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Evaluation and Analysis of Harmonic Distortion on 330kV Network Case Study Selected Sub-Region Nigerian Power System for Improve Power Quality

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Abstract

This paper presented fundamental characteristics of harmonic studies and its related work. The total harmonic distortion (THD) of the transmission line were computed using harmonics contents parameters of the waveform (harmonic voltage and impedance magnitude values). Results of THD for the 330kV transmission line are presented using harmonic load flow analysis in ETAP—domain on the view to measure the level of distortion in the network. Figure 2 shows the section of the harmonic load flow simulation in order to check for degree of harmonic distortion in the system under investigation. The provision of the harmonic frequency with greater magnitude exceeding THD and IHD limits are violated in accordance to IEC 61000-3-6:2008 (European Standards) are used as benchmark for measurement. That is the distortion for current and voltage (THDi% and THD%) are 0.5 and 1.5 respectively particularly harmonic order (h) ≤ 13. Consequently, the harmonic frequency violations with greater magnitude of 5^{th}, 7^{th}, 11^{th}, and 13^{th} order in the network are mitigated with 3-unit of single tuned filter to the affected buses for improved power quality.

Keywords: harmonic distortion, frequency violation, wave form, fundamental, power quality, load flow, voltage limit

1. Introduction

The activities of harmonies distortion in power system operation are a major concern that needed considerable attention particularly three phase (3 -phase) power systems. Concern of third harmonic currents caused by saturated iron in transformer and machines need to be attended to, although delta-connections was proposed for blocking third –harmonic currents. The emergence and penetration of power electronics loads in power systems has becomes a matter of concern for mitigation. However, it offers the advantages of efficiency and controllability, but the negative implication is that they draw non-sinusoidal currents from AC power systems and these currents interacts adversely with power systems impedance to create voltage harmonics and some cases of resonance. The occurrence of distortion in transmission network has given rise to an increase so as long as power electronics equipment continue to proliferate. Consequently, the main effects of harmonics in power system are heating, overloading, and ageing of equipment thereby increases losses. This means that been increase in the number of harmonic sources, number of devices sensitive to the harmonic distortion has also increased. Harmonics may lead to malfunctioning of power system components. Since harmonic distortion is one of the indices of power quality measurement of a power system. The IEEE standard 519-1992 provides a solution for the limitation and mitigation of harmonics occurrence. The total harmonic distortion (THD) is a measurement index of harmonic distortion (THD) which is used in both current and voltage defined as root mean square (rms) value of the h^{th} harmonic voltage divided by the rms value of the fundamental harmonic voltage multiplied by 100%. The THD of a current varies from few percent to more than 100%. THDs of voltage are usually less than 5% are considered declared acceptable while values above 10% are not accepted because it will be dangerous and become more problem to sensitive equipment/devices (S.L. Braide, 2014; S.L. Braide, D.C. Idoniboyeobu & A.O. Idachaba, 2018).

2. Review of Previous Paper

Harmonic modeling is a mathematical way of predicting harmonic distortion levels and potential resonance on electrical network based on available system data. The steps required for making harmonics study are based on research experience involved in obtaining single line diagram of the network, highlighting the point of common coupling, identification of harmonic sources and carrying out harmonic measurements, modeling the network components using a simulation software like ETAP and comparing results obtained to national standards. Power quality meters may be installed on a number of buses having large non-linear load in order to determine the level of disturbance. The locations of these measurements should be the Point of Common Coupling (PCC) which is the customer-utility interface. A minimum measurement period of one week is normally recommended as it provides a representative loading cycle for most industrial and commercial loads. To obtain reliable harmonic model of any network all components of the network must be precisely modeled. In order to carry out a comprehensive harmonic modeling and simulation of a given system two salient consideration are identified and reviewed in order to establish the gap and come up with more reliable result. Various simulations software is used including ETAP on-site harmonic current measurements which are used to tune the computer based harmonic current models to match and validate the measured data. Power System Computer Aided Design/Electromagnetic Transients including DC (PSCAD/EMTDC) was deployed to develop simulation models based on laboratory measured waveforms. A generalized model for distribution systems was successfully implemented for practical case studies using verified simulation models for various industrial and household electrical equipment and appliances. Similarly, DigSilent/Power factory is the simulation software used to evaluate the future levels of harmonic distortion in power grid based on the present harmonic current source model developed from measured data (T. Belgin & T. C. Kaypmaz, 1999).

Literature review also proposed the use of equivalent circuit models to represent characteristic harmonic producing loads. The Norton/Thevenin equivalent circuit provides a reliable model for harmonic current and voltage sources in a distribution network. The contribution of the power utility equipment and customer loads to the total harmonic distortion are observed at the point of common coupling (PCC) which can separately be evaluated using field data and analytical techniques. The major challenge of Thevenin/Norton equivalent circuit models is the determination of impedance and other parameters of power network. Evolutionary algorithm has been tested and verified in the estimation of Thevenin/Norton equivalent circuit parameters without knowing the network impedance. An equivalent circuit that considered the modeling of harmonic current emission on the AC side of a diode bridge rectifier while evaluating the harmonic voltage contribution of the DC side of the rectifier was successfully developed. In the drawback of modeling only the harmonic current was successfully addressed for more accurate harmonic analysis (C. Wu, and Y. Chan, n.d.).

3. Materials and Method

Case 1: Harmonic Distortion Content Standard

The application of IEEE 519 provides the guide for harmonic control and reactive compensation of static power converters following to the rising increase of utility of industrial non-linear loads (variable frequency drives). Significantly higher measured harmonic recommended levels are considered unacceptable. Thus, total harmonic distortion (THD) voltage or currents, defined as; (L. S. Czarnecki, 2000)

$$THD = \frac{100\sqrt{\sum_{h=2}^{k} U_{hrms}^2}}{U_{1rms}} \quad (1)$$

Where U_{1rms} and U_{hrms} are the fundamental and h^{th} (higher order) harmonic voltage components respectively.

Case 2: Determination of Total Distortion (THD)

In most cases harmonic content of power system may be quite small relative to fundamental condition that is the exact rms value of a current or voltage waveform requires harmonic content to be considered that is, (Siemens, 2013)

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty} \left(\frac{1}{\sqrt{2}} U_h\right)^2} \quad (2)$$

Where U_{rms} and U_h are the rms value and peak h^{th} harmonic component of voltage and current.

Essentially, rms voltage or current can also be used to quantify the level of distortion of the waveform. The total harmonic distortion (THD) of voltage or current waveform (THD_U) is calculated using; (IEEE Standard 519-1992, 1993)

$$THD_U = \sqrt{\sum_{h=2}^{\infty} (U_h)^2} = \sqrt{\left(\frac{U_{rms}}{U_{1rms}}\right)^2 - 1} \quad (3)$$

Where:

THD_U: represents voltage or current total harmonic distortion which can also be represented as THD_V and THD_I respectively while,

U_{1rms}: The rms fundamental voltage or current. (S. M. Halpin, 2003)

Thus, rms voltage or current can be represented in terms of total harmonic distortion given as;

$$U_{rms} = \sqrt{\sum_{h=1}^{\infty} U_{hrms}^{\ 2}} = U_{1rms}\sqrt{1 + THD_U^2} \quad (4)$$

Case 3: Modified Index for Harmonic Distortion Waveform

Fundamental currents that fall close to zero at certain periods of the day results into large value of THD_I. This mean that modified index for harmonic distortion may be used with harmonic current of the waveform expressed as percentage of a fixed nominal value rather than the fundamental value thus total demand distortion (TDD_U) given as;

$$TDD_u = \frac{1}{U_{nom}} \sqrt{\sum_{h=2}^{\infty} \left(\frac{1}{\sqrt{2}} U_h\right)^2} \quad (5)$$

Where:

The fixed value U_{nom}: This is required to be specified and may be a maximum rms value, maximum demand, average or selected nominal system value are key driver. This means estimation of harmonics is of high importance for purpose of efficiency for power system network. (Kumar, Bhunesh, 2011)

Harmonics data contains Amplitude, Phase Angle and Inter-harmonics Amplitude of both current and voltage captured separately on a ten-minute interval daily for the three phase lines referred to as; (L. M. Adesina & O. A. Fakolujo, 2015)

$$f(t) = \frac{1}{2} a_0 + \sum_{k=1}^{\infty} (a_k cos2\pi kt + b_k sin2\pi kt) \quad (6)$$

f: *represents frequency of the Kth harmonics order.*

Continuous Fourier transform given as:

$$X(F) = \int_{-\infty}^{\infty} x(t).e^{-j2\pi Ft} dt \quad (7)$$

Where $x(t)$ is a function and $e^{-j2\pi Ft}$ is the analyzing function (sinusoid).

Discrete Fourier transform is given as:

$$X_K = \sum_{n=0}^{N-1} x_n \, e^{-\frac{2_{\pi} Kn}{N}} \quad (8)$$

Where K is the Kth frequency, n is the sampled frequency and N is the number of samples.

$$\frac{k}{N} \stackrel{\Delta}{=} F, n \stackrel{\Delta}{=} t \text{ and } b_n = \frac{2\pi Kn}{N} \quad (9)$$

For harmonics analysis, X_k will be replaced with H_k,

$$K_k = h_0 e^{-b_0 J} + h_1 e^{-b_1 J} + \cdots + h_n e^{-b_N J} \quad (10)$$

4. Results and Discussions

4.1 Determination of Operating Voltage of the Study Case

Table 1. Bus Operating Voltage

Bus ID	Nominal Voltage (kV)	Pre-Upgrade (p.u)	Post-Upgrade (p.u)
Adiabor	330	0.991	0.991
Afam Gs	330	1.000	1.000
Aja	330	0.974	0.974
Ajakuta	330	0.992	0.993
Akangba	330	0.947	0.953
Aladja	330	0.993	0.993
Alagbon	330	0.956	0.956
Alaoji Gs	330	1.000	1.000
Alaoji Ts	330	0.991	0.990
Asaba	330	0.972	0.971
Ayede	330	0.951	0.951
B.Kebbi	330	0.997	0.997
Benin	330	0.998	0.998
Damaturu	330	0.911	0.967
Delta Gs	330	1.000	1.000
Egbin Gs	330	1.000	1.000
Ganmo Ts	330	0.967	0.967
Geregu Gs	330	1.000	1.000
Gombe	330	0.909	0.961
Gwagwalada	330	0.953	0.969
Ihovbor Gs	330	1.000	1.000
Ikeja West	330	0.960	0.963
Ikot Ekpene	330	0.974	0.973
Jalingo	330	0.891	0.951
Jebba Gs	330	1.000	1.000
Jebba Ts	330	1.000	1.000
Jos	330	0.962	0.975

Kainji Gs	330	1.000	1.000
Katampe	330	0.947	0.972
Kumbotso	330	0.964	0.973
Lekki	330	0.974	0.974
Lokoja	330	0.959	0.962
Maiduguri	330	0.909	0.965
Makurdi	330	0.957	0.955
Mando	330	0.970	0.979
N.Haven	330	0.965	0.964
Odukpani Gs	330	1.000	1.000
Okearo	330	0.964	0.966
Okpai Gs	330	1.000	1.000
Olorunsogo Gs	330	1.000	1.000
Omotosho Gs	330	1.000	1.000
Onitsha	330	0.971	0.970
Oshogbo	330	0.970	0.970
Sakete	330	0.958	0.961
Sapele Gs	330	1.000	1.000
Shiroro Gs	330	1.000	1.000
Ugwuaji	330	0.965	0.964
Yola	330	0.900	0.961

Table 1 shows the result of the load flow simulation performed on the existing Nigerian 330kV network using ETAP 19.1 software. The nominal and operating voltage of the system for pre-upgrade network condition was presented. The following buses (Maiduguru, Jalingo, Yola, Damaturu & Gombe) violates the bus voltage statutory limit condition of 0.95p.u–1.05p.u as provided by TCN. The corresponding values of the affected busses are (0.909p.u, 0.891p.u, 0.900p.u, 0.911p.u, 0.909p.u) respectively. While after capacitor bank placement of 75MVA was added to (Maiduguru, Jalingo, Yola, Damaturu & Gombe) respectively to fortify the network, which shows was no violations of the bus voltage statutory limit that occurred at the affected buses (0.955p.u, 0.9511p.u, 0.961p.u, 0.967p.u, 0.961p.u).

4.2 Introduction of Harmonic Source

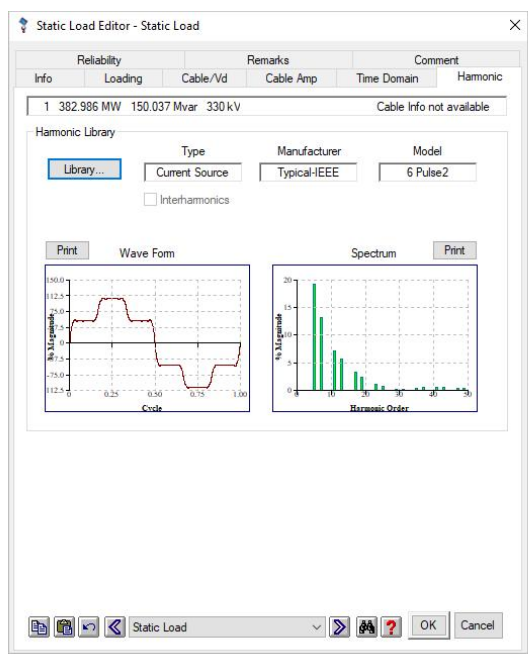

Figure 1. Harmonic Source (Static Load)

Figure 1 shows static load of 411.326MVA was connected to Afam GS bus as a source of harmonic. With Alaoji GS bus selected as point of common coupling (PCC) all buses in the network are designed in accordance to the IEC 61000-3-6:2008 European standards. The action of this harmonic source on the power network was investigated using Harmonic Analysis and the mitigation techniques taken to eliminate any form of harmonic distortion are presented.

4.3 Performance of Harmonic Load Flow Analysis

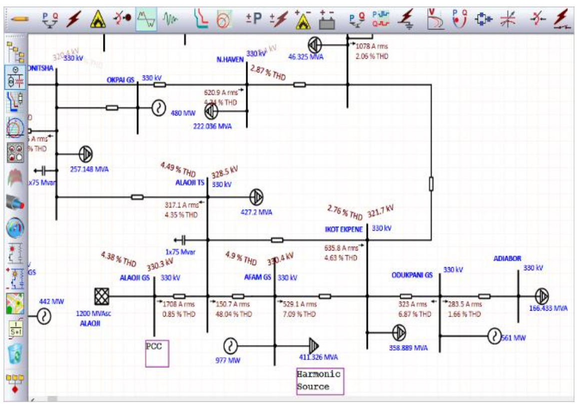

Figure 2. Harmonic Source Load Flow Simulation

Figure 2 shows a section of the harmonic load flow simulation to check the harmonic distortion or effect of harmonic source on the power network. In this paper harmonic load flow is performed for general loading condition. On running the harmonic load flow study there are some harmonic frequency with greater magnitude exceeding the THD and IHD limit violation using the IEC 61000-3-6:2008 European standards total harmonic distortion for current and voltage (THDi% and THD%) are 0.5 and 1.5 respectively for harmonic order (h) ≤ 13.

4.4 Determination of Short Circuit and Load Flow Current

Table 2. Short Circuit and Full Load Current

S/N	Bus ID	Isc(kA)	I_L (A)	I_{sc}/I_L
1	Afam GS	12.72	718.9	18
2	Alaoji Gs (PCC)	13.02	1707	8
3	Alaoji TS	17.89	743.3	24
4	Asaba TS	11.17	136.0	82
5	IkotEkene TS	16.78	611.8	27
6	Markurdi TS	7.55	163.5	46
7	New Heaven TS	15.56	206.6	75
8	Onitsha TS	16.19	436.7	37
9	Ugwaji TS	15.76	87.2	181

Table 2 shows the full load and short circuit current used for checking limit violation for total harmonic distortion and also in filter design for mitigating harmonics. Short circuit analysis is first performed to update the short circuit in all the buses secondly load flow analysis is performed to determine the load current in the selected buses for short circuit and load flow updates. Similarly, to check limit violation using the IEC 61000-3-6:2008 European standards total harmonic distortion for current and voltage (THDi% and THD%) are 0.5 and 1.5 respectively for harmonic order (h) ≤ 13.

Table 3. Determination of Harmonic Distortion, Alert View for Harmonic Load Flow

Harmonic Load Flow Analysis Alert View - Output Report: Untitled

Study Case: HA | Data Revision: Base | Configuration: Normal | Date: 15-06-2022 | Filter: Zone

Critical

Device ID	Type	Condition	Rating /Limit	Operating	% Operating	Harmonic
AFAM GS	Bus IHD	Exceeds Limit	2	3.45	172.64	5.00
AFAM GS	Bus IHD	Exceeds Limit	2	2.41	120.68	7.00
AFAM GS	Bus IHD	Exceeds Limit	1.5	1.54	102.35	11.00
AFAM GS	Bus IHD	Exceeds Limit	0.5	0.51	101.99	41.00
AFAM GS	Bus IHD	Exceeds Limit	0.47	0.51	106.94	43.00
AFAM GS	Bus THD	Exceeds Limit	3	4.9	163.49	Total
ALAOJI GS	Bus IHD	Exceeds Limit	1	2.96	296.49	5.00
ALAOJI GS	Bus IHD	Exceeds Limit	1	1.94	193.59	7.00
ALAOJI GS	Bus IHD	Exceeds Limit	1	1.84	183.81	11.00
ALAOJI GS	Bus IHD	Exceeds Limit	1	1.63	163.2	13.00
ALAOJI GS	Bus THD	Exceeds Limit	1.5	4.38	291.91	Total
ALAOJI TS	Bus IHD	Exceeds Limit	1	3.04	304.12	5.00
ALAOJI TS	Bus IHD	Exceeds Limit	1	1.98	198.46	7.00
ALAOJI TS	Bus IHD	Exceeds Limit	1	1.88	188.2	11.00
ALAOJI TS	Bus IHD	Exceeds Limit	1	1.67	166.97	13.00
ALAOJI TS	Bus THD	Exceeds Limit	1.5	4.49	299.16	Total
ASABA	Bus THD	Exceeds Limit	3	3.02	100.78	Total
BENIN	Bus IHD	Exceeds Limit	1	1.13	113.12	7.00
IKOT EKPENE	Bus IHD	Exceeds Limit	1	2.33	233.13	5.00
IKOT EKPENE	Bus IHD	Exceeds Limit	1	1.24	123.6	7.00
IKOT EKPENE	Bus THD	Exceeds Limit	1.5	2.76	183.98	Total
MAKURDI	Bus IHD	Exceeds Limit	2	2.09	104.56	5.00
MAKURDI	Bus IHD	Exceeds Limit	2	2.58	128.84	7.00
MAKURDI	Bus THD	Exceeds Limit	3	3.44	114.64	Total
N.HAVEN	Bus IHD	Exceeds Limit	2	2.16	108.1	5.00
ONITSHA	Bus IHD	Exceeds Limit	1	2.12	211.63	5.00
ONITSHA	Bus IHD	Exceeds Limit	1	1.66	165.78	7.00
ONITSHA	Bus IHD	Exceeds Limit	1	1.36	136.3	11.00
ONITSHA	Bus THD	Exceeds Limit	1.5	3.08	205.27	Total
UGWUAJI	Bus IHD	Exceeds Limit	2	2.19	109.72	5.00

Table 3 shows the alert view after performing the harmonic analysis in order to investigate the effect of harmonic source in the power system network. The predefined limit condition for THD and IHD are compared with the calculated THD and IHD values after performing harmonic load flow study. If any bus goes beyond the alert message indicates whether rated limit or operating limit, then violation could access either critical (where the conditions need to be checked as soon as possible) or marginal (where load alternation would fix the problem). Figure 2 shows harmonic frequencies with greater magnitude of 5th, 7th ,11th, and 13th order are presented in the network.

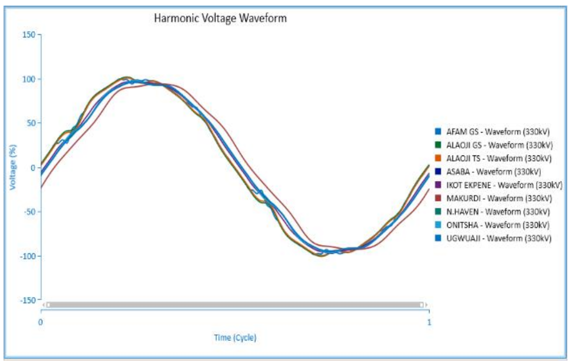

Figure 3. Harmonic Plot without Filter

Figure 3 shows voltage waveforms of all nine (9) buses without filter simulated with harmonic load flow analysis. It can be observed that the most distorted wave form was Afam Gs (330 kV) followed by Alaoji Gs (330kV), and Alaoji Ts (330kV). The reason is that the aforementioned buses are closer to the harmonic source (see appendix I for individual plot).

4.5 Eliminating of Harmonic Distortion

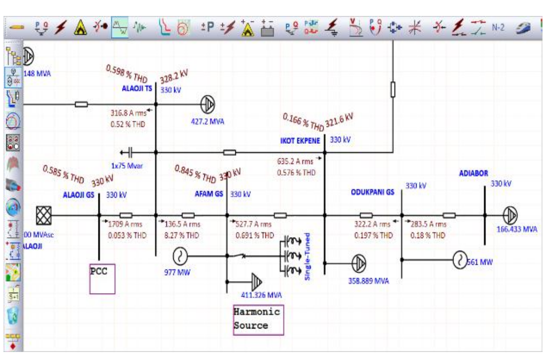

Figure 4. Harmonic Load Flow with Single Turned Filter

Figure 4 shows harmonic load flow with single-tuned filter are chosen to eliminate harmonics distortion for this using ETAP, the filter is designed to provide sufficient reactive power to the power network and minimize the losses at the fundamental frequency. This filter automatically calculates parameter value depending on the modelling of the filter. Single-Tuned filter is selected because it can be sized directly from the drop-down option using Harmonic Filter Sizing option. From the harmonic load flow alert view, in table 3 shows four (4) harmonics of orders 5th, 7th 11th and 13th which are contributing to the harmonic distortion problem in the network. This means, in an attempt to mitigate the harmonic distortion in the four (4) harmonic order will enhanced reliable power supply when the distortion is eliminated. For this paper, three (3) single tuned filters are designed each for a particular harmonic order (see appendix J for filter sizing calculations).

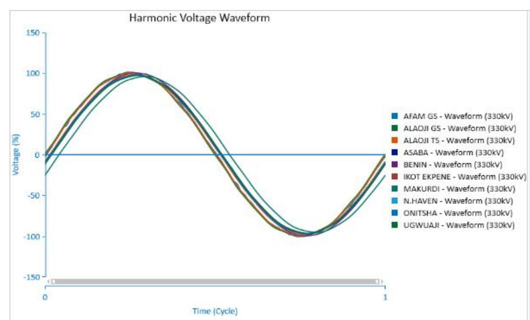

Figure 5. Harmonic Plot with Filter

Figure 5 shows the voltage waveforms of all the nine (9) buses with three (3) single turned filters simulated with harmonic load flow analysis. It is observed that with the proper sizing of the single turned filters eliminated harmonic distortion from the buses as the wave form becomes smooth. It can be made smoother by designing single tuned filter for other harmonic order where the IHD and THD exceeds their limits.

5. Conclusion

Deregulation of the Nigerian power system has led to increase in down-time particularly to the power quality to the industry, commercial/residential consumptions to the point of utilization. The data collected from the study case harmonic frequency simulation was carefully studied. Harmonic modeling is a mathematical way of predicting harmonic distortion levels and potential reference on the networks since power quality has been affected by harmonic distortion of voltage and currents with its attendant unpleasant consequences due to the increasing use of power electronics devices and equipment (variable speed drives, uninterruptible power supplies (UPS) and static power converters as well as large number of industrial loads).

The simulated single line diagram (ETAP) is captured in figure 2 which shows section of the harmonic load flow which shows the degree of proliferation by introduction of several kind of systems that have negative effects on the network which shows 5^{th}, 7^{th}, 11^{th} and 13^{th} order harmonic in the network. Figure 4 shows the voltage waveform of all the nine (9) buses without filter simulated. The most distorted waveform is Afam GS (330kV) followed by Alaoji GS (330kV) and Alaoji TS (330kV), this is because the buses are closer to the harmonic buses. Evidently the penetration with single-tuned filer is designed to eliminate harmonics distortion to give a sinusoidal smooth waveform when the distortion are eliminated this will thereby improve power quality and voltage profile to enhance better system performance.

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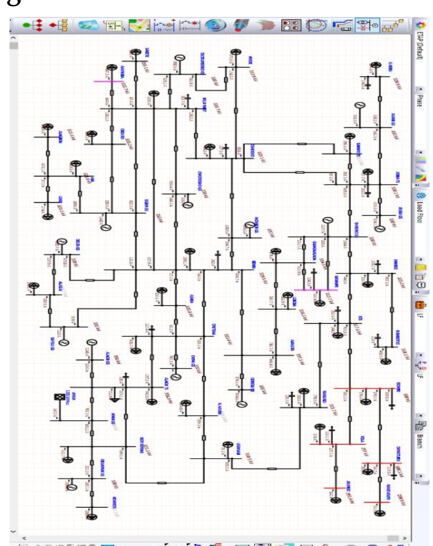
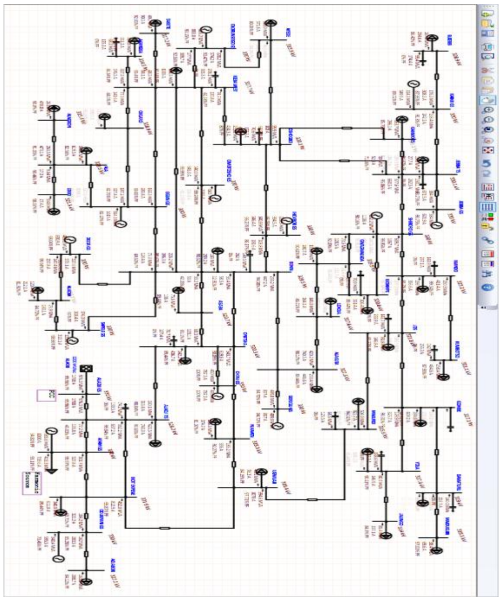
Appendix A

Load Flow Simulation Single Line Diagram for Pre-Upgrade Network



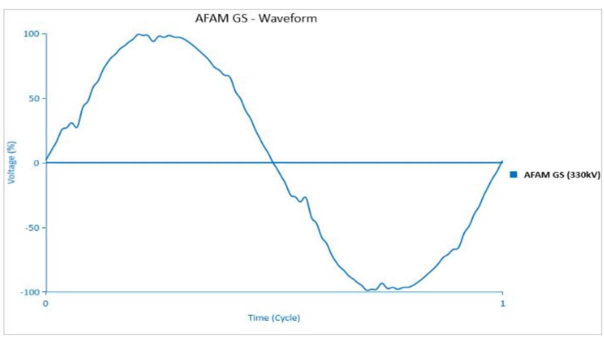
Appendix B

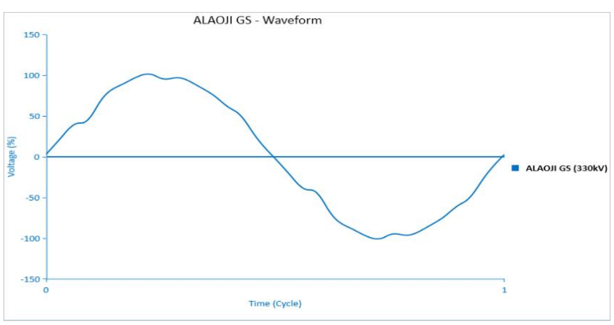
Load Flow Simulation Single Line Diagram for Post-Upgrade Network

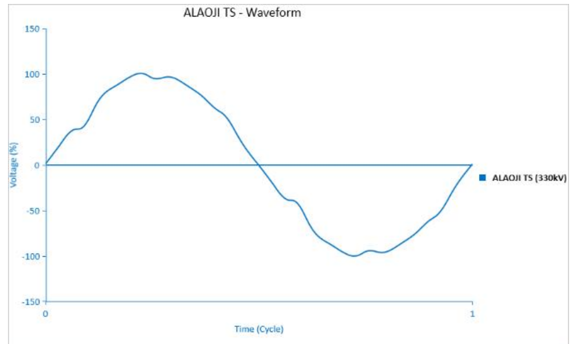


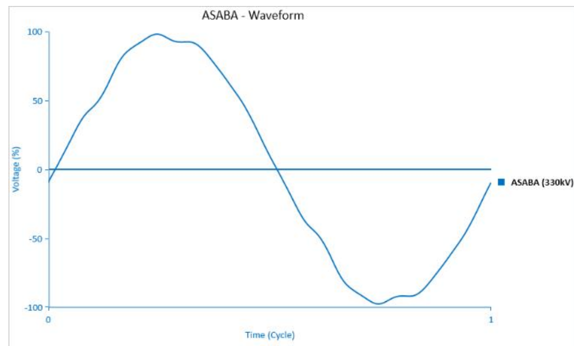
Appendix C

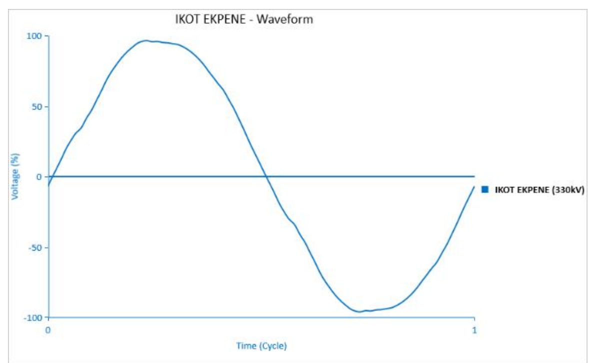
Individual Wave Form

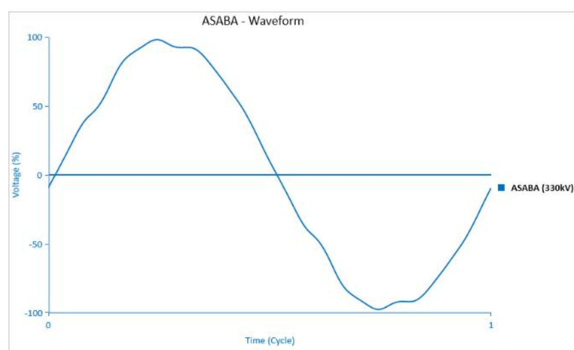


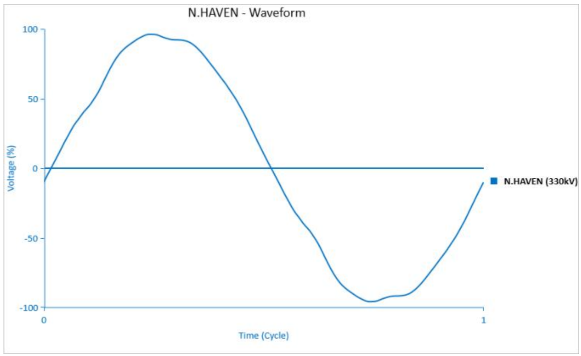


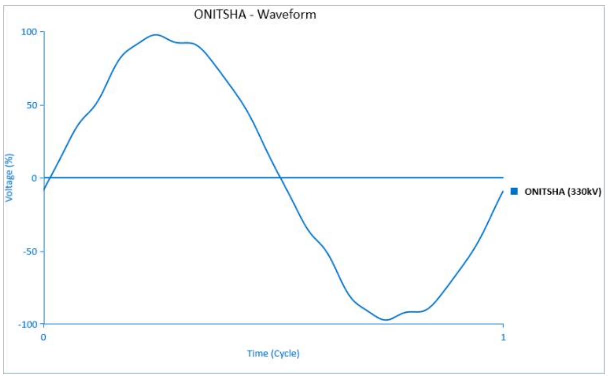


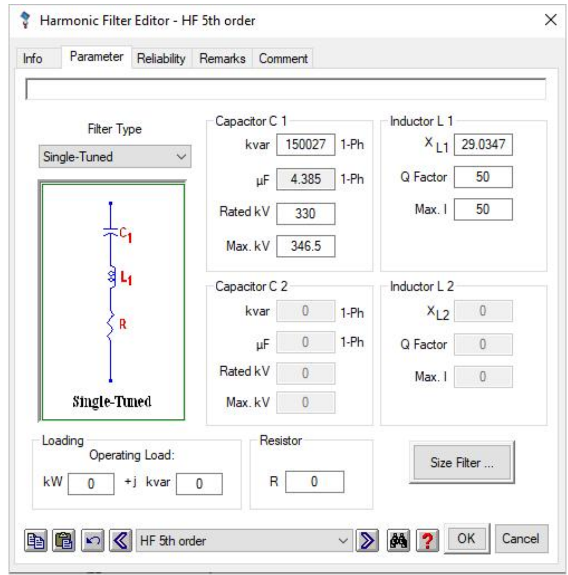












Appendix D

Filter Sizing Parameter

Rated kV=330kV

Max.kV=1.05*330kV=346.5kV

Max.I=50A

Qfactor=30-60

Harmonic Order=5

Harmonic Current=37.9A

Existing P.F=93.11

Desired P.F=100

Load MVA=411.3MVA