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Power quality issues in steel re-rolling mills in India

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The steel re-rolling industries are one of the major industries in the world. As they are growing with very fast rate with an increase in demand, their power quality problems are also increasing with the same rate. This paper presents these power quality impediments, its causes, effects and solutions. This paper encourages the organizations who deal with international standards to develop some standards for controlling these kinds of problems. Real time measurements and simulation modelling both have been presented in this paper, for the steel re-rolling industries and their results have been compared.

Keywords: *Steel Re-Rolling Mill (SRRM), Power Quality (PQ), harmonics, saturation, voltage sag, voltage swell, Total Harmonic Distortion (THD).*

1.0 INTRODUCTION

The growth in steel manufacturing in India since its independence has been a key factor to recognise its development. The modernisation and expansion of the new small/medium scale units of Steel Re-Rolling Mills (SRRMs) with cost effective and state of-the-art technologies are poised to come so as to beat the competition in this sector with international counterparts. The major concern is to improve the product quality and productivity. One of the key contributors on this front is the electricity and its quality. In our increasingly digital economy, maintaining the Power Quality (PQ) is a growing problem. Non-linear load distorts the voltage as well as current and therefore, they are responsible for harmonic pollution. But, sometimes due to non-linear behaviour of linear load also creates the harmonic environment of electrical distribution system is known as saturation mode of operation [1-2]. Owing to this type of behaviour of linear load also causes the both voltage and current to get distort, but largely the current. PQ issues are still largely underestimated, mainly because the losses are often hidden or not known. In more than one sense for many business/industrial users, the cost of poor PQ could be higher than their electricity bill. International organisations and associations develop a number of standards for providing the guidelines on better practice and controlling the ill aspects of system. IEEE standard 519-1992 is a well known and universally accepted standard for controlling the harmonics in electrical power systems [3].

In steel re-rolling industries, use of induction/electric arc/ballast/ladle arc furnaces, power electronic converters based drives, electronic equipments and electronic controls are the causes to shape PQ related problems. PQ analysis of iron and steel industry with electric arc/induction furnaces has been carried out previously by many researchers [4-9]. Detailed and nice presentation of PQ audit of Steel industries with electric arc furnaces in Turkey has been done in [4] with

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some new important terms and methods. Terms like cumulative probability function and methods like harmonic and inter-harmonic groups, harmonic and inter-harmonic subgroups and single line harmonic frequency. Study made on the both electric arc and induction furnaces in [6] and encouraged to specify the harmonic limits for induction and arc furnaces.

Rolling/pinching/squeezing the hot raw material between the rollers, is a main part of process flow of any SRRM, through three stages roughing, intermediate and finishing mills. Applying overvoltage to rolling motor/s results into motor saturation and generates the PQ impediments. This same problem with some solution has been presented in [10].

Major loads of any SRRM are heating furnace (can be induction, electric arc or coal furnace) and rolling motor/s (may be roughing, intermediate and/or finishing mill motors). But, there are number of research paper written on PQ audit of heating furnaces, therefore, second part (rolling mill) of SRRM has been chosen for PQ audit to get insight of main process of SRRM from electrical point of view. Hence, focus of this paper is on SRRM's rolling motor load only. The proposed study will also address various issues related with particular type of installations, consequences of poor PQ and mitigation techniques available. Modelling of saturated induction motor obtained in MATLAB is also presented in this paper.

Section 2 presents the general overview of system model of SRRM and describes the process flow of SRRM. It also provides the brief information about field measurements of PQ indices in SRRMs. Section 3 explains the problem statement of this paper and provides the methodology for the solution of that problem. Section 4 summarizes the detailed PQ analysis of collected data from field measurements and information got from SRRMs authorities. Impacts of poor PQ are shown and discussed in detail in Section 5. All the results of field measurements and simulation modelling are presented and compared in Section 6.

2.0 SYSTEM MODEL AND FIELD MEASUREMENT DESCRIPTION

PQ measurement of 15 SRRMs has been carried out in two cities of Central India; Nagpur from Maharashtra State and Raipur from Chhattisgarh State. Out of that, 10 steel industries are from Nagpur and 5 steel industries are of Raipur. Electrical distribution network of each and every SRRM is not possible to show in this small paper; hence, the generalised single line diagram of steel industry is shown in Figure 1. Rolling motor is getting supplied through a generator following a transformer of rating, 220 kV/11 kV and/or 11 kV/433 V or 33 kV/433 V. There is a flywheel connected on rolling motor shaft, before the mechanical load, to avoid voltage sag and mechanical acceleration or deceleration of rotor, in other words, mechanical damages. At the Point of Common Coupling (PCC), other industrial, commercial and residential customers are also connected. For reducing the complexity and sophisticated analysis, 15 SRRMs have been divided into three categories, with 5 industries under each group namely; Micro, Small and Medium SRRMs, depends upon industry configuration, size and plant capacity. Brief idea of this segregation is showcased in Table 1. Products of these steel industries are angles, rods, thin rods, wire rods, steel wires, TMT bars and channels.

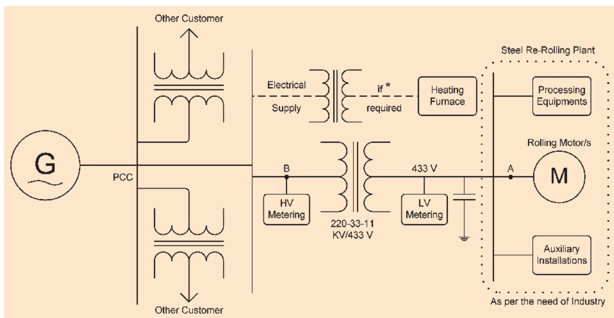


FIG. 1 GENERALISED POWER DISTRIBUTION NETWORK OF STEEL RE-ROLLING PLANT

*HEATING FURNACES USED IN RE-ROLLING MILLS ARE MOSTLY CONVENTIONAL FURNACES TAKING COAL AS A FUEL NOT THE ELECTRICITY. INDUCTION AND ARC FURNACES REQUIRE ELECTRICAL SUPPLY FOR HEATING PURPOSE.

TABLE 1			
CATEGORISATION OF SRRMS			
SRRM's Type	**Micro SRRMs**	**Small SRRMs**	**Medium SRRMs**
Incoming Voltage at PCC	11 kV	Mostly 33 kV and somewhere 11 kV	Mostly 33 kV and somewhere 11 kV or 220 kV
Transformer Configuration	Separate Transformer for each mill	Separate Transformer for each mill or same for both AC and DC drives	Separate Transformer for each mill or same for both AC and DC drives or Transformers operating in parallel supplying more than one mill

Equipment used for these field measurements is Megger make PA9 PLUS V604 portable power auality analyzer, which can measure and record the PQ parameters like voltage sag and swell, voltage and current imbalance, RMS voltage and current values, voltage and current total harmonic distortion (THD), demand data, etc. In steel industries, there are a number of terms, but two important terms are there which need to be defined for this paper; ingot or billet and rolling pass. The raw materials used in steel industries are called as ingots or billets which are manufactured from scrap and sponge iron. This ingot or billet, has any random shape like thick bars or rods, rectangular block, etc gets heated into furnace and then send to the re-rolling motors for further process. Main load of a SRRM is the roughing mill motor is used to roll an ingot or billet between the two moulding rollers to get a desired shape and thickness of steel by a number of passing steps. An instant when heated material comes to a rolling motor to an instant when it completes its number of rolling passes, to become as a finished product, is known as one rolling pass of a particular rolling mill. In general, time required to complete the one rolling pass is 0.5 minute to 2 minutes. Hence, for each and every industry of 15 SRRMs, 5 minutes to 20 minutes recording has been done so that at least 2 to 3 rolling passes can be captured for analysis. In some industries, field measurement has been done at point ‘A’ only and in some, PQ analyzer has been connected at both the points ‘A’ and ‘B’ as shown in Figure 1.

3.0 PROBLEM STATEMENT

SRRM sector is prone to poor PQ and could have serious problems if not addressed in proper way. Maintaining the PQ is a major concern to utilities and their customer alike. Problem statement of this paper is, also same as above mentioned concern, to find out PQ impediments already in & generated by SRRMs and to identify their effects on other equipments or installations used in the same industry and other customers at the PCC. In steel industries, use of induction furnaces, power electronics based drives and electronic controls are contributing to PQ related problems. Improper electrical system designs adopted in these industries are also contributing to PQ related problems. These problems are causing significant contribution in loss of production or quality of the product due to breakdown and down time besides the inefficient operation of the plant. Each and every issue related to this problem statement will be discussed in detail in later sections. This paper is developed with following objectives:

- Investigate the present PQ status in the SRRMs (SRRM) with the help of case studies.
- Identify the sources of the poor PQ areas and PQ issues plaguing the sector through PQ audit and analyse the collected data in view of its compliance with the standards available.

- Financial implication of poor PQ (Considering the loss of production/ maintenance/quality of the finished product).
- Prepare the educational material for these industries to create awareness about the effects of the poor PQ.
- Encourage the international standards developing associations to develop some standards, in view of these PQ problems.
- Encourage the state electricity board of all states in India to do the billing for the harmonic power also so that the PQ problems creating customers get bothered about poor PQ consequences.
- Scenario of available mitigation techniques and its impact.

4.0 POWER QUALITY ANALYSIS OF COLLECTED DATA

Saturable devices are designed to normally operate just below the "knee" point of the magnetizing saturation characteristic [1]. Characteristic is linear up to rated i.e. 100% voltage, but it becomes non-linear whenever voltage beyond the 100% is applied to saturable device because core of saturable device gets saturated. For small change in voltage, it shows large change in current due to the saturation of core material of saturable element and hence it draws harmonic current components from the source to meet the higher demand of saturated magnetizing current. If an operating point goes above the "knee" point of the magnetizing characteristic, then the element or device goes under the saturated operating condition. Hence, the magnetizing current will be composed of harmonic frequency currents, mainly 3rd harmonic component in Figure 2. Harmonics are generated due to the nonlinear magnetizing characteristics of the steel. Saturable element includes transformers, motors and other electromagnetic devices with a steel core.

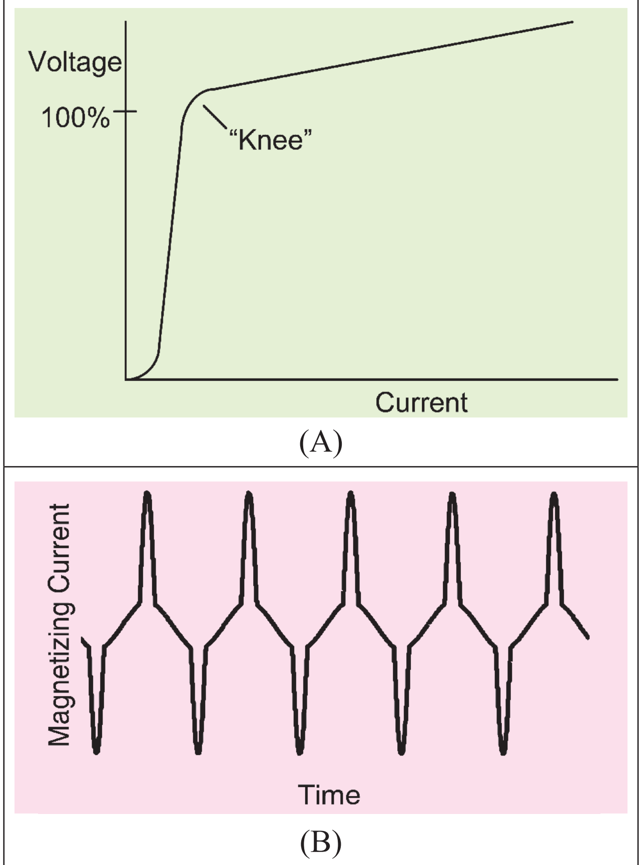


FIG. 2 (A) MAGNETIZING CHARACTERISTIC AND (B) MAGNETIZING CURRENT OF SATURABLE ELEMENT

Instantaneous values of voltage and current with harmonic components are shown in (1) and (2) respectively [11].

$$v(t) = \sum_{n=1}^{\infty} v_n(t) = \sum_{n=1}^{\infty} \sqrt{2}\ V_n \sin(n\omega_1 t + \theta_n) \quad ....(1)$$

$$i(t) = \sum_{n=1}^{\infty} i_n(t) = \sum_{n=1}^{\infty} \sqrt{2}\ I_n \sin(n\omega_1 t + \delta_n) \quad ....(2)$$

where; n is harmonic order, V_n and I_n are voltage and current values for harmonic order of n, w_1 is angular frequency of fundamental component and θ_n and δ_n are phase angles of voltage and current respectively.

TABLE 2

OVERVIEW OF TOTAL ANALYSIS

SRRM's Type	RMS		THD		Ia Harmonics	
	Va (V)	Variation (V)	Va %	Ia %	5th %	7th %
Micro	217-250	33	1-9	4-55	13-52	8-45
Small	235-264	29	1-6	3-54	8-50	5-27
Medium	234-249	15	1-16	1-70	2-30	2-11

The THD is a measure of the effective value of the harmonic components of a distorted waveform. That is, it is the potential heating value of the harmonics relative to the fundamental. This index can be calculated for either voltage or current [1]:

$$THD = \frac{\sqrt{\sum_{h>1}^{\infty} {M_h}^2}}{M_1} \quad ....(3)$$

where; M_h is the rms value of harmonic component h of the quantity M.

Major PQ problems found out after analyzing the collected data of PQ audit of 15 SRRMs are voltage sags, voltage swells and harmonics. While the rolling process as already discussed in section 2, voltage sags and swells occur during loading and unloading of rolling motor respectively. Next, the very big PQ problem is the harmonic distortion in the motor current is owing to the motor saturation, and it occurs because of over excitation of motor. Keeping the secondary side voltage of a distribution transformer at higher tapings than that of the required amount, is the general practice of medium scale SRRMs in India so that the voltage sag does not appear across the motor and the motor does not draw the heavy current when steel ingots or materials come in between the rollers for re-rolling with a number of passing steps. But, practically, this is not true because overexcited induction motor operates in the saturation region and in this region of operation, small increase in the motor supply voltage leads to high rise in the motor current. The basic reason of this saturation is the magnetizing inductance L_m of induction motor, decreases with an increase in the voltage across the motor. Hence, instead of decreasing the current by increasing the voltage, not only the motor current gets increased but also the harmonic components get included in the motor current due to the saturation mode of motor operation. During the site visits, it is also seen that the ratio of the time period of unloaded motor to loaded motor is 4:1. It means that the higher saturation condition exists for a more time period than the lower saturation condition because during unloading voltage dip does not appear across the motor and total voltage that is more than that of rated value is applied across the motor.

TABLE 3

VOLTAGE DISTORTION LIMITS [3]

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

Table 2 consists of overall variation ranges of voltages, currents and harmonics of all three categories (as already given in Table 1). Overall RMS Voltage variations for micro, small and medium SRRMs, seen during the analysis, are 217-250 V, 235-264 V and 234-249 V respectively. Even though power grid is strong & rigid, voltage variations occur in SRRMs in very much large amount. Hence, it is a major concern. The variation in the THD of the Current for Micro, Small and Medium SRRMs observed during the analysis are in between 4-55%, 3-54% and 1-70% respectively. IEEE standard 519-1992 gives the harmonic distortion limits for Voltage and Current as shown in Table 3 and 4 spectively [3]. For ratio of I_{sc}/I_L<20 and voltage 120V through 69000V, harmonic components of harmonic order less than 11 should have harmonic limit up to 4% of I_L and TDD limit up to 5% according to IEEE standard 519-1992 given in Table 4, but all the three categories of SRRMs are exceeding these harmonic limits.

TABLE 4

CURRENT DISTORTION LIMITS FOR GENERAL DISTRIBUTION SYSTEMS (120 V THROUGH 69 *000* V) [3]

MAXIMUM HARMONIC CURRENT DISTORTION IN PERCENT OF IL						
INDIVIDUAL HARMONIC ORDER (ODD HARMONICS)						
I_{SC}/I_L	**h<11**	**11≤h<17**	**17≤h<23**	**23≤h<35**	**35≤h**	**TDD**
<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.

*All 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.
IL = maximum demand load current (fundamental frequency component) at PCC.
TDD = Total demand distortion, harmonic current distortion in % of maximum demand load current (15 or 30 min demand).
PCC = Point of common coupling.

While analyzing each and every issue related to PQ problems, it has been got to know that electrical distribution configuration or system design of a steel plant also plays an important role in maintaining a good PQ. From Table 1, some Medium SRRMs have more than one transformer operating in parallel supplying more than one re-rolling mill. It is a better installation practice, instead of supplying each rolling mill through a separate transformer in a same plant (which is being done in micro type of SRRMs), because more than one transformer connected to single bus bar makes the bus bar rigid. Therefore, variation in voltage will be less during loading & unloading operation on rolling motors and hence, less number of voltage sag and swell events will be occurring. Total burden also does not come on any one transformer due to parallel operation of transformers. All above discussed advantages have been seen in one of the Medium SRRMs. If AC and DC drives both are connected to same AC bus bar or transformer (in some Small and Medium type of SRRMs), then there will be an ill effect of DC drives on AC drives performance because voltage waveform of AC bus will be distorted by a rectifier which is used for DC drives. So, here in this situation, voltage and current both will get distorted due to rectifier operation and motor saturation respectively. This effect has been clearly observed in one of the Small SRRMs.

There are several effects of harmonics, voltage sags and swells on power system, machines and devices such as saturation of saturable devices due to voltage swell, power factor improvement capacitor failure due to harmonic injection, electronic equipments damaging due to sags and swells, derating and thermal degradation of the motor due to the harmonic currents and many more. Impacts of motor saturation on torque-speed and current-speed curves have been investigated in [12-13]. Effects of PQ issues are discussed in detail in next section.

5.0 EFFECTS OF POOR POWER QUALITY

Despite the flywheel connected on motor shaft, PQ impediments are arising and in consequence their impacts. It means that connected flywheel is not fully capable for that specific requirement. This section presents the effects of poor PQ on transformer, motor, cable, power factor, K-factor, capacitor bank and neutral conductor. Out of 15 SRRM plants, results of Plant 1, Roughing Mill 2 from Medium SRRM group are shown for observing all these effects. And all these effects have been presented in the form of graph for one rolling pass of an industry. Some important terms are required to be understood before going for effects.

One method by which transformers may be rated for suitability to handle harmonic loads is by 'k' factor ratings. The 'k' factor is equal to the sum of the square of the harmonic frequency currents (expressed as a ratio of the total RMS current) multiplied by the square of the harmonic frequency numbers:

$$K = \sum_{h=1}^{n} {I_n}^2 \times h^2 \qquad \text{....(4)}$$

where; I_n is harmonic frequency current (ratio of the h^{th} harmonic current to total RMS current) and h is harmonic order or number.

This k-factor can also be called as a derating factor of a transformer which is used to supply non-linear loads.

Voltage Drop (VD) in a transformer increases with due regards to harmonic currents because in addition to fundamental voltage drop, harmonic voltage drop will also come into a picture as given in (5):

$$V_n = I_n \times |Z_n| = I_n \times |R + j.X_n| = I_n \times |R + j.n.X| \qquad \text{....(5)}$$

where; V_n is n^{th} harmonic voltage drop in a transformer, I_n is n^{th} harmonic current flowing through a transformer and X_n is n^{th} harmonic reactance of a transformer offered to n^{th} harmonic current I_n flowing through a transformer.

Voltage drop in a cable will also have same equation as that of transformer with addition to change in resistance also owing to skin effect which is more effective in a cable as compared to transformer because cable conductor has large cross-sectional diameter. Cable is more affected by skin effect than that of change in reactance at harmonic frequencies. Hence, voltage drop occurring in a cable only due to skin effect is presented in graph results. So, I^2R loss increases in a cable and transformer as an effect of harmonic current components and winding eddy current losses are also increased. Hence, it affects the cooling of a transformer and cable with increase in heating problem.

Power factor improving capacitor bank acts as a harmonic filter owing to harmonic current components included in the line current. Capacitor bank may come across the resonance condition occurring at resonant frequency and draw large value of resonant frequency harmonic component. It may damage the capacitor bank because it is only designed for 50 Hz frequency component. Expression for harmonic current drawn by the capacitor bank is:

$$I_{Cn} = \frac{V_{Cn}}{|X_{Cn}|} = \frac{n.V_{Cn}}{|X_C|} \qquad \text{....(6)}$$

where; I_{Cn} is n^{th} harmonic current drawn by a capacitor, V_{Cn} is n^{th} harmonic voltage across a capacitor and X_C is a capacitive reactance of a capacitor.

During harmonic distortion condition, Power Factor (PF) also doesn't leave by harmonics; it also gets reduced to some extent. Therefore, there was a generation of three new terms related to PF as an effect of harmonics; Displacement Power Factor (DPF), Distortion Power Factor (DiPF) and True Power Factor (TPF) are defined as:

$$\text{Cos}\,\emptyset = DPF$$
$$= Fundamental\ PF\ (without\ harmonics)$$

$$DiPF = \frac{1}{\sqrt{1 + {I_{THD}}^2}} = \frac{I_{1RMS}}{I_{TRMS}}$$

$$TPF = DPF.DiPF$$
$$= \cos\emptyset \, . \frac{1}{\sqrt{1 + {I_{THD}}^2}} \quad ....(7)$$

where; I_{THD} is current THD value, I_{1RMS} is fundamental RMS current and I_{TRMS} is total RMS current including harmonic components.

Unbalance in voltages is caused by neutral shift or unbalanced loads and as an effect of unbalance, current flows through a neutral bus. Secondly, harmonic distortion increases the burden on neutral conductor because of zero sequence harmonic components. So, here also unnecessarily I^2R loss increases and thereby, increases the heating of a neutral conductor.

Winding of the motor deteriorates due to drawing of continuous harmonic currents which is more than required and therefore, lifespan of motor decreases. Owing to derating of motor, full-load capacity of motor can't be used. Harmonic current increases I^2R losses and heat dissipation in the motor. The major harmonic components, found in a motor line current after analysis, are 5^{th} and 7^{th} harmonics. As a result of 5^{th} and 7^{th} harmonics, the net magnetic field revolves at a relative speed of six times the speed of the rotor [2]. This induces currents in the rotor bars at a frequency of six times the fundamental frequency and in consequence, severe damage (excessive vibration and noise) to the motor can result.

All the above discussed effects are presented in the form of graph results. All results are displayed for the measurement done on 433 V side at point 'A' shown in the respective Figures. 5^{th} and 7^{th} harmonic component curves are only presented in the following results as they are the major harmonic components as far as the SRRMs are concerned. Skin effect has been shown by considering a Copper (Cu) and Aluminium (Al) cable of same cross-sectional area of 400 mm^2 with the highest current rating of 435 A and 375 A respectively. Capacitor banks are assumed for improving the PF from 0.8 to unity and accordingly results are shown. On y-axis, in each graph, event number is the number automatically given to an event/s, captured during the data collection process, by Megger PQ analyzer. Bunch of events shown on y-axis in each graph makes a rolling pass of a particular steel industry.

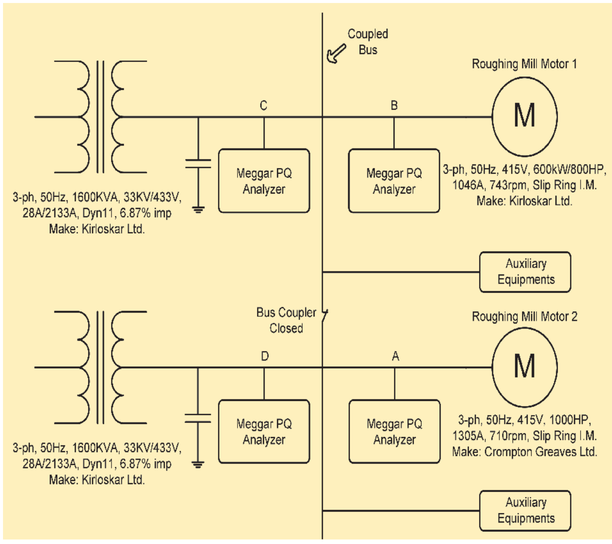
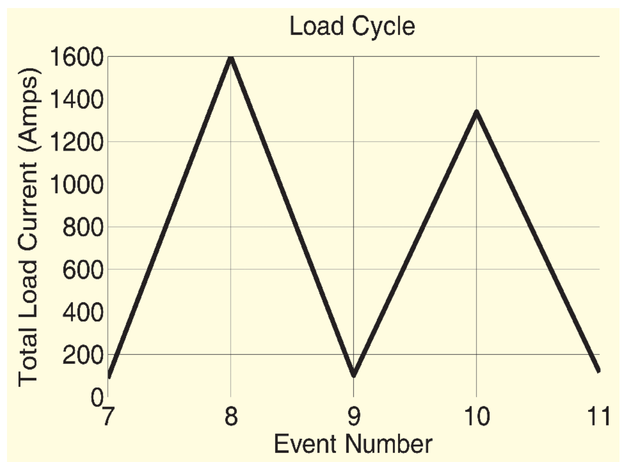


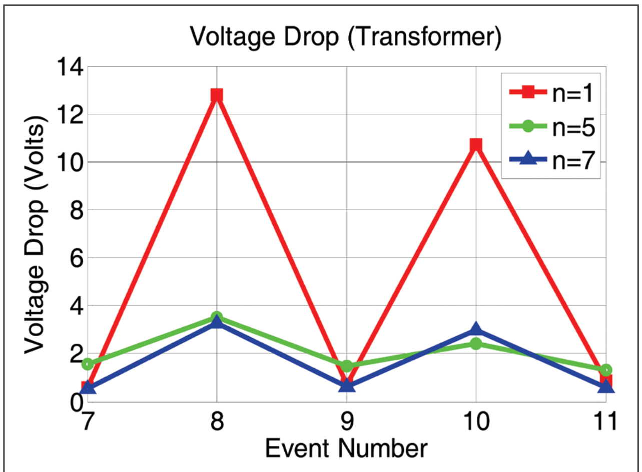
FIG. 3 ELECTRICAL POWER DISTRIBUTION NETWORK OF PLANT

Electrical network configuration of Plant 1 is presented in Figure 3 and Figure 4 shows the effects of poor PQ for roughing mill 2 of plant 1, of medium SRRM category. VD in transformer, Cu and Al cable follows the load cycle curve of a rolling pass. 5^{th} and 7^{th} harmonics VD values are countable and 5^{th} is maximum out of two. VD in Al cable is more than that of Cu cable as because of its characteristics. Interesting curve i.e. k-factor curve is the reverse of load cycle curve as the THD decreases with increase in load current. From figures, it can be seen that 5^{th} and 7^{th} harmonic capacitor currents are around 50 to 200 A which may damage the capacitor bank permanently.

In this modern era, there are many several technologies available for the solution of these PQ problems. Even though this paper is majorly focused on PQ audit, some generalised solutions can be suggested as: voltage sag and swell can be eliminated by FACTS devices such as DVR, STATCOM, SVC, SSSC, etc. But, FACTS devices are very costly, so most of the industries do not opt for this solution.In addition to these FACTS devices, Static Electronic Tap Changer (SETC) and Step Dynamic Voltage Regulator (S-DVR) are the cost effective solutions available for the mitigation of voltage sags and swells. Flywheel energy storage system is also a newly advanced technology available for voltage sag correction [14] in electrical power system. For harmonic reduction, active, passive or hybrid filter can be used.



(A)



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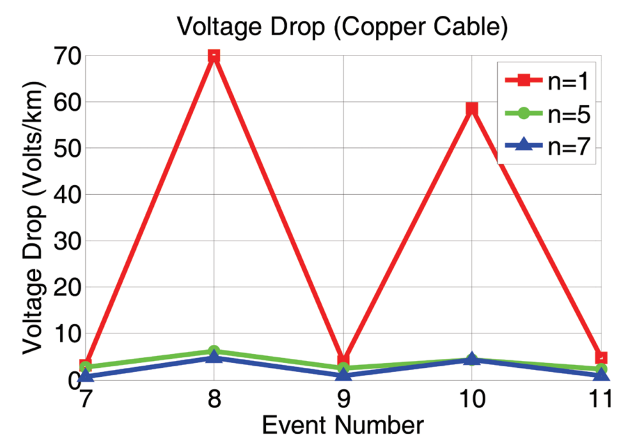

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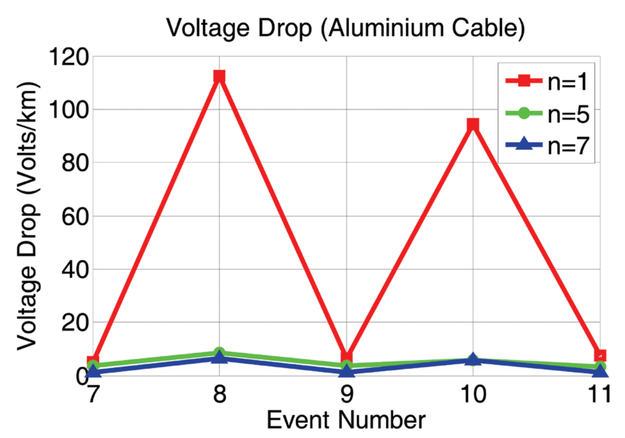

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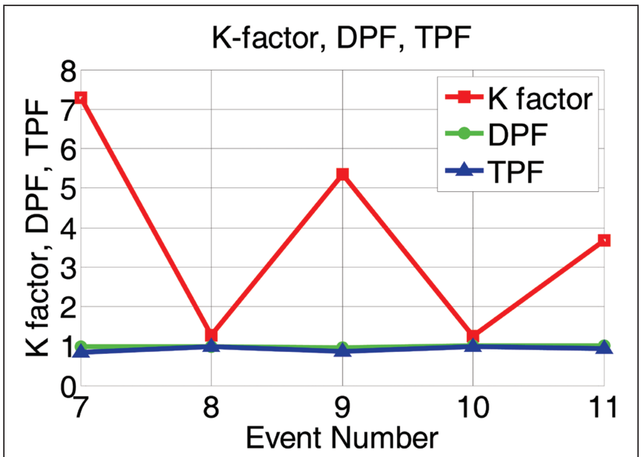
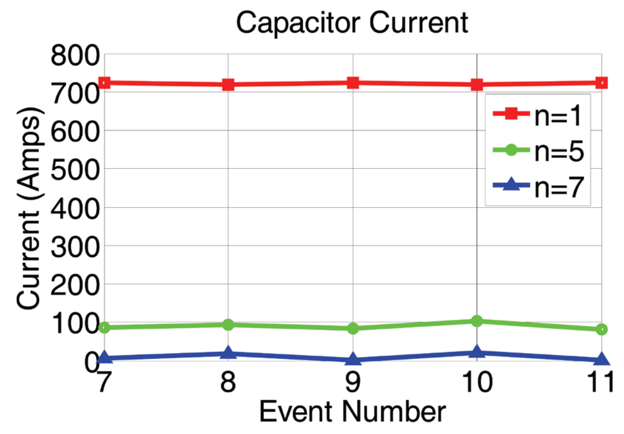


(E)

FIG. 4 (A) LOAD CYCLE (B) VOLTAGE DROP T/F (C) VOLTAGE DROP FOR COPPER CABLE (D) VOLTAGE DROP FOR ALUMINIUM CABLE (E) K-FACTOR, DPF, TPF (F) CAPACITOR CURRENT

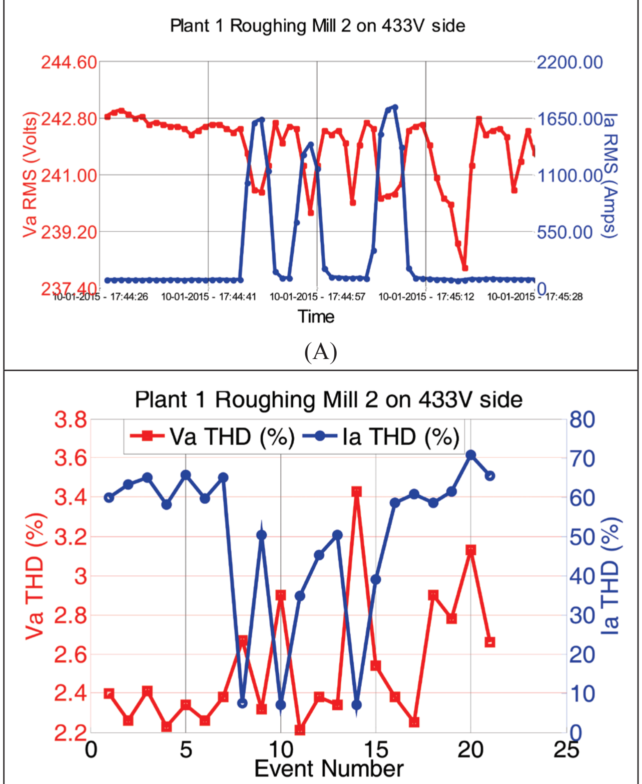


(F)

6.0 FIELD MEASUREMENT AND SIMULATION RESULTS

RMS voltage and current variations with variations in voltage and current THD during field measurements are shown in Figure 5. From figure it can be concluded that load on the motor changes suddenly and therefore, voltage sag appears across the motor during loading condition. Here, line current THD is going up to 70% and it is very high percentage according to IEEE 519 standard. The major focus of this PQ audit is on the main load of SRRMs that is the roughing mill drives. Induction machine modelling with saturation has been discussed in [15-16]. In [15], very good saturated induction motor modelling in phase quantities has been achieved with all supporting equations. Induction motor modelling with saturation impact is developed for roughing mill motor 1 and 2 both of plant 1. Modelling diagram and its parameters are same as given in Figure 3. Actual and simulation current waveform of roughing mill 2 and 1 under no-load condition are presented in Figure 6 and 7 respectively. Line current THD of field and simulation waveforms of mill 2 are 29.93% and 29.86% respectively. Line current THD value for measured & simulation results of mill 1 are 18.38% & 16.13% respectively.

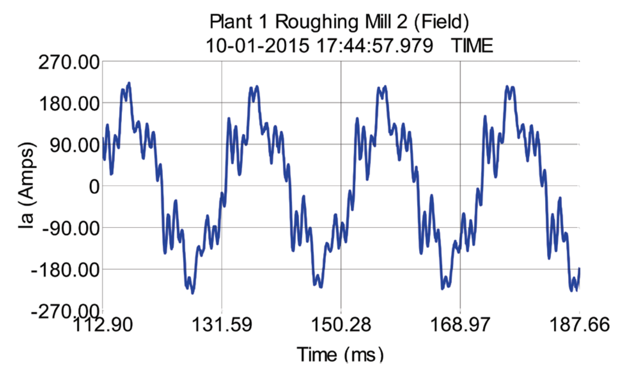
It has been found that modelling results and measured results of both rolling mill 1 and 2 of Plant 1 are, nearly exact and accurate. Some more results of rolling mill 1 model with higher voltages are shown in Figure 8 and 9 to show the effects of saturation on motor characteristics. Figure 8 presents the saturation effects on current waveforms, and to show that, the transformer secondary side line voltage has been varied from 100% of rated stator voltage to 115% of rated stator voltage in the steps of 5%. With an increase in voltage across the motor, a saturation effect on motor current also increases and hence, harmonic distortion of motor current also gets increased. Figure 9 shows the variation of current THD with an increase in voltage across the motor from 100% to 115% of rated stator voltage.



(A)

(B)

FIG. 5 (A) RMS VOLTAGE AND CURRENT VARIATIONS (B) VOLTAGE AND CURRENT THD VARIATIONS OF PLANT 1, ROUGHING MILL 2



(A)

(B)

FIG. 6 (A) ACTUAL AND (B) SIMULATION STATOR LINE CURRENT OF A DELTA CONNECTED ROUGHING MILL 2 INDUCTION MOTOR AT 433 V LINE VOLTAGE UNDER NO-LOAD

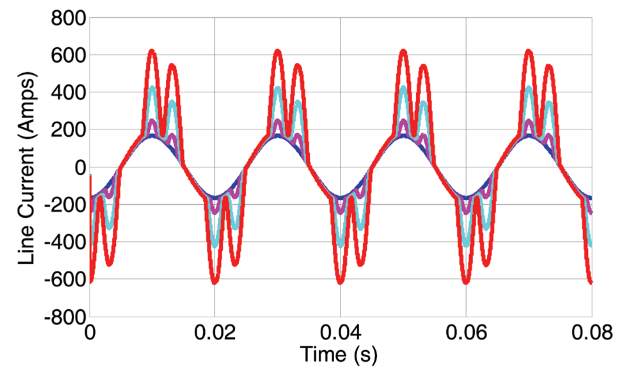
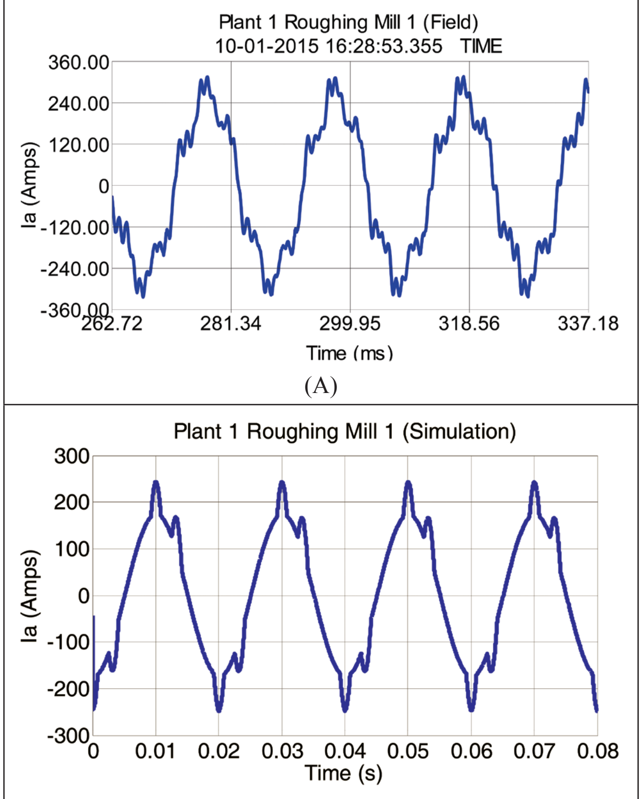


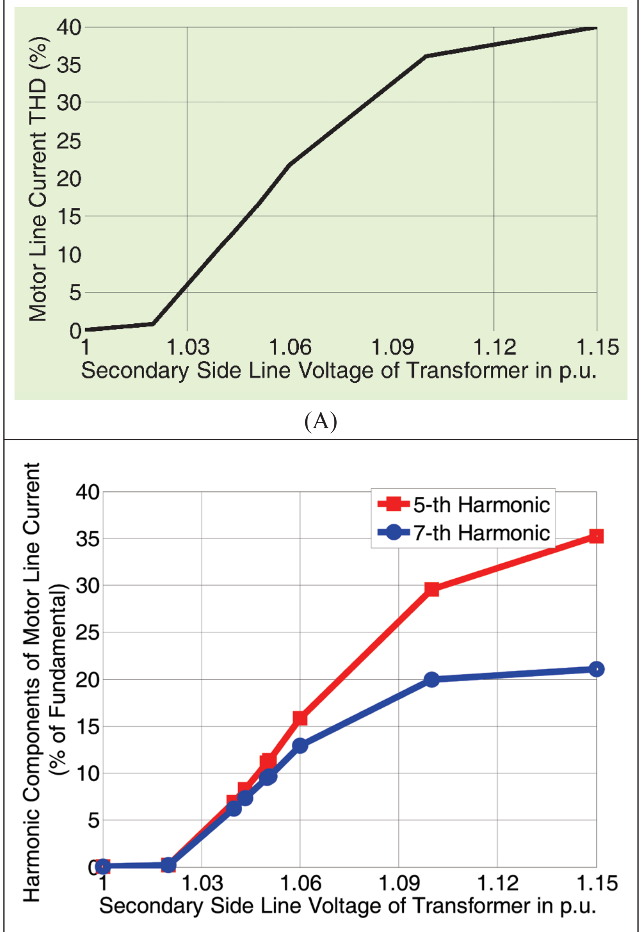
FIG. 8 STATOR LINE CURRENTS OF A DELTA CONNECTED INDUCTION MOTOR FOR 100%, 105%, 110% AND 115% OF RATED STATOR VOLTAGE (415 V)



(A)

(B)

FIG.7 (A) ACTUAL AND (B) SIMULATION STATOR LINE CURRENT OF A DELTA CONNECTED ROUGHING MILL 1 INDUCTION MOTOR AT 433 V LINE VOLTAGE UNDER NO-LOAD



(A)

(B)

FIG. 9 VARIATIONS OF (A) THD AND (B) 5^{TH} AND 7^{TH} HARMONIC COMPONENTS OF STATOR LINE CURRENT WITH VARIATIONS IN STATOR LINE VOLTAGE FROM 1 P.U. TO 1.15 P.U.

7.0 CONCLUSIONS

PQ audit of SRRMs in central India has been performed and PQ problems, their impacts and solutions are investigated. Modelling and simulation of saturation of rolling motor have been done and field and simulation results are shown and compared. The following conclusions can be drawn from the PQ Audit and presented field & simulation results:

1. RMS and THD variations of voltage and current have been observed for all three types of SRRMs and it has been found that the graphs are crossing the all harmonic limits as per IEEE 519 standard.
2. PQ Study has investigated that saturation of induction motor is responsible for polluting the electrical environment with harmonics.
3. For the transformer derating, k-factor is defined, but for the motor derating, due to the problems previously discussed in section 5, k-factor is not defined, therefore, it should also be taken care.
4. There is no any limit specified, in any standard, for an individual harmonic component and THD of the current of any equipment or machine when it goes under the saturation mode of operation. Hence, the harmonic limits should be developed, with concerned to saturation condition.
5. Major cause of voltage distortion is the non-linear loads. To solve this problem, it is suggested to connect AC and DC drives on separate transformers.
6. Voltage sag is mostly caused by a sudden increase in load current. Hence, to reduce voltage sag up to large extent, operate transformers in parallel for better performance.
7. Many mitigation techniques like filter, FACTS devices, etc are available for harmonic elimination. Cost effective technique like fly wheel connected on motor shaft with transformer at nominal taping can be a solution to minimize the voltage sag and swell and hence, in effect reduces the overvoltage, saturation and harmonics provided that properly designed or correct type and size of flywheel is used for particular type and requirement of SRRM.

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