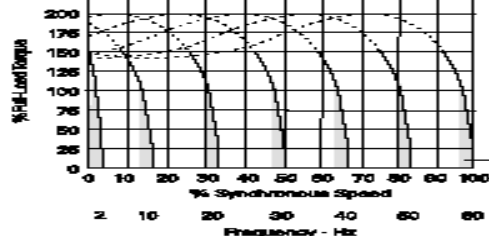
- In textile mills the VFD fed motors are used for the various textile machinery as well as for other utilities like fans, pumps and compressors.
- The textile machinery equipment are constant torque loads and the variable speeds are employed for operational requirements / to match the production speeds. Fans, pumps and compressors are variable torque loads; here variable speeds are employed to achieve proportional variable flow and achieve energy conservation.
- Induction motor speeds are expressed by the equation: $RPM = (f \times 120) / P$ Where f is the frequency in Hz, and P is the number of poles in any multiples of 2.
- VFD-s convert the fixed voltage and frequency to a variable voltage and frequency (VVVF) maintaining the ratio between voltage and frequency under variable speed mode
- Rewriting the motor EMF equation, $E = 4.44 * \phi * f * N * s$, $flux \phi = k' * \frac{E}{f}$ where $k' = 4.44 * N * s$
- Hence, when the supply frequency is reduced below 50 Hz, the supply voltage, $V (E)$ should also be reduced (the ratio kept constant) to avoid over-excitation of the machine. This constancy requirement must be satisfied under lower than rated speeds.
- The developed torque is constant under this condition $T = k * \phi * I_w = k * k' * \frac{E}{f} * \sqrt{I_s^2 - I_M^2}$
- As per the above equation, the torque developed by the motor will be constant for all the below rated speeds, if the flux is kept constant by ensuring constant V/f (or E/f) ratio.
- Hence the two most basic functions of a VFD are to provide conversion from one frequency to another, and to control the output voltage to achieve the ratio as above.

16

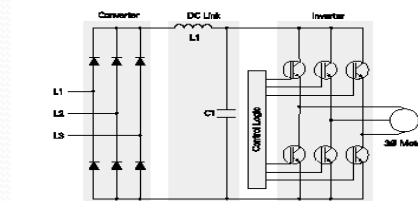
3. Variable Frequency drives for Textile Industries

- A DOL started motor at full voltage and constant frequency supply will develop approximately **150% starting torque at 600% starting current**. Compared to this, with AC drives, the motor is started developing 150 % torque with a starting current of 150 % by maintaining constant flux (volts per hertz ratio) from almost zero speed to base speed.
- The operating torque/speed curve shifts from left to the right as frequency and voltage are increased.

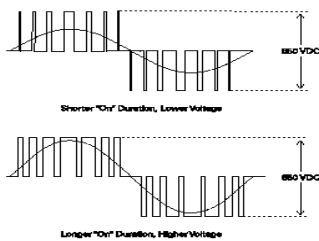
Torque –speed ch. under VVVF control



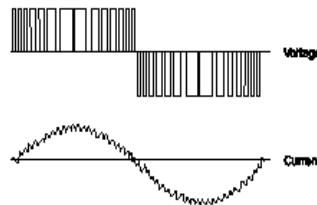
VVVF power circuit



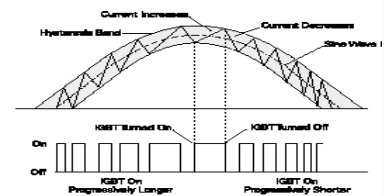
PWM controlled voltage waveform



PWM controlled Current waveform



PWM control strategy



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17

4. Power factor compensation and Harmonic mitigation equipment in Textile Industries

Power factor compensation and harmonic filters form essential equipment , normally on the LT side of the transformer in a plant.

Common panels for Power Factor Correction (PFC) as well as **harmonic filters** are located mainly in the mill power distribution room and also nearer to the load centres.

The **AC induction motor loads are operating at lagging power factor** and need good amount of reactive power compensation.

Low power factor (typically $\cos \phi \leq 0.9$) at the plant PCC **results in** 1) Less power distributed via the network 2) Higher transformer losses 3) Increased voltage drop in power distribution networks.

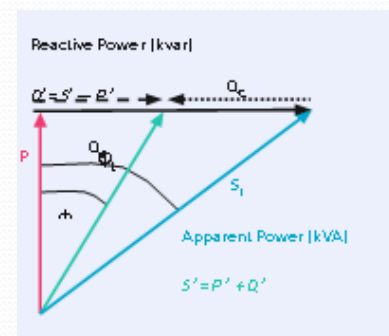
In addition ,when the **motors are getting controlled through** non linear power electronic devices based **variable frequency drives** , extensive harmonic currents are also injected into the power system and these are also to be mitigated.

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18

4. Power factor compensation for motor loads in Textile Industries

- The operation of AC induction Motors and transformers are enabled by the magnetic field excitation produced by their windings which are essentially inductances.
- The excitation current (reactive) inputs to the motor windings are in quadrature to the working (active/ torque producing) component of the input currents and do not contribute to torque production.
- The resultant stator / primary input currents are due to the vector addition of these two components and is having a lagging power factor angle with respect to the input voltage wave. This is called as displacement power factor angle. In case of the linear loads , this is also the true power factor.
- The power triangle (fig.) showing the active, reactive and the apparent powers reflects this.
- The figure also shows how the reactive power is compensated partially by supplying Q_C , whereby reducing the pf angle from ϕ_1 to ϕ_2 .



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19

4. PFC calculation

Calculation of the required PF compensation.

PFC table is used to calculate the required PF compensation for a load circuit from the existing PF level to a desired PF level. The table provides the multiplication factor for the calculation.

- Required Compensation kVAR , $Q_C = P_A \times (\tan \phi_1 - \tan \phi_2)$.
- i.e. $Q_C \text{ (kVAR)} = P_A \text{ (kW)} \times \text{Multiplication factor from the table , r}$

$$s = \frac{P_A}{\cos \phi} ; \text{ For a required } P_A, S1 = \frac{P_A}{\cos \phi_1} \text{ and } S2 = \frac{P_A}{\cos \phi_2}$$

- $\tan \phi_1 - \tan \phi_2$ is the the multiplication factor , This can be found from the table provided.

• (i) Assume the actual motor power $P = 100 \text{ kW}$; ACTUAL displacement PF $\cos \phi_1 = 0.8$ and the target displacement PF $\cos \phi_2 = 0.96$; Factor F from table is **0.458** for the assumed power factors .The reactive power to be supplied to compensate the displacement power factor is the Reactive power $Q_C = 100 \times 0.458 = 45.8 \text{ kvar}$.

- (ii) If the target displacement PF is selected as $\cos \phi_2 = 1.0$, the factor is 0.75. ; hence $Q_C = 100 \times 0.75 = 75 \text{ kvar}$

• The above calculations (i),(ii) are provided to indicate that reactive power requirement is almost 1.5 times for improving the PF to unity instead of 0.96.

• It can be seen in the coming slides that above optimum level of compensation results in undesirable Harmonic amplification ; in addition, the pf increase from 0.96 to 1.0 requires much larger compensation. Thus optimization of Pf compensation needs to be considered.

- Depending on the actual power level the pf controller switches minimum number of capacitors to achieve the desired power factor.

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20

4. True Power factor compensation

- If the motor is fed through a VFD, the current waveforms are, distorted as shown below.
- This distorted waveforms have the super-imposed fundamental frequency current as well as different harmonic current components of multiple frequencies.
- Thus there will be a **displacement power factor** due to the **lagging angle** of the fundamental current as well as **the harmonic power factor** due to the various harmonic currents.
- Hence, in case of the non- linear loads, **the true power factor is the product of the displacement power factor and the harmonic power factor.**



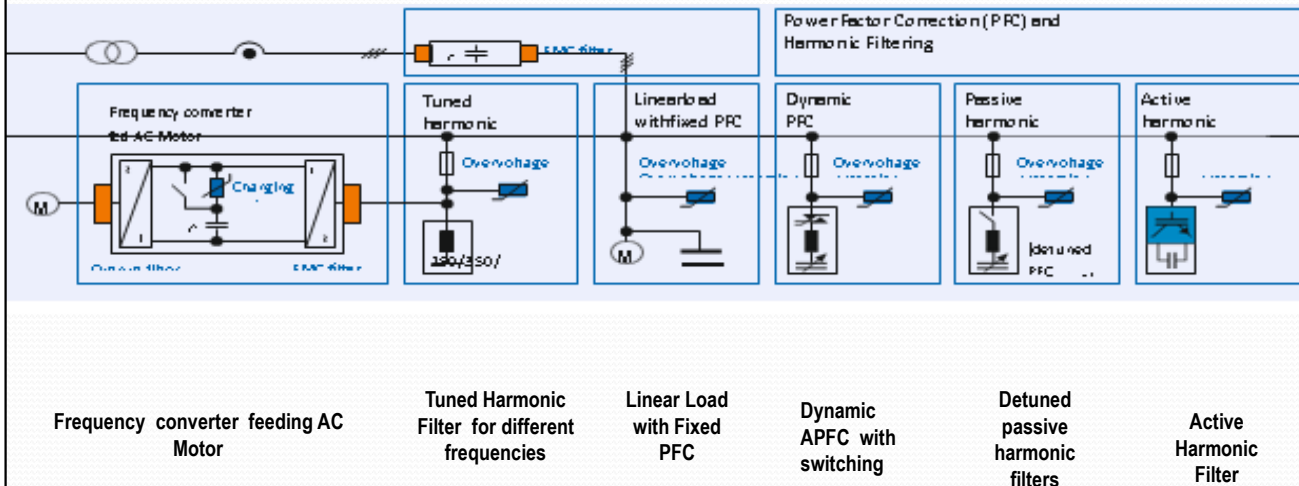
Power factor due to a linear load

Power factor due to a non-linear load

4. Textile Mill – True Power factor compensation

- In earlier days **simple AC induction motors** were used for the various mill loads ; thus the **loads were linear in nature.**
- Many applications, are nowadays , **operating with VFD driven motors** for speed controls .
- Thus the mill feeders handle high percentage of non-linear loads **and these harmonic currents are getting injected** into the supply system.
- The power factor correction capacitors (**PFC**) along with the system reactance (transformer / line) present a **low impedance resonance circuit** for these **high frequency harmonic currents** which **result into further amplification** of these harmonic currents.
- The **power factor compensation (PFC)** in the harmonic rich environment require a more complex equipment selection and **not just kVar calculation** from power triangle for PFC.
- The **mill personnel** should take care of the implications of the **harmonic rich situation** for their **PFC.**

4. Different PFC and Harmonic filtering Schemes



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23

4. Components for PFC in Mills

1.PFC capacitors :

Electrical features : (1.) High peak in-rush current capability (up to $400 \cdot I_R$) (2.) High over current capability (up to $2.0 \cdot I_R$) (3.) Limited to less than 0.45 W/kVar (4.) Number of switching operations : maximum 10,000 switching per year

2.Power factor controller

PF controllers are micro-processor-based which analyzes the signal from current transformers and produces **switching commands to control the contactors to add or remove capacitors**. After the required capacitor output has been determined, the number of steps will be defined by this controller.

3.Switching devices

Two types of switching devices are normally used: (1)**capacitor contactors** (pre-switching auxiliary contacts of the capacitor contactors close before the main contacts to avoid peak current values by pre-loading the capacitor) (2) **Thyristorized switches** (for fast changing loads ; zero crossover switching to limit transients – not required for textile mills).

4. Discharge devices

Discharge resistors discharge the capacitors and **protect human beings against electric shock hazards** as well as to **switch the capacitors under limiting mode of the switching currents** in automatic PFC equipment (opposing phase).

5. Protection

An HRC fuse or MCCB acts a safety device **for short-circuit protection**. HRC fuses do not protect a capacitor against over-load, they are designed for short-circuit protection only. The HRC fuse rating should be 1.6 to 1.8 times the nominal capacitor current.

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24

4. Comparison of PFC solutions

- Comparison of Power factor compensation solutions in the presence of harmonics :

- The following three situations are compared :

1. Pure power factor compensation **with only capacitors** (results in **possible resonance and amplification of harmonics**)
2. Use of **tuned filter** (**filters the frequencies** for which they are tuned; **however possibility of sucking harmonic currents from even outside** the plant campus)
3. Use of **detuned filter** (it is **not a filter in the correct sense**; it mainly **eliminates the amplification of low frequency harmonics** which are normally **observed in the plants with simple capacitor** compensation as under 1.

- Thus **detuned filters** have become the **most popular first level practice for power factor compensation** in all the **harmonic rich power systems**. This will bring down the harmonics to minimum levels.

- The solutions **like active filters** can be **employed subsequently**, if necessary.

4. PFC in harmonic rich environments & Detuning

- The following methods are used to address the harmonic issues – (i) provide tuned passive filters (ii) provide tuned active harmonic filters and (iii) provide detuned filter .

- **The tuned passive filter** achieves the best attenuation figures. However requires specifically designed filters for a plant and different filters for different frequencies. Thus not preferred .

- **The tuned active filter** attenuates all the selected harmonics. The rating of the filter is selected based on the total RMS harmonic current to be handled. These are expensive and many customers find it difficult to invest in these.

- The detuned filters **do not basically remove / filter** the harmonic currents . Normally plants have power factor compensation capacitors. In a harmonic rich environment, **these capacitors resonate with the upstream supply transformer reactance and causes amplification of the harmonic currents - different frequencies to different levels -** and hence the **overall percentage harmonic currents will be about 20 % to 30 % higher than the situation without the power factor compensation capacitors** in circuit.

- **The detuned filters** only removes such amplification of the harmonic currents **by detuning the resonance frequency to a value quite away from(normally below) the significant existing harmonic currents**.

- It is **necessary to provide the detuning for all the pf compensation capacitor banks to eliminate any amplification effect** due to the above mentioned phenomenon. This reduces the sizing of the active filter - required to eliminate the harmonics introduced due to non- linear loads and can substantially reduce the investment for the active filters.

4. Detuned PFC

- Detuned PFC uses detuning reactors along with compensating capacitors to remove the resonance possibility of the capacitors with the supply network inductance (the incoming transformer etc.) since the present day power distribution networks are increasingly subjected to harmonic pollution from modern power electronics devices.
- Harmonics could become dangerous for capacitors connected in the PFC circuit, especially if they operate at a resonant frequency. The most critical frequencies are **the 5th and 7th harmonics** (250 and 350 Hz) and the corresponding harmonic **currents are likely to be amplified many times**. This **increases the distortion level** of the system.
- The series connection of a reactor and capacitor is done to **detune / shift the series resonance frequency (the capacitors and the system reactors / input transformer combination) to a lower value**.
- Due to this , the **harmonic current amplification** is minimized and the capacitor damage is prevented .
- The reactors are designed to absorb the odd harmonic voltages like V_3, V_5, V_7 etc. They are designed to carry the effective fundamental and harmonic currents – i.e. $I_{eff} = \sqrt{I_1^2 + I_3^2 + I_5^2 + \dots + I_{13}^2}$
- Appropriate **standard reactors are calculated for connection with 10, 12.5, 15, 20, 25 kVAR capacitor banks** to achieve the over all desired reactive power compensation at the recommended detuning factors (and the corresponding resonant frequencies) of 5.67% (210 Hz) , 7% (189 Hz), 14% (135 Hz) depending on the predominant low frequency harmonics present in the system.

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27

4. Design of Detuned PFC

- Components for PFC detuned filters must be designed and selected according to the (i) the **desired purpose of the PFC** (ii) **the harmonics present** in the system, (iii) the features of the system like **short circuit power and impedances**, (iv) the **desired filtering** effect and (v) the **characteristics of the resonant circuit** configured.
- One major requirement which comes out due to the design is **the voltage across the capacitors will be higher than the nominal grid voltage** when they have a reactor connected in series.
- The reactors must be selected in line with the **system inductance** value to obtain the **desired tuning frequency** and **high enough current capability** for absorbing the harmonic current that can be expected. **The tuning frequency is indirectly referred by the detuning factor p** expressed as a percentage as per the given formula. The **standard detuning figures, p** used are **5.67 %, 7 % and 14%**.

$$p = 100 * \frac{X_L}{X_C} = \left\{ \frac{f}{f_{Res}} \right\}^2 * 100$$

- The resonance frequency is also determined as $f_r = \sqrt{kVA_{sc} / kVA_{rc}}$ where,

f_r = resonant frequency as a multiple of the fundamental, kVA_{sc} = Short circuit rating

at the point of installation, kVA_{rc} = Capacitor rating at the installation.

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28

4. Detuning of PFC in harmonic rich environments

Detuning is done by retuning the resonance frequency of the combination of **Pf compensation capacitor and the system inductance** (due to the transformer etc.) to a lower frequency **well below the normal existing harmonic frequencies of the system** , say 5th (250 Hz) and 7th (350Hz) . The standard detuning figures, p used and the corresponding resonant frequencies are 5.67 % (210 Hz) , 7 % (189 Hz), and 14%. (135 Hz) .

Detuning results in a flattened portion - **means minimum amplification** - in the **frequency v/s impedance curve** for the various harmonic frequencies introduced in the supply system .

On the contrary, without detuning , there will be significant amplification of the normal harmonic currents by a factor up to 5. Refer the following curves for the situation without and with detuning.

It is also seen that with larger and larger compensation capacitor the resonance amplification curve becomes more peaky in the vicinity of the low frequency harmonics and the resultant amplification is also higher.

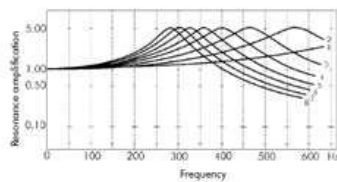


Figure 9 - Resonance curves of different compensators ranging from 50 kvar (curve 1) to 400 kvar (curve 8), operated on a 1250 kVA transformer (Frako)

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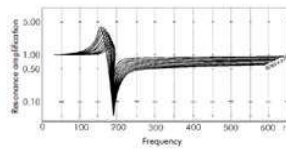


Figure 10 - Resonance curves of different detuned compensators ranging from 50 kvar (curve 1) to 400 kvar (curve 8), operated on a 1250 kVA transformer (Frako)

29

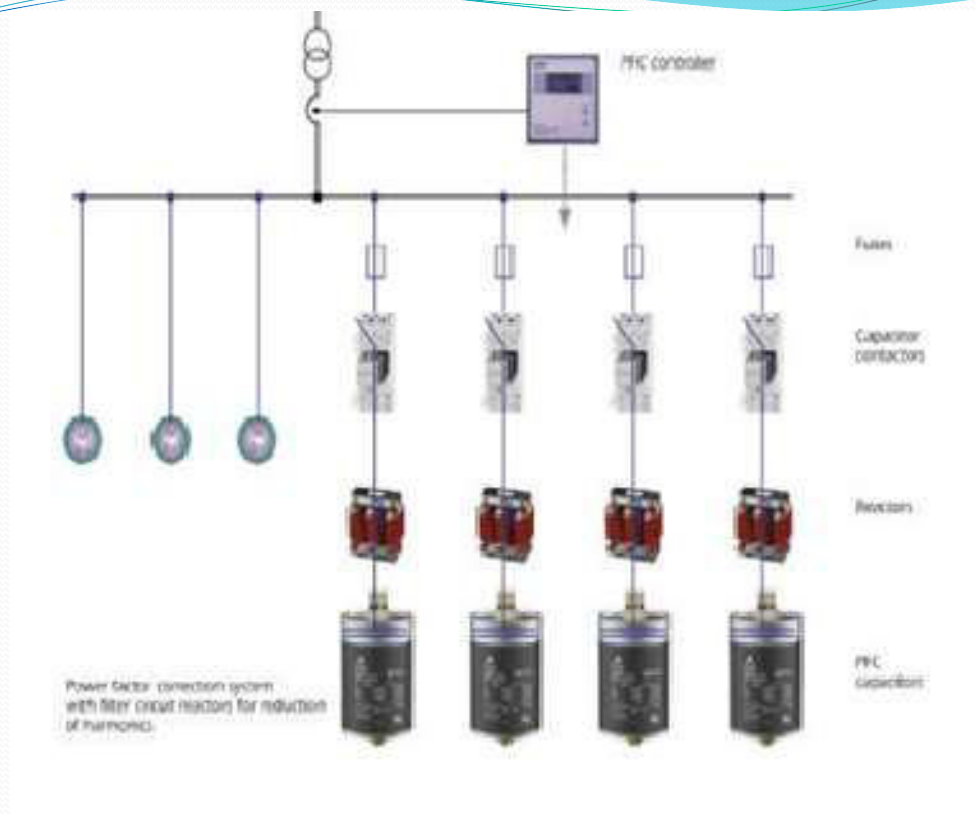
4. Calculation of typical Detuning reactors for 7% (189 Hz), 14% (135 Hz) detuning

Detuning factor	Effective 3-phase Filter output, kVAR @ 440 V network	Specification of the three phase capacitor bank	Specification of the three phase reactor
7%	10	15 kVAR, 525 V ac, 50 Hz, delta connection	4.64 mH, 14.9 A
7%	12.5	15 kVAR, 480 V ac, 50 Hz, delta connection	3.71 mH, 18.7 A
7%	20	25 kVAR, 480 V ac, 50 Hz, delta connection	2.32 mH, 29.8 A
7%	25	2 nos of 16.7 kVAR, 525 V ac, 50 Hz, delta connection	1.856 mH, 33.13 A
14%	10	12.5 kVAR, 525 V ac, 50 Hz, delta connection	10.04 mH, 14.0 A
14%	12.5	15 kVAR, 525 V ac, 50 Hz, delta connection	8.03 mH, 17.5 A
14%	20	25 kVAR, 525 V ac, 50 Hz, delta connection	5.02 mH, 28 A
14%	25	2 nos of 15 kVAR, 525 V ac, 50 Hz, delta connection	4.02 mH, 35 A

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30

4. Typical Circuit Schematic with detuned filter



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31

4. Identification of Optimum level of Power factor compensation without Harmonic Amplification

- Additional measurements are undertaken at PCC for different combinations / conditions of power factor correction capacitors switched **on and off** ; **shorter sample time** of ten seconds are used for a shorter recording periods of 15 minutes to 30 minutes
- Most of the mills have provided PFC **through simple plain capacitors** ; due to the interaction of these capacitors and the system inductors at certain harmonic frequencies, **resonance amplification of the harmonic currents and voltages take place** exporting higher than normal harmonic levels into the power system.
- It is also observed that the **trend in most of the mills (refer slide # 43 analyzing the power factor recording of mills) is to operate at power factors in the range of 0.99 lag to 0.99 lead** ; some of the mills are **operating at leading power factors for significant period of time**. Over compensated PFC causes **over voltages on load throw conditions**, also adds to the **harmonic amplification by resonance** (the resonance amplification is more with more PF capacitors connected to the network) as shown by the resonance characteristics in slide #26.
- Optimum PFC without harmonic amplification is checked by **progressively switching off** of the power factor correction capacitors **which shows reduction in the voltage and current harmonic levels at PCC** ; **but results in the power factor worsens and the input demand increases**.
- In such cases , detuning is suggested by **adding additional reactors in series with the capacitors** by which the system **resonance frequency is shifted well below the existing harmonic currents**.
- **Typical recordings exhibit the effect of switching off of the capacitor on the measured harmonic levels.**

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32

4. Assessing the harmonic amplification

The plant is having power factor compensation capacitors 350 kVAR {(APFC-150)+50+75+75} connected at the main PDB and 100 kVAR connected at load end. The performance under different conditions - different combinations of these facilities are monitored and given below:

No.	Measurement condition	I_{RMS} A	Tpf	% V_{THD}	% I_{THD}	Active Power(kW)	Appar. Power(A)
1	APFC on & 200KVAR Capacitor at also 100 kVAR load end cap on	1100	0.98	10.25	21.2	750	770
2	APFC off & 200KVAR Capacitor at also 100 kVAR load end cap on	1140	0.97	8.3	14	775	800
3	APFC off & 150KVAR Capacitor at also 100 kVAR load end cap on	1145	0.97	7.5	11.6	770	795
4	APFC off & 75KVAR Capacitor and also 100 kVAR load end cap on	1175	0.95	6.4	8.6	770	810
5	APFC off & 0KVAR Capacitor and 100 kVAR load end cap on	1210	0.92	5.6	7.0	780	845
6	APFC off & and all capacitors inclu load end capacitor 100KVAR off	1215	0.91	5.6	7.0	780	855

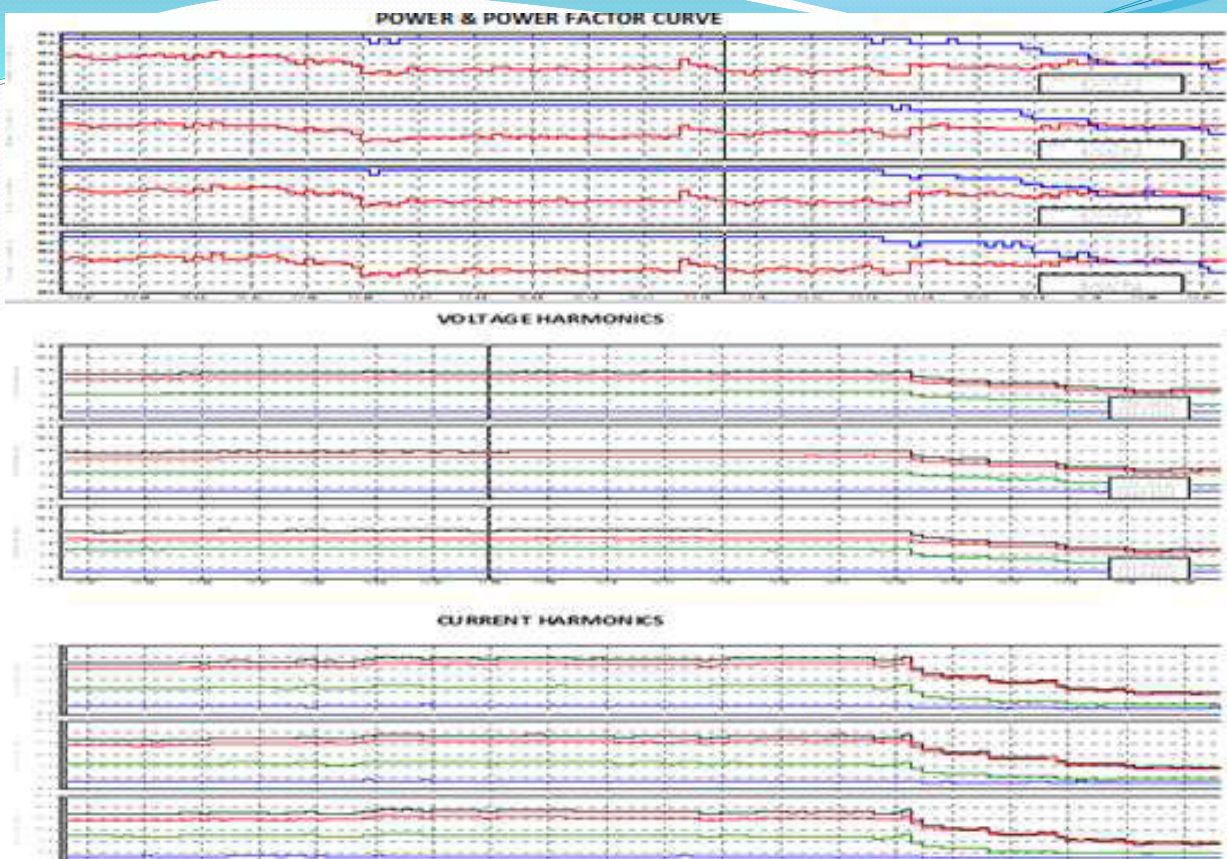
•As per the above table and the related recordings given below, the active power is almost constant in the range 750 kW to 780 kW ; the apparent power increases from 770 kVA to 850 kVA as the capacitors get switched off resulting in poorer power factor (from 0.98 to 0.91) .

• However it is seen that the V_{THD} reduces from 10.25% to 5.6 % and I_{THD} reduces significantly from 21.2 % to 7% as the power factor compensation capacitors are getting switched off, indicating the mitigation of the resonance amplification with lower value of plain capacitors.

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33

4. Recording of PF and THD-s under the switching off of pf compensation capacitors



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34

Methodology Adopted for PQ Survey

Methodology adopted for PQ survey

- The measurements are undertaken using **Fluke 435 Power Quality Analyzer** at the plant PCC for nearly 20 odd mills . The particulars of the mill are as per the link
- In **some of the mills** with HT input, the accessible **PT-s and CT-s of the incoming transformer** are available only **on the secondary side** ; here the PCC measurements for these mills are actually carried out at the LT side ; hence likely to see larger harmonic levels.
- The relevant electrical parameters (as per the next slides)are recorded by the above instrument with the **sample time of 15 minutes**.
- To cover the load variations as a result of the different production schedules, the measurements are undertaken **continuously for three days**. With this, around 288 data sets are recorded over the three days.
- The continuous recordings are **done under the normal operating condition with the power factor correction capacitors**; If the 'solar power' is available for the plant, the same is kept 'ON'
- If the mill has incorporated **active harmonic filter**, the same is kept **OFF** during the above mentioned measurement period .
- All the electrical parameters monitored are **the average of the individual 3 phase values measured** and the power values are the **total three phase power**

Summary and significance of the monitored Electrical parameters

1. **3 phase average RMS line voltages** are measured at PCC ; The 288 sets of voltage data recorded are generally within $\pm 5\%$ of the nominal voltage
2. **3 phase average RMS line currents** are measured at PCC ; For a spinning mill the load variations are slow and within narrow bands. If the PCC load current is reduced the current harmonic THD , will show a higher value; hence the IEEE 519 standards have defined another parameter ' I_{TDD} ' which is a normalized parameter based on the maximum demand current over a long period .
3. **3 phase average RMS fundamental line voltages** (part of the V_{THD} definition)are also measured to arrive at the actual individual harmonic voltages to design the suitable harmonic filter. The fundamental value is less than total RMS value , as per the relation $V_{RMSL} = \sqrt{V_{1L}^2 + V_{HL}^2}$
4. **3 phase average RMS fundamental line currents** (part of the I_{THD} definition) are measured to arrive at the actual individual harmonic currents to design the suitable harmonic filter. The fundamental value is less than total RMS value , as per the relation $I_{RMS} = \sqrt{I_{1L}^2 + I_{HL}^2}$
5. **The voltage unbalance** , V_{ub} is defined as the ratio of the maximum deviation of the three individual voltages to the average value and is required to be within $\pm 1\%$. **Larger V_{ub} figures causes reduced operating efficiency** of motors, transformers and reduced life of assets.
6. **The current unbalance I_{ub}** is defined as the ratio of the maximum deviation of the three individual currents to the average value and is required to be within $\pm 10\%$. **Current unbalances can be due due to leakage of the current through the bearings / motor body to ground** and hence large current unbalances can indicate such faults.
7. If the voltage and current unbalance figures are found to be significantly large, it is recommended to record the individual 3- phase voltages and currents for further analysis.

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37

Summary and significance of the monitored Electrical parameters

8. **The line frequency** is an important parameter ; The permissible frequency band specified by Indian Electricity Grid Code (IEGC) is 49.5 Hz to 50.2 Hz with further reduction of the band recommended to the desirable range of 49.8 to 50.1 Hz progressively. The power demand by the motors vary as the cube of the speed. Thus higher frequencies can result in larger power consumption and hence require attention.
9. **Total 3 phase active power in kW** : Assuming voltage and current unbalances are within limits, it is normal to record the total 3 – phase active power at PCC instead of individual 3 phase power levels; It may be noted *The active power* $= \sqrt{3} * V_{1L} * I_{1L} * \cos\phi_f$ where V_{1L} is the fundamental line voltage, I_{1L} is the fundamental line current and $\cos\phi_f$ is the displacement power factor for the fundamental values ; This is also equal to $\sqrt{3} * V_{RMSL} * I_{RMSL} * \cos\phi_{rms}$ * harmonic power factor
Here $\cos\phi_{rms}$ is the displacement power factor for the RMS values . This is also equal to $\sqrt{3} * V_{RMSL} * I_{RMSL} * \text{total power factor}$
This figure represent the **actual power consumed by the plant** at any instant. It may be noted that $\cos\phi_f = \cos\phi_{rms} \times \text{harmonic power factor} = \text{total power factor}$
10. **Total 3 phase apparent power in kVA** : Assuming voltage and current unbalances are within limits, it is normal to record the total 3 – phase apparent power at PCC . The apparent power is equal to and hence represents the **actual loading of the power supply network** by the plant concerned at any instant .
11. **Total 3 phase reactive power in kVAR** : Assuming voltage and current unbalances are within limits, the total 3- phase reactive power consumption is recorded . It is **the resultant reactive power after the compensation by the PFC capacitors**. This provides information on the leading power factor condition, with a negative value , when the power factor is over compensated .
•These are related by, **Apparent Power** $= \sqrt{\text{Active power}^2 + \text{Reactive power}^2}$

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38

Summary and significance of the monitored Electrical parameters

12. Neutral to Ground voltage : Most of the mills which take in HT power have Dyn vector group for the HT transformer. The star secondary has its neutral grounded through earthing pits. The neutral to ground voltage becomes an important measure from the safety point of view; in case this voltage is greater than 1 V the earthing condition will require improvement

13. Average displacement power factor , : The displacement power factor is the cosine of the displacement angle between the RMS voltage and the RMS current; This is the true power factor when only the linear loads are fed.

14. Average Total Power factor : Called true power factor and this is the product of the displacement power factor (13) and the harmonic power factor as explained under #9. The harmonic power factor is the result of feeding non-linear load

15. Average Percentage 3 phase voltage THD : The 3 phase V_{THD} is measured is the ratio of the vector sum of all the significant harmonic voltages $\sqrt{V_5^2 + V_7^2 + \dots + V_n^2}$ to the RMS fundamental voltage (as per #3) at PCC. As per the IEEE 519 recommended limit this percentage should be limited to 5 % for 69 kV and below systems.

16. Percentage 3 phase current THD : As already explained under #4, the 3 phase I_{THD} is measured by the instrument as a ratio of the vector sum of all the significant harmonic currents $\sqrt{I_5^2 + I_7^2 + \dots + I_n^2}$ to the RMS fundamental current (as per #4) at PCC. As per the IEEE 519 recommended limit this percentage should be limited to 8 % for 69 kV system and below systems assuming that the ratio of the I_{SC} to the I_L at the PCC is 20

17. Percentage individual 3 phase odd voltage harmonics up to 17th The individual harmonics of significance after the fundamental are 5,7,11,13,17,19 are recorded.

18. Percentage individual 3 phase odd current harmonics up to 17th The individual harmonics of significance after the fundamental are 5,7,11,13,17,19 are recorded.

39

Various Observations and Analysis Of the PQ survey

Typical Observations and Recommendations for HT spinning Mills with MD greater than 1000 kVA

- **Mill -1** :A 1650 kVA MD mill at 22 kV PCC has capacity of 12000 spindles . The input transformer at PCC (3150 kVA) **is over rated**.
 - Considering the total loading of 1500 kW maximum , there will be more fixed / iron losses continuously (24x7) but less copper loss. . Customer to justify the economics of using **the over rated transformer** based on the losses.
 - Existing power factor compensation capacitors connected at various locations are to the extent of 875 kVAR including **one ‘detuned’ (?) harmonic filter of 100 kVAR** ; The **simple PFC capacitors are likely to experience over loading due to low impedance for these high frequency currents.** recommended **to go for detuning for all the PFC** (power factor correction) capacitors .
 - The study by recording the effect on harmonics by switching off the simple pf correction capacitors, is not undertaken as per the plant management discretion.
- **Mill #2** :This 2292 kVA MD mill at 11 kV PCC has capacity of 30912 spindles ; Voltage parameters are normal except that **the V_{THD} values are high** ; Similarly current parameters are normal except that **the I_{THD} values are high**.
 - The power factor is leading for 65 % of the time.** Around 1237.5 kVAr power factor correction capacitors are presently connected . Recommended to **operate the plant at nearly 0.98 lag power factor.** Necessary optimum setting of the power factor **by APFC** may be undertaken.
 - Only simple power factor correction is carried out ; recommended to **incorporate full detuned power factor compensation for all capacitors to reduce the amplified harmonic currents and voltages.**
 - The K-factor calculation of the incoming transformer at maximum THD condition and considering 3,5,7,11,13,17th harmonic currents result in 2.07 K-factor with 5th and 7th harmonics having significant effect.

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41

Typical Observations and Recommendations for HT spinning Mills with MD less than 1000 kVA

- This 500 kVA MD mill at 11 kV PCC has capacity of 18000 spindles
- All the **PQ related parameters are almost within the normal limits** ;
 - The V_{THD} is well within limits – less than 3% and I_{THD} is generally below 8% (except for about 10 % of the time) without any special provisions.
 - The power factor is remaining in the range of 0.99 lag to 0.99 lead for most of the time. It is in leading mode for about 37 % of the time.** With appropriate APFC controller pf may be regulated at 0.98 lag. The power factor **correction to be provided with detuned filter network** (7% detuning for 189 Hz) to avoid resonance amplification of harmonics when the plant adds VFD driven equipment. **The K-factor** calculation of the incoming transformer at maximum THD condition and considering 3,5,7,11,13,17th harmonic currents is **1.634 K-factor** with 5th and 11th harmonics being significant.

Typical Observations / Recommendations for HT Weaving / Knitting Mills with MD < 500 kVA

- A 500 kVA MD feeder is supplying a cluster of **knitting and weaving units** ; **Operation at high voltage levels** especially in the night time
- Wide range of **loading - 20 % to 90 % . 8 % current unbalance for 10 to 15 % of total time**
- The MV panel feeding the loads is with **fixed 115 kVAR capacitor** ; recommended **to connect APFC to maintain the power factor** around 0.98 lag
- Recommended to **have detuned PFC compensation for this feeder** with harmonic loads .
- The feeder with **AHF** , but **without detuned filter** as normally recommended.
- The V_{THD} is in the range of 3 to 5 % and I_{THD} is in the range of 10 % **even with the AHF** ; hence the **detuned compensation network** is highly recommended.
- The **K-factor** calculation of the incoming transformer at maximum THD condition and considering 3,5,7,11,13,17th harmonic currents result in **4.231 K-factor** with 5th ,7th and 13th harmonics having significant effect .

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42

Typical Observations and Recommendations for LT spinning Mills with MD less than 500 kVA

- This is a LT-CT spinning Mill with 320 spindles.
- The **voltage levels are varying over a wide range**; the voltage unbalance is within normal levels. The current levels are varying over a wide range.
- The **current unbalance is in the range of 5 to 12 %** for 40 % of the time
- The V_{THD} range is normal, but the **current THD is widely varying in the range of 10 % to 34 % with the variation of the load current**. The plant do not have variable speed drives, hence **this may be due to external harmonic injections**.
- The **power factor is also widely varying and for 30 % of the time the same is below 0.9**. The 70 kVAR simple **compensation should be enhanced** preferably with a APFC.
- There is **harmonic resonance amplification (significant reduction in I_{THD} is observed** when the compensation capacitors are switched off); Recommended to go for detuned PFC to mitigate the resonance amplification.
- Overall the **power supply situation is not ideal**. partially due to the LT-CT nature of the power supply.
- **Require further study** if the plant desires improvement of the power situation for higher productivity

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43

Overall common observations / recommendation based on the study of all the mills

- **Voltage and frequency stability is generally good for the HT fed mills**. Proper transformer tapping to be selected to operate the plant in the region of 95% to 105% voltage. On load tap changers to be installed to avoid over voltage situation when under loaded in 12 hour shift weaving mills.
- While the **spinning mills showed loading in the range of 80 to 105 %**, the **non-spinning mills showed wide variation of the loads**. Lower loads result in the higher value of measured I_{THD} ; hence either the production be regulated or provide automatic on load tap changers, APFC.
- **Mills with solar power (to reduce energy bill) results in reduced demand from EB side and hence the increased I_{THD} / I_{TDD}** . This requires a solution
- **Most of the mills (out of 18) have less than 1 % V_{ub}** ; 2 mills have unbalance between 1 to 2 % and one of the below 3%. **Two of the mills have I_{ub} more than 10 to 15 %**. **Customer to try and balance the single phase loading to avoid the unbalance situation**.
- It is found that **majority of the spinning mills are found to be operating in the near unity or leading power factor mode**. The optimum maximum recommended value of operational power factor is 0.96/ 0.98. *Lower power factor do increase the demand resulting in more loading and energy loss in the supply network*. As a responsible consumer, it is necessary to maintain good power factor of around 0.96/ 0.98 lag using **automatic power factor compensation (APFC) unit** setting the value at 0.98 lag. **Unity and leading power factor situations can result in over voltage condition during sudden load throw-off situations**.

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44

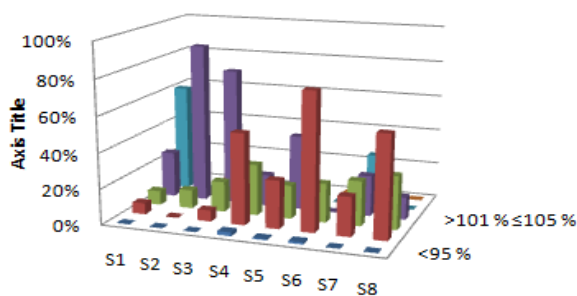
Overall common observations / recommendation based on the study of all the mills

- In harmonic rich environments – which is most prevalent nowadays – use of **detuned filter based power factor compensation** (7% for 189 Hz resonant frequency which take care the lower harmonics up to 5th Harmonic) **is highly recommended** .
- It is necessary to provide **detuning before even providing active harmonic filter** ;
- It is found that **most of the mill measurements show I_{THD} figures higher than 8 % for the maximum instants of measurements**. Even some of the industries , *without non-linear loads* , display the harmonics. It is also seen **that higher the value of simple capacitors connected, more the harmonic levels due to the resonance amplification** and vice-versa.
- It is felt that **the mills with the I_{THD} -s in the range of 8 to 12 / 15 % can bring down this to the acceptable levels with detuned filter based power factor compensation**
- The above can be tested and confirmed **by switching off the normal power factor capacitors** for a short duration – **few minutes** - and measuring the harmonic levels; **Harmonic amplification, if present, will be revealed by this test**. Some of the customers are unwilling to switch off the compensation capacitors for short duration (perhaps fearing the MD penalty) ; as the MD measurements is based on the average value over 15 minutes minimum, this fear is not valid.
- In most of the mills, the V_{THD} is well below 5%, in fact below 3% , **except three mills where the same is higher than 5 %** for significantly large period of time. **This require further study regarding the system impedance at the PCC**. Customer to collect the information from the supply company.

45

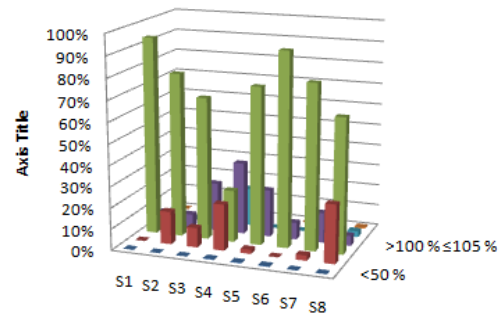
Analysis of the measurements for For the Spinning mills with MD greater than 1000 kVA

Voltage



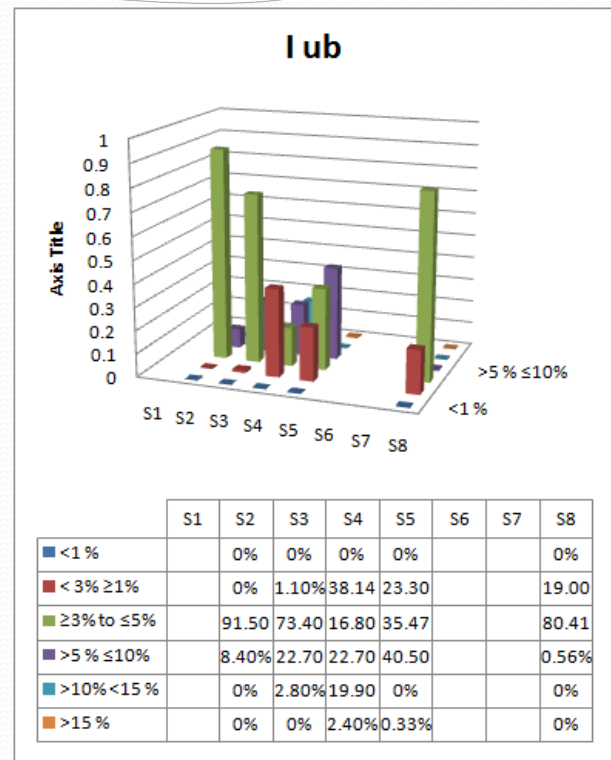
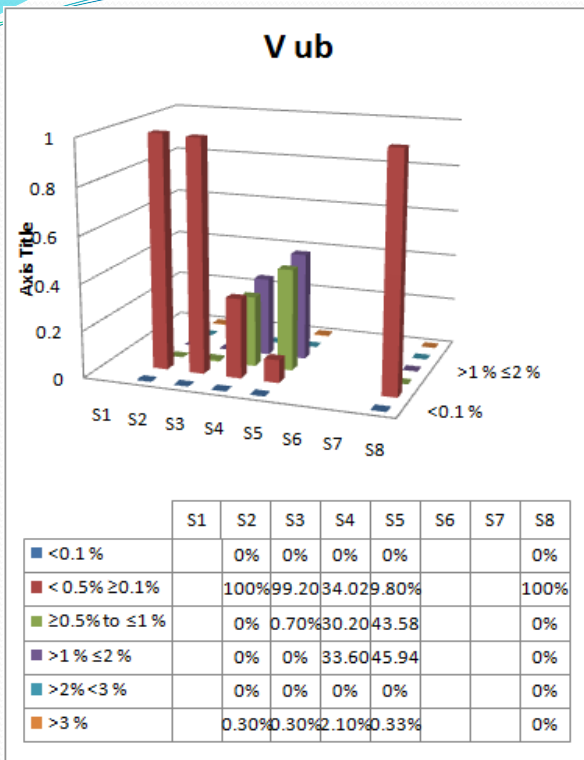
	S1	S2	S3	S4	S5	S6	S7	S8
■ <95 %	0%	0%	0%	2.10%	0.67%	1.20%	0%	0%
■ <99% ≥95 %	6.30%	0%	6.30%	5.12%	27%	76.85	22%	57.42
■ ≥99% to ≤101 %	8%	10.44	17.20	28.90	18.90	21.87	25.22	29.97
■ >101% ≤105 %	25.80	89.55	76.50	17.80	41.90	0%	22.90	12.60
■ >105% <110 %	60.60	0%	0%	0%	11.10	0%	29.70	0%
■ >110 %	0%	0%	0%	0%	0%	0%	0%	0%

Current



	S1	S2	S3	S4	S5	S6	S7	S8
■ <50 %	0%	0%	0%	0.30%	0.33%	0.33%	0%	0%
■ <80% ≥50%	0%	15.66	9.30%	22%	2.02%	0%	2.50%	27.73
■ ≥80% to ≤100 %	93.80	77.90	67.50	24.70	74.66	91.88	78.35	63.86
■ >100% ≤105 %	5.20%	5.40%	23.20	34.36	22.60	8.11%	14.31	4.76%
■ >105% <110 %	0%	0%	0%	18.20	0%	0%	3.57%	2.80%
■ >110 %	0%	0%	0%	0.30%	0%	0%	1.07%	0.56%

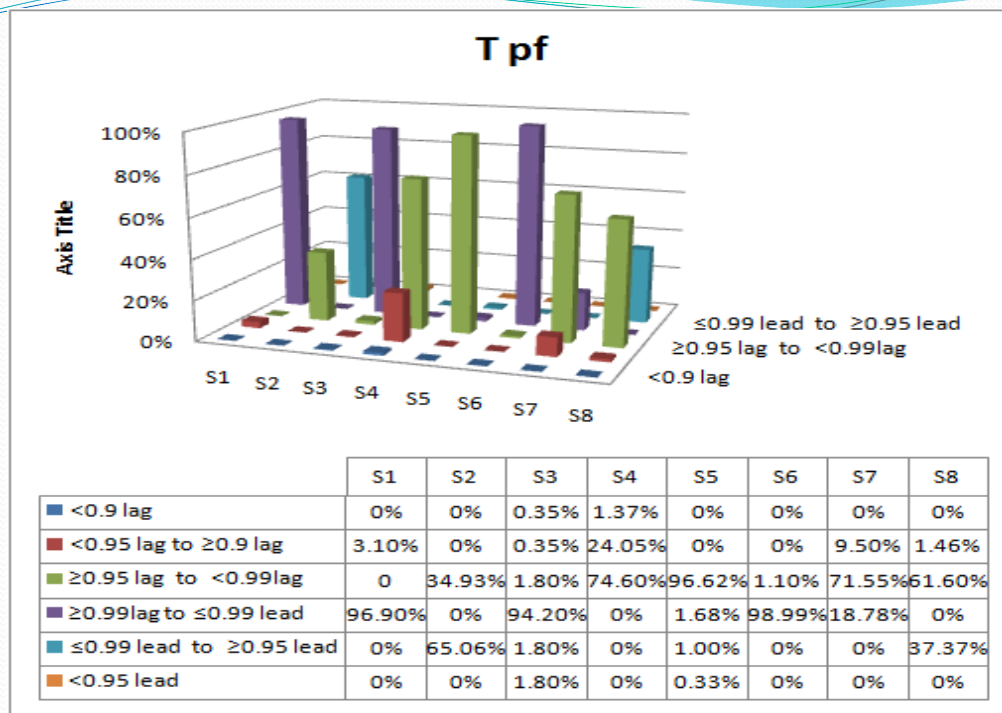
Analysis of the measurements for For the Spinning mills with MD greater than 1000 kVA



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47

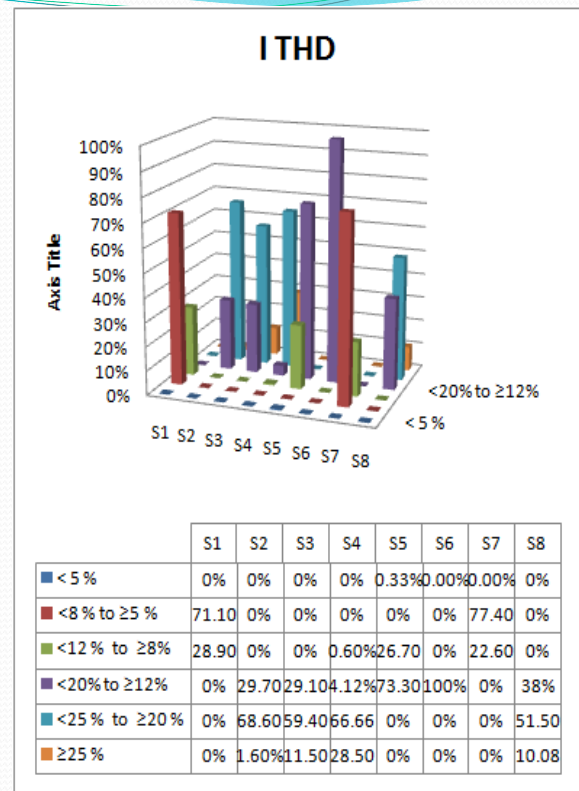
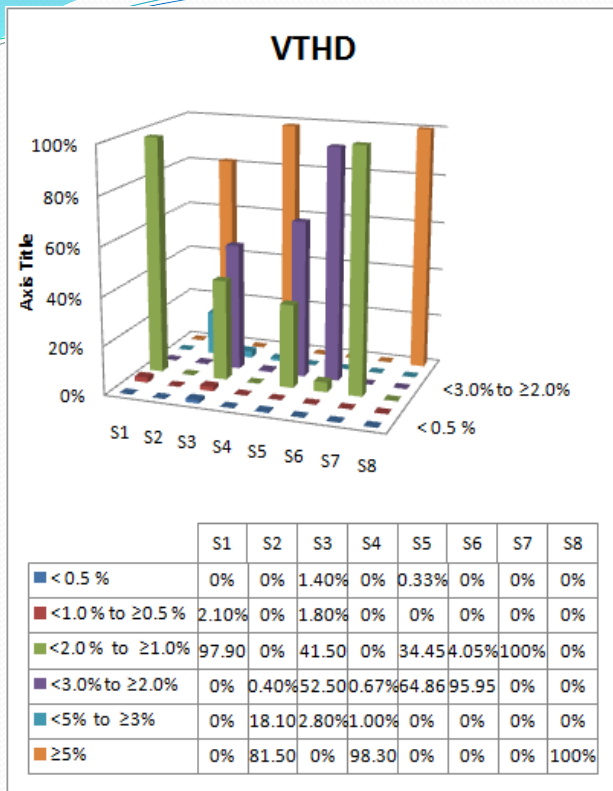
Analysis of the measurements for For the Spinning mills with MD greater than 1000 kVA



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48

Analysis of the measurements for For the Spinning mills with MD greater than 1000 kVA



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49

A summary - Harmonic Generation and Mitigation

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50

Harmonic standards

Table.2 Voltage Distortion Limits [13]

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Table.3 Current Distortion Limits for General Distribution Systems (120 V Through 69 000 V) [13]

Maximum Harmonic Current Distortion in Percent of IL Individual Harmonic Order (Odd Harmonics)						TDD
I_{SC}/I_L	$h < 11$	$11 = h < 17$	$17 = h < 23$	$23 = h < 35$	$35 = h$	
$< 20^*$	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

Even harmonics are limited to 25% of the odd harmonic limits above.

Current distortions that result in a dc offset, e.g. half-wave converters, are not allowed.

power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L .

Where

I_{SC} = maximum short-circuit current at PCC; I_L = maximum demand load current (fundament frequency component) at PCC; TDD = Total demand distortion, harmonic current distortion in % maximum; demand load current (15 or 30 min demand); PCC = Point of common coupling.

51

Harmonic generation and mitigation in the power system for textile Mills- A summary

1. **Odd harmonics** are generated during normal operation of 3- phase rectifier type nonlinear loads. **Even harmonics are absent** in waveforms which are symmetrical about X-axis.
2. **Zero sequence currents (3rd harmonics and their multiples)** of the three phases add up causing large neutral currents of the Y connected secondary). A delta wound primary winding of three phase transformer isolates the third harmonic currents from flowing into the input line;
3. 6-pulse rectifier transformers(diode front-end of the VFD) handle mainly 5th and 7th harmonic currents . The 5th and subsequently 11th harmonics **have negative phase sequence** and these currents cause counter or braking torques in the motor .
4. Harmonic amplitudes normally decrease as the frequency goes up. **If for a frequency, the amplitude is significantly larger than at lower frequencies, a resonant condition can be suspected.** It is seen that **resonance** occurs in the presence lower harmonic currents due to PFC capacitors and line reactance combination. **Detuning** hence is must in case of harmonic rich environments.
5. **The harmonic currents** are originally generated due to non-linear loads; **when they travel through the system impedance, harmonic voltage drops** develop resulting in **distorted grid voltage waveform** which in turn is fed to the other industries connected to this grid.
6. **Voltage distortion**, however, depends on the **system capacity** . **A large capacity power system has a small system impedance and vice-versa** and hence results into less voltage distortion as compared to **a low capacity, high impedance , lower SCR** value (explained later) power system.

Harmonic generation and mitigation in the power system for textile Mills- A summary

8. While the IEEE 519 gives the limits for the V_{THD} , **it is not there for I_{THD}** ; instead gives the limit for I_{TDD} only which is **the normalized version of the measured I_{THD}** ; the difference being, for I_{TDD} the ratio is **calculated for the maximum demand current** and not the load dependent instantaneous current, used by the instrument to calculate the I_{THD} value.
9. **This limit depends on the SCR (Short Circuit Ratio) of the system**. The SCR is a measure of the power capacity of the utility source in relation to the capacity of the customer.
10. **A plant required to limit the I_{TDD} to 8 % is entitled for a power system with the SCR value in the range of 20 to 50** as per the stipulation. This capacity confirmation is required in Indian context.
11. In case of transformers handling rich harmonic currents, (i) **install a K-factor rated transformer** or (ii) **de-rate a standard transformer**.
12. Harmonic current measurement of a typical textile industry transformer provides the following measurements of the individual odd harmonics measured up to 17th harmonic : **3rd – 5.29 %, 5th - 18.82%, 7th – 7.73 %, 11th- 1.06% ,13th – 1.41 %,17th– 0.35 %**. Using the formula $K\text{-factor} = \sum \frac{I_h^2}{I_1^2} \cdot h^2$ where $h = 1, 3, 5, 7, 11, 13, 17$ and $i_h = \frac{I_h}{I_1}$, **the K-factor is calculated as 2.158**.
13. Normally with **three phase transformer with generally balanced loads** (hence the 3rd harmonic is not significant) , **the K- factor will be less than 4**. It is also seen that for certain plants, apart from the 5th and 7th harmonics, 11th, 13th and 17th harmonics also prominently contribute to the k-factor.

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53

Thank you

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54