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Industrial Electric Power Supply Reliability, Power Quality Problems and Mitigation Techniques

Wondwossen A. Haile, Chandrasekar Perumal

***Abstract*: This paper is concerned about power supply reliability and quality analysis work done at Zuqualla steel rolling Mill Enterprise. The factory is found in Debre Zeit town 45km east direction from the Ethiopian capital Addis Ababa. The analysis focused mainly on the evaluation of power supply reliability and power quality in the factory premises and at the distribution substation and thereby proposing recommendations to the supply authority and factory for better improvement. The methodologies followed for the investigation and analysis are direct measurement at the substation supply transformers and by using data gathered from the substation and factory loads.**

This particular analysis work indicated that the fifth and seventh spectral harmonic components have a major effect in the supply system of the factory with 25% and 20% harmonic distortion level respectively. The factory has been working with poor power factor of 0.75 which is below the minimum threshold standard of 0.85 which is set by the Ethiopian Electric Utility (EEU). Finally, MATLAB/SIMULINK model of shunt harmonic filters were designed. By this, the fifth and seventh harmonic components are reduced to less than 5% and average power factor upgraded to 0.93.

Keywords: adjustable speed drives, harmonic distortion, supply interruptions, Voltage dips, supply reliability.

I. INTRODUCTION

The Ethiopian power grid and the generation capacity are expanded quickly in the last years and will continue to grow in the years to come. As it is widely known, the weaker the power grid, the more worse the power quality will be. The relative low amounts of generation plus a weak grid will create a power grid with poor power quality. Unreliable and poor quality Power in and around the industry of Addis Ababa has occurred, where the IEEE standard 1159-1995 was violated. These violations were found in voltage variations, frequency fluctuations, voltage unbalances, supply interruptions and high THD currents. Among the different power quality problem issues occurred in the Ethiopian power supply system, voltage variations and supply interruptions are the worst and most severe problems for the industry [1].

Studies done on the Ethiopian power supply reliability indicated that power interruption frequency and duration are higher than international standards. Compared to other parts of the country, both the frequency and duration of supply power interruption are very high in and around Addis Ababa. More operational Interruptions due to high relocation works and higher growth of power demands in and around Addis Ababa city leads to system overloading and frequent supply interruption[2].

In the present era industrial machines control operation, Adjustable speed drives (ASDs) have played an important role in controlling industrial motors. Besides this fact, Adjustable speed drives are very sensitive to voltage dips which are one type of power quality problem issues in industrial premises. The other load types which are sensitive to voltage dips in industrial complex are Lighting loads. The conventional fluorescent lighting has one of the worst responses facing voltage dips, tripping the lamps when the supply voltage drops only 26% from its nominal value. Metal halide lamps, commonly used for lighting huge industrial areas, show a very similar response for voltage dips. On the other hand, lamps including electronic ballast depict a less critical sensitivity curve; maintain working conditions until the supply voltage significantly drops to 22% of nominal value for fluorescent lamp and 16–84% depth for induction lamp. Generally, the effect of voltage dips is causing unwanted losses both in time and money so that it should be avoided from the industrial supply system [3].

Shunt Hybrid Power Filter and Thyristor-Controlled Reactor are used to achieve harmonic elimination and reactive power compensation. The shunt active filter and shunt power filter have a complementary function to improve the performance of filtering and to reduce the power rating requirements of an active filter. The shunt hybrid power filter-thyristor-controlled reactor compensator can effectively eliminate current harmonic and give reactive power compensation during steady and transient operating conditions for a variety of loads. It reduces the THD of supply currents well below the limit of 5% of theIEEE-519 standard [4, 5]. Isolated and independent hybrid Power supply system can deliver reliable and cost effective electric power to industrial loads and/or rural communities.

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* Correspondence Author
Wondwossen Astatike Haile*, Electrical and Electronics Engineering department, Vel tech Rangarajan Dr. Sagunthala R&D Institute of Science And Technology, Chennai, India.
Perumal Chandrasekar, Electrical and Electronics Engineering department, Vel tech Rangarajan Dr. Sagunthala R&D Institute of Science And Technology, Chennai, India.

It can be used as a backup power supply source especially when long duration grid power interruption occurred.

The hybrid system can be designed by combining diesel generator with wind turbine generators, solar PV panels or both as components of supply system. Such systems will have better operational performance characteristics than using of standby generator alone as standalone backup source during grid supply interruption both in terms of supply reliability and cost [6].

Non-Linear loads are the main sources of Harmonics in an electric supply system especially in industries. Non-Linear loads draw non-sinusoidal current from a sinusoidal voltage source. Some examples of Non-linear loads are AC or DC motor drives, electric arc furnaces, static VAR compensators, inverters, and switch-mode power supplies, lighting ballasts, and industrial electronic gear. Industrial customers are increasingly using drives for more precise motor control and to improve energy efficiency. Hence, the potential for higher harmonic distortion rises [7].

II. RESEARCH METHODS

The methodology followed in this power supply reliability and quality investigation looks like the following as in the block diagram in figure 1.

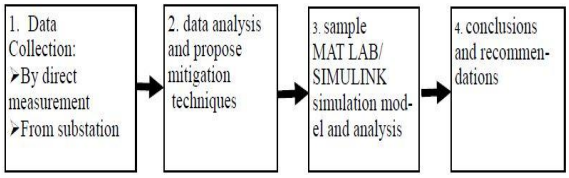


Fig.1.Flow diagram for Research Methodology.

III. DATA COLLECTION, ANALYSIS OF POWER SUPPLY RELIABILITY & QUALITY ISSUES AND PROPOSED MITIGATION TECHNIQUES

The schematic diagram of Zuqualla steel rolling mill is shown in figure 2. It has two transformers each for different section of loads.

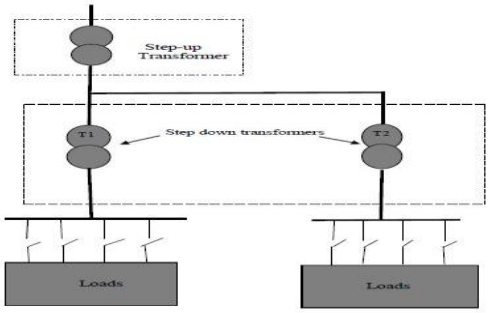


Fig.2. One Line Diagram representation of power distribution system of Zuqualla Steel Rolling Mill

Data have been collected from the secondary windings of the transformers with respective ratings of 1600KVA, 15/0.38KV, and 6% impedance.

The factory has two sections:

1. Old production line with an electrical load capacity of 106.709kVA and power factor of 0.754.
2. New production line with an electrical load capacity of 67.673 kVA and power factor of 0.868.

The transformers supplying the two sections of the factory are:

- Transformer supplying old production line (Transformer 1)
- Transformer supplying new production line (Transformer 2)

3.1 **data collection and analysis**

A. **Sustained Interruption Data Analysis**

The distribution substation has five feeders of 15kV customer side voltage rating. This voltage is stepped down to 380V by factory premise transformers. Zuqualla Steel Rolling Mill is supplied directly from 15kV line so that it is better to study the electric power interruption of the feeder from the substation side.

From the monthly average interruption data gathered from the substation, the reliability indices are computed and tabulated as in table 1.

Table 1.Reliability indices of 15 kV feeders at Debre Zeit substation.

No	Feeders	Monthly Average No.of Interruptions	Monthly Average Interruption Duration (Hr)	SAIFI	SAIDI (Hr)	CAIDI (Hr)	ASAI
1	L1	20.75	21.95	20.75	21.95	1.05	0.96951
2	L2	18.75	18.25	18.75	18.25	0.97	0.97465
3	L3	16.25	19.5	16.25	19.5	1.2	0.97291
4	L4	23.75	20.03	23.75	20.03	0.84	0.97218
5	L5	4.25	8.48	4.25	8.48	1.99	0.98822

Table 2. Design target values of reliability indices on per-annum basis

Design Target values	
Indicator	Values
SAIFI	2
SAIDI	2-2.5Hr
CAIDI	2-2.5Hr
ASAI	0.99983

The following conclusion can be done by observing the computed reliability indices of table 1 with the design target value of table 2:

1. The system-average interruption frequency (SAIFI) of the feeders is extremely high as compared to the design target value.

The target value is 2-interruption per-annum, while the monthly-average interruption frequency of the substation feeders reaches 23.75. This will become 285 per annum. The minimum SAIFI is 4.25 which occurred on feeder *L*5. This shows that even the minimum interruption frequency is much higher than the typical interruption frequency of the design target value. Therefore, the feeders are frequently interrupting.

2. Availability of all the feeders as observed from the ASAI values is below the typical target value of 0.99983. This indicates that the feeder lines get interrupted for a long duration of time.

3. The feeders have large CAIDI value. The minimum CAIDI value is 0.84 hour per month. On per annum basis, it becomes 10.08 hour which is very high compared to the design target value which is 2-2.5Hr. This means that the feeders require much higher time to restore service.

4. The computed values of the system average interruption duration indices (SAIDI) showed that there is long duration of interruption compared to the design target value. The minimum monthly average interruption duration is 8.48 hours. This becomes 101.76 hours of average interruption duration per annum. It shows that electric power is interrupted for a long period of time.

B. **Voltage variation data Analysis**

Figures 3 and 4 below show RMS voltage variation of transformers supplying the old production line and new production line loads respectively. The measurement data was taken during working hours of the factory by using Power Quality Analyzer. The graphs show the long duration voltage variations at specific time interval.

Figure 3 shows RMS voltage variation graph taken from transformer supplying old production line loads. It shows single phase voltage variation along with the RMS current of the system. As it can be seen from the figure, voltage variation is not significant during load variation; rather it comes from fault on the source side.

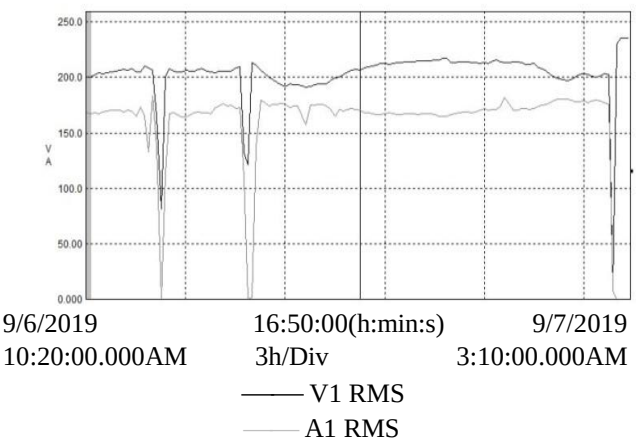


Fig. 3. Voltage variations measured from transformer supplying old production line loads

Figure 4 shows RMS voltage variations graph taken from transformer supplying new production line loads. Figure 4a shows RMS three phase voltage variations while figure 4b shows single phase voltage variations along with the RMS current of the system. From figure 4b, it is clear that voltage variations are not significant during load variations; rather it come from source side faults.

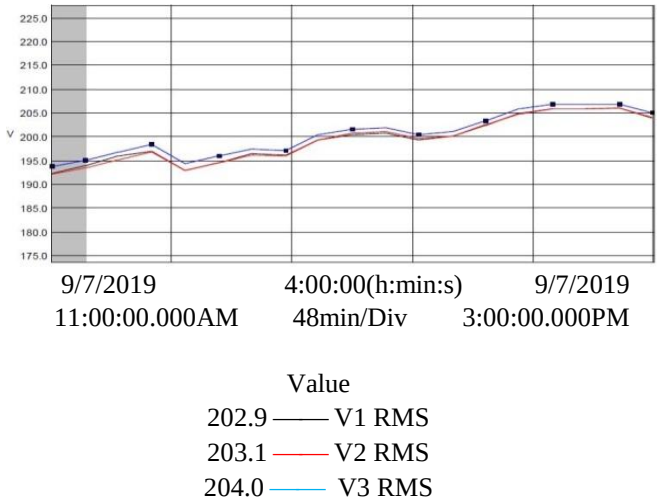


Fig.4a. three phase voltage variations from transformer supplying new production line loads

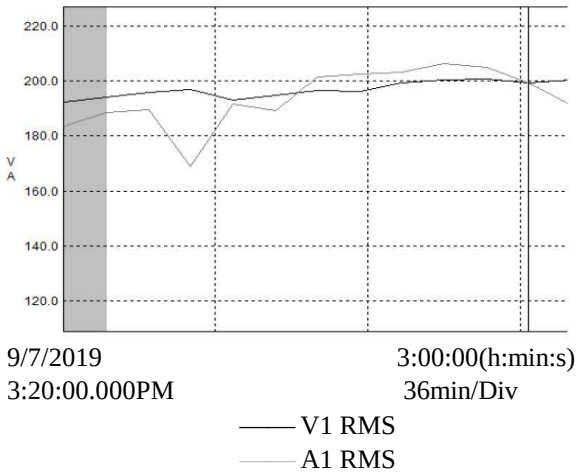


Fig. 4b. Single phase voltage and current variations from transformer supplying new production line loads

Fig. 4. Voltage variations measured from transformer supplying new production line loads

The RMS voltage variations graphs in figures 3 and 4 show that under voltage observed at Different intervals not due to the load of the factory. The reason is that the problem of under voltage observed even when the factory is working under partially loaded condition. The main cause of voltage variation is faults on distribution feeders and poor voltage regulation at the substation.

C. **Waveform distortion data Analysis**

Standard IEEE 519-1992 was developed to evaluate harmonic voltages and currents at a point of common Coupling (PCC) between the end user and the utility supply system.

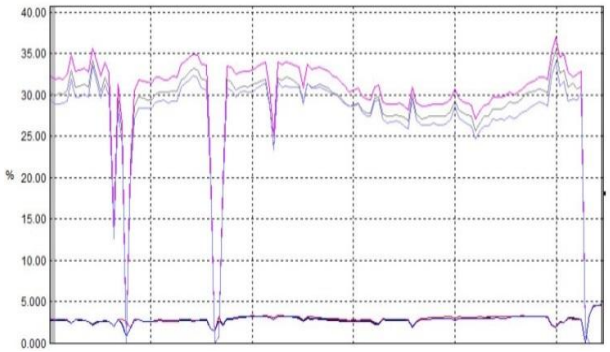
Table3. Harmonic current limits for individual end users from IEEE standard 519-1992.

V≤69kv						
Ish/IL	h<11	11<h<17	17<h<23	23<h<35	h>35	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

Table 4. Harmonic voltage limits, IEEE standard 519-1992

Utility bus voltage	Maximum individual Harmonic component (%)	Maximum THD (%)
<69kv	3.0	5.0
69kv to 137.9kv	1.5	2.5
138 and above	1	1.5

Figure 5 below shows the variation of voltage and current total harmonic distortion (THD) per phase measured from transformer 1 supplying old production line at full load. The vertical axis shows percentage of total harmonic distortion on the fundamental component and the horizontal axis shows time duration of measurement. The upper graphs show THD for current and the lower shows THD for voltage. The value indicated under the graph is the value at that particular time.



9/6/2019 16:50:00 (h:min:s) 9/7/2019
10:20:00.000AM 3h/Div 3:10:00.000AM
Measured value on 9/7/2019—1:20:00.000AM:
1.800 —— U1 THD 34.30 —— A1 THD
1.800 —— U2 THD 35.90 —— A2 THD
1.800 —— U3 THD 32.90 —— A3 THD

Fig. 5. THDI and THDv from transformer 1 supplying old production line at full load

The data has been gathered for about seventeen hours during working hours of the factory. The horizontal division shows three hour per column as it can be seen from the graph. The graph trend shows harmonic distortion level during different loading condition and different voltage variation. The distortion becomes zero at some points on the graph which shows system was turned off due to under voltage condition. This can be clearly understood by comparing the distortion trend to the voltage variation trend shown in figure 3 above. The main source of the current harmonic distortion in the factory is Adjustable Speed Drive (ASD).

Table5. Voltage data collected from transformer 1 supplying old production line loads at full load

No of measurement	Freq Hz	V RMS	V2 RMS	V3 RMS	V1 THD %	V2 THD %	V3 THD %	V Unbal %
1	50	201	201	201	2.4	2.5	2.5	0.2
2	50.1	203	203	202	2.6	2.8	3	0.3
3	50	204	204	202	2.5	2.7	2.5	0.3
4	50	206	205	201	2.6	3	3	0.2
5	50.1	200	199	195	2.6	2.4	3	0.2
6	50.1	206	199	204	2.4	2.6	2.5	0.2
Average	**50.05**	**203**	**202**	**202**	**2.5**	**2.7**	**2.8**	**0.23**

Table 5 shows the voltage distortion level and RMS value of each phase taken from the transformer 1 of the feeder of old production line. The measurement was done on individual phases. The average full load measurement shows that the THDv is 2.5%, 2.7% and2.8% for the respective phases. As per IEEE standard the voltage distortion should be below 3% for individual harmonic components and below 5% for total harmonic distortion. Hence, the values in table 5 shows there is no sign of significant voltage distortion.

The voltage unbalance limit at the terminal of the motors in the industry should be below 1% as per IEEE standard. The unbalance greater than 1% makes motor operation difficult and the motors are over heated and forced to function below their rated power. The measurement taken at the terminal of the motors indicates that the voltage unbalance is not beyond the IEEE standard. The average measured supply frequency is 50.05 Hz which is in the range of acceptable limit.

Table 6. The average RMS current, THDI, current unbalance taken from the transformer 1 supplying old production line loads at full load

No of measurement	*A1*	*A2*	*A3*	*A1 THD %*	*A2 THD %*	*A3 THD %*	*A Unbalance %*
1	*170*	*171*	*169.5*	*32.5*	*34.5*	*31.5*	*0.9*
2	*171*	*172.5*	*170*	*33*	*31.5*	*30.5*	*0.7*
3	*169.5*	*170*	*166.5*	*31.5*	*31*	*30*	*0.6*
4	*167*	*170.5*	*166*	*31*	*33.5*	*30.5*	*0.9*

5	170	173	168.5	30.5	33	29.5	0.6
6	170.5	171.5	168	30	32	29.5	0.7
Average	**169.7**	**171.4**	**168**	**31.4**	**32.6**	**30**	**0.73**

The table 6 shows RMS current, THDI per phase and current unbalances between the phases for different readings. The reading in the table shows average values of the parameters at the bottom. The average current unbalance value is 0.73% which is not beyond limit value given by standard, 10%. But the THDI measured shows there is high value of distortion of 31.4%, 32.6% and 30% in each phase.

Bar graph on figure 6 shows the individual current harmonic components for each phase: 1, 2, and 3 with their distortion level in percentage. The horizontal line of the bar graph contains odd harmonic number from 1 to 21 and the number 123 represents phase numbers. From the bar graph it is clear that the 5th and the 7th harmonic distortions are the major spectral components on transformer 1 supplying old production line loads.

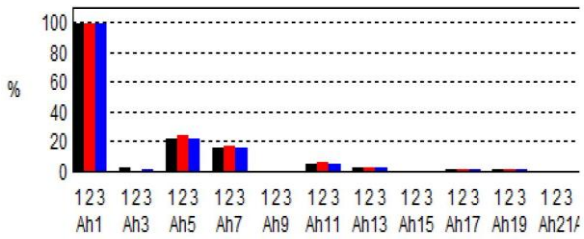


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Fig.6. Current harmonic component measured at transformer 1 which supply old production line loads

The total average current harmonic distortions for different readings are presented for each phases in Table 6. THDI for phases one, two and three are 31.4%, 32.6% and 30% respectively and from table 5, the THDv is 2.5%,2.7% and 2.8% for phases one , two and three respectively. RMS value of individual harmonic components for current and voltage are tabulated as in Table 7.

Table 7. RMS value of individual harmonic currents and voltages from transformer 1

Harmonic components	h=1	h=3	h=5	h=7	h=11	h=13	h=17
RMS current (pu)	1	0.01774	0.241	0.234	0.0445	0.01761	0.01776
Voltage (pu)	1	0	0.0143	0.0163	0.0163	0.013	0.0058

Using table 7, the harmonics existing in the system can be simulated using the mathematical expression of harmonics given by equation (1).

$$f(t) = \sum_{h=1}^{hmax} Ahsin(2\Pi hfot + \varphi h) \text{.....Eqn 1.}$$

The distorted and individual harmonic spectral component wave forms have been simulated and displayed in figures 7, 8, 9 and 10 below. The harmonic numbers greater than 17th are neglected since they are not significant.

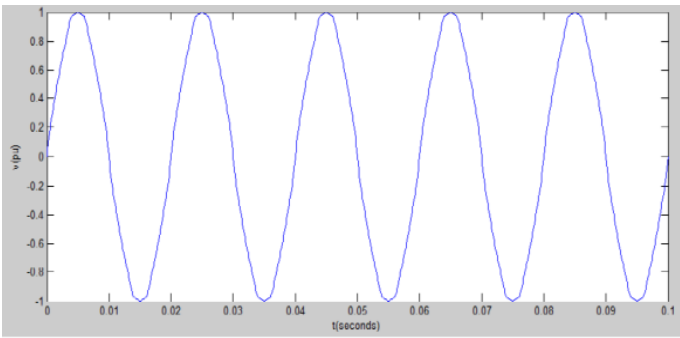


Fig. 7. Simulation of distorted waveform of single phase voltage for transformer 1

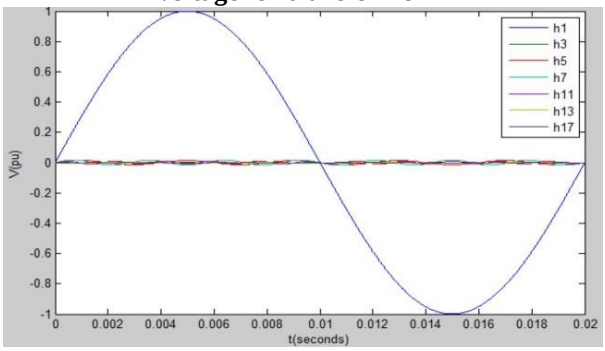


Fig.8. Harmonic spectral components of single phase voltage for transformer 1

Figure 7 shows the simulated distorted voltage waveform on the transformer 1 supplying old production line loads. And figure 8 shows voltage spectral harmonic components on transformer 1. By comparing these two wave forms I can conclude that the voltage distortion is not significant.

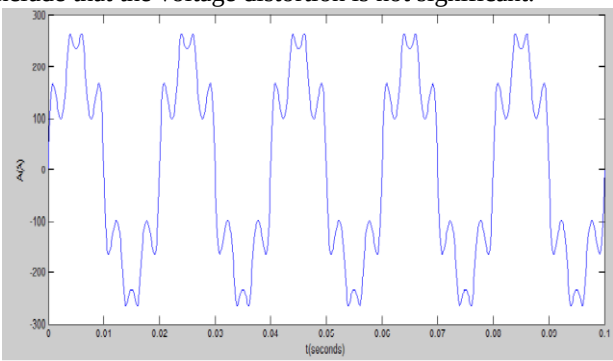


Fig.9. Simulation of single phase distorted current wave form for transformer 1

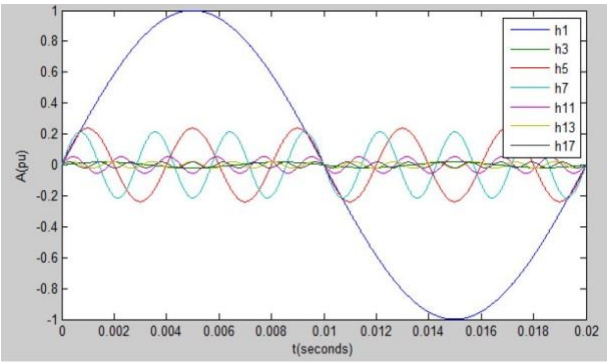


Fig.10. Harmonic Spectral component of single phase current for transformer 1

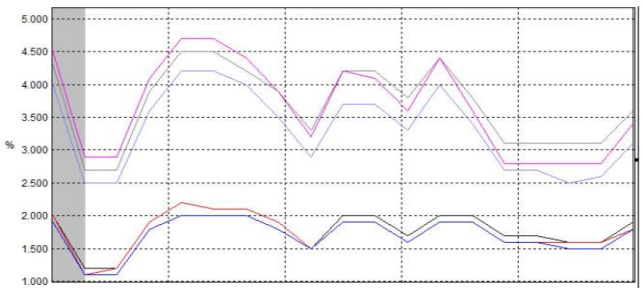
Using these two graphs, it is evident that the current harmonics are the main problems in the factory. The worst effect comes from the fifth and seventh harmonic spectral components with harmonic orders of 25% and 20% respectively.

Table 8. Average real power and power factor data measured on transformer 1

Average power					*Average power factor*			
W1	*W2*	*W3*	*W total*	*VA total*	*PF1*	*PF2*	*PF3*	*PF mean*
26,919.5	*26,901.5*	*26,637.8*	*80,458.6*	*106,709.0*	*0.786*	*0.722*	*0.754*	*0.754*

Table 8 shows single phase and three phase average real power, apparent power and power factor readings. The average power factor of the three phases is low, 0.754. Hence, the power factor of the factory should be improved near to one or should be taken above the minimum threshold power factor standard of 0.85 set by the supply authority.

The figure 11 below shows the variations of voltage and current total harmonic distortion per phase measured from transformer 2 supplying new production line loads. The graph shows both voltage and current total harmonic distortions for the three phases .



9/8/2019 3:00:00(h:min:s) 9/8/2019
10:00:00.000AM 36min/Div 1:00:00.000PM
Measured value on 9/8/2019—11:00:00.000AM:
2.100 U1 THD 4.300 A1 THD
2.100 U2 THD 4.500 A2 THD
1.900 U3 THD 4.000 A3 THD

Fig.11. THDv and THDI from transformer 2 supplying new production line loads

The upper graph shows current total harmonic distortion and the lower shows the voltage total harmonic distortion. The vertical axis shows percentage of total harmonic distortion on the fundamental component and the horizontal axis shows time duration of measurement. The values under the graph show the measured parameter at that particular time. The horizontal division shows thirty six minutes per column as it can be seen from the graph. The main source of the current harmonic distortion in the factory is Adjustable Speed Drive. The harmonic current distortion in adjustable-speed drives is not constant. The waveform changes significantly for different speed and torque values.

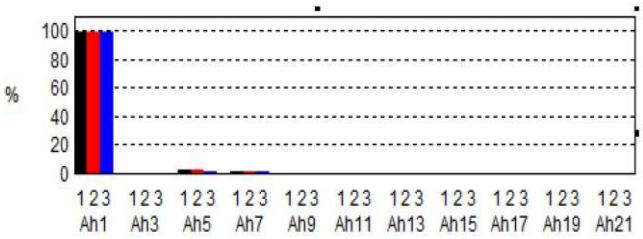


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Fig.12. Individual current harmonic distortions at transformer 2 supplying new Production line loads

Figure 12 shows the individual harmonic components for the respective phases with their distortion level in percentage to the fundamental current. The horizontal line of the bar graph contains odd harmonic number from 1 to 21 and the number 123 represents phase numbers. It is evident that harmonic distortions are very low in figure 12. Only the 5th and 7th harmonics are visible on each phase. The main reason identified is that most of the motors in this section of the factory are controlled by breaker. Only some motors are controlled by adjustable speed drives. These harmonics are not significant compared to the standard.

Table 9. RMS current, THDI and current unbalance from transformer 2 supplying new production line loads

No of measurement	A1	A2	A3	A1 THD %	A2 THD %	A3 THD %	Current Unbalance %
1	183.7	183.7	196.4	4.3	4.5	4	4.40
2	188.4	186.1	200.1	2.7	2.9	2.5	4.16
3	189.6	185	200.3	2.7	2.9	2.5	4.30
4	168.9	168.5	179.8	3.9	4.1	3.6	4.50
5	191.6	191.6	204.2	4.5	4.7	4.2	4.18

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6	189.4	188	200.5	4.5	4.7	4.2	3.90
Average	**185**	**184**	**197**	**3.8**	**3.9**	**3.5**	**4.24**

Table 9 shows RMS current, THDI per phase and current unbalances between the phases for different readings. The readings in the table show average values of the parameters in the bottom row. The average current unbalance value is 4.24% which is not beyond limit value given by standard, 10%. The THDI measured also shows there is low value of distortion compared to the standard.

Table10. RMS voltage, THDv and voltage unbalances measured from transformer 2 supplying new production line loads

No of measurement	V1	V2	V3	V1 THD %	V2 THD %	V3 THD %	V Unbalance %
1	196	196	197	2.2	1.6	1.8	0.6
2	199	199	200	1.6	1.6	1.3	0.25
3	200	200	201	2.2	1.8	1.9	0.34
4	200	201	202	2.1	1.9	1.9	0.49
5	199	199	200	1.8	1.6	1.6	0.25
6	200	200	201	2.1	1.9	1.9	0.1
Average	**199**	**199**	**200**	**2**	**1.7**	**1.7**	**0.33**

Table 10 shows the voltage distortion level and RMS values measured from transformer 2 supplying new production line loads. The average measured during full load show that the THDv is 2%, 1.7% and 1.7% for phases one, two and three respectively. As per IEEE standard, the voltage distortion should be below 3% for individual harmonic components and below 5% for total harmonic distortion. Hence, the results in table 10 indicate there is a voltage distortion within acceptable range. The voltage unbalance limit at the terminal of the motors in the industry should be below 1% as per IEEE standard. The unbalance greater than 1% makes motor operation difficult and the motors are over heated and forced to function below their rated power. From the last column of table 10, the voltage unbalance is not beyond the standard and in this particular case it is 0.33%.

By using table 11 below, the harmonics existing in the system can be simulated using mathematical expression. The distorted and individual harmonic component waveforms have been simulated and presented as in figures 13, 14, and 15. The harmonic numbers greater than 17th are neglected since they are not significant.

Table 11. RMS value of individual harmonic currents and voltages from transformer 2 supplying new production line loads

Harmonic Components	h=1	h=3	h=5	h=7	h=11	h=13	h=17
Current(pu)	1	0	0.01	0.01	0.006	0.002 6	0.002 8
Voltage(pu)	1	0.003	0.03	0.02	0.008	0.004	0.002

Figure 13 shows the simulated distorted voltage wave form on the transformer 2 supplying new production line loads. And figure 14 shows voltage spectral harmonic components on the same transformer.

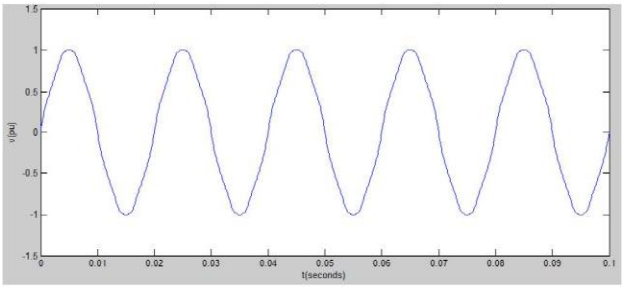

Fig.13. waveform of distorted single phase voltage for transformer 2 supplying new Production line loads

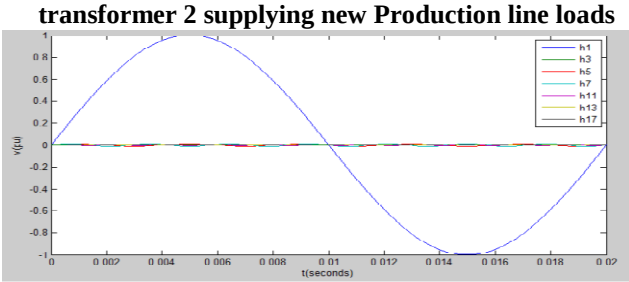

Fig.14. spectral harmonic components of single phase voltage for transformer 2 supplying new production line loads.

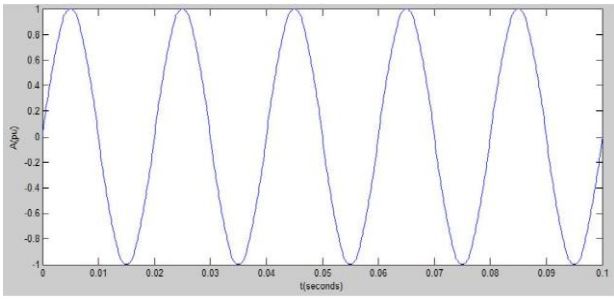

Fig.15. waveform of single phase current for transformer 2 supplying new Production line loads.

From the wave forms on the figures 13, 14, and 15 there is no significant current and voltage distortions on transformer 2 supplying new production line loads.

Table 12. Frequency, Real power and Power factor data measured from transformer 2 supplying new production line loads.

Freq		Average Power					Average power factor			
Hz		W 1	W 2	W 3	W total	VA total	PF 1	PF 2	PF 3	PF mean
Min	Max									
49.9	50.2									
50.05		18,580	17,380	16,780	52,740	67,673	0.85	0.754	0.74	0.78

Table 12 shows single phase and three phase average real power, apparent power and power factor readings. The average power factor value is 0.78 which is below the minimum threshold standard of 0.85 which is set by Ethiopian Electric Utility.

3.2. Proposed Mitigation Techniques

A. Harmonics mitigation systems

• Use of shunt filters. These may be either shunt active filters or shunt passive filters. The passive shunt filters are simple and low in cost. But the active filters are complex and costly and their operational characteristics are better than the passive filters.

B. Power factor Mitigation

• By injecting reactive power near to inductive loads using capacitor banks or any other type of reactive power sources.

C. Power Interruption Mitigation Techniques

• By reducing distribution lines Maintenance and component replacement work cycle and duration

• By upgrading the distribution lines capacity so as to overcome distribution lines overloading problem.

IV. MODEL SIMULATION STUDY

The Mat lab Simulink model is used to visualize the improvement obtained through simulation before and after the connection of shunt filters. The simulation results are shown in figures 17 to 20. Simulation has been done only for transformer 1 which supplies old production line loads. Both current and voltage harmonics have been simulated before and after the integration of shunt harmonic filters.

Figures 17 and 18 show simulations of three phase waveforms of current on the transformer supplying old production line loads. Figure 17 shows the simulated distorted waveform of current before shunt filters are connected to the model. And figure 18 shows the current waveform after shunt harmonic filters connected (5th and 7th harmonics removed).

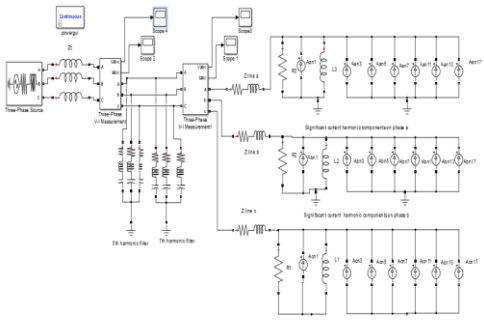

Fig.16. three phase model for simulation of the factory supply system.

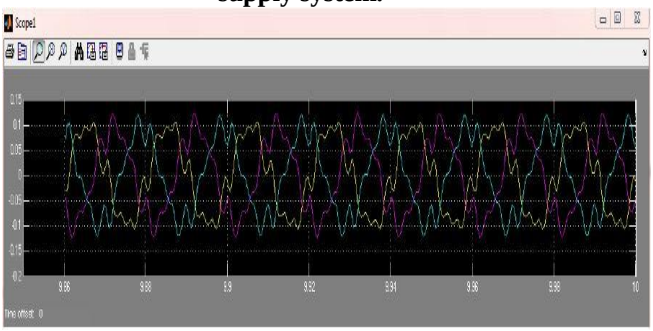

Fig. 17. Simulation waveform of three phase current before filter is connected to transformer 1 supplying old production line loads.

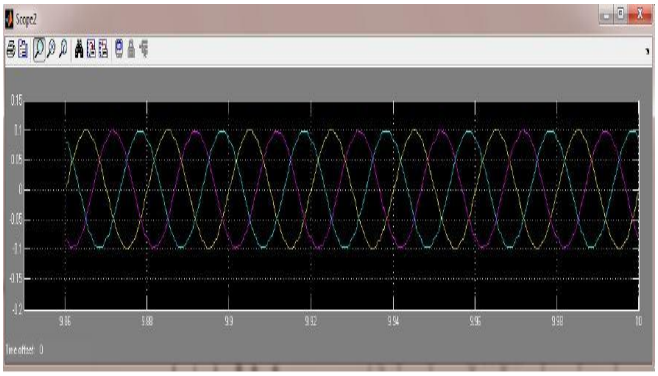

Fig.18. Simulation waveform of three phase current after filter is connected to transformer 1 supplying old production line loads.

Figures 19 and 20 shows simulation of waveforms of voltage on the transformer supplying old production line loads. Figure 19 shows the simulated waveform of voltage before shunt filters connected to model. Figure 20 shows the voltage wave form after shunt harmonic filters connected.

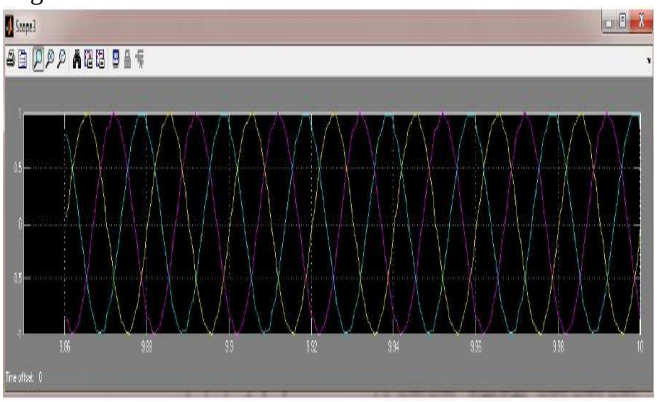

Fig. 19. Simulation waveform of three phase voltage before filter is connected to transformer 1 supplying old production line loads

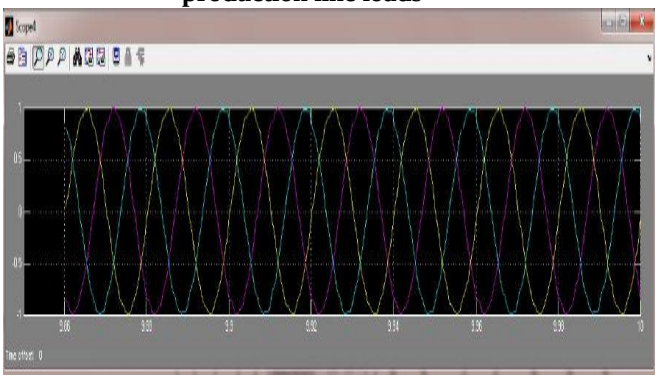

Fig. 20. Simulation waveform of three phase voltage after filter is connected to transformer 1 supplying old production line loads.

V. CONCLUSIONS

The following conclusions can be made from this industrial plant power quality evaluation works:

1. From the analysis of the reliability indices of the factory supply system, the factory is facing serious power interruption problem.
2. Voltage variation has been seen in the supply system of the factory at different occasions. As to standards Voltage variation up to 10% deviation is permissible.

3. The voltage and current unbalances observed in the analysis are within the tolerable limit of operation.

4. No problem of power frequency variation was observed in this power quality investigation work.

5. The major power quality problems identified in Zuqualla steel rolling mill factory are power interruption, current harmonic distortion and poor power factor.

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AUTHORS PROFILE

Wondwossen Astatike Haile, Ph.D. Research scholar affiliated to Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science And Technology, Chennai, India.
Research focus areas: Power systems, power electronics and drives, power quality, renewable sources.
PH.NO. +91-9940514968,
Mail:woasha2011@yahoo.com

Dr. chandrasekar p., associate professor and acting head of electrical and electronics engineering department, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai, India. **Research focus areas**: power quality; power electronics, smart grid, and micro-grid.
PH.NO. +91-7338803043,
Mail: hodeee@veltech.edu.in

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