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Research Article

EFFECTS OF STEEL PLANTS WITH THREE-PHASE INDUCTION FURNACES ON POWER DISTRIBUTION QUALITY OF THE EXISTING 33 KV NETWORK IN NIGERIA

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ABSTRACT
This study aimed at evaluating and analyzing the voltage and current distortions on the introduction of a steel production plant in a typical 33 kV distribution system in Nigeria, with a view to assisting decisions made in the present system operation and planning effective service delivery in terms of quality. A three phase induction furnace was developed using MatLab Simulink software and the effects of steel plant loads on the quality of electric power system supply to electricity users on the same distribution network was analyzed in terms of total harmonic distortions of voltage and current. In order to evaluate voltage magnitude profile on the network, load flow computation and analyses were carried out on the 33 kV distribution network before and after the introduction of steel plant loads, using Successive Approximation Method. The results showed critical voltage magnitude profile below -5% of nominal voltage at the receiving end nodes. With the aid of the Matlab Simulink model, inadmissible voltage and current distortions of 15.47% and 10.35% were measured. Passive filter was proposed, designed and simulated, in order to mitigate these distortions caused by the steel production plant loads. By simulation, the installation of the designed passive filter gave a reduction of the distortions to permissible values. Further, for every 1 MW load increment when the steel plant is connected, network losses increased by 94%; however, for every of Mvar of filter capacity, loss reduction in the network is 5.1 MW.

Keywords: electric power quality, total harmonics distortion, induction furnace, passive filter, steel plant and ikirun.

INTRODUCTION

In the past, electric power quality problem especially harmonics represented less of a problem due to the conservative design of power equipment and to the common use of delta-grounded wye (Δ/Y) connections in distribution transformers, but only recently their effects have gained public awareness [5]. The great advance of power semiconductor devices and popularization of their use in equipment in several areas such as heating, melting and so on causes a large decrease in the electric power quality. Gradually as the power electronics technology applications begin to grow rapidly, the detection of the harmonics arising due to the use of non-linear loads increased [3]. Presently, the occurrence of harmonic distortions constitute one of the main concerns for engineers in the several stages of energy utilization within the power industry. The majority of industrial non-linear loads are rectifiers and inverters in induction furnace, for converting alternating current to direct current and vice versa, which are the most common nonlinear loads found in steel production plant [5]. However, the significance of the study in Nigerian systems is that only voltage frequency is monitored and controlled and not possible distortion due to harmonics. Consequently, the effects of harmonics on the quality of the supplied voltage are not measured or controlled. The costs to utility and voltage users in the system are unknown. This is critical with the prospective rise in investment in the industry.

The induction furnace is used to provide high quality steels from a raw material of steel scrap in steel production plants. This kind of furnaces is known for generation of a considerable harmonic distortion due to the variation of the arc during metal melting, making the furnaces unbalanced, nonlinear and time varying loads, which can cause many problems to the power system quality. The dramatic increase in the use of induction furnaces (IFs) has been acknowledged since the early 1990s [4]. The prevailing demand for steel and iron and the yearning for investors into the industry have opened the Nigerian Systems to installations and operation of small-scale steel (iron) producing plants without apparent control for generated harmonics. Poor voltage quality in networks with steel plant loads are detected in adjoining township loads in term of magnitude and distortions.

Harmonic pollution on a power line can be quantified by a measure known as total harmonic distortion (THD). High harmonic distortion can negatively impact a facility's electric distribution system, and can generate excessive heat, loss of efficiency and increase in audible noise in motors and also cause false tripping of ground fault circuit interrupters (GFCIs) which is a nuisance to the end user, if the distortions exceed the recommended limit [8]. There are limits to the amount of harmonic pollution a power supply is allowed to inject onto the power line. These limits (<=8% and <=5%) depend on the frequency of operation, and the power level of the power supply used.

A solution to the problem of harmonic distortion is the application of passive filter, which can reduce high frequencies injected into the AC line, thereby preventing the power line from radiating electromagnetic interference [8]. Appraisal of harmonic distortion and prospective solution using filter are not apparent in the existing Nigerian systems. Consequently, penalties to mitigate harmonic distortions are not in effect in the system. In order to mitigate expected and conditions, passive filters are proposed and designed. Before designing any corrective action, it is necessary to assess the expected distortions introduced by the studied installation into the distribution network. This was carried out in an earlier study [7] but for single phase induction furnaces using three-phase to single phase frequency inverter. A review of [7] shows that a more appropriate model will be with the use of three-phase induction furnaces, which is modeled and applied in this study. In this study, as in [7], modeling and simulation are applied, which allows safe measuring of the harmonic distortion created by a system before and after any corrective action is introduced.

LOCATION AND DESCRIPTION OF STUDIED STEEL PLANT AND DISTRIBUTION NETWORK

The selected network is 33 kV distribution network (DN), supplying Ila-Orangun, Ekonde, Inisha and Ikirun townships, Osun State, Nigeria. The study area, is situated between latitude 7°50' N of Equator and longitude 4°40' E of Greenwich meridian. The feeder emanates from 60 MVA, 132/33 kV main substation in Transmission Company of Nigeria (TCN), Osogbo as shown in Figure 1.

The steel production plant (SPP) is located between TCN-Ikirun route. The SPP's 33/11kV-2×7.5 MVA substation is fed from DN as shown in Figure 1. The electric load of the plant is composed of two three-phase induction furnaces, continuous casting section and finishing mill. The distribution transformer of the finishing mill is also used for general services which composed of standard transformers of 2.5 MVA with secondary voltages of 398–230 V. The general services consist of shot suction conveyors, offices, lighting, and a 1000 kVA transformer for the continuous casting section with secondary voltage of 575–332 V. The distribution transformer capacity of the induction furnaces is 2×3.6 MVA, with secondary and tertiary voltages of 660 V each. The steel plant comprises 2 medium frequencies induction furnaces, which require a significant 500 kWh of electricity to produce a ton of steel.

METHODOLOGY

This study was carried out as follows: collection of loading readings from TCN; power flow analysis of the network with steel plant loads; modeling and simulation of the electrical circuit of the induction furnaces on the SPP and Ikirun 33 kV DN and designed passive filter in Matlab Simulink, running the models to obtain voltage and current profiles before and after installation of filter.

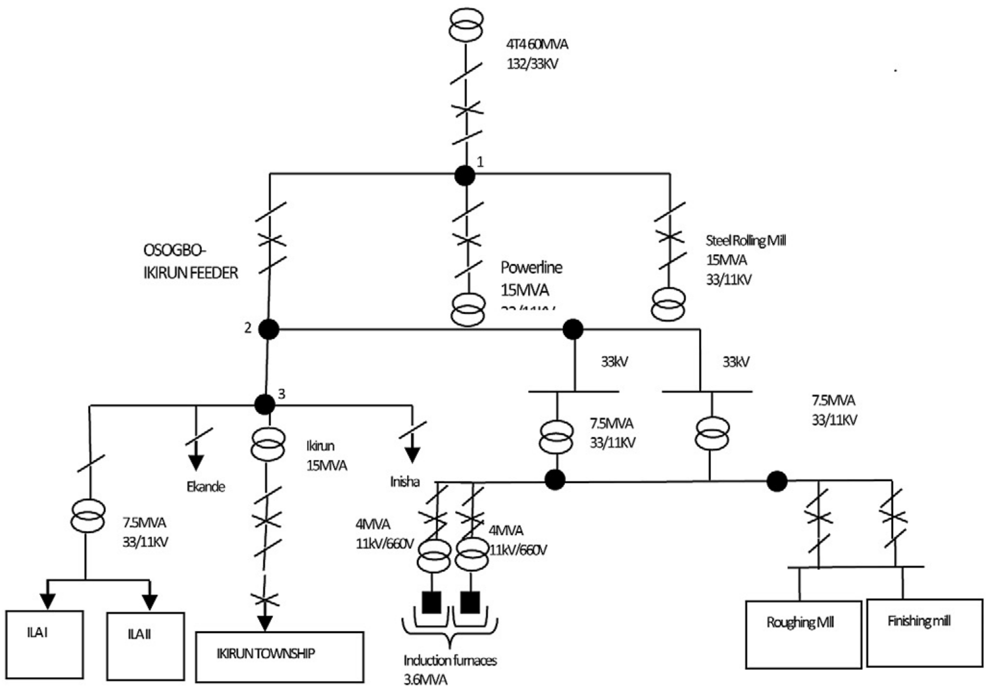

Fig. 1. Single line diagram of steel plants distribution network on Ikirun 33 kV network

Power flow analysis of the network with steel plant loads

Successive Approximation Method was used to evaluate the maximum load on the network with the connected steel plant loads using the equations 1 to 4. These were carried out so as to determine the flow of active and reactive power required for estimation of power losses caused by the nonlinear load, hence the estimation of voltage profile along the feeders particularly at other user locations under heavy nonlinear load conditions, and verification of the voltage profile whether is still in permissible limits were evaluated. Power factor was also observed to assure a proper balance between active and reactive power to minimize losses in the distribution system, since every harmonic provides a contribution to the average power that can be positive or negative.

Equivalent circuit diagram of Figure 1 is presented in Figure 2.

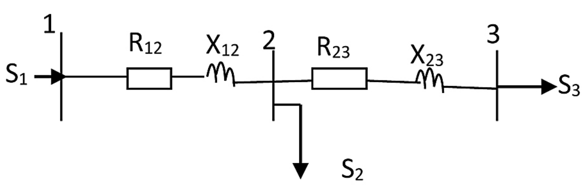

Fig. 2. Equivalent circuit of the DN with steel plant loads: S_1 – injected complex power (P_1+jQ_1); S_2 – complex load of the steel plant; S_2 – complex load of the connected townships

Applying the method of successive approximation method (SAM) [5], the complex power flow between cct nodes *i* and *j*, S_{ij}, is modeled as:

$$\dot{S}_{ij} = \dot{S}_j + \Delta\dot{S}_{ij} = \dot{S}_j + \frac{P_j^2+Q_j^2}{U_N^2}R_{ij} + \\ + \frac{P_j^2+Q_j^2}{U_N^2}X_{ij};\ i,j = (1,2,3) \qquad (1)$$

where: S_j is complex load at node *j*, R_{ij} and X_{ij} are resistance and reactance per unit length respectively.

$$\Delta\dot{S}_{ij} = \Delta\dot{P}_{ij} + j\Delta\dot{Q}_{ij} \qquad (2)$$

where: ΔS_{ij}, ΔP_{ij} and ΔQ_{ij} are complex, active and reactive losses respectively between bus *i* and *j*.

$$R_{ij} = \frac{\rho_{ij}}{A_{ij}}\, l_{ij}\ ;\ X_{ij} = 0.144 log\frac{Dgmd_{ij}}{r_{ij}} + 0.016 \qquad (3)$$

where: ρ_{ij} is the resistivity of the conductor, A_{ij} is the cross sectional area of the 150 mm^2 aluminum conductors, $Dgmd_{ij}$ is the geometric means distance between the three phases (= 1 m), r_{ij} and x_{ij} are active resistance and reactance respectively.

Apparent voltage in receiving end node j can be obtained using (4):

$$U_j = \sqrt{(U_i - \frac{P_iR_{ij}+Q_iX_{ij}}{U_i})^2 + (\frac{P_iX_{ij}-Q_iR_{ij}}{U_i})^2} \qquad (4)$$

where: ΔU_{ij} and δU_{ij} are direct and quadrature components of voltage losses between node *i* and *j*.

The voltage deviation on the line, $U_{dev\,i}$, was determined using equation (5):

$$U_{dev\,i} = \frac{U_i - U_N}{U_N} \cdot 100\% \qquad (5)$$

where: U_N is nominal voltage and U_i is the calculated node voltage.

Total harmonic distortion (THD) considers the contribution of every individual harmonic component on the signal. THD is defined for voltage and current signals respectively as follows:

- Total harmonic distortion for voltage is:

$$THD_V = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \qquad (6)$$

- Total harmonic distortion for current is:

$$THD_I = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_1} \qquad (7)$$

where: V_n and I_n are the amplitude of the harmonic components of order *n* for voltage and current respectively.

Simulation of induction furnace using Matlab/Simulink

The medium frequency induction furnaces were modeled using Matlab Simulink (SymPower Systems). As there is no induction furnace block in Simulink, new blocks were developed for the induction furnace, and the obtained circuit is as shown in Figure 3.

The furnace circuit is fed from a 3.6 MVA-11/0.66/0.66 kV three winding transformer. The secondary winding feeds a thyristor controlled rectifier and the tertiary feeds another identical rectifier. The rectification has a 12-pulse configuration. Both rectifiers are connected in series including filtering coils that improve the direct current obtained. The direct voltage outputs of the rectifiers were coupled and connected to a medium frequency inverter to generate a three-phase 500 Hz alternating current of controllable amplitude. This AC supply of the inverter is connected in series with induction coil. A capacitor bank is connected in parallel with the induction furnace coil to achieve a controllable resonance of the coil. The voltage at the coils that melt the steel is 1200 V (500 Hz), and the approximate energy consumption rate of the coil is 3000 kW. The induction furnaces work in the resonant frequency with the capacitor banks connected in parallel. The coils have no core, as it is the scrap that takes its place. The resonant frequency value varies with the condition of the scrap as the self-inductance of the coil changes. Therefore, this frequency value is controlled by the inverter control system so that capacitors and coil are always in resonance. When the furnace starts working the frequency is low (400 Hz) and its values increases as the scrap is melted.

Table 1 shows the parametric values of all elements in the designed furnace model, which include: input voltage to the furnace transformer (Vrms); input frequency (f); MVA rating; magnetic resistance (R_m); magnetic inductance (L_m); output voltage at the secondary winding of the furnace transformer (W_1); output voltage at the tertiary winding of the furnace transformer (w_2); phase angle modulation in degree (Pw); step resis-

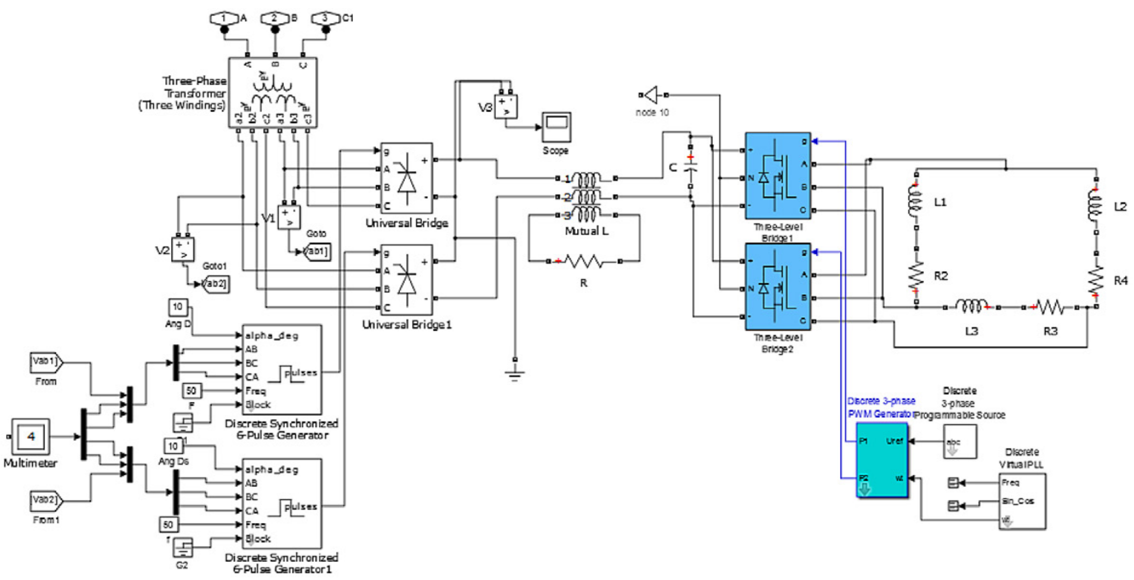

Fig. 3. Matlab-Simulink model of three-phase induction furnace

Table 1. Parameters of Matlab-Simulink model of three-phase induction furnace

Furnace elements	Parameters																
	Vrms (kV)	f (Hz)	MVA	Rm (pu)	Lm (pu)	W_1 (kV)	W_2 (kV)	Pw (°)	time steps	bridge arm	Rs (Ω)	Cs (F)	carrier freq (H)z	O/p volt freq (Hz)	O/P volt phase	L (H)	R (Ω)
Transformer	11	50	3.6	500	500	660	660										
Pulse generator								30	1/1000								
IGBT Inverter										2	5000	∞					
PWM generator										2			2000	500	30		
Magnetic coil																$1.27E^{-04}$	0.4

tance of insulated gate bipolar transistor (IGBT) inverter (Rs); step capacitance of the IGBT inverter; modulated carrier frequency (f); output frequency of the inverter (f); output phase angle of the three phases; induction coil inductance (L); and the induction coil resistance (R).

Simulation of the distribution network with the steel plant loads using Matlab/Simulink

All the elements of the distribution network were modeled using existing Simulink blocks contained in the SymPowerSystems blockset. The Simulink model of the furnaces of Figure 3 was incorporated into the Simulink model of the network of the network in Figure 4. In order to perform the harmonic analysis of the voltage and current signals present in the steel plant, a block was developed and programmed to make the required calculations using equations 6 and 7. This was done to determine the resultant waveform distortion and to verify the order and magnitude of harmonic currents at the plant substation and at remote locations where customer harmonic sources may be affecting neighboring installations.

Simulation of passive filter using Matlab/Simulink

The passive filter was designed analogical to the one applied in [9]. The difference however is that in this study, it represents a phase of the three phases required. The model is as shown in Figure 5.

The filter was inserted in parallel with the induction furnace loads and it was located very close to harmonic generator (induction furnaces), as shown in Figure 6. In this section the simulation analysis of the filter was described for induction furnace loads and the FFT analysis has been carried out simultaneously. A Simulink block was developed to perform the harmonic analysis of the voltage and current signals present in the network.

The design parameters for each filter per phase of induction furnace were evaluated as in equation (8):

$$Q_{C\,ph}^{req} = Q_{C\,ph}^{(0.85)} - Q_{C\,ph}^{(0.95)};\; Q_{C\,ph}^{n} = \frac{Q_{C\,ph}^{req}}{4};$$

$$X_C^n = \frac{U^2}{Q_{C\,ph}^n};\; X_L^n = \frac{X_C^n}{n^2};\; L^n = \frac{X_L^n}{2\pi f_c};\; C^n =$$

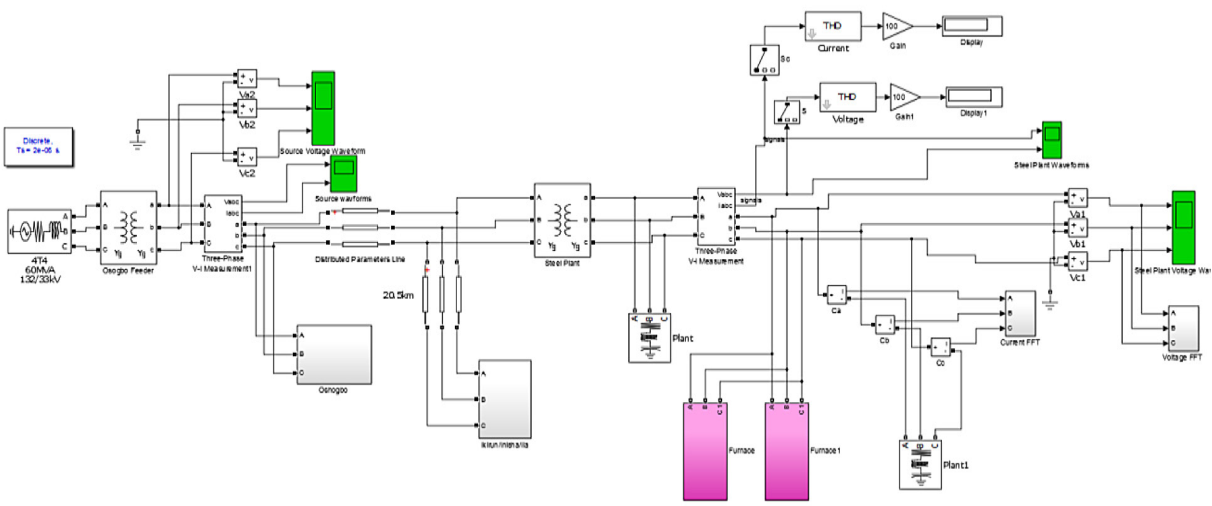

Fig. 4. Model of the DN with steel plant loads

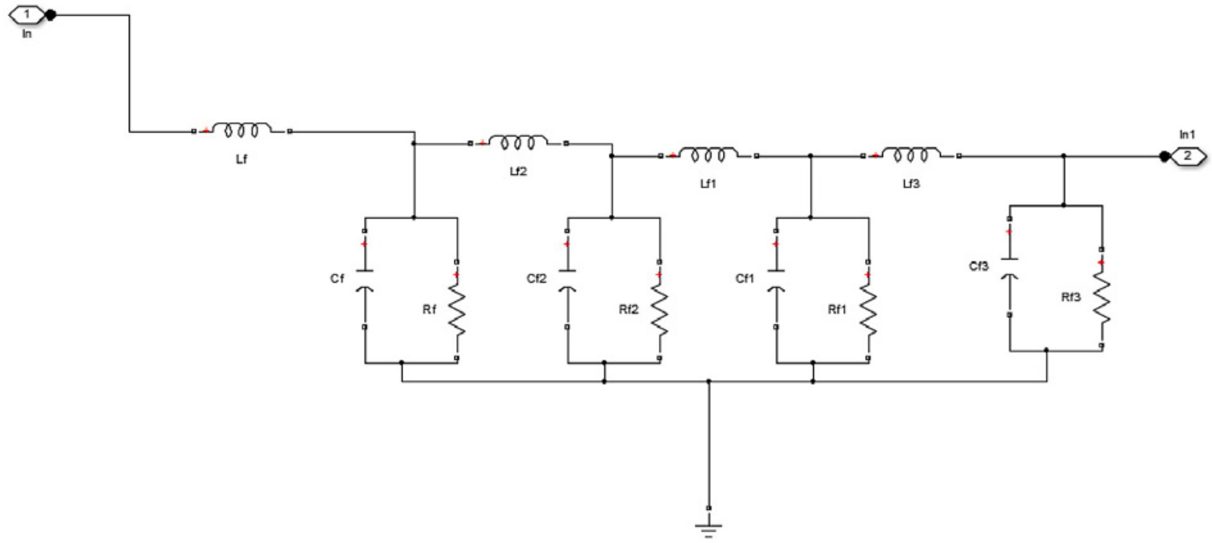

Fig. 5. Model of passive filters

$$= \frac{1}{2\pi f_C X_C^n};\ R^n = \frac{nX_L^n}{q}, 0.5 < q < 5; q = 3 \quad (8)$$

where: R^n, L^n, C^n, f_C, X_L^n, X_C^n are active resistance, inductance, capacitance, cut-off frequency, inductive reactance, and capacitive reactance per filter per phase for nth harmonic respectively; q is quality factor; $Q_{C\,ph}^{req}$ is total required compensation of reactive power of the steel plant, is reactive power capacity per filter; $Q_{C\,ph}^{(0.85)}$ and $Q_{C\,ph}^{(0.95)}$ are total reactive loads of steel plant at power factors of 0.85 (existing) and 0.95 (desired) per phase respectively.

In this study, two additional metrics were proposed: increase in the network losses per MW load increment, α, when steel production plant is connected; and loss reduction per MW of filter capacity, β, when steel production plant and filter are connected. α is expressed as in equation 9:

$$\alpha = \frac{\Delta P_{Losses}^{Nwk}}{\Delta P_{Load}^{Nwk}} = \frac{P_2^{Nwk} - P_1^{Nwk}}{P_{L2}^{Nwk} - P_{L1}^{Nwk}} \quad (9)$$

where: P_2^{Nwk} is the losses on the network with steel production plant, MW; P_1^{Nwk} is the losses on the network without steel production plant, MW; P_{L2}^{Nwk} is the load on the network with steel production plant, MW; and P_{L1}^{Nwk} is the load on the network without the steel production plant, MW.

β is expressed as in equation 10:

$$\beta = \frac{\Delta P_{Losses}^{red}}{Q_C^{req}} = \frac{\Delta P^{without\ filter} - \Delta P^{with\ filter}}{Q_C^{req}} \quad (10)$$

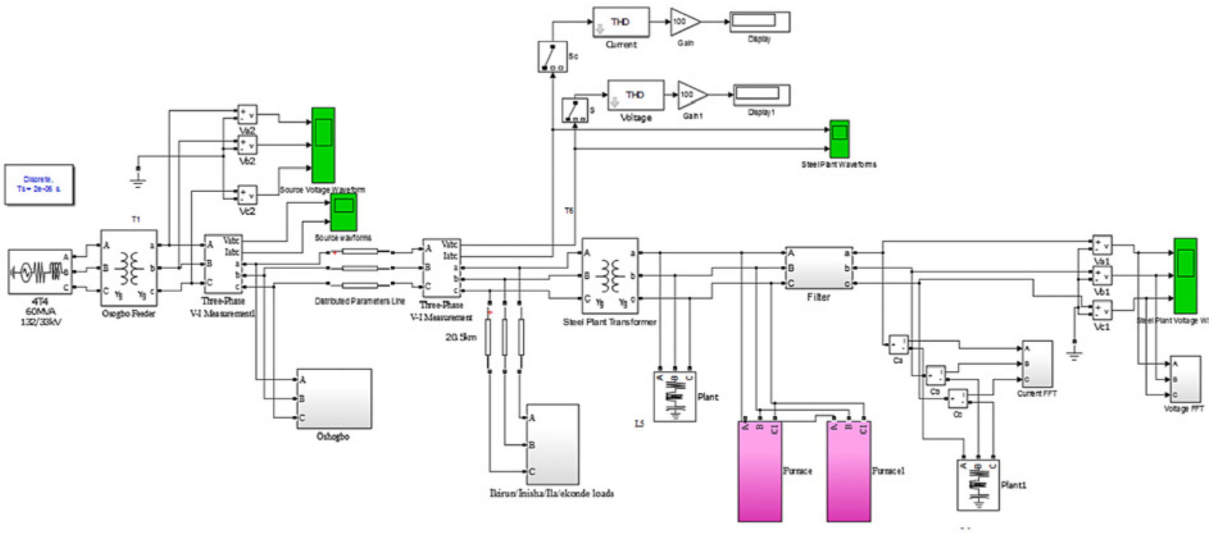

Fig. 6. Model of the DN with steel plant loads and passive filter

where: ΔP_{Losses}^{red} is change in losses on the network with foundry; $\Delta P^{without\ filter}$ is the losses on the network without filter, MW; $\Delta P^{with\ filter}$ is the losses on the network with the application of filter, MW; and Q_C^{req} is required compensating reactive power.

RESULTS AND DISCUSSION

The results of evaluation of the power flow carried out on the network at the other connected townships, peak load of 18 MW and on the introduction of steel production plant loading of 10 MW making a total load of 28 MW on the DN are presented in Table 2.

Table 2 shows the percentage voltage deviation at node 2 and node 3 as -6.2% (30.96 kV) and -18.6% (26.85 kV). This implies that the voltage has falls below the permissible limits of %. Table 3 shows that losses on the DN due to harmonics caused by connecting the steel plant is 44%, which is higher than the value (38%) when no steel plant is connected. When the steel plant is connected, it was observed that for every 1 MW load increment, network losses will increase by 94% (4.74 MW); and for every Mvar of filter capacity, losses reduces by 5.86 MW. This implies that for 0.87 Mvar filter capacity loss reduction in the network is 5.1 MW. Application of designed filter contributed to the reduction of network losses by approximately 5.1 MW (71%). Therefore, the designed filter contributes to significant reduction of the load losses on the DN.

The distortion of voltage and current were measured in terms of THD_V and $THD_{I,}$ captured in the scopes of the designed model. The level of distortion on the current and voltage waveforms at the steel plant network is shown in Figure 7. The is 15.47% and is 10.35%, it can be seen that the voltage has many distortions as compare to the current waveform due to the commutation of current from one phase to another during the rectifying process in the converter and these values exceeded the recommended values. This reveals that the harmonics content produced by an induction furnace are relatively high.

Figure 8 shows the voltage and current waveform distortions at the power utility side. Here, the current waveform is more distorted than the voltage.

Table 2. Power flow results on the distribution network

Mode parameters	Without the steel plant	With the steel plant
S_3	18+j8.72 MVA	18+j8.72 MVA
S_2	18.5+j10.81 MVA	28.5+j17.53 MVA
ΔS_{23}	0.5+j0.209 MVA	0.5+j0.209 MVA
S_1	19.07+j11.57 MVA	29.89+j21.85 MVA
ΔS_{12}	0.57+j0.76 MVA	1.39+j4.32 MVA
V_1	34.65 kV	34.65 kV
V_2	32.55 kV	30.96 kV
V_3	30 kV	26.85 kV
U_{dev2}	-1.4%	-6.2%
U_{dev3}	-9%	-18.6%

Table 3. Losses due to harmonics on the distribution network

Parameters	Without the foundry plant	With the foundry plant	With filter	Gain with filter
P_1, MW	6.44	16.2	8.4	7.8
P_3, MW	3.98	9.0	6.3	2.7
$\sum \Delta P_{i,j}$, MW	2.46	7.2	2.1	5.1
$\sum \Delta P_{i,j}$,%	38	44	25	–
α, %	–	94	–	–
β, %	–	–	5.86	–

Table 4. Parameters of the passive filters per phase

S/N	Filters	Parameters											
		Given					Computed						
		f_n	F_c (Hz)	q	$Q_{C\,ph}^{\prime 0.85\prime}$	$Q_{C\,ph}^{\prime 0.95\prime}$	$Q_{C\,ph}^{req}$	$Q_{C\,ph}^{n}$	X_C^n	X_l^n	C^n (μf)	L^n(Ω)	R^n (Ω)
1	3rd Filter	150	100	3	1.86	0.985	0.873	0.25	554	61.56	2.87	0.098	92.34
2	5th Filter	250	200	3	1.86	0.985	0.873	0.228	554	22.16	1.43	0.018	55.4
3	7th Filter	350	300	3	1.86	0.985	0.873	0.223	554	11.3	95.8	6	39.57
4	9th Filter	450	400	3	1.86	0.985	0.873	0.22	554	6.84	71.8	2.72	30.78

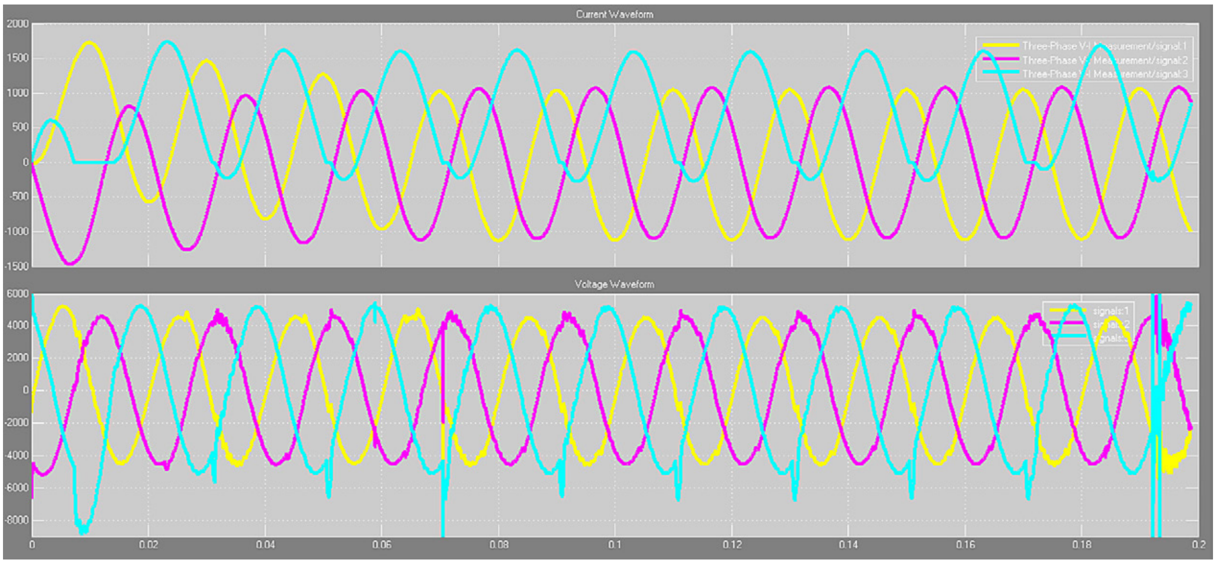

Fig. 7. Waveforms of distorted current and voltage on the foundry network (THD_v = 15.47%; THD_I = 10.35%)

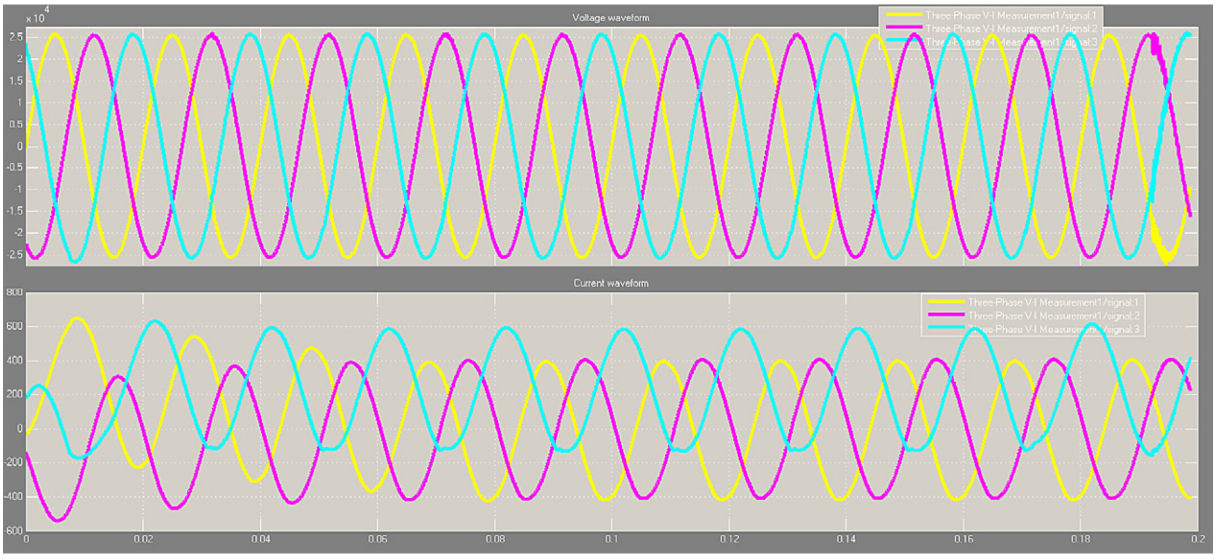

Fig. 8. Waveforms of distorted voltage and current at the source network

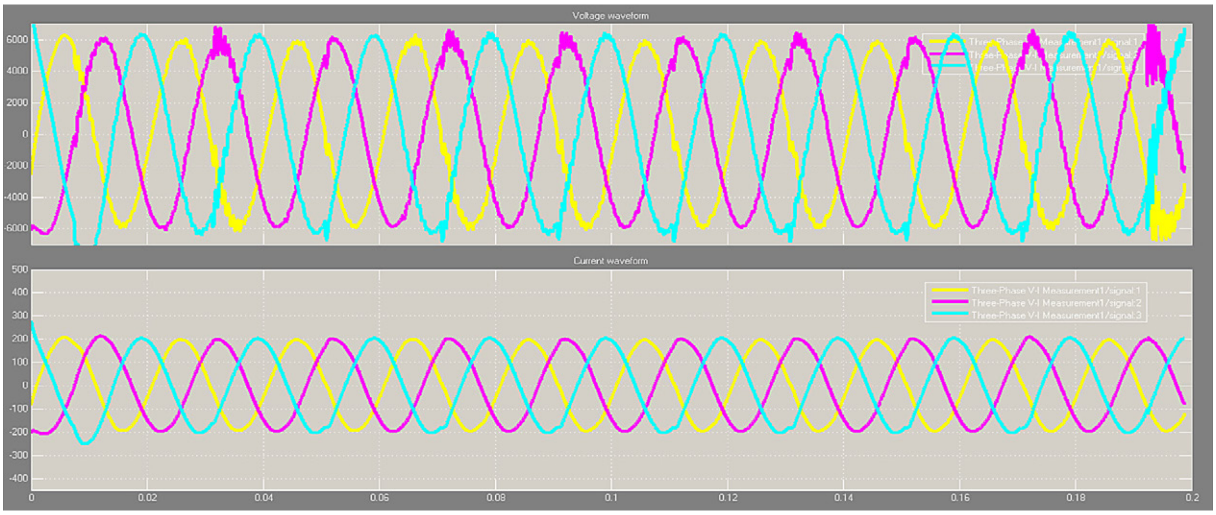

Fig. 9. Waveforms of distorted voltage and current of ikirun network

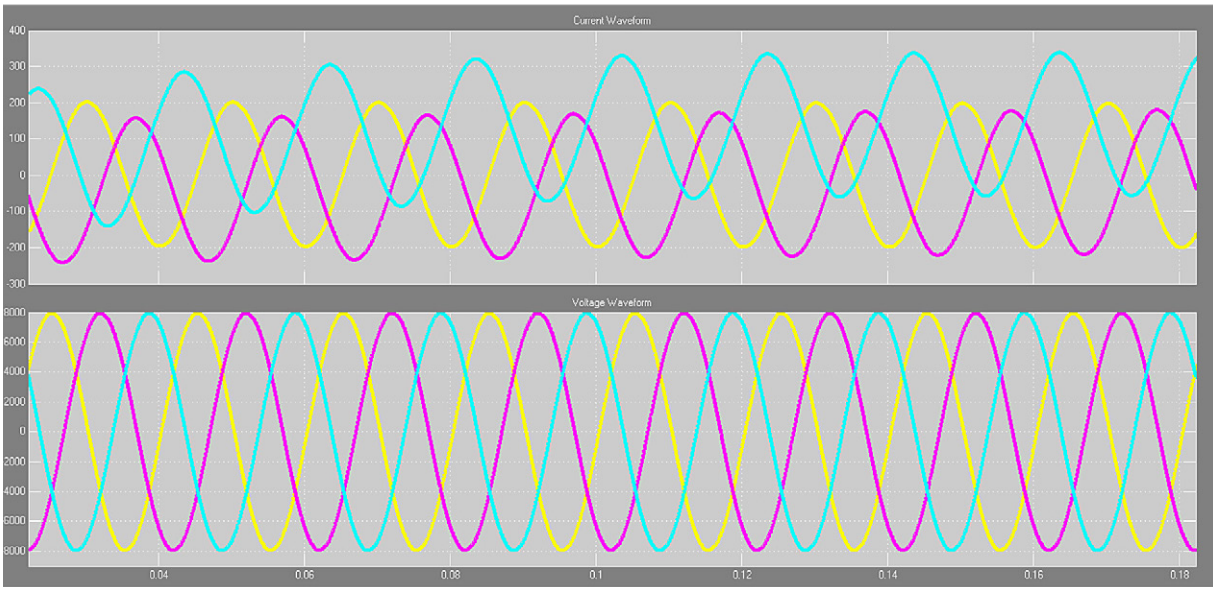

Fig. 10. Waveforms of current and voltage on the steel plant network with filter (THD_v = 5.63%; THD_I = 1.34%)

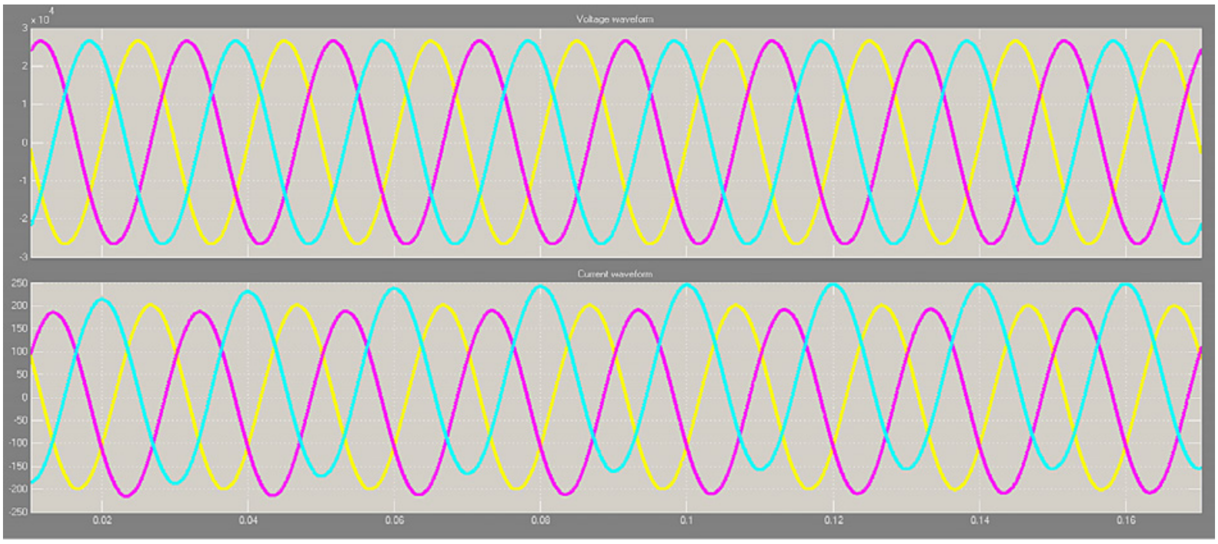

Fig. 11. Waveforms of voltage and current at the source with filter

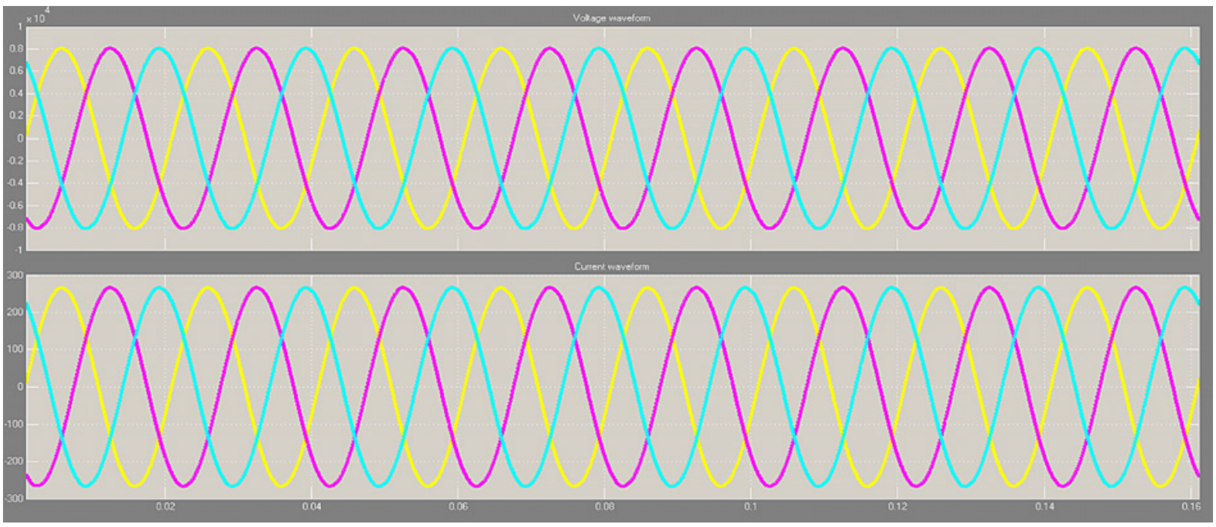

Fig. 12. Waveforms of voltage and current of ikirun network with filter

Figure 9 shows distorted network of other users on the 33 kV distribution network, it was observed that the smaller the load at the customers end, the more the distorted current and voltage waveform signals. The distortions should be mitigated as this is unhealthy for their system loads.

Table 4 shows the parametric values of the passive filters designed in mitigating the effect of harmonic disturbance on the network.

When the passive filters were applied, the distortion was reduced as shown by the waveforms in Figures 10 to 12. The THD_I of the current was reduced from 10.35% to 1.34% and the THD_V from 15.47% to 5.63%.

CONCLUSIONS

The three phase furnace developed proved to be effective in harmonic distortion analysis in a steel plant as carried out in this study, the furnace reflected significant amount of distortion on the 33 kV distribution network as compared to a single furnace in the earlier studies presented in [7]. Here, the total harmonic distortion (THD) was measured by the THD block in Simulink.

From the simulation, the introduction of the steel plant contributed to the losses on the distribution network by 44% due to harmonics. These losses were excessive and could be mitigated using filter of commensurable design as herein proposed. Due to the estimated level of distortions on the 33 kV distribution network, it was certain that other connected townships supplied from the same network were adversely affected.

Moreover, in the simulations, the application of designed passive filter was effective in mitigating distortion to below tolerance limit and reducing technical losses significantly. Based on these conclusion, it is recommended that power distribution companies, especially in the Nigerian condition, should consider as mandatory the introduction of power filters into the supply network where a steel plant installation exists or is proposed in order to mitigate the adverse effects of the generated harmonic distortion on the other load categories such as the adjoining township distribution network loads.

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