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Performance Evaluation and Analysis of Harmonic Filter on Power Network for Improved Power Quality

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***Abstract* - The fundamental components of harmonic analysis and works linked to it were the main emphasis of this study. The total harmonic distortion is a measurement of the harmonic content in the network as a result of power electronics devices. Electrical Transient Analyzer Program (ETAP) software was used to model and simulate the Okwuzi 33/11/0.415kV distribution network. To ascertain the degree of harmonic distortion in the network, the harmonic load flow analysis tool integrated into the ETAP 19.0 software is used to show the results of the total harmonic distortion (THD) for the network. The results revealed that, at buses 3, 4, 5, 6, 7, and 10, the total harmonic distortion limitations as specified by IEC 61000-3-6:2008 were breached when a harmonic source was connected at bus 6; the point of common coupling (PCC). The first harmonic of bus 6, the point of common coupling, is 8.69 kV, the third harmonic is nonexistent, the fifth harmonic is 0.439 kV, and the seventh harmonic is 0.261 kV. The THD of bus 6 is 6.43%. Bus 8 has the most distorted waveform due to its proximity to the harmonic source relative to all other buses. To remove the network's 5th, 7th, and 11th order harmonics, three single tuned filters were connected. Simulations were performed with and without the single tuned filter to demonstrate the filter's influence in reducing harmonic content, and the results revealed a notable reduction, which improved the power quality and voltage profile.**

Keywords: Harmonics, single tuned filter, power quality, harmonics.

I. INTRODUCTION

Due to the fact that poor power quality can cause both the energy supply and the end user to lose money, it has recently become one of the most crucial topics in the field of power systems. For transmission and distribution utilities, businesses, and the transportation and infrastructure sectors, power quality is a crucial challenge. Low power quality reduces the productivity and dependability of the grid, increases operational expenses, and increases the risk of grid code violations [1].

Harmonics, reactive power, and load imbalance are the three main factors that contribute to poor power quality, which culminates in energy losses and high operating costs. Poor power quality is defined as any electrical network-related event that causes the end user to incur financial losses. A large harmonic content or a considerable phase difference between the voltage and current at the load terminals can both contribute to a low power factor. A poor load current phase angle is typically the outcome of an inductive load, such as induction motors, power transformer, etc. [2]

Power systems are made to operate at 50Hz or 60Hz frequency. Yet, various kinds of loads produce currents and voltages at integer multiples of the fundamental frequency of 50 or 60 Hz. These higher frequencies fall within the category of electrical pollution known as power system harmonics [3]. Power system harmonic compliance is investigated using harmonic studies, and harmonic mitigation strategies are designed, if necessary.

A harmonic analysis examines the entry of harmonic currents from the source into the power system and calculates the associated harmonic voltage distortion. In power system applications, distorted waveforms come from non-linear system components. Examples that are frequently used are variable speed drives (VSD), frequency converters in wind and solar power facilities, and high voltage direct current (HVDC). The resulting non-sinusoidal periodical waveform has a fundamental component as well as undesirable harmonic components that can seriously disrupt the power supply. Since power electronics applications have grown significantly over the past ten years, harmonics and how to control them have become major research concerns. In power systems, distortion of both the current and voltage is frequent. Voltage distortion typically results from current distortion. Current distortion causes a modest amount of voltage distortion and can be disregarded in the case of a strong grid, or low short circuit impedance [4]. The permitted voltage and/or current distortion are specified by harmonic standards. One of the most widely used harmonic standards are the IEC 61000 and the IEEE 519 for Harmonic Control [5].

II. REVIEW OF PREVIOUS WORKS

Harmonics can be categorized into characteristic, non-characteristic, and inter-harmonics. Odd harmonics are characteristic; there are no triple harmonics. According to his

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research, even harmonics are rare since most power system components have half-wave symmetry. Inter-harmonics are harmonics with multiples of the fundamental frequency that are not integers. Inter-harmonics are harmonics that have frequencies lower than the fundamental one and are produced by some power electronics equipment, such as fractional-slot concentrated-winding synchronous machines and current source converter driven synchronous machines, as well as by some loads like arc furnaces [6].

For industrial distribution systems with voltages up to 35 kV and frequencies of 50 Hz or 60 Hz, IEC 61000-2-4 [7] provides compliance requirements.

Table 1: Limits for harmonic voltage distortion according to IEC61000-2-4, pages 16–18 of [7]

Odd Harmonics		Even Harmonics		Triplen Harmonics		THD (%)
h	Vh	h	Vh	h	Vh	8
5	6	2	2	3	5	
7	5	4	1	9	1.5	
11	3.5	6	0.5	15	0.4	
13	3	8	0.5	21	0.3	
17	2	10	0.5	$21 < h \leq 45$	0.2	

IEEE 519 [2] defines compliance levels and is a recommended practice for harmonic control in electric power systems.

Table 2: Limits for harmonic voltage distortion according to IEEE 519-2014 [2]

Bus Voltage (kV)	Individual V_h (%)	THD (%)
$V < 69kV$	3	5
$69 \leq V161kV$	1.5	2.5
$V \geq 161kV$	1	1.5

The voltage quality a consumer can anticipate at the time of coupling is described by EN 50160 [8]. Together with other voltage quality indicators, it also specifies harmonic values, which shouldn't be taken as rigid upper bounds. Harmonic filters can be classed as either active or passive, according to [9]. The most used topology is for passive filters.

Passive filters can be categorized as:

- Series filter (high impedance at tuning frequency)
- Shunt filter (low impedance at tuning frequency)

Series filters are adjusted to have a high impedance at the desired frequency in order to eliminate a certain harmonic. Series filters can be cascaded so that each one is tuned to a different harmonic order if there are numerous undesired harmonics. The main drawbacks of series filters, which account for their infrequent use, are that they must resist their full current and voltage ratings and those they require reactive power.

[10] Worked on the concept of total harmonic distortion and how it affects the interpretation of measurements. He claimed in his study that there are two distinct definitions of total harmonic distortion, one in relation to the fundamental and the other in relation to the root-mean-square of the signal. In his work, he measured extremely distorted signals using four power quality analyzers, compared the results' accuracy, and discussed the findings. According to the findings, the first definition provides more accurate THD measurement than the second definition.

[11] Delivered a presentation on harmonics at San Diego Gas & Electric in August 2018. He covered a number of topics in his talk, including what harmonics are, where they may be found, why they are problematic, how to calculate harmonics, and harmonic control and mitigation.

[12] Investigated how grid harmonics will affect eddy current loss, other stray losses, and distribution transformer longevity. Using six 100KVA transformers as a test case, he analyzed their current harmonics using an HIOK19624 power quality analyzer for a week. The results showed that current harmonics had a more detrimental effect on the transformer's eddy current losses than other stray losses. He advocated for the government to control grid current harmonics through proper technological standards and business laws.

[13] In his study, he went into great length about what power quality is, what causes it, and how it affects the grid's equipment. The use of devices like DVR, AVR, etc., use of tap changing transformers, SVC, and filters to block harmonics are just a few of the ways he highlighted how to improve power quality. He also mentioned that harmonics are one of the causes of bad power quality.

This research work focuses on harmonic analysis and mitigation of Okwuzi network using single tuned filter so as to analyze its performance and make recommendations regarding the use of power electronic devices so as not to operate the power network beyond the harmonic distortion limits.

III. MATERIALS AND METHODS

3.1 Design of Single-tuned filter [14]

The reactor is given by

$$X_L = \frac{X_C}{h_n^2} \qquad 2.1$$

The harmonic order to which the filter should be tuned is given by h_n^2. The characteristic impedance Xn is given as:

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$$X_n = \sqrt{X_L X_C} \qquad 2.2$$

The resistance of the reactor is:

$$R = \frac{X_n}{Q} \qquad 2.3$$

Where Q is the filter's quality factor, which typically ranges from 30 to 100 [5]. The filter size is determined as follows:

$$Q_{filter} = \frac{kV^2}{X_C - X_L} \qquad 2.4$$

3.2 Network Description

The study case is Okwuzi 33/11/0.415 kV network consisting of $1x15MVA$, 33/11kV power transformer and $8x0.5MVA$, 11/0.415kV distribution transformers and 8 feeders. The single line diagram was modelled using ETAP 19.0 software and the simulation was done using the harmonic analysis tool embedded in the ETAP software.

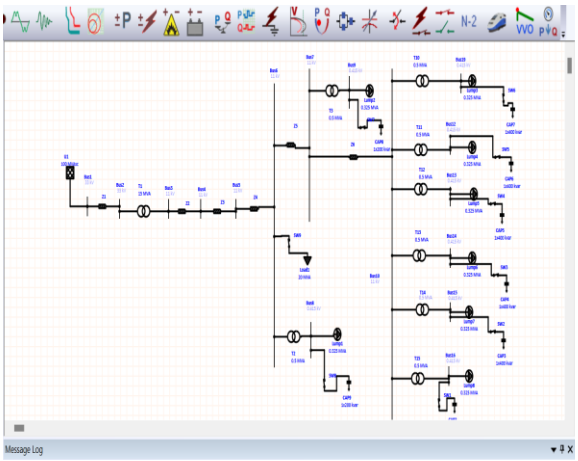

Figure 1: The Single Line Diagram of Okwuzi 33/11/0.415 kV network

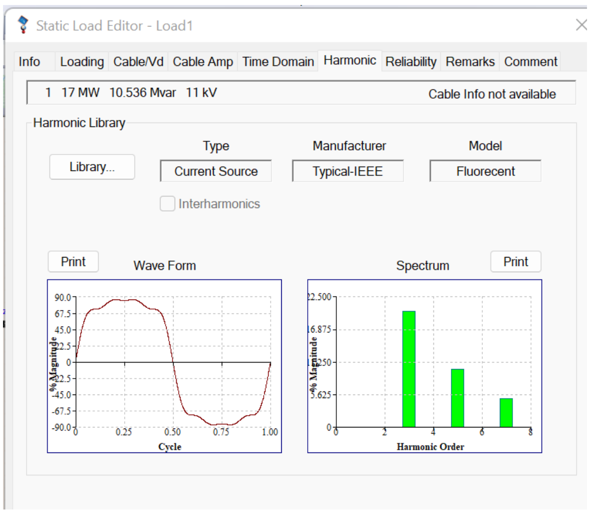

Figure 2: Harmonic source (static load)

Figure 2 shows static load of 20 MVA used as the harmonic source and was connected to bus 6. This bus is used as the point of common coupling (PCC) of all buses in the network, designed in accordance to the IEC 61000-3-6:2008 European standards. Investigations were done on how the harmonic source affected the power network using harmonic analysis tool embedded in the ETAP 19.0 software.

IV. RESULTS AND DISCUSSIONS

4.1 Harmonic load flow analysis

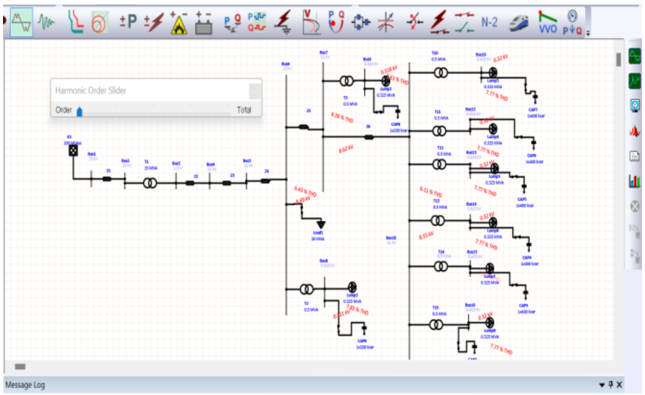

Figure 3: Load flow simulation of harmonic source

Figure 3 illustrates a harmonic load flow simulation of the study case used to assess the degree of network harmonic distortion and look for individual harmonic distortion (IHD) and total harmonic distortion limit violations (THD). The first harmonic of bus 6, the point of common coupling, is 8.69 kV, the third harmonic is nonexistent, the fifth harmonic is 0.439 kV, and the seventh harmonic is 0.261 kV. The THD of bus 6 is 6.43%.

4.2 Determination of Harmonic Voltage Distortion and THD

Table 3: System bus information after harmonic load flow

Bus ID	kV	Fundamental harmonic voltage distortion (%)	THD
Bus 1	33	100	2.77
Bus 2	33	99.47	2.80
*Bus 3	11	93.69	5.05
*Bus 4	11	88.71	5.46
*Bus 5	11	83.76	5.91
*Bus 6	11	78.84	6.43
*Bus 7	11	78.18	6.26
Bus 8	0.415	77.02	7.82
Bus 9	0.415	76.33	7.63
*Bus 10	11	77.62	6.11
Bus 12	0.415	76.79	7.11
Bus 13	0.415	76.79	7.11
Bus 14	0.415	76.79	7.11

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Bus 15	0.415	76.79	7.11
Bus 16	0.415	76.79	7.11
Bus 17	0.415	76.79	7.11
Bus 18	0.415	76.79	7.11
Bus 19	0.415	76.79	7.11

Table 3 shows harmonic voltage distortion of the buses in percentage and THD. The buses marked asterisk shows they have critical harmonic distortion requiring immediate attention. The harmonic waveforms and spectrums of buses 6, 7, 10, 13, 14, 15, 16, 19 are shown in the figure 4. These buses have higher magnitudes of 5^{th}, 7^{th}, 11^{th}, and 13^{th} harmonic order.

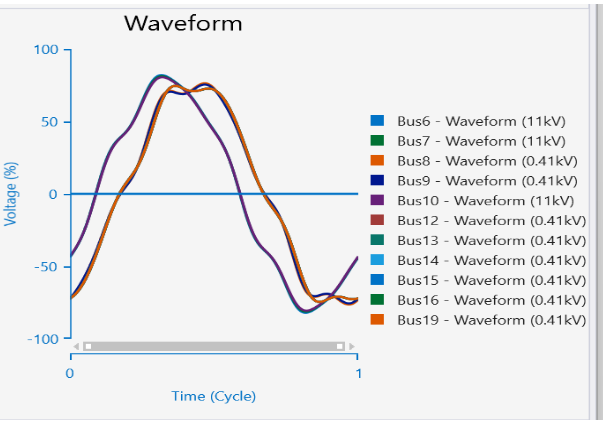

Figure 4: Harmonic voltage distortion waveform

Figure 4 shows voltage waveforms of eight (8) buses without filter simulated with harmonic load flow analysis tool.

It can be observed that the most distorted wave form was bus 8(0.41kV). The reason is that the bus 8 is closer to the harmonic source than the other buses in the network.

4.3 Removal of Harmonic Distortion

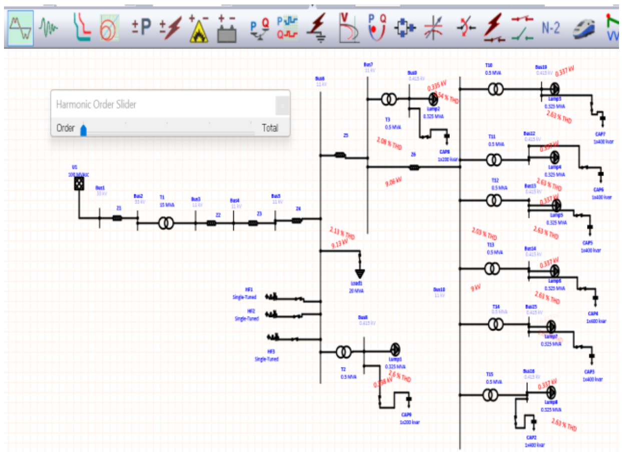

Figure 5: Harmonic Load Flow Analysis with three (3) Single Tuned Filter

Figure 5 shows harmonic load flow analysis with three (3) single-tuned filters which are selected to remove 5th, 7th, and 11th order harmonics. The filter is designed to provide enough reactive power to the network and reduce the losses at the fundamental frequency. Placement of the filters to eliminate distortion in the network will improve power supply when the distortion is eliminated.

Table 4: Harmonic voltage and THD without harmonic filter

	Without Harmonic Filter			
Bus Number	**Fundamental harmonic voltage (kV)**	**5th order harmonic voltage (kV)**	**7th order harmonic voltage (kV)**	**Total Harmonic Distortion (THD) %**
Bus 6	8.67	0.493	0.261	6.43
Bus 8	0.32	0.023	0.011	7.82
Bus 9	0.317	0.022	0.01	7.63

Table 5: Harmonic voltage and THD with harmonic filter

With Harmonic Filter				
Bus Number	**Fundamental harmonic voltage (kV)**	**5th order harmonic voltage (kV)**	**7th order harmonic voltage (kV)**	**Total Harmonic Distortion (THD) %**
Bus 6	9.13	0.178	0.078	2.13
Bus 8	0.338	0.008	0.003	2.6
Bus 9	0.338	0.008	0.003	2.54

From table 4 and 5 and figure 6, there was drastic reduction in the total harmonic distortion (THD) and the harmonic voltage when the harmonic filter was coupled to the network to reduce the harmonic distortion.

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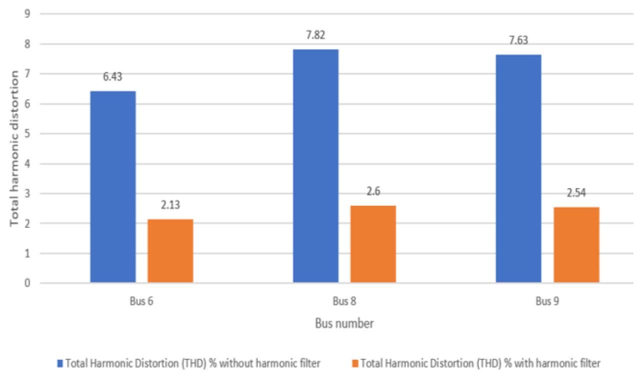

Figure 6: Total harmonic distortion with and without harmonic filter

Table 6: Branch losses with and without harmonic filter

	Without harmonic filter		**With harmonic filter**	
Bus ID	**kW losses**	**kVar losses**	**kW losses**	**kVar losses**
T1	106.7	2133.1	97.2	1943.3
T10	5.3	8.0	5.2	7.8
T11	5.3	8.0	5.2	7.8
T12	5.3	8.0	5.2	7.8
T13	5.3	8.0	5.2	7.8
T14	5.3	8.0	5.2	7.8
T15	5.3	8.0	5.2	7.8
T2	4.9	7.4	4.5	6.7
T3	5.0	7.5	4.6	6.8
Z1	103.0	11.5	93.8	10.5
Z2	926.7	103.3	844.2	94.1
Z3	926.7	103.3	844.2	94.1
Z4	926.7	103.3	844.2	94.1
Z5	16.4	1.8	15.8	1.8
Z6	12.4	1.4	12.2	1.4
Total Losses	3060.2 kW	2520.2 kW	2791.9 kW	2299.4

From table 6 and figure 7, it can be clearly observed that there was reduction in total branch losses of the power network when harmonic filter was added.

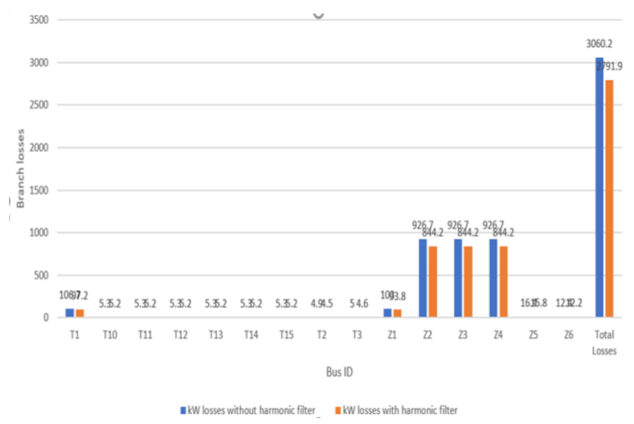

Figure 7: kW losses with and without harmonic filter

V. CONCLUSION

Analyzing harmonic distortion levels of voltage and current caused by power electronic equipment like uninterruptible power supply (UPS), variable speed drives, etc. present in the network that affect power quality is done through harmonic studies. Figure 1 displays the single line diagram that ETAP's modeling program generated. According to Figure 3, which depicts the network's harmonic load flow, there are 5th, 7th, 11th, and 13th order harmonics present in the network, which distort the waveform. The voltage waveform of the buses without a single tuned filter is shown in Figure 4 of the network. Bus 8 has the most distorted waveform due to its proximity to the harmonic source relative to all other buses. Single-tuned filter's introduction enhanced the power quality and voltage profile by removing harmonic distortion from the network and providing a smooth sinusoidal waveform.

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