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Investigation of Electrical Energy Efficiency and Current Harmonic Mitigation of Electrical Drive: A Case Study of Sunti Golden Sugar Company Nigeria

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ORIGINAL RESEARCH

Abstract— The sustainability of any nation's development depends on an adequate and consistent supply of energy. However, using and converting primary energy leads in energy waste, which raises the cost of energy. The study focused on energy audit and power quality issues at Sunti Golden Sugar Company (SGSC) since it has been observed that, on average, 45.12kWh of energy is needed to crush one ton of sugarcane, compared to the suggested standard of 35kWh. During the plant tour, sources of energy waste were noted, including the use of underloaded motors. In addition, the issues with harmonics in the power system brought on by the significant number of non-linear loads frequently result in motor overheating. This leads to motor burnout, as well as false tripping of protective relays, which results in an unnecessary downtime. Similarly, certain standard motors that were underloaded were found using the Motor Master software, and proper replacement with premium energy-efficient motors was recommended. As a result of replacing ordinary motors with energy-efficient motors, that is, replacing under-load motors with properly sized motors, payback period ranging from 1.17 to 5.85 years, the energy savings of 71,605kWh/year and cost savings of €3,938.00 per year which is equivalent to ₦3,256,579.05 was achieved. Shunt Hybrid Power Filters (SHPF) are designed and simulated in order to reduce current harmonics using MATLAB/Simulink software. As a result, the Total Harmonics Distortion (THD)% for Current Source Inverter (CSI) is reduced for the source current from 20.41% to 7.33% and the load current from 24.31% to 7.44%, respectively. While in the case of Voltage Source Inverter (VSI), the THD% is reduced from 17.99% to 6.67% for supply current and 20.20% to 9.62% for load current, respectively.
Keywords— Energy Audit, MATLAB Simulation, Power Quality, Shunt Hybrid Power Filter, THD%.

1 Introduction

Manufacturing industries are regarded as the foundation of both general and economic growth (Michael Appiah et al., 2023). It is impossible to overstate how crucial industrial growth is to reducing unemployment and poverty in any country (Racheal & Uju, 2018). And nation's economic strength can be determined by tracking the growth of its manufacturing sector (Radetzki, Marian & Wårell, 2022). Developing nations are always affluent because they convert their raw materials into higher-value finished goods. Such a nation must guarantee that its goods are of the highest quality if it is to maintain its competitiveness in the international market.

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Electrical energy has a crucial part in determining energy conservation strategies, as well as in the economic development of a nation and the standard of living of its population (Bukarica & Tomšić, 2017). Energy audit offers a solution on how electrical energy should be used and potential conservation opportunities in boosting energy efficiency of any company (Mohammed et al., 2018). In contrast to the rising energy demand and pricing. When it comes to the cost of producing goods and services in the industrial sectors, around 35 to 45% of the potential for energy conservation is identified or observed in this sector. As a result, there is a need for more efficient energy systems. The performance of electrical distribution businesses was improved with the introduction of a new incentive regulation structure (Mostaghim et al., 2017). It makes use of several efficiency evaluations and a three-dimensional reward-penalty system. Each company's permitted revenues for the upcoming regulatory period are determined by efficiency assessments based on the efficiency outcomes.

As the primary component needed for all commercial and industrial functions, electrical power must always be accessible (Grigg, 2010). Power quality refers to a set of factors that describe the qualities of the power supply as it is provided to customers under typical operating conditions,

including the reliability of the supply and voltage characteristics like frequency, magnitude, wave form, and symmetry (Bagdadee et al., 2020). In recent years, power quality has become a challenge that affects both technical and financial aspects. Numerous studies have demonstrated that industrial sectors suffer significant economic losses due to poor power quality. Furthermore, the electrical system's low power quality wastes a significant amount of energy (Beleiu et al., 2018).

Engineers in the power sector now face problems with power quality due to nonlinear loads in the distribution system (Chindris et al., 2017). Because of the advancements in semiconductor technology, the use of power electronics devices at the end user side is expanding significantly. The usage of power electronics devices leads to issues such as heating of devices, reactive power disturbance, disturbance to other consumers, harmonic production, poor power factor, low system efficiency, and so forth (Abas et al., 2020; Mohammadi & Shamsi Nejad, 2021). The need to reduce these issues is crucial because this negative influence could grow significantly in the near future. In order to reduce harmonic content in electrical supply systems with active power filters, researchers in (Adejumobi et al., 2017; Mobarrez et al., 2021), (Deshpande, 2021) demonstrate how filtering and active rectifier are necessary for drives in the industry. The authors of (Haseeb et al., 2023; Kularbphettong & Boonseng, 2020; Mishra et al., 2021) suggest employing hybrid power filters to increase the power quality by using harmonic current for all power supply units and ac drives.

The daily energy consumption of Sunti Golden Sugar Company is roughly 72,464 kWh, while the monthly consumption is roughly 2,173,920 kWh. According to the data, 1000 kg of cane requires 45.12kWh of energy to crush, as opposed to the typical 32–33kWh. Due to losses and the inefficient use of electrical energy that could have been put to better use, it is obvious that Sunti Golden Sugar Company's (SGSC) energy consumption status is inefficient; as a result, an energy audit and power quality improvement are required. The harmonic is another main issue at SUNTI Sugar Company. Consecutive heating causes the electric motors to overheat, which causes them to burn out. Furthermore, the company experiences issues with falsely tripping protective relays, which slows down the company's production process unnecessarily.

In order to minimize current harmonics in the facility's electric drive systems and increase electrical energy efficiency, the study set out to examine problems in the particular context ofSunti Golden Sugar Company, pinpoint their underlying causes, and offer remedies. The sugar industry's electric drives' energy efficiency in the Nigerian environment has not been extensively studied. Inadequate case studies comparing various energy-efficient systems for the processing of sugar in poor nations. Additionally, there is a lack of information regarding the sugar industry's long-term economic and environmental effects of energy-efficient electric drives(Kalantzis & Revoltella, 2019; Petek et al., 2015; Yaw et al., 2017).
The highlight of the study's demonstrates how productivity and power quality could account for expenditures in energy-saving and harmonic mitigation devices, resulting in long-term financial savings.

2 Methodology

2.1 Electric motor analysis

The majority of electric motors are built to operate between 50% and 100% of rated load. Typically, maximum efficiency is within 75% of rated load. Below roughly 50% load, a motor's efficiency tends to decline significantly. The range of good efficiency, however, differs for each motor and has a tendency to cover a wider range for larger motors. A corporation can decide when to replace motors and which replacements to select by determining whether its motors are correctly loaded.

Based on a survey conducted at the Sunti Sugar Company and a test of all electric motors with an

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annual operating time of over 1000 hours. The software Motor Master+ was used to conduct the analysis.

For replacement of oversized and underloading analysis, the Motor Master program is used. It has a correction algorithm, so when the replacement motor's nameplate full-load speed is entered, the load increase or decrease is automatically determined. The annual energy and monetary savings as well as the quick return on investment from purchasing a new, energy-efficient motor are thus calculated using the change effects.

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2.1.1 Motor Loading Estimation

The estimation is done using direct read power measurement of the motor parameters from the hand-held devices and the needed power when operating at rated capacity. Using the kilowatt ratio technique, the motor load was estimated as:

$$Loading = \frac{P_i}{P_{ir}} \qquad (1)$$

where P_i is the measured three-phase power in kW and P_{ir} is the power at full-rated load in kW. The measure power depends on power factor, rms voltage and current, while the full-rated load power depends on the nameplate horsepower and efficiency at the full-rated load.

All of the factory's motors' percentage loading is estimated and examined using the motor nameplate specifications. As shown in Fig. 1 for the 1.5 KW motor, the motor master+ international program was used to examine the underloaded motors whose percentage loading is less than 50%.

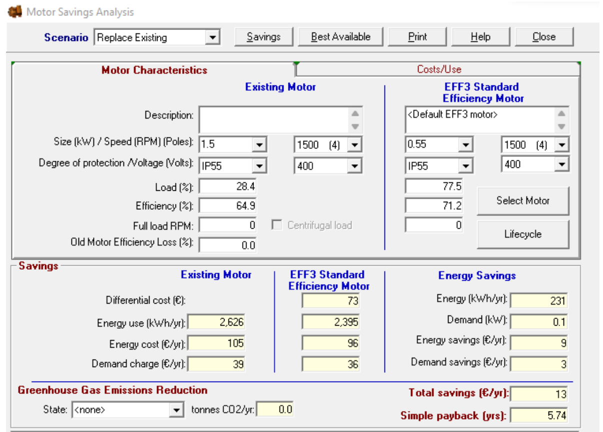

Fig. 1. Motor saving analysis for 1.5 KW motor

Fig. 1 illustrates the annual energy and cost savings from switching from a 1.5kW existing motor to a 0.55kW standard efficiency motor with a simple payback period of 5.74 years.

2.2 Modeling of Shunt Hybrid Power Filter

The a,b,c reference frame for a time varying and the d-q model of nonlinear loads are model based on Fig. 2.

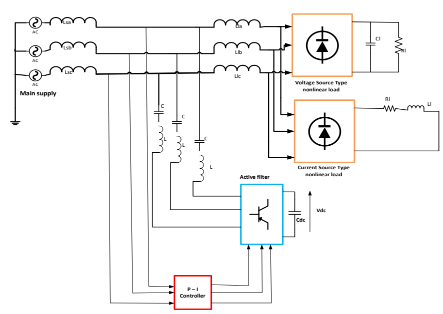

Fig. 2. Three-phase SHPF with voltage and current source nonlinear.

The converter voltage and current for a time varying and nonlinear model assumed a balanced three-phase system are given as

$$V_{sn} = L_{PF}\frac{di_{cn}}{dt} + R_{PF}i_{cn} + \frac{1}{C_{PF}}\int i_{cn}dt + V_{nM} + V_{MO} \qquad (2)$$

for $n = 1, 2, 3$

$$\frac{V_{sn}}{dt} = L_{PF}\frac{d^2 i_{cn}}{dt^2} + R_{PF}\frac{di_{cn}}{dt} + \frac{1}{C_{PF}}i_{cn} + \frac{dV_{nM}}{dt} + \frac{dV_{MO}}{dt}$$
(3)

Assumed zero sequence current is absent then

$$V_{MO} = -\frac{1}{3}\sum_{n=1}^{3} V_{nM} \qquad (4)$$

The converter switching function f_n of n[th] legs are assumed binary state of the two switches S_n and $S_n^{'}$.

Therefore, the switching f_n (for $n = 1, 2, 3$) is define as (Abel et al., 2023)

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$$\begin{cases} f_n = 1 \, if \; S_n \; is\, ON \; and \; S_n^{'} \; is \, OFF \\ f_n = 0 \, if \; S_n \; is \, OFF \; and \; S_n^{'} \; is \, ON \end{cases} \quad (5)$$

Thus combine this $V_{nM} = f_n V_{dc}$ and from (4) the following is obtained

$$\frac{d^2 i_{cn}}{dt^2} = \frac{R_{PF}}{L_{PF}} \frac{di_{cn}}{dt} - \frac{1}{C_{PF} L_{PF}} i_{cn} - \frac{1}{L_{PF}} \left(f_n - \frac{1}{3} \sum_{m=1}^{3} f_m \right) \frac{dV_{dc}}{dt} + \frac{1}{L_{PF}} \frac{dV_{fn}}{dt} \quad (6)$$

Thus, the switching can be defined as

$$q_{kn} = \left(f_n - \frac{1}{3} \sum_{m=1}^{3} f_m \right)_k \quad (7)$$

But q_{kn} depend on the switching state k and on n phase. And the interaction between phases is given as

$$\begin{cases} q_{k1} = \frac{2}{3} f_1 - \frac{1}{3} f_2 - \frac{1}{3} f_3 \\ q_{k2} = -\frac{1}{3} f_1 + \frac{2}{3} f_2 - \frac{1}{3} f_3 \\ q_{k3} = -\frac{1}{3} f_1 - \frac{1}{3} f_2 + \frac{2}{3} f_3 \end{cases} \quad (8)$$

$$\begin{bmatrix} q_{k1} \\ q_{k2} \\ q_{k3} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} \quad (9)$$

Therefore, the DC component analysis of the system is given as

$$dV_{dc} = \frac{1}{C_{dc}} i_{dc} = \frac{1}{C_{dc}} \sum_{n=1}^{3} q_{kn} i_{cn} \quad (10)$$

Similarly, the first two in (12) can be expressed as

$$\frac{d^2}{dt^2} [i_{c12}] = -\frac{R_{PF}}{L_{PF}} \frac{d}{dt} [i_{c12}] - \frac{1}{C_{PF} L_{PF}} [i_{c12}] - \frac{1}{L_{PF}} [q_{k12}] \frac{dV_{dc}}{dt} + \frac{1}{L_{PF}} \frac{d}{dt} [v_{f12}] \quad (17)$$

The reduced conversion constant is given as

Thus, for a balanced system based in i_n and q_{kn}

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} (2q_{k1} + q_{k2}) i_{c1} + \frac{1}{C_{dc}} (2q_{k1} + q_{k2}) i_{c2}$$
(11)

Consider (5), (6) and (9) with (14) leads to the following which is the complete model of the active filter

$$\begin{cases} L_{PF} \frac{d^2 i_{c1}}{dt^2} = -R_{PF} \frac{di_{c1}}{dt} - \frac{1}{C_{PF}} i_{c1} - q_{k1} \frac{dV_{dc}}{dt} + \frac{dV_{f1}}{dt} \\ L_{PF} \frac{d^2 i_{c2}}{dt^2} = -R_{PF} \frac{di_{c2}}{dt} - \frac{1}{C_{PF}} i_{c2} - q_{k2} \frac{dV_{dc}}{dt} + \frac{dV_{f2}}{dt} \\ C_{dc} \frac{dV_{dc}}{dt} = (2q_{k1} + q_{k2}) i_{c1} + (2q_{k1} + q_{k2}) i_{c2} \end{cases}$$
(12)

The d-q reference frame model

The transformation constant is given as

$$K_{dq}^{123} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{4\pi}{3}\right) \\ -\sin\theta & \sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \quad (13)$$

Where $K_{123}^{dq} = \left(K_{dq}^{123} \right)^{-1} = \left(K_{dq}^{123} \right)^T$ (14)

And (11) can be expressed as

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} (q_{k123})^T (i_{c123}) \quad (15)$$

With the transformation constant

$$\frac{dV_{dc}}{dt} = \frac{1}{C_{dc}} \left(K_{123}^{dq} [q_{k123}]^T K_{123}^{dq} [i_{dq}] \right) = \frac{1}{C_{dc}} [q_{k123}] \quad (16)$$

$$K_{dq}^{12} = \sqrt{2} \begin{bmatrix} \cos\left(\theta - \frac{\pi}{6}\right) & \sin\theta \\ -\sin\left(\theta - \frac{\pi}{6}\right) & \cos\theta \end{bmatrix} \quad (18)$$

$$K_{12}^{dq} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\left(\theta - \frac{\pi}{6}\right) & \cos\left(\theta - \frac{\pi}{6}\right) \end{bmatrix} \quad (19)$$

$$K_{dq}^{12} = \left(K_{12}^{dq} \right)^{-1} = \left(K_{dq}^{12} \right)^T \quad (20)$$

Applying the conversion constant

$$\frac{d^2}{dt^2} \left[K_{12}^{dq} [i_{dq}] \right] = -\frac{R_{PF}}{L_{PF}} \frac{d}{dt} K_{12}^{dq} [i_{dq}] - \frac{1}{C_{PF} L_{PF}} K_{12}^{dq} [i_{dq}] - \frac{1}{L_{PF}} K_{12}^{dq} [q_{kdq}] \frac{dV_{dc}}{dt} + \frac{1}{L_{PF}} \frac{d}{dt} K_{12}^{dq} [v_{dq}] \quad (21)$$

And the following are derived

$$\frac{d^2}{dt^2} [i_{dq}] = -\begin{bmatrix} \frac{R_{PF}}{L_{PF}} & -2\omega \\ 2\omega & \frac{R_{PF}}{L_{PF}} \end{bmatrix} \frac{d}{dt} [i_{dq}] - \begin{bmatrix} -\omega^2 + \frac{1}{C_{PF} L_{PF}} & -\omega \frac{R_{PF}}{L_{PF}} \\ \omega \frac{R_{PF}}{L_{PF}} & -\omega^2 + \frac{1}{C_{PF} L_{PF}} \end{bmatrix} [i_{dq}] - \frac{1}{L_{PF}} [q_{kdq}] \frac{dV_{dc}}{dt} + \frac{1}{L_{PF}} \frac{d}{dt} [v_{dq}] + \frac{1}{L_{PF}} \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} [V_{dq}] \quad (22)$$

where $\theta = \omega t$

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Therefore, the complete model of active filter in d-q reference frame is given as

$$\begin{cases} L_{PF}\frac{d^2 i_d}{dt^2} = -R_{PF}\frac{di_d}{dt} + 2\omega L_{PF}\frac{di_d}{dt} - \left(-\omega^2 L_{PF} + \frac{1}{C_{PF}}\right) i_d + \omega R_{PF} i_q - q_{kd}\frac{dV_{dc}}{dt} + \frac{dV_d}{dt} - \omega V_q \\ L_{PF}\frac{d^2 i_q}{dt^2} = -R_{PF}\frac{di_q}{dt} - 2\omega L_{PF}\frac{di_d}{dt} - \left(-\omega^2 L_{PF} + \frac{1}{C_{PF}}\right) i_q - \omega R_{PF} i_d - q_{kq}\frac{dV_{dc}}{dt} + \frac{dV_q}{dt} + \omega V_d \\ C_{dc}\frac{dV_{dc}}{dt} = q_{kd} i_d + q_{kq} i_q \end{cases} \quad (23)$$

3 Results and Discussion

3.1 Factory's Motor Improvement (Replaced with Premium Efficiency Motors)

Table 1. Energy Efficient Motors

No.	Motor's name	kw	Efficiency (η%)	Loading (%)	Energy Cost euro/yr	Energy Saving Kwh/yr	Money Saving euro/yr	Payback period in years
1	Surplus belt conveyor	0.55	71.2	77.5	96	231	13	5.74
2	Ash Inertial Rotary	0.55	71.2	77.5	96	227	12	5.85
3	Back wash pump	1.5	85.2	80	105	231	13	5.74
4	Rotary valve feed silo	0.3	85.2	75.5	56	167	9	4.24
5	Phosphate dosing	0.3	85.2	75.7	56	165	9	4.28
6	ACOP Motor (x2)	1.5	88.3	92	259	3382	186	1.76
7	EOT CT	0.55	99	65.5	83	485	27	2.73
8	Lime bin rotary valve (x2)	0.25	86.1	72	44	203	11	5.72
9	GVC Motor (x2)	0.9	82.2	98.8	187	804	44	2.1
10	Barring gear Motor	4	98.7	77.6	225	3257	179	1.83
11	PH dosing pump (x2)	2.2	92.7	86.5	296	2444	134	2.89
12	SMBC (X2)	3.7	88.6	66.9	447	1106	61	4.58
13	Vacuum filters (x2)	1.1	84.1	91.2	191	801	44	5.12
14	Service water pumps (x3)	15	91.9	67.3	1758	18186	1000	1.29
15	C-Mascuite Liquid	7.5	95.6	92	1218	12012	661	1.28
16	B-Masuite Tr. Motor	7.5	95.6	92	1218	12012	661	1.28
17	Flash tank Recirculation (x2)	5.5	91.2	63	622	5780	318	2.12
18	Mill ACW fan	5.5	91.2	63	622	5780	318	2.12
19	Ash silo	3.7	98.8	71.1	474	4332	238	1.17
	TOTAL					**71,605.00**	**€3,938.00**	

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Table 1 presents the results of using Motor Master + to replace standard motors with energy-efficient motors. Table 1 presents the results of using Motor Master + to replace standard motors with energy-efficient motors. It displays the annual energy savings in kWh and the annual cost savings in euros (71,605kWh and €3,938.00 per year respectively). The Electric motors at various section of the company with power rating, efficiency and loading capability were also presented. It displays the annual energy savings in kWh and the annual cost savings in euros (71,605kWh and €3,938.00 per year respectively).

It is important to replace large, partly loaded motors for smaller, fully loaded and energy-efficient motors. Therefore, replacing standard motors with energy-efficient motors, i.e., replacing under-load motors with correctly sized motors, can result in annual savings of 71,605kWh of energy and €3,938.00, with payback durations ranging from 1.17 to 5.74 years.

3.2 Results of Current Source Inverter (CSI) Type Nonlinear Load

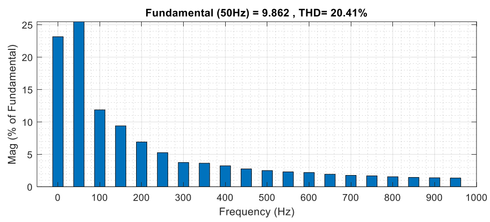

Fig. 3. THD% of supply current without SHPF

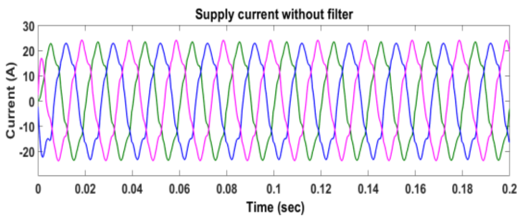

Fig. 4. Three-phase supply current without SHPF

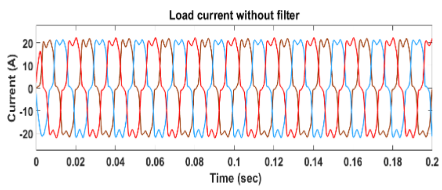

Fig. 5. Three-phase load current without SHPF

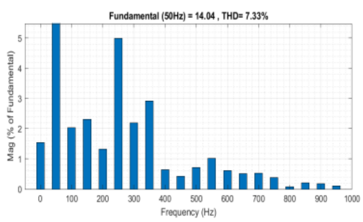

Fig. 6. THD of supply current with SHPF

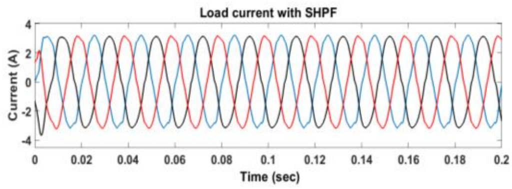

Fig. 7. Three-phase load current with SHPF

3.3 Results for Voltage Source Inverter (VSI) Type nonlinear load

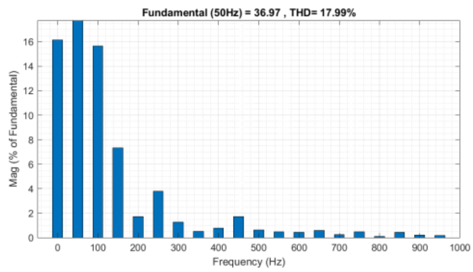

Fig. 8. THD of the supply current without SHPF

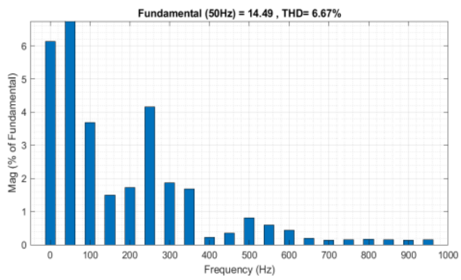

Fig. 9. THD% of the supply current with SHPF

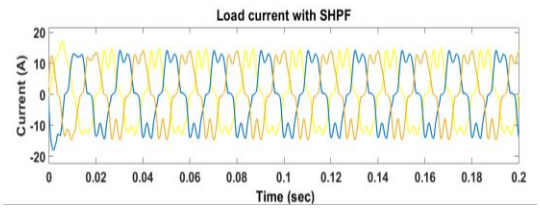

Fig. 10. Three-phase load current with SHPF

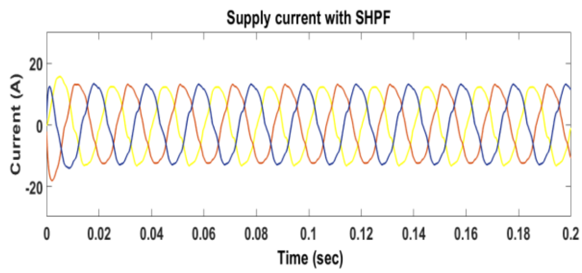

Fig.11. Three-phase supply current with SHPF

Table 2. CSI type of nonlinear load

Current	THD% Without SHPF	THD% With SHPF
Supply current	20.41%	7.33%

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Load current	24.31%	7.44%

Table 3. VSI type of nonlinear load

Current	THD%	THD%
	Without SHPF	With SHPF
Supply current	17.99%	6.67%
Load current	20.20%	9.62%

A P-I controller is used in the MATLAB/Simulink environment to test the shunt hybrid power filter. Figures 3 through 7 show the findings for the current source inverter feed drive system without a filter. Additionally, from Fig. 8 to Fig. 11, the outcomes of the P-I controller based on a shunt hybrid filter are presented. In Table 2, the harmonic is reduced for the CSI type of nonlinear load from 20.42% to 7.33% for supply current and from 24.31% to 7.44% for load current with P-I based SHPF. In Table 3, the VSI type of nonlinear load feeding the drive system, the harmonic is reduced from 17.99% to 6.6% for supply current and from 20.20% to 9.62% for load current.

4 CONCLUSION

Due to issues with electrical energy efficiency and current harmonic distortion in its electric drive systems, Sunti Golden Sugar Company (SGSC) in Nigeria faces challenges of higher energy cost, deteriorated equipment, and decreased system performance. The company's profitability and market competitiveness may be severely impacted by the combined effects of harmonic distortion and energy inefficiency. A detailed energy audit has been analyzed. Based on the loss's energy efficiency assessments on the major energy equipment's like electric motors and drives system have been done. As a result of replacing ordinary motors with energy-efficient motors, that is, replacing under-load motors with properly sized motors, payback period ranging from 1.17 to 5.85 years, the energy savings of 71,605kWh/year and cost savings of €3,938.00 per year which is equivalent to ₦3,256,579.05 in Nigeria currency was achieved., Shunt Hybrid Power Filters (SHPF) are designed and simulated in order to reduce current harmonics using MATLAB/Simulink software. As a result, the THD% for CSI is reduced for the source current from 20.41% to 7.33% and the load current from 24.31% to 7.44%, respectively. While in the case of VSI, the THD% is reduced from 17.99% to 6.67% for supply current and from 20.20% to 9.62% for load current, respectively. This offers a thorough framework for examining how energy inefficiencies and harmonic distortion affect the sugar company operations. The approaches and results could be adapted for comparable research in other energy-intensive sectors, supporting larger-scale initiatives for industrial energy efficiency and power quality improvement.

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