The Effects of Induction Furnace on Electric Distribution Network

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Abstract- Induction furnaces are high powered electrical loads that exhibit non-linear features. They have the tendency to affect the quality of power being delivered to other loads by the electric distribution grid they are connected to; by introducing electrical power problems such as voltage sags, voltage flickers, harmonics, and so on. A three phase induction furnace was modelled using ETAP software package; and the effects of the induction furnace on the quality of electric power system supply to electricity users on the same distribution network were analysed in terms of total harmonic distortions of voltage. A passive RLC shunt filter was designed and simulated in order to mitigate these distortions caused by the induction furnace. Power flow computation was done on the network before and after the introduction of the induction furnace in order to evaluate voltage magnitude profile on the network.

Indexed Terms- Total Harmonics Distortion (THD), ETAP (Electric Transient Analyser Program), and Point of Common Coupling (PCC), Resistor, inductor and capacitor (RLC).

I. INTRODUCTION

In recent times there has been a massive increase of non-linear loads connected to power systems all over the world [1, 2, and 3]. Some non-linear loads include power converters, energy efficient bulb and other electronic devices [1]. These loads do not obey ohms law; in that, their impedances do not vary directly with applied voltage [2, 4]. The resultant current drawn by such loads are non-sinusoidal in nature and if they are connected to a power utility system, the non-sinusoidal current being drawn by the load ultimately introduces harmonics at the Point of Common Connections (PCC). The propagation of the harmonics introduced at a PCC depends on the rating of the load, and also the short circuit capacity (SCC) of the PCC [5]. If the ratio of the SCC of the PCC to that of the load is large, the propagation of harmonic components from the PCC further in to the rest of the power system will be mitigated. Though, the loads do not draw voltages but current however there is a relationship between current drawn and voltage developed, this implies that the non-sinusoidal current drawn from the power system by non-linear loads will ultimately distort the voltage waveform at the PCC.

Harmonic distortion is evaluated by determining the total harmonic distortion (THD) of the current and voltage waveforms. Uncontrolled levels of harmonic distortion impacts the power system negatively. According to [2,3,4], the consequences of harmonic distortion are excessive heating of lines, transformers and motors, loss of efficiency in electric machines, increased heating and voltage stress in capacitors, increased probability of the occurrence of series and/or parallel resonance and malfunctioning of electronics, switchgears and relays. Harmonics are sinusoidal voltages or currents having frequency that are multiples of the fundamental frequency at which the supply system is designed to operate. The limits of distortion at different voltage levels as stipulated by IEEE in [6] are shown in the Table I.

Table 1: Voltage distortion limits.

Bus Voltage V at PCC (kV)	IHD (%)	THD (%)
$V \leq 1.0$	5.0	8.0
$1 < V \leq 69$	3.0	5.0
$69 < V \leq 161$	1.5	2.5
$161 < V$	1.0	1.5a

High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected

According to [3], there has been an increase in the adoption of induction furnaces for melting steel largely due to its simplicity and modularity. Induction heating is a form of non-contact heating for conductive materials. An electrically conductive material placed in a variable magnetic field will experience electromagnetic induction. At high frequencies, the induced current will be concentrated on the surface of the conductive material. This will eventually lead to joule heating [7]. Due to the frequency requirements of such furnaces which are usually higher than the operating frequency of a typical power system, power converters are used to power up the induction furnace. A typical module has a rectifier which rectifies the source voltage and an inverter to give the required AC at a certain frequency.

As part of power system planning, it is pertinent that the effects of such non-linear loads on a power distribution network be evaluated before hooking them up to the grid. This paper investigates the effect of the induction furnace in University of Lagos (Unilag) on the distribution network to which it is connected to as well as designing a passive filter to suppress the harmonics generated by the induction furnace.

II. METHODS AND MATERIALS

Load flow:

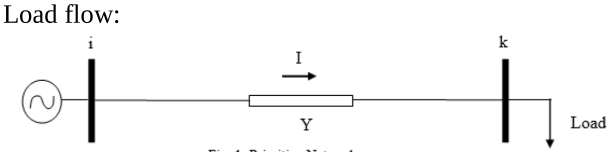


Fig. 1: Primitive Network

Considering the two buses network shown in figure 1, the complex power injected at bus i is give as:

$$S_i = P_i - jQ_i = V_i^* I_i \quad (1)$$

The current flowing from bus i to k through the line admittance Y is given as:

$$I_i = Y_{ik} V_k \quad (2)$$

Substituting (2) in (1):

$$S_i = P_i - jQ_i = V_i^* (Y_{ik} V_k) \quad (3)$$

The real power and reactive power flow from bus i to k is given as:

$$P_i = Re\{V_i^* (Y_{ik} V_k)\} \quad (4)$$
$$Q_i = -Im\{V_i^* (Y_{ik} V_k)\}$$

Re writing equation (4):

$$P_i = |V_i||V_k||Y_{ik}|cos(\theta_{ik} + \delta_k - \delta_i)$$
$$Q_i = -|V_i||V_k||Y_{ik}|sin(\theta_{ik} + \delta_k - \delta_i) \quad (5)$$

Newton Raphson method was applied to get approximate solutions of equation (5).

III. MODELLING AND SIMULATIONS

This study was carried out as follows, viz., collection of load data at each injection station from Ijora District of Eko Distribution Company (EKDC); which is the area of case study, modelling and simulation of the section of EKDC, modelling and simulation of the induction furnace according to specifications, carrying out the harmonic analysis of the network without the furnace connected to it as well as repeating the analysis with the furnace being connected to it. This analysis was conducted on all the buses in the network with consideration given to the bus supplying the PCC and the PCC itself.

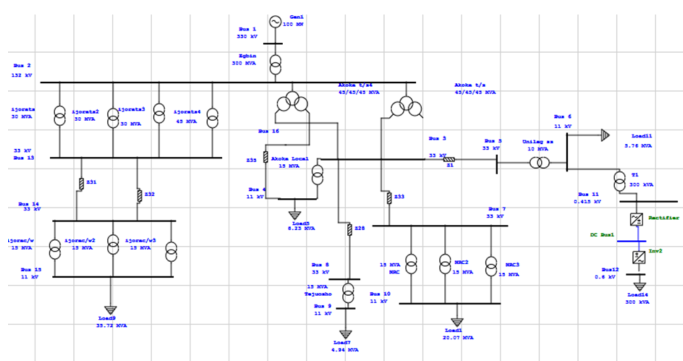


Fig. 2: Model of Ijora District with the Induction Furnace

- Power Grid Description and Modelling: The EKDC consists of 11 districts. These districts are powered by three 330/132 kV transmission stations, namely, Ikeja West, Akangba and Ajah local. All the districts in the network have at least one 132/33 kV transmission station except but one. The injection stations in the various districts receive 33 kV from the transmission stations which is subsequently transformed to 11 kV.

The area of interest is the UNILAG injection substation which is in the Ijora district. This district consists of two 132/33 kV transmission stations at Ijora and Akoka and five 33/11 kV injection stations. Typical impedance data that applies to cable/conductor size was used to model the existing 33 kV feeder lines. The transformers were also modelled according to specification except for the impedance values which were unavailable. Typical data was used for the impedance ratings of the various transformers with respect to their MVA rating. The load at each 11 kV bus were modelled in accordance with the data collected from Eko Electric Distribution Company. Since there was no information about the nature of the electrical loads connected to the network, the existing loads were assumed to be linear. The power factor of network was pegged at 0.85 by the distribution company.

- Modelling of The Induction Furnace: The ETAP model of the induction furnance is presented in Figure 3; while the Electrical Parameters of the Induction Furnace are presented in Table 2.

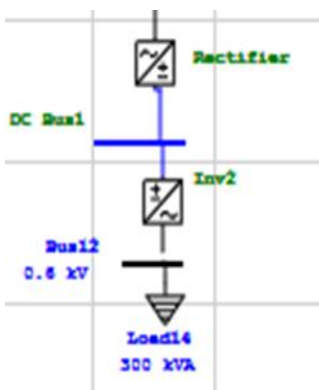


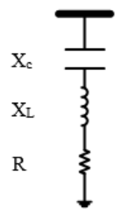
Fig. 3: Model of the Induction Furnace

The induction furnace was connected to the grid via a six pulse controlled rectifier rated at 250 kW. This rectifier feeds a DC link which is interfaced with an inverter that converts the DC to AC, operating at a frequency of 1000 Hz. A summary of the electrical specifications of the induction furnace and its ancillaries can be found in the table below.

Table 2: Electrical Parameters of the Induction Furnace

Rated Power of the Furnace	250 kW
Input Voltage	415 V 3phase
Working Frequency	1000 Hz
Rectifier Type	6 Pulse SCR

- Filter Modelling: To improve the power quality at bus 11 which is the PCC, a passive shunt RLC filter was proposed to mitigate the harmonics produced as well supply the reactive power to improve the voltage profile of the PCC. This filter mitigates harmonic currents by creating a low impedance path to ground for harmonic currents present in PCC [8]. These type of filters are usually tuned to a certain cut off frequency. To achieve the required performance, the filter parameters must be carefully selected



$$Z = R + j(X_l - X_c) \tag{6}$$

Fig. 4: Schematic Diagram of a Typical Passive RLC Shunt filter.

First and foremost the reactive power required from the passive filter will form the basis for the selection of the filter capacitance. The relationship between the capacitance and reactive power is shown in equation (7)

$$C = \frac{Q}{2\pi f V^2} \tag{7}$$

Where C is the capacitance of the filter, Q is the Reactive power of the filter, f is the nominal frequency of the system and V is the System voltage. The impedance of the filter capacitor is defined in equation 6.

$$X_c = \frac{1}{2\pi f c h} \tag{8}$$

Where h is the harmonic order (tuning point of the filter). At resonance the inductive reactance equals the capacitive reactance as shown in the characteristic curve of the single tuned RLC filter. Using this relationship, the inductance of the filter can be found.

At resonance:

$X_c = X_l$

$$l = \frac{X_c}{2\pi f h} \quad (9)$$

Where L is the inductance of the filter, X_L is the inductive reactance and X_C is the capacitive reactance. The Q factor of a filter has a direct relationship to the bandwidth of the filter. A low Q factor will result in a high operating bandwidth around the cut off frequency while a high Q factor will result in a low operating bandwidth around the cut off frequency [9]. The resistance required to give the specified quality factor of the filter can be found using the relationship below.

$$R = \frac{X_l}{Q_f} \quad (10)$$

Deviation of system frequency, inductance values and capacitance values will likely shift the tuning point of the filter. If the frequency inductance and capacitance value deviation is known, the relationship in can be used to normalize the tuning point of the RLC filter.

$$\varphi = \frac{1}{2}\left(\frac{\Delta C}{C} + \frac{\Delta L}{L}\right) + \frac{\Delta f}{f}$$

$$h = h_n + (\varphi + h_n) \quad (11)$$

IV. RESULTS AND DISCUSSIONS

The two buses of interest are the bus at Unilag Injection Station (Bus 6) and the PCC (Bus 11). Harmonic load flow was done on the Ijora network before connecting the harmonic filter to determine distribution of the harmonics generated by induction furnace. The analysis was repeated after connecting the harmonic filter to the PCC. The THD limits for each bus was set in line with the limits set out in [6].

After the induction furnace was connected to the network, the following results were gotten as shown below.

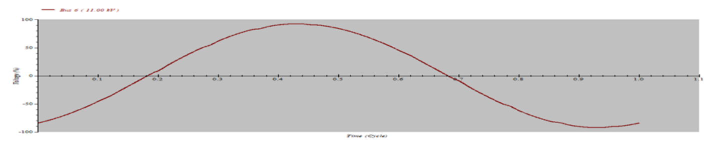


Fig 5: Waveform of the Voltage at the Injection Substation after Connecting the Induction Furnace

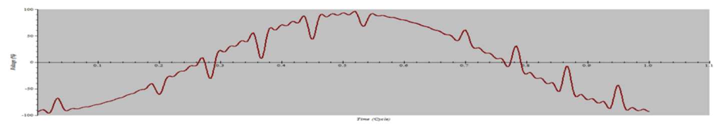


Fig. 6: Waveform of the Voltage at the PCC after Connecting the Induction Furnace

Table 3: Shows the Voltage Individual Harmonic Distortion at the PCC

Bus		Voltage Distortion		
ID	Voltage (V)	Fundamental %	VIHD %	Order
Bus 11	415	87.58	8.40	11
Bus 11	415	87.58	8.32	13
Bus 11	415	87.58	7.77	23
Bus 11	415	87.58	7.62	25
Bus 11	415	87.58	6.56	35
Bus 11	415	87.58	6.28	37
Bus 11	415	87.58	4.58	47
Bus 11	415	87.58	4.19	49

Table 4: Shows the Voltage Total Harmonic Distortion at the PCC & Unilag Subsation

Bus		Voltage Distortion	
ID	Voltage (V)	Fundamental %	VTHD %
Bus 11	415	80.53	19.47
Bus 6	11000	99.93	0.07

As shown in Table 3 & 4, it was discovered that the harmonics generated by the induction furnace was localised at bus 11 which is the point of common coupling. The THD of bus 11 and 6 is shown in table 4. The THD of bus 11 extends the limits specified in [6]. The 11th order harmonic component is most dominant as it has the biggest magnitude compare to the others.

To mitigate the harmonics at the PCC, a filter tuned to the 11th harmonic was designed applying the procedure outlined above. Table 5 shows the parameters of the designed RLC filter. The designed filter was connected to the PCC and the analysis was repeated.

Table 5: Parameters of the Passive Shunt Filter

Q	150 kVar
C	2800 µF
h	11
R	2e-3 Ω
Q_f	50
L	0.00003 H

After incorporating the 11th order tuned RLC passive shunt filter, the following results were realized:

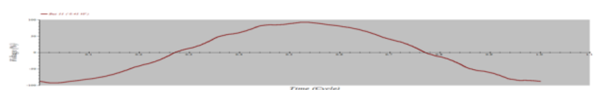


Fig. 7: Waveform of the Voltage at the PCC after Connecting the Shunt Passive RLC Filter

Table 6: Shows the Voltage Individual Harmonic Distortion at the PCC

Bus		Voltage Distortion	
ID	Voltage (V)	VIHD %	Order
Bus 11	415	2.69747	11
Bus 11	415	1.69227	13
Bus 11	415	0.370118	23
Bus 11	415	0.291336	25
Bus 11	415	9.47e-02	35
Bus 11	415	7.55e-02	37
Bus 11	415	2.13e-02	47
Bus 11	415	1.58e-02	49

Table 7: Bus Parameters of the Network with No Filter Connected

Bus ID	Nominal kV	Voltage (%)	MW Loading
Bus 1	330	100	51.024
Bus 2	132	98.34	50.985
Bus 3	33	95.79	22.799
Bus 4	11	95.33	4.812
Bus 5	33	95.57	4.478
Bus 6	11	92.19	4.462
Bus 7	33	87.29	12.733
Bus 8	33	93.56	3.62
Bus 9	11	92.46	3.589
Bus 10	11	85.9	12.587
Bus 11	0.415	87.58	0.298
Bus 13	33	96.62	24.414
Bus 14	33	89	23.183
Bus 15	11	86.49	22.712

Table 8: Bus parameters of the Network with the RLC Filter Connected

Bus ID	Nominal kV	Voltage (%)	MW Loading
Bus 1	330	100	51.05
Bus 2	132	98.35	51.012
Bus 3	33	95.81	22.824
Bus 4	11	95.35	4.814
Bus 5	33	95.6	4.493
Bus 6	11	92.35	4.477
Bus 7	33	87.31	12.739
Bus 8	33	93.59	3.622
Bus 9	11	92.48	3.591
Bus 10	11	85.92	12.592
Bus 11	0.415	90.27	0.299
Bus 13	33	96.62	24.416
Bus 14	33	89	23.185
Bus 15	11	86.49	22.715

Note: The PCC (bus 11) and the injection station bus (bus 6) are highlighted in yellow.

After incorporating the filter at bus 11, it was noticed that the harmonics that were initial present were reduced to allowable limits. The 11th order single tuned filter reduced the 11th order harmonics from 8.4 % to 2.69%. Conversely, the THD at that bus was negligible. The voltage profile was also improved because of the reactive power supplied by the filter.

CONCLUSION

The induction furnace model developed proved to be effective in harmonic distortion analysis. The effects of the harmonics developed at the PCC wasn't significantly propagated to other buses in the network, this can be attributed to the fact that the short circuit capacity of the injection station serving the induction furnace is large enough to absorb the harmonics being generated at the PCC. After incorporating the filter, it was realised that the THD was reduced from 19.47% to an insignificant value. The voltage profile of bus 11 and 6 were also improved

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