

is essential for ensuring the reliability, efficiency, and longevity of transformers in power systems.

Power quality refers to the consistency and stability of the voltage, frequency, and waveform of electricity supplied to consumers. It is influenced by a variety of factors, including grid faults, electrical equipment malfunctions, and the integration of non-linear loads that generate harmonics. Voltage sags, which are short-duration reductions in voltage, are one of the most common power quality disturbances and can occur due to short circuits, equipment failures, or switching operations in the power grid (Srinivas et al., 2013). These disturbances, even if brief, can have detrimental effects on sensitive electrical equipment, particularly transformers, which are highly susceptible to thermal and electrical stresses.

Harmonics, another prevalent power quality issue, are caused by non-linear loads such as rectifiers, variable speed drives, and electronic equipment that draw current in a non-sinusoidal manner. Harmonics distort the current waveform, creating additional losses in electrical systems, including transformers (Zhang et al., 2016). Transformer cores and windings, which are designed to handle pure sinusoidal waveforms, are particularly vulnerable to the effects of harmonic currents, leading to increased eddy current losses, heating, and potential insulation failure (Bose & Hall, 2012). Additionally, transients, which are short-duration high-frequency disturbances, can result from switching operations, lightning strikes, or faults in the electrical system. These events can induce voltage spikes and oscillations that stress transformer insulation, potentially causing breakdowns and failures (Liu et al., 2018).

The increasing integration of renewable energy sources, such as solar and wind power, into the grid has further exacerbated power quality concerns. These energy sources often introduce voltage fluctuations, frequency variations, and harmonics due to their intermittent nature and the use of power electronics for integration with the grid (Lopes et al., 2018). The widespread adoption of electric vehicles (EVs) and the increasing use of power electronic devices in various industries also contribute to the rising levels of harmonic distortions and transients in the power system (Wu et al., 2020). These developments underscore the need for

more robust and resilient power systems capable of withstanding power quality disturbances while ensuring the optimal performance of critical infrastructure, including transformers.

Numerous studies have examined the impact of power quality disturbances on transformer performance, highlighting the importance of understanding these effects for improving the design and operation of transformers. According to (Iyer and Prabhu, 2017), voltage sags can cause transformers to overheat, especially when the load current is high, leading to a reduction in their overall efficiency. Overheating can accelerate the aging of transformer insulation, reducing the transformer's lifespan and potentially resulting in failures that are costly and disruptive to the power supply. In addition, high harmonic content in the power supply can lead to increased losses in the transformer, particularly in the core, where harmonic currents induce additional eddy currents, causing localized heating and reducing efficiency (Fleming & Henry, 2015). The severity of these effects depends on various factors, including the transformer's design, the level of harmonic distortion, and the duration and magnitude of the voltage sags.

While much of the research on power quality disturbances has focused on the impacts on transformer performance in developed countries, there is a growing body of literature addressing the issue in developing regions, including sub-Saharan Africa. In many of these regions, power quality issues are more pronounced due to outdated infrastructure, poor maintenance practices, and the increasing integration of renewable energy sources with inconsistent output characteristics. For instance, a study by (Okoro et al., 2020) on the Nigerian power system found that voltage sags, harmonics, and other power quality disturbances were common in both urban and rural areas, leading to significant operational challenges for transformers and other electrical equipment. Similarly, a study by (Nkongho et al., 2021) in Cameroon highlighted the importance of addressing power quality issues to improve transformer efficiency and reduce operational costs, particularly in areas with frequent grid faults and unreliable power supply.

In response to these challenges, various solutions have been proposed to mitigate the effects of power quality disturbances on transformer performance. One

approach is the use of power quality conditioners, such as active filters and voltage stabilizers, which can help reduce harmonics and mitigate voltage sags (Pechine et al., 2014). These devices can improve transformer efficiency by maintaining stable voltage levels and reducing the additional losses caused by harmonic currents. Additionally, the design of transformers can be optimized to improve their resilience to power quality disturbances. For instance, transformers with advanced insulation systems and improved core materials are better equipped to withstand the thermal and electrical stresses caused by harmonics and voltage fluctuations (Marques et al., 2019).

Moreover, the integration of intelligent monitoring systems into transformers has gained attention as a way to detect and respond to power quality disturbances in real-time. These systems, which use sensors and communication technologies, can monitor transformer temperature, voltage, and current conditions, allowing for early detection of abnormal operating conditions. By providing real-time data on power quality disturbances and transformer performance, these systems enable operators to take corrective actions before transformer damage occurs, thus improving the reliability and longevity of transformers (Saurabh et al., 2016).

The impact of power quality on transformer performance has been the subject of extensive research, and numerous studies have demonstrated the importance of addressing these issues to maintain the reliability and efficiency of power systems. However, despite the growing body of research, there remains a need for further investigation into the specific effects of power quality disturbances on transformer behavior, particularly in the context of developing regions with less reliable power infrastructure. This study aims to contribute to this body of knowledge by developing a comprehensive model to simulate the effects of voltage sags, harmonics, and transients on transformer performance. By using advanced simulation tools, this research will provide valuable insights into the optimal design and protection of transformers, as well as strategies for mitigating the effects of power quality disturbances in real-world power systems.

In conclusion, the increasing prevalence of power quality disturbances presents significant challenges to

the operation and longevity of transformers in electrical power systems. Through a better understanding of these effects and the implementation of appropriate mitigation strategies, it is possible to enhance transformer resilience and ensure the reliable operation of power systems. This study will contribute to these efforts by providing a detailed analysis of the impact of power quality disturbances on transformer performance and offering solutions for improving transformer design and protection.

Materials and Methods

A. Materials

The following are the materials required to carry out this study.

- i. Three Phase Two Windings Transformer
- ii. Transformer Operational Data
- iii. Power Quality Data
- iv. Power Quality Analyzer
- v. MATLAB/Simulink Tools
- vi. ETAP Simulation Tools

B. Method

This study is carried out using the Simscape Electrical Tools in the Simulink library to model the three phase two windings transformer, separating into step up mode, step down mode and isolation mode while undergoing different loading conditions. The output is determined at the visual display and scope. The power quality is then carried out using the ETAP simulation tools to determine its load flow, transient, voltage harmonics and power optimization for the selected system. This involves several systematic steps, including data collection, model development, simulation, validation, and evaluation.

C. Model Equations

The model equations are divided into different components such as the transformer model equations, electrical model equations and the general performance of the system model equation.

Transformer Model Equations

Ideal Transformer Equations

$$\frac{V_p}{V_s} = \frac{N_p}{N_s} \quad 1$$

$$\frac{I_p}{I_s} = \frac{N_s}{N_p} \quad 2$$

$$V_p I_p = V_s I_s \quad 3$$

Real Transformer Model Equations

$$V_p = I_p \cdot (R_p + jX_{L.p}) + \frac{V_s}{a} \quad 4$$

$$V_s = I_s \cdot (R_s + jX_{L.s}) \quad 5$$

Electrical Model

Reactive power

$$Q = VI \sin(\phi) \quad 6$$

Real power

$$P = VI \cos(\phi) \quad 7$$

Overall impedance Equation

$$Z_{s,ref} = \left(\frac{N_p}{N_s}\right) 2 \cdot Z_s \quad 8$$

D. Simulation of Power Quality and Transformer Model

These three phase two windings transformer model with respect to power quality was made from the library tools of Simscape Electrical in the Simulink block components of the MATLAB simulation tools. The specialized power gui was change from continuous to discrete to enable the system respond promptly to different mode set up.

Figure 1 presents the Power quality three phase transformer model in Simulink tools shows the primary windings and secondary windings. The primary side of it is made up of current measurements and voltage measurements as well as the secondary side possessing both current measurement and voltage measurements. This systematic placement of these measuring instrument is to ensure adequate capturing of every quantity of any output made by the transformer either in step up mode, step down mode or isolation mode.

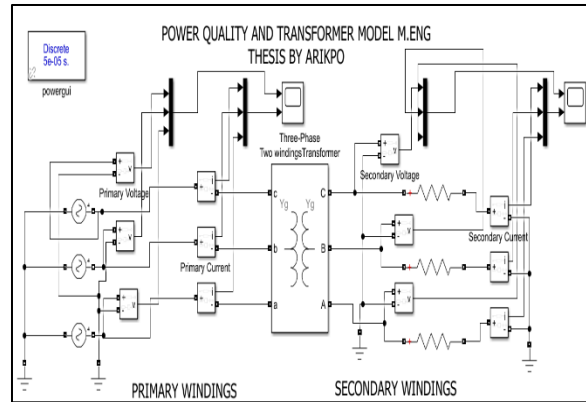


Figure 1. POWER QUALITY THREE PHASE TRANSFORMER MODEL IN SIMULINK TOOLS

The figure 2. presents the power quality single line diagram showing the model, load flow and harmonics. The single line diagram is used to analyse the power quality by using both load flow and harmonics analysis. The harmonics analysis was made possible by integrating harmonic sources like inverters into the line diagram. To determine the power quality in this case, the harmonics factor is very crucial because the harmonics current flows against either the connected grid of generator flow, hence this becomes very important in analysing the quality of the power generated or transmitted.

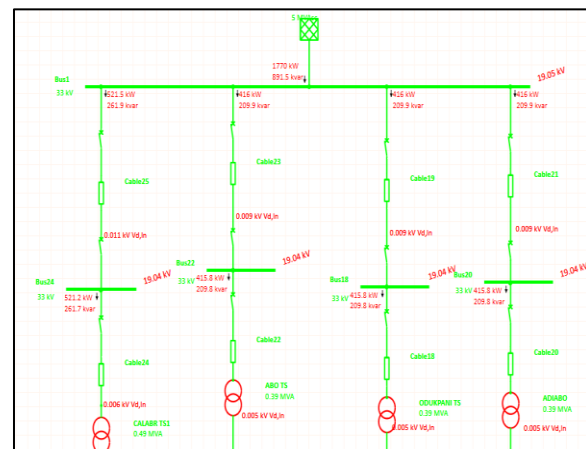


Figure 2. POWER QUALITY SINGLE LINE DIAGRAM SECTIONAL VIEW

Figure 3. presents the response of the single line diagram with respect to harmonics caused by varied loads. Get it straight will enhance power quality of the system.

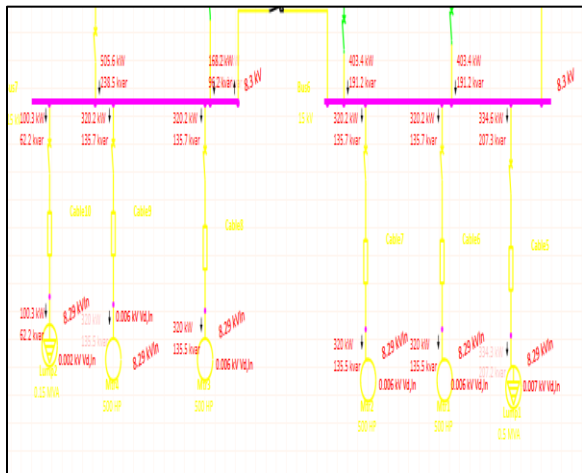


Figure 3. HARMONICS DUE TO VARIED LOADS

Results and Discussion

Figure 4. presents the modelled three phase two winding transformer performance, it showed the performance characteristics of the transformer at its initial state before any form of injection or subtraction. The three phases have their even distribution of magnetic properties throughout the operation process. This was done without the magnitude inclusive but only the phase.

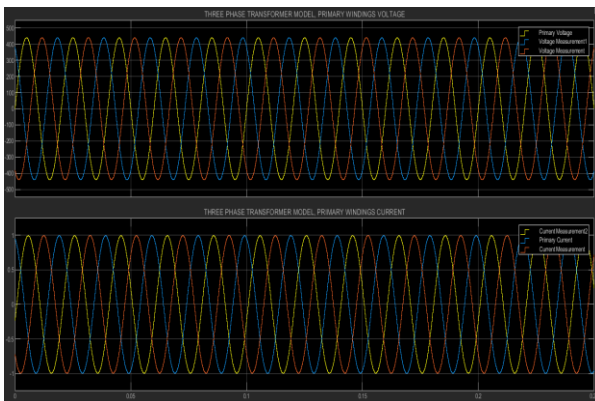


Figure 4. MODELLED THREE PHASE TWO WINDING TRANSFORMER PERFORMANCE

Figure 5. presents the modelled three phase two winding transformer performance in magnitude and phase sequence, here the transformer performance was represented in magnitude and phase sequence. The

primary voltage had both magnitude and phase value but the primary current had only magnitude with no phase. The magnitude was 400V and phase of 100 degrees. At this point, the performance characteristics of the transformer were conversely relative between the primary windings and the secondary windings.

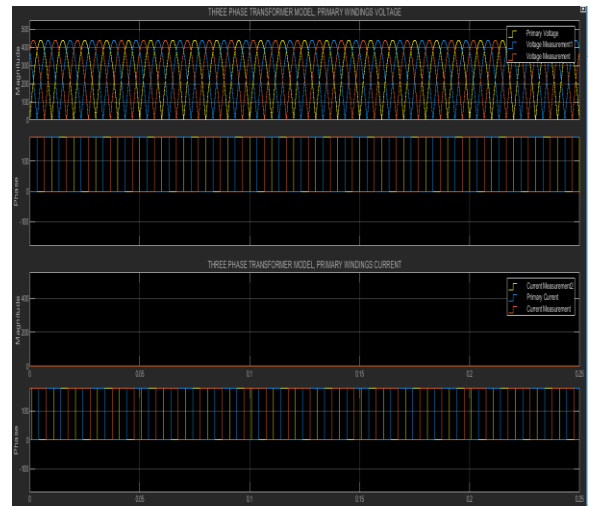


Figure 5. MODELLED THREE PHASE TWO WINDING TRANSFORMER PERFORMANCE IN MAGNITUDE AND PHASE SEQUENCE

Figure 6. presents the three-phase transformer two windings model in step down mode, both secondary voltage and currents had the same amplitude of display at a frequency of 50Hz. This signifies a balanced output power from the transformer during operations.

Figure 7. presents the three-phase transformer two windings model in step down mode with respect to magnitude and phase representations. Both magnitude and phase values were obtained. The magnitude for secondary voltage and current were 400V, 3A and the values for both phase voltage and phase currents were 120 and 100 electrical degrees. This illustrates why the transformer can with stand different load variations without failure.

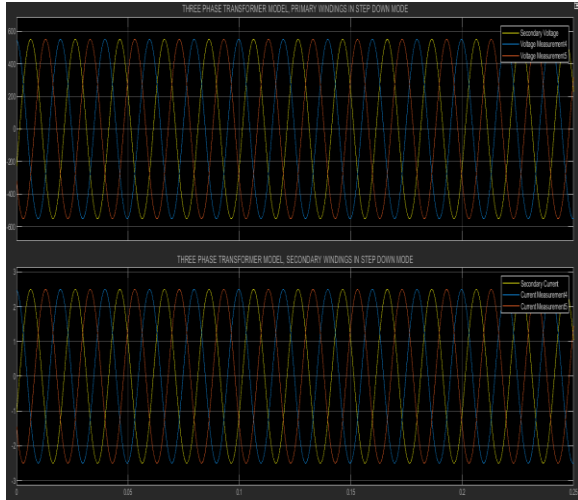


Figure 6. THREE PHASE TRANSFORMER TWO WINDINGS MODEL IN STEP DOWN MODE 1

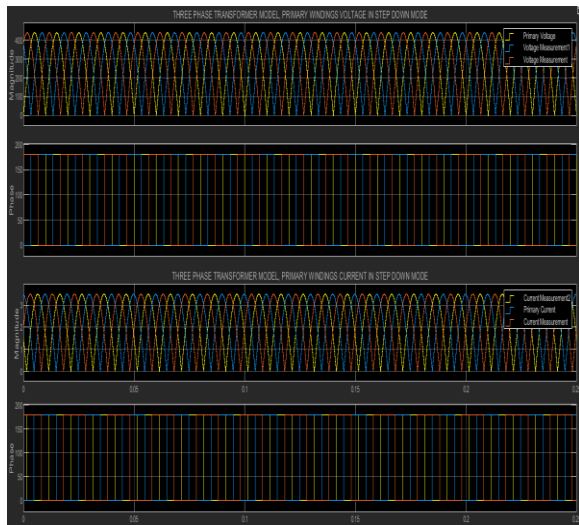


Figure 7. THREE PHASE TRANSFORMER TWO WINDINGS MODEL IN STEP DOWN MODE 2

Figure 8. presents the three-phase transformer two windings model in step up mode, both secondary voltage and currents had the same amplitude of display at a frequency of 50Hz. This signifies a balanced output power from the transformer during operations.

Figure 9. presents the three-phase transformer two windings model in step down mode with respect to magnitude and phase representations. Both magnitude and phase values were obtained. The magnitude for secondary voltage and current were 400V, 3A and the values for both phase voltage and phase currents were

120 and 100 electrical degrees. It gives room for real and reactive power transformation. This illustrates why the transformer can with stand different load variations without failure.

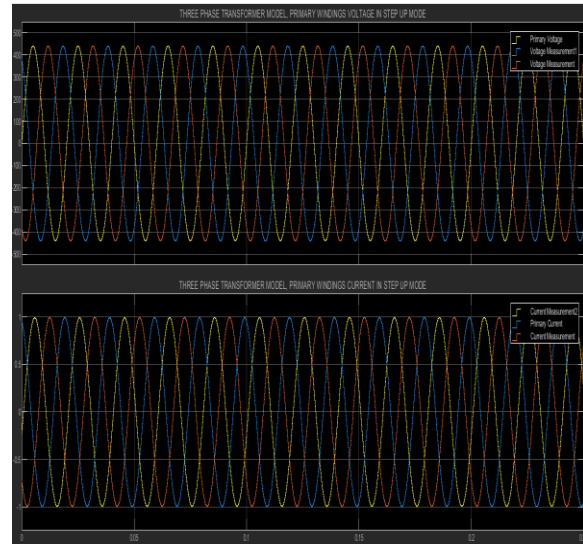


Figure 8. THREE PHASE TRANSFORMER TWO WINDINGS MODEL IN STEP UP MODE

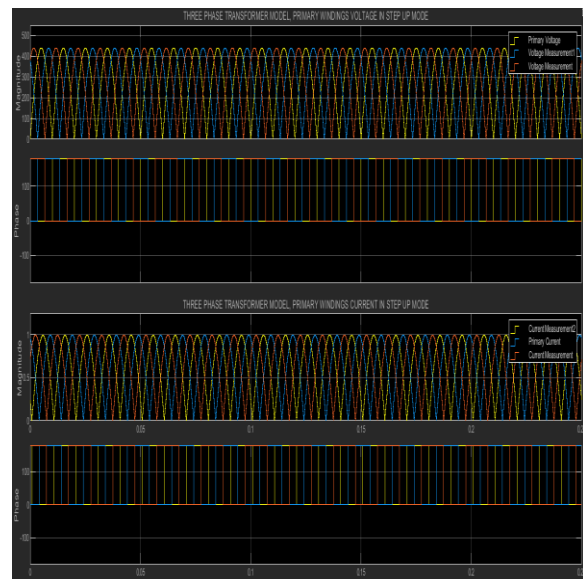


Figure 9. THREE PHASE TRANSFORMER TWO WINDINGS MODEL IN STEP UP MODE IN MAGNITUDE AND PHASE REPRESENTATION

Figure 10. presents the isolated modeled three phase two winding transformer performance, this showed the output performance of the simulated three phase two

windings transformer when the transformer was operating under the isolation mode. During this period, the system tends to be in an ideal state where both primary and secondary inputs and outputs were equal.

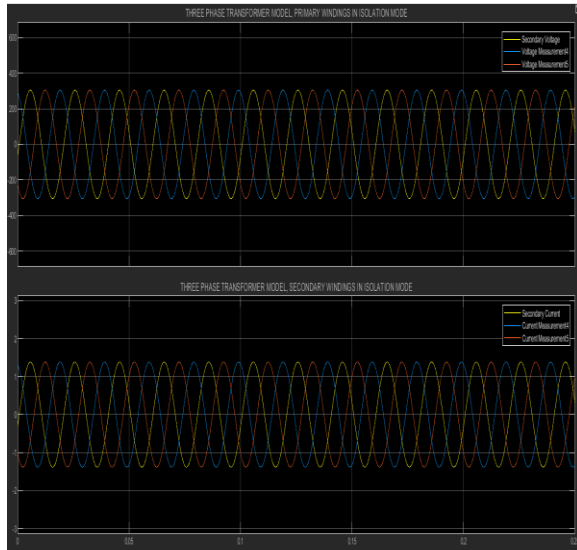


Figure 10. ISOLATED MODELED THREE PHASE TWO WINDING TRANSFORMER PERFORMANCE

Figure 11. presents the isolated modeled three phase two winding transformer performance, this showed the output performance of the simulated three phase two windings transformer when the transformer was operating under the isolation mode. During this period, the system tends to be in an ideal state where both primary and secondary inputs and outputs were equal. Both voltage and current magnitudes of the windings were 30V and 30A. Their phase representations were 100 degrees electrical.

Figure 12. presents the modelled three Phase two winding transformer performance at saturation, at this point both windings got saturated while the transformer was in operation. This level of saturation compensates ideally on the power quality output of the transformer. This entire process started at point zero and progressed to point 0.25 which represents one quarter of the quality of power produced by the transformer.

Figure 13. presents the simulated output power quality waveform, it shows the kind of power quality that the modelled system gave out. Using bus 1 and bus 4 in the single line diagram of load flow and harmonics

analysis, the output of bus 1 started at origin 0.00 and progressed up to point 100 while the output of bus 4 started at point -50 and progressed positively to a maximum point of 100. From this, it can be deduced that the power quality from bus 4 is higher and better than that of bus 1 but bus 1 has less harmonic effect on the model.

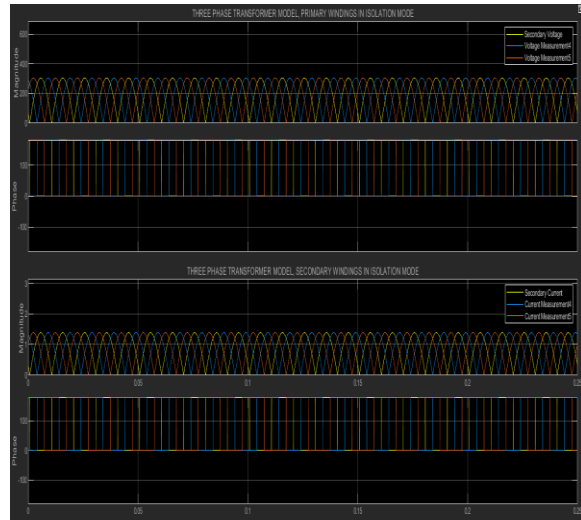


Figure 11. ISOLATED MODELLED THREE PHASE TWO WINDING TRANSFORMER PERFORMANCE PRESENTED IN MAGNITUDE AND PHASE

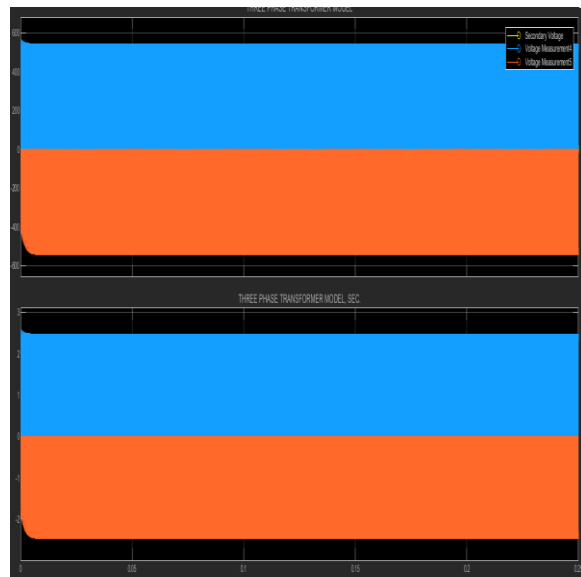


Figure 12. MODELLED THREE PHASE TWO WINDING TRANSFORMER PERFORMANCE AT SATURATION

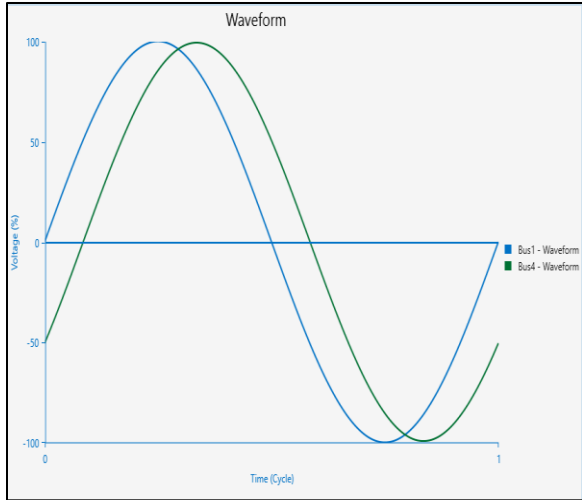


Figure 13. SIMULATED OUTPUT POWER QUALITY WAVEFORM

TABLE I

Bus Loading Summary Report

Bus ID	kV	Rated	Directly Connected Load						Total Bus Load				
			Constant kVA		Constant Z		Constant I		Generic		MVA	%	Amp
			MW	Mvar	MW	Mvar	MW	Mvar	MW	Mvar			
Bus1	33.000								1.982	89.3	34.7		
Bus6	15.000								1.086	89.8	43.6		
Bus7	15.000								1.005	90.4	40.4		
Bus8	15.000		0.320	0.136					0.347	92.1	14.0		
Bus9	15.000		0.082	0.051	0.019	0.012			0.118	85.0	4.7		
Bus10	15.000		0.320	0.136					0.347	92.1	14.0		
Bus11	15.000		0.320	0.136					0.347	92.1	14.0		
Bus12	15.000		0.320	0.136					0.347	92.1	14.0		
Bus13	15.000		0.272	0.169	0.062	0.039			0.393	85.0	15.8		
Bus14	15.000												
Bus17	33.000								0.466	89.3	8.2		
Bus18	33.000								0.466	89.3	8.2		
Bus19	33.000								0.466	89.3	8.2		
Bus20	33.000								0.466	89.3	8.2		
Bus21	33.000								0.466	89.3	8.2		
Bus22	33.000								0.466	89.3	8.2		
Bus23	33.000								0.583	89.4	10.2		
Bus24	33.000								0.513	89.4	10.2		

* Indicates operating load of a bus exceeds the bus critical limit (100% of the Continuous Amps rating).

Indicates operating load of a bus exceeds the bus marginal limit (95% of the Continuous Amps rating).

TABLE II

Simulated Load Flow Report for Power Quality modeled

Bus ID	kV	Voltage		Generation		Load		Load Flow				XFMR	
		%Mag	Ang	MW	Mvar	MW	Mvar	ID	MW	Mvar	Ang	%PF	%Tap
Bus1	110.000	100.000	0.0	0	0	0	0	Bus1	-2.979	-0.030	15.6	100.0	
								Bus3	2.979	0.030	15.6	100.0	
*Bus2	110.000	100.000	0.0	2.979	0.030	0	0	Bus1	2.979	0.030	15.6	100.0	
Bus3	110.000	100.000	0.0	0	0	0	0	Bus1	-2.979	-0.030	15.6	100.0	
								Bus5	2.979	0.030	15.6	100.0	
Bus4	11.000	99.325	-30.6	0	0	0	0	Bus5	-2.959	0.000	158.4	100.0	
								Bus6	2.959	0.000	158.4	100.0	
Bus5	11.000	99.334	-30.6	0	0	0	0	Bus4	2.959	0.000	158.4	100.0	
								Bus3	-2.959	0.000	158.4	100.0	
Bus6	11.000	99.311	-30.6	0	0	2.955	0.000	Bus4	-2.959	0.000	158.4	100.0	

* Indicates a voltage regulated bus (voltage controlled or swing type machine connected to it).

Indicates a bus with a load mismatch of more than 0.1 MVA.

Table 1. presents the different bus loading capacities for the selected single line diagram. Twenty-four buses were considered here but only six of it were used to ascertain the harmonics level in order to improve the power quality of the network system.

Table 2 presents the simulated load flow report for power quality modelled, showed the fundamental load flow report obtained from the single line diagram analysis. There were six buses involved in the process, the load flow had voltage regulation encounter at bus 2 and this makes the system unique for this purpose of yielding a dependable quality of power output.

TABLE III

SIMULATED SYSTEM HARMONICS BUS REPORT FOR POWER QUALITY

Bus ID	kV	Voltage Distortion								
		Fund	RMS	ASUM	THD	TIF	THD	TSHD	THDC	THDS
		%	%	%	%	%	%	%	%	
Bus1	110.000	100.00	100.00	100.00	0	0.42	0.00	0.00	0.00	0.00
Bus2	110.000	100.00	100.00	100.00	0	0.42	0.00	0.00	0.00	0.00
Bus3	110.000	100.00	100.00	100.00	0.01	0.42	0.00	0.00	0.00	0.00
Bus4	11.000	99.32	99.32	99.32	0	0.42	0.00	0.00	0.00	0.00
Bus5	11.000	99.33	99.33	99.33	0	0.42	0.00	0.00	0.00	0.00
Bus6	11.000	99.31	99.31	99.31	0	0.42	0.00	0.00	0.00	0.00

* Indicates THD (Total Harmonic Distortion) Exceeds the Limit.

Indicates THD (Individual Harmonic Distortion) Exceeds the Limit.

Table 3. simulated system harmonics bus report for power quality, it showed that total harmonic distortion was experienced in bus 3, while the quality of power analyzed from the system was unique for bus1 and bus

2. The variation between other buses was just a 1% value.

TABLE IV
SIMULATED SYSTEM HARMONICS BREACH REPORT
FOR POWER QUALITY

Bus		Current Distortion											
From Bus ID	To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %	TIF	IT Amp	ITn Amp	ITn Amp	THD %	TSHD %	THDG %	IT
Bus1	Bus2	15.64	15.64	15.64	0	0.50	7.82	7.82	0.00	0.00	0.00	0.00	
	Bus3	15.64	15.64	15.64	0	0.50	7.82	7.82	0.00	0.00	0.00	0.00	
Bus2	Bus1	15.64	15.64	15.64	0	0.50	7.82	7.82	0.00	0.00	0.00	0.00	
	Bus5	15.64	15.64	15.64	0	0.50	7.82	7.82	0.00	0.00	0.00	0.00	
Bus3	Bus1	15.64	15.64	15.64	0	0.50	7.82	7.82	0.00	0.00	0.00	0.00	
	Bus5	15.64	15.64	15.64	0	0.50	7.82	7.82	0.00	0.00	0.00	0.00	
Bus4	Bus5	156.37	156.37	156.37	0	0.50	78.19	78.19	0.00	0.00	0.00	0.00	
	Bus6	156.37	156.37	156.37	0	0.50	78.19	78.19	0.00	0.00	0.00	0.00	
Bus5	Bus4	156.37	156.37	156.37	0	0.50	78.19	78.19	0.00	0.00	0.00	0.00	
	Bus3	156.37	156.37	156.37	0	0.50	78.19	78.19	0.00	0.00	0.00	0.00	
Bus6	Bus4	156.37	156.37	156.37	0	0.50	78.19	78.19	0.00	0.00	0.00	0.00	

Table 4. presents the simulated system harmonics breach report for power quality, it showed that the quality of power generated, transmitted and distributed had two branches of harmonics distortions. Branch 1 includes bus1, bus2 and bus 3 while branch 2 includes bus 4, bus 5 and bus 6. The total harmonics distortion here was 0%, this indicates that the quality of power was good free from associated losses.

Conclusions

This study investigates the performance of transformers under various power quality disturbances, such as voltage sags, swells, harmonics, and transients. It aims to develop a comprehensive understanding of how these disturbances affect transformer longevity and reliability. The research provides a significant contribution to transformer performance and power quality research by addressing several critical gaps. The comprehensive analysis of long-term transformer degradation due to power quality disturbances and the integration of renewable energy sources is a key contribution to enhancing transformer reliability. The study's development of advanced harmonic mitigation strategies, real-time monitoring models, and eco-friendly transformer designs offers valuable insights for improving power systems. Additionally, the integration of simulation tools for a holistic understanding of transformer behavior is a noteworthy step towards more

accurate predictions and better-informed maintenance strategies. Ultimately, the research will aid in the creation of more resilient, sustainable, and efficient transformers, supporting the stability and growth of electrical grids worldwide.

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