POWER QUALITY ASSESSMENT AND MITIGATION AT WALYA-STEEL INDUSTRIES AND ETHIO-PLASTIC SHARE COMPANY

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ABSTRACT

In this paper, electric power quality (PQ) in Walya-Steel Industries PLC (WSIPLC) and Ethio-Plastic Share Company (EPSC), which are customers of Ethiopian Electric Power Corporation (EEPCo), are studied. PQ indicators of the two industries are recorded and analyzed. The study demonstrated that harmonic distortion is high relative to the corresponding IEEE recommended maximum permissible values while power factor of the two factories' power systems are low. Other PQ indicators are within the range of allowable values. The simulation done on the modeled power system of the two factories demonstrates that major source of harmonic distortion is power electronic converters, which are in use in both factories. Based on the simulation results, capacitive filter for the harmonic distortion and low power factor mitigation have been designed.

Keywords*: Power Quality, PSCAD, Sag, Total Harmonics Distortion (THD), voltage unbalance, K-factor, Single-tuned Filter, Harmonic Resonance*

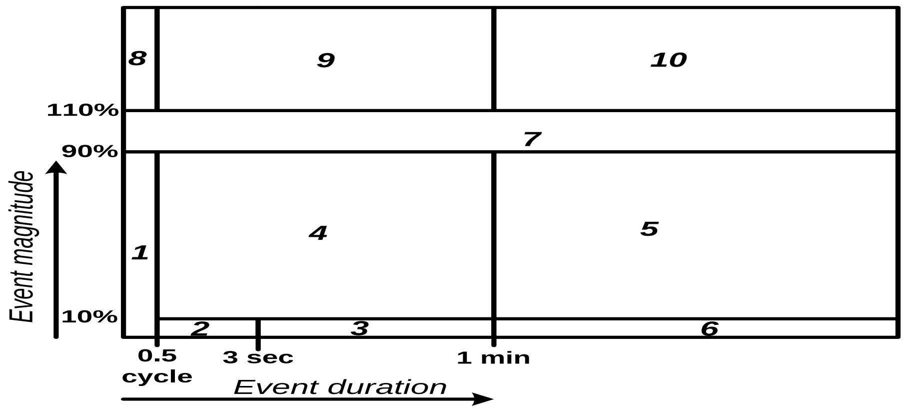
INTRODUCTION

Power Quality (PQ) problem refers to voltage, current and frequency deviation from nominal value in electrical distribution and utilization system, which may result in failure or malfunctioning of equipment [1, 2, 3]. Today, PQ is a concern to electric utilities, and customers alike, with the proliferation of electronic and computing equipment, which are sensitive to disturbances. The industrial processes are also becoming complex, resulting in huge economic losses if equipment fails or malfunctions [4]. The electrical power interconnection through grids, even across boarders, results in the effect of PQ problem to be felt in a wider area and to have an extended serious economic impact particularly for large industrial type consumers connected to the grid.

Voltage quality problem is usually the most important in PQ, such that standards in PQ areas are devoted to maintaining the supply voltage within certain limits. Commercial AC electric power systems are to operate at a sinusoidal waveform of 50 or 60 Hz and rated voltage magnitude. Any significant deviation in the waveform magnitude, frequency, or purity is a potential power quality problem [1-3]. Depending on their duration and magnitude, voltage deviations are categorized as voltage swells, voltage sags, interruptions, over voltage, under voltage, transients, voltage imbalance, and voltage flickering as shown and defined in Fig. 1. Harmonics in voltage and current are also power quality problems [1, 5, 6].

Nonlinear type loads contribute to the degradation in the electric supply's Power Quality through the generation of harmonics and voltage spikes. Sources of nonlinearity are overloaded electric machines, transformers, power electronics converters and inverters, among others. The increased use of nonlinear loads makes the harmonic issue (waveform distortion) a top priority for all equipment manufacturers, users and electric utilities [6].

Online starting of electric machines, faults in electrical distribution and utilization systems, use of power electronic switching devices, welding, lightning, etc are causes of various magnitude and period voltage variation from normal value.



1. Notch/Transient
2. Momentary
3. Temporary
4. Voltage sag
5. Under voltage
6. Sustained interruption
7. Normal operating voltage
8. Transient
9. Swell
10. Overvoltage

Figure1. Voltage variation magnitude and period as defined by IEEE standard 1159-1995

Today, in Ethiopia, there is industrial expansion. Converter-inverter supplied electric motors, heaters, frequency converters with renewable energy sources, etc are usually parts of the new industries, all resulting nonlinearity and power quality problems. At the same time, there is proliferation of equipment sensitive to PQ throughout the country in the industry, residential and commercial buildings. Customers' use personal computers, building and industrial automations, which are equipped with power electronic systems and are also sensitive to power quality.

The country has also embarked on electric power export, which demands PQ level at international standards. Hence, it is high time to understand the PQ phenomenon in our power system and work on mitigation techniques.

In this paper, surveys on power quality problems in Walya-steel industries and Ethio-plastics Share Company were done. Ethio-plastic Share Company has a number of converter-inverter systems supplying electric machines. Walya Steel Industries also has induction heaters, which are supplied from converter-inverter system to melt the steel.

The two industries use power electronic converters intensively. Hence, the high potential power quality problem in these two factories, their location, EPSC on the east and WSIPLC on the west side of Addis Ababa, and willingness and support of the management for the survey were motivations for the work.

This paper is organized into five sections, including this introduction. The second section, Power Quality Problem Monitoring and Data Collection describes the data collection setup, methods, techniques and some key measurement results. The third section, Analysis and Discussion interprets and compares results with standards wherever applicable. The fourth section, Mitigation Technique, is design of suggested mitigation technique while section five is Conclusion.

POWER QUALITY PROBLEM MONITORING AND DATA COLLECTION

Survey of power quality problems at EPSC, WSIPLC was carried out for more than two months (total of 74 days) using MicroVip Energy and Harmonic Analyzer, Fluke 43B Power Quality Analyzer and dip-8000 Energy and Harmonic Analyzer. The variables measured were load unbalance, Power Factor, Reactive and Active power, voltage waveforms to catch voltage sag & swell, harmonics, transients, and frequency variations.

Data logging was continuously done, during the survey period, from 8:30 AM to 5:30 PM transferring the data to computer every two hours. The data presented below is representative once, taken from the bulk data collected.

Table 1: Survey period

Factory	Duration
EPSC	30 days, 24/ 10/ 09-24/11/09
WSIPLC	44 days, 19/12/09-3/2/10

Electric Power System in the two Factories

EPSC is located at Eastern part of Addis Ababa near AMCE while WSIPLC is located at Western Addis Ababa, Alemgena town. Table 2 shows description of the power supply to EPSC and WSIPLC.

Table 2: Description of supply network

Network Parameters	Sites	
	Ethio-Plastic Share Company	Waliya Steel Industry PLC
Source of supply	Weregenu-Substation	Sebeta-I Substation
MV feeder (Line)	Wer-02	Seb-05
Length of MV Line	1.282 Km	7.950Km
Conductor type & Size	AAC-95	AAC-95
Conductor configuration	Hock-type	Hock-type
Transformer type and capacity	4x800KVA, 15/0.4 KV	1X800KVA 15/0.4KV
		2X630KVA 15/0.4KV
		1X1600KVA 15/0.7KV
		1X3200KVA 15/0.75KV

In EPSC, the measurement was taken on the low voltage side of distribution transformer at the point of common coupling. In WSIPLC, the size of LV cable is very large for clamping with the monitoring device. As the result, the measurement was taken on load supply cables. Single-line diagram of EPSC electric power supply system is as shown in Fig. 2.

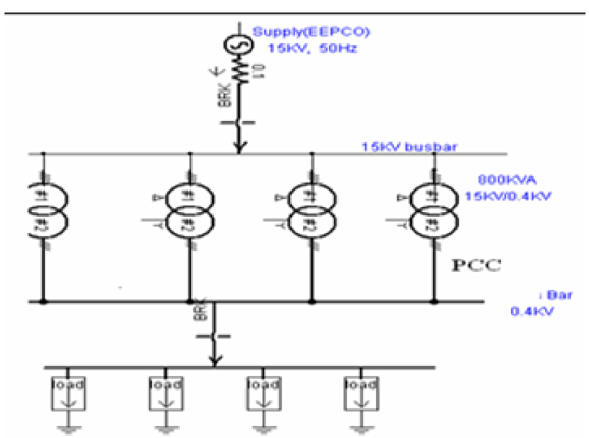


Figure 2 EPSC Single-line Electric Power Supply System

Measured Parameters and Variables

Steady state power parameters that include three phase voltage, current, active power, reactive power, apparent power, power factor, and power frequency and harmonic current and voltage magnitudes were measured.

Table 3: Summarized survey result of power parameters, PF & frequency

Parameters	EPSC			WSIPLC		
	Max	Min	Average	Max	Min	Average
V(Volt)	401	385	396	387	367	378
I(Amper)	537.95	95.95	302.1	387	367	377.7
P(Kw)	365.7	38.425	132.9	217.8	156.42	189.9
Q(Kvar)	265.0	40.81	163.6	173.88	144.48	155.2
PF	0.89	0.47	0.6	0.80	0.73	0.77
F(Hz)	50.3	49.8	50.1	50.6	49.8	50.2

Table 4: Measured result power parameters at PCC

Parameters	EPSC			WSIPLC		
	Max	Min	Average	Max	Min	Average
V(Volt)	401	385	396	387	367	378
I(Amper)	203	36	114	233	185	208.7
P(Kw)	138	145	50.1	121	86.9	105.5
Q(Kvar)	100.0	15.4	61.7	96.6	78.6	86.2
PF	0.89	0.47	0.60	0.80	0.73	0.77
F(Hz)	50.3	49.8	50.1	50.6	49.8	50.2

Table 5: Summarized harmonic distortion measured value

Harmonic Distortion Parameters	EPSC			WSIPLC		
	Max	Min	Average	Max	Min	Average
Current (THD_I)%	32.2	20.1	24.2	24.6	20.0	21.38
Voltage (THD_V)%	2.70	1.30	1.97	20.20	5.02	6.94
Dominant Harmonic Number	5,7,11			5,7,11,13		

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	Max	Min	Average	Max	Min	Average
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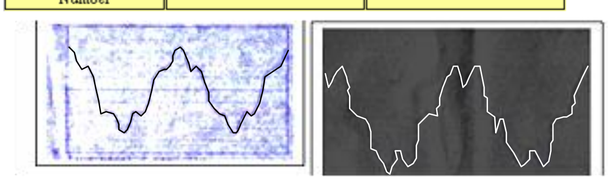
Voltage(THD_V)%	2.70	1.30	1.97	10.10	5.02	6.94
Dominant Harmonic Number	5,7,11			5,7,11,13		



(A) (B)

Figure 3 Typical captured current waveform at EPSC (left) and WSIPLC (right)

Transient parameters like voltage sag, short-term interruption and capacitor-switching transient problems at WSIPLC were also monitored; but not included here, as their magnitude and frequency of occurrence was insignificantly small.

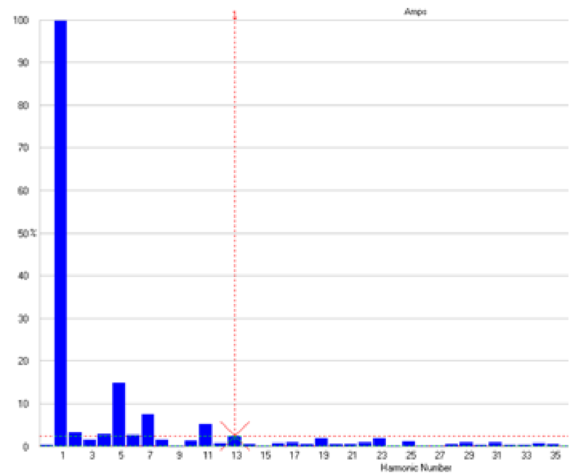


Figure 4 Sampled harmonic spectrum at WSIPLC

ANALYSIS AND DISCUSSION

This section deals with data analysis and discussion focuses on voltage unbalance, power frequency variation, power-factor and harmonic distortion.

Harmonic Distortion

Possible Source of Harmonic Distortion

In Fig. 3, typical distorted voltage waveforms of WSIPLC and EPSC are shown. In order to determine the source of the distortion, the major loads in the factories were investigated and found out that, both factories utilize power electronic converters extensively. Especially in EPSC, inspection resulted that six step inverters supplied electric machines are major loads. In WISPLC, six-pulse converters supplied induction heaters for steel melting furnaces were major loads.

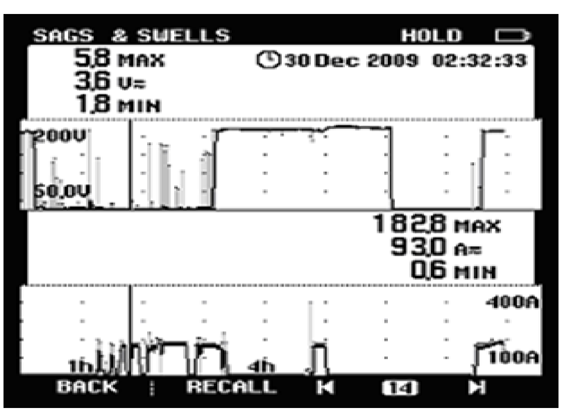


Figure 5 Sampled captured Sag Event of WSIPLC

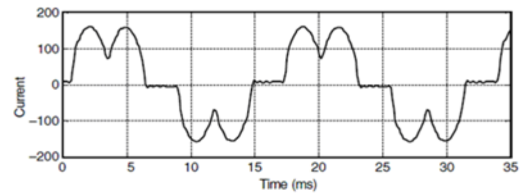


Figure 6 Voltage waveform of typical CSI-ASD drive

Figure 6, shows a typical current waveform of a six pulse converter supplying AC supply. The waveform recorded in Fig. 3 above, especially which corresponds to WSIPLC, is closely related to that of Fig. 6. Therefore, the major cause of distortion in voltage and current waveforms can be attributed to the extensive use of power electronic converters in the factories.

Effects of Harmonic Distortion

Harmonics distortion in power system increases loss by raising RMS value of load current, generating distortion component power factor, aggravating resonant frequencies and de-rating of electric machines, etc. Table 6 below shows the first four current harmonic components in per unit values recorded in the two factories.

Table 6: Voltage harmonic distortion

Harmonic Numbers	EPSC	ESIPLC
	Harmonic current (Pu)	Harmonic current (Pu)
5	0.298	0.20
7	0.08	0.12
11	0.05	0.07
13		0.04
THDI (%)	31.30%	24.60%

In EPSC, maximum voltage distortion level recorded is 2.7%, relatively low, even if there is 31.30% current harmonic distortion as shown in Table 6.

Calculation performed demonstrates that 75.31KVA power, which is 30% of the apparent power (136.5KVA), is contributed by the harmonic distortion. Furthermore, the increase in total current, as the result of harmonics, resulted de-rating of the supply transformers. The rated capacity of 800 KVA transformers is de-rated to 576KVA and 598.8KVA at EPSC and WSIPLC respectively.

WSIPLC has installed capacitor banks of 200Kvar for reactive power compensation. However, capacitor bank placement in distribution or industrial network will influence harmonic resonance frequency. In the case of parallel resonance, the total impedance at the resonant frequency is very large (theoretically tending to infinite). This condition may produce a large overvoltage between the parallel-connected elements, even under small harmonic currents.

Parallel resonance (F_P) is calculated at supply system (15 kv) using Eq. (1) [6].

$$F_P = \frac{1}{2*\Pi} * \sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}} \quad (1)$$

Where; F_p is parallel resonance frequency in Hertz, L and C are supply network equivalent inductance in Henry and capacitance in Farads respectively, and R system resistance in Ohms. The following table shows the parameter values and calculation results of the parallel frequency.

Table 7: WSIPLC supply system parameters and associated parallel resonant frequency

Parameter	Value
Supply line impedance at PCC	0.0017+ j0.0019Ω
Distribution transformer	0.01Ω
L	0.0379mH
C (capacitor bank)	0.0045F
Parallel resonant frequency	387.4 Hz
Resonant harmonic number (387.4/50)	7.56

The system parallel harmonic number 7.56 is close to the 7th harmonic and can reinforce this harmonic.

Harmonics distortion and Power Factor

In the sinusoidal current and voltage, the cosine of phase angle between the two is the power factor and is known as displacement power factor (PF_{DISP}).

In the non-sinusoidal case, the power factor that takes into account the contribution from all active power, including both fundamental and harmonic frequencies is known as the true power factor (PF_{TRUE}). It is clear that PF_{TRUE} is always less than PF_{DISP}. They are related by Eq. (2).

$$PF_{True} = \frac{PF_{DISP}}{\sqrt{1+THD_i^2}} \quad (2)$$

Table 8: Typical Power factor calculated from current distortion

Factory	PF_{DISP}	THD_i	PFTrue	Reduction
EPSC	0.6	0.246	0.57	5%
WSIPLC	0.77	0.32	0.75	3%

Harmonic current with a maximum distortion level of 31.50% and 24.6%, result in 5%and 3% reduction of power factor at EPSC and WSIPLC respectively.

Voltage Unbalance

Phase voltage unbalance results in unnecessary circulating current, which results additional loss. Unbalance factor (*UF*) can be calculated using Eq. (3).

$$UF = \frac{\Delta V_{\max}}{V_{av}} \times 100 \quad (3)$$

Where; ΔV_{max} is the maximum voltage deviation from average, while V_{av} is average of the phase voltages.

Calculation on data from EPSC and WSIPLC using Eq. (3) resulted *UF* of 0.658 and 0.34 respectively.

Power Frequency Variation

Any deviation of the power system fundamental frequency from its nominal value (50Hz) is power frequency variations. As the balance between load and generated power differs from zero, variations in frequency occur. The size and duration of the frequency shift depends on the load characteristics and the response of the generation control system to load changes. The percentage change in frequency Δf from the fundamental frequency is calculated using Eq. (4).

$$\Delta f = \frac{f_{\max} - f_{fund}}{f_{fund}} \times 100 \quad (4)$$

The maximum frequency deviation from 50 Hz, can be calculated as 0.6% and 1.2% for EPSC and WSIPLC, respectively, using the equation.

According to IEEE standard, power frequency at customer premises should not exceed 2% the rated value. Therefore, the frequency variations at EPSC and WSIPLC are below the threshold.

Reactive power generation

The Ethiopian Electric Corporation penalizes customers whose load power factor is less than 0.85. From the measured values at the two sites, it is clear that both factories are operating within the penalty range.

Table 8: Power Factor Measurements

	EPSC	*WSIPLC*
Power	132.9	189.9
PF	0.6	0.77

Table 5: Line parameters of distribution network

Parameters	EPSC	WSIPLC
Measured Average Power (Kw)	132.9	189.9
Measured Average Load (A)	302.1	377.7
Resistance of Supply (Ω)	0.397	2.46
Resistance of LF (Ω)	0.03	0.0262
Rated Transformer Loss (Kw)	6.655	6.655
Turn Ratio	37.5	37.5

Voltage Sag

The primary source of voltage sag is the electrical short circuit occurring on the power supply system. The short circuit causes a very large current, and this, in turn, gives rise to large voltage drops across the impedances of the supply system.

In fact, the measurements setup to capture voltage sag and voltage swell was not sophisticated enough to catch all voltage sag events. Captured voltage sag values in the factories as shown in Tables 8 and 9 are not severe.

Voltage-Sag Energy Index (E_{vs}), Voltage–Sag Severity Index (S_e) and SARFI-90 calculated using Eqs. (5), (6) and (7) are shown in Tables 8 and 9.

Table 8: Voltage –Sag Energy values for different events per site (WSIPLC)

Magnitude (V)	Duration (S)	U/U_{nom}	E_{vs}
210.0	0.48	0.95	0.04
150.0	0.52	0.68	0.28
150.0	0.55	0.68	0.29
100.0	0.50	0.45	0.40
0.0	0.20	0.00	0.20
50.0	0.36	0.23	0.34
50.0	0.40	0.23	0.38
0.0	0.28	0.00	0.28
200.0	0.34	0.91	0.06
205.0	0.46	0.93	0.06
210.0	0.50	0.95	0.04
50.0	0.22	0.23	0.21
200.0	0.52	0.91	0.09
190.0	0.28	0.86	0.07
50.0	0.48	0.23	0.46
200.0	0.44	0.92	0.08
50.0	0.52	0.23	0.49
50.0	0.38	0.23	0.36
50.0	0.32	0.23	0.30
160.0	0.40	0.73	0.19
		$\sum E_{vs}$	4.62

Table9: Voltage–Sag Severity values for different events at WSIPLC site

Magnitude (V)	Duration (S)	P_u	$U_{curve(d)}$	S_e
210.0	0.48	0.95	0.90	0.00
150.0	0.52	0.68	0.80	1.59
150.0	0.55	0.68	0.80	1.59
100.0	0.50	0.45	0.70	1.82
0.0	0.20	0.00	0.70	3.33
50.0	0.36	0.23	0.70	2.58
50.0	0.40	0.23	0.70	2.58
0.0	0.28	0.00	0.70	3.33
200.0	0.34	0.91	0.70	0.30
205.0	0.46	0.93	0.90	0.00
210.0	0.50	0.95	0.90	0.00
50.0	0.22	0.23	0.70	2.58
200.0	0.52	0.91	0.90	0.00
190.0	0.28	0.86	0.70	0.45
50.0	0.48	0.23	0.70	2.58
200.0	0.44	0.91	0.90	0.00
50.0	0.52	0.23	0.80	3.86
50.0	0.38	0.23	0.70	2.58
50.0	0.32	0.23	0.70	2.58
160.0	0.40	0.73	0.70	0.91

$$E_{vs} = \left\{1 - \left(\frac{U}{U_{nom}}\right)^2\right\} \times T \qquad (5)$$

Where; T is duration in seconds, U is the retained voltage of the Event and U_{nom} is nominal voltage

$$S_e = \frac{1-U}{1-U_{curve(d)}} \qquad (6)$$

Where; Reference curve (CBEMA curve).

$$SARFI_{90} = \frac{N_E}{D} * 30days \qquad (7)$$

Where; N_E is number of events in single site and D is number of days measurement was taken.

HARMONICS DISTORTION MITIGATION

The harmonics distortion in both factories has resulted low power factor and loss. Therefore, filters were designed for mitigation. First the harmonics were identified by impedance method [7]. Then filters were designed targeting the harmonics.

Electric Distribution Systems Equivalent Circuit

The electric equivalent circuit models of EPSC & WSIPLC are as shown in Figs. 7 and 8 respectively.

The impedance values of the distribution network components such as supply line, transformers and low voltage cables calculated are shown on the equivalent circuit.

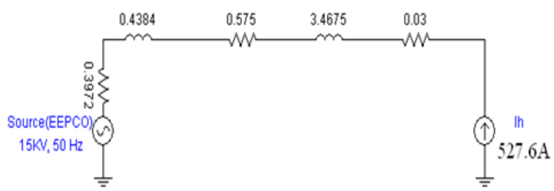


Figure 7 Equivalent circuit Model of EPSC electric system

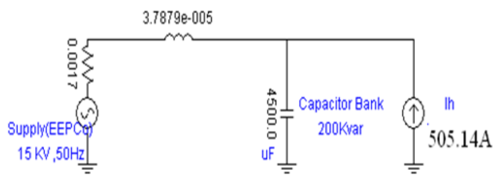


Figure 8 Equivalent circuit Model of WSIPLC electric system

Identification of Harmonics by Simulation

PSCAD software is used to simulate EPSC power system with controlled amount of injected harmonic current, Fig. 9. The measured harmonic current values are injected with the load represented by the measured active and reactive power. Fig. 10 A shows the current waveform captured by meter in actual system while 10 B shows the simulation result.

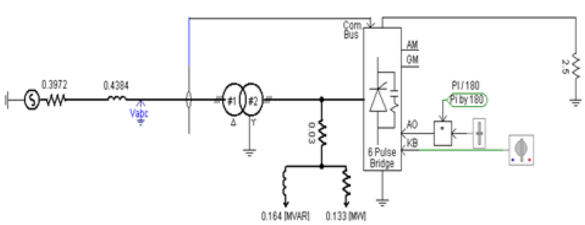
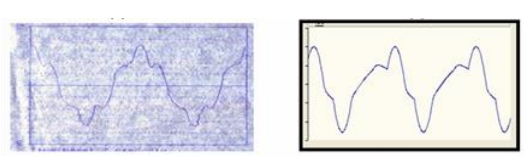


Figure 9 PSCAD configuration of EPSC system



A B

Figure 10 Voltage waveform at EPSC (A) Typical captured (B) simulated

Similarly, Fig. 12 shows the equivalent circuit of WSIPLC while Fig. 12A and Fig. 12B show respectively the simulated and captured waveforms. In both cases, the simulated and the captured waveforms are closely related. Therefore, the filter can target the fifth harmonic, the largest harmonic.

Designing Mitigation for Harmonics Distortion

Among different mitigation techniques, single-tuned passive filter is selected due to its simplicity, less costy and duality for controlling both harmonic and power factor and reliability for industries. The design resulted capacitor value of 4753 □F and inductor value of 0.0965 mH.

The equivalent circuit of WSIPLC with the single-tuned passive filter is as shown in Fig. 13. The evaluation of overall performance of the system with the Single-tuned Passive Filter is conducted resulting values shown in table 10.

Table 10: Power factor and THD improvement

Variable	Before filter	After filter
Power factor	0.77	0.885
Resonant frequency	385	200
THD_i	24.6%	13.31%
5th harmonic	20.43%	3.33%
7th harmonic	10.17%	9%

The resonance frequency change from 385 Hz (7th harmonic) to 200 (4th harmonic).

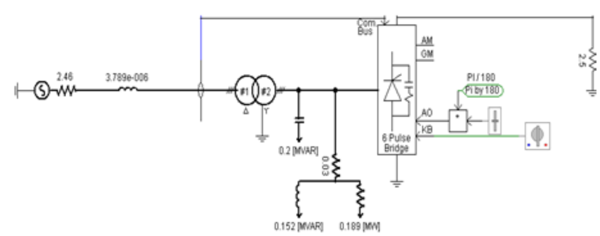
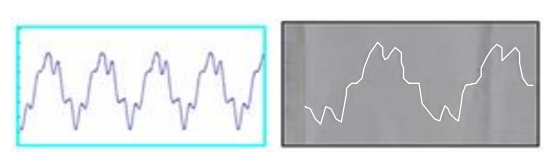


Figure 11 PSCAD configuration of the WSIPLC system



A B

Figure 12 Voltage waveform at WSIPLC (A) Simulated, (B) typical Captured by instrument

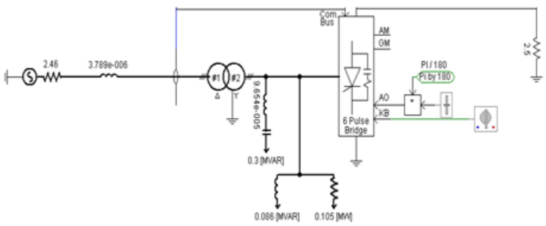


Figure 13 PSCAD equivalent circuit of WSIPLC power system with single-tuned passive filter.

CONCLUSION AND RECOMMENDATION

CONCLUSION

In this paper, electric power quality problems at Walya Steel Industries PLC and Ethio-Plastics Share Company have been investigated. The investigation demonstrated the existence of sever harmonic distortion and poor power factor. The captured voltage sags in both factories were not significant. The present reactive power compensating capacitor bank in WSIPLS creates harmonic resonance at the 7th harmonic.

Single-tuned passive filter has been designed to mitigate the harmonics and poor PF problems. Simulation result demonstrates that the designed filter improves power factor and reduce the harmonic resonance.

RECOMMENDATION

The paper demonstrated the existence and importance of power quality problems in Ethiopian electric power system. Strategic approach to system Power Quality problem status understanding and introduction of mitigation techniques should be in place.

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