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Improved Technique for Penalizing Electricity Users that Generate Harmonics

Osita Uchechukwu Omeje, Olukunle James Amore, Linus Idoko

***Abstract:** The increase in harmonic distortion in power networks due to non-linear loads is now a major challenge for utilities, and utilities are finding ways to reduce these harmonics by imposing penalties on customers that generate them. This research aimed to design a fairer harmonic penalty model for customers who inject harmonics into power systems, accounting for harmonics injected from both the customer and utility sides. The harmonics injected from the customer and utility sides of the PCC (Point of Common Coupling) were evaluated, and the resulting Total Harmonic Distortions (THD) were used to assess the penalty and compensation due to the customer. The customer's electricity bill was also evaluated using this penalty model. The application of this penalty model results in a fairer model in which utility-penalised customers are compensated for harmonics injected from the network that exceed the limits, as well as for harmonics injected from the utility side. This research offers a substantial improvement over existing penalty models, as customers were treated fairly by considering the harmonics generated by their networks and the utility networks.*

***Keywords:** Harmonic Distortion, Non-Linear Loads, Harmonic Penalty, Total Harmonic Distortion.*

Nomenclature:
THD: Total Harmonic Distortions
ISO: Independent System Operator
THD: Total Harmonic Distortion
GIS: Geographic Information System
AFL: African Foundries Limited

I. INTRODUCTION

With the increased use of non-linear loads such as battery chargers, rectifiers, electronics, computers, printers, copiers, fluorescent lights, inverters, and variable-speed drives, harmonic distortion is increasingly caused in power distribution networks. This harmonic distortion is causing power quality problems [1], and the harmonics produce currents that are injected back into the power networks, causing some power system equipment, such as transformers, motors, and capacitors, to suffer losses due to overheating and overloading [2], [3].

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Thus, the increase in harmonic pollution is now a major concern to utilities, as it is responsible for the deterioration of power quality in power networks in the form of voltage and current waveform distortions [4]. The utilities are regulating permissible harmonic distortion in power networks by establishing harmonic limits [5]. Hence, penalise electricity users who introduce harmonics above the acceptable limit into the networks by imposing additional charges. The utility needs to determine who is responsible for injection harmonic distortion in power networks and penalize them [6]. Total Harmonic Distortion (THD) is the index used for measuring harmonic distortion in the power networks and is used for both voltage and current distortion measurement [7]. It is essential to find the harmonic contribution of both the customers and the utility at the PCC [8]. Hence, there is a need to identify harmonic sources and determine the contribution of each source to the harmonic distortion in the power network [9]. The utilities are faced with the task of developing a method of penalizing and compensating customers for harmonics injected into power networks [10]. The research proposes a fairer harmonic penalty model in which customers are penalised for harmonics injected from their networks and also compensated for harmonics injected from the utility side.

In [11], Foad. H. Gandomanet A presented a new penalty model for electricity users that injected harmonics into distribution networks by using Geographic Information System (GIS) to collect network data relating to harmonics and analyse the data collected with associated software (DigSILENT) to generate harmonic penalties for customers who injected harmonics into the power system. A novel method for calculating harmonic penalty was used to evaluate the effects of harmonic distortion on distribution networks, and a new penalty model was also proposed for customers that inject harmonics into power systems. The model is not applicable when a large volume of data is involved, and the methodology does not account for harmonic pollution responsibilities between the same customers or between the utility and its customers.

Amin Saadat et al. [1] also presented a new harmonic pricing model to penalise customers fairly for harmonics they generate, requiring customers to pay a fair fine for their harmonic contributions to the power networks. The Independent System Operator (ISO) would then use the penalty charges collected from customers for installing harmonic filters to reduce harmonic distortion in the power system. The weakness of the price model is that it does not account for harmonics generated on the utility side of the PCC.

A novel method for the equitable distribution of harmonics compensation costs among customers who generate harmonics was presented by Tadayon et al [12]. The method produces a continuous penalty curve for each harmonic source (customer), which can be used to estimate annual penalties for harmonic sources in power systems and for harmonics compensation planning. The setback of this model is that there is no compensation to customers for harmonics generated from the utility side.

Jun Li et al [13], presented a new method for determining the harmonic responsibility of both customers and the utility by evaluating economic loss and relevant data obtained from the PCC. The parameters of the Norton-equivalent model for the utility and customer sides were obtained using the reference impedance method. The economic loss incurred was used to evaluate the harmonic responsibility of the utility and its customers. The method can comprehensively evaluate harmonic responsibility across different harmonic frequencies, compare it with the harmonic responsibility based on the combination weighting method, and be easily applied to real-world problems. The weakness of this method was that harmonic limits were not taken into account during its application.

HongKun Chen et al [14], presented a modified method to achieve a fairer, more reasonable harmonic pricing model for customers. A new quantitative index for determining harmonic contributions, with no prior assumptions about harmonic impedance, was used. The penalty model also includes the harmonic metering price and the harmonic distortion responsibility. The method performed better in accuracy when evaluating overall harmonic distortion responsibility at the PCC and also provided a partial fee waiver as compensation to customers. The weakness of this method was that the customers were not adequately compensated.

II. MATERIALS AND METHODS

A. The Proposed Penalty Model

This research work was presented to address the limitations of the existing penalty model. The proposed model is developed to adequately compensate customers for the harmonics injected into their networks from the utility side. In the model, the customer who injects harmonics into the network is penalised, and the utility will also compensate the customer for harmonics generated in their network by other customers. The total amount of the electricity bill due for a customer is given by Eq. (1).

$$M_b = M_e + M_d + M_{hc} - M_{hu} \qquad (1)$$

Eq. (1) can be simplified as shown in Eq. (2)

$$M_b = M_e + M_d + P_{hc} * THD_{vc} - C_{hu} * THD_{vu} \qquad (2)$$

Where M_e is the energy charge, M_d is the power demand charge, M_{hc} is the total amount of penalty due to the customer, M_{hu} is the compensation to the customer by the utility, P_{hc} is the penalty rate due to customer, C_{hu} is the compensation rate due to customer from the utility, THD_{vc} and THD_{vu} are the Total Harmonic Distortion voltage of the customer and the utility respectively.

The energy charge Me is expressed as shown in Eq. (3)

$$M_e = EC_1 \qquad (3)$$

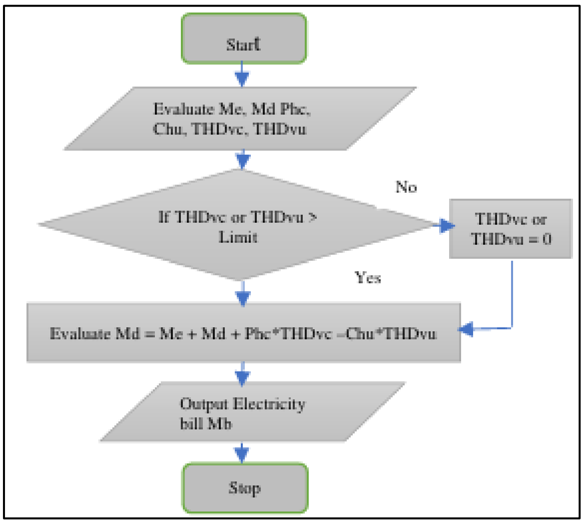
Where E is the amount of energy consumed by a customer in kWh, C1 is the energy rate.

The power demand charges, $M_{d,\ are}$ expressed as shown in Eq. (4)

$$M_d = C_2 S \qquad (4)$$

Where C2 is the demand charge rate, and S is the customer's maximum demand.

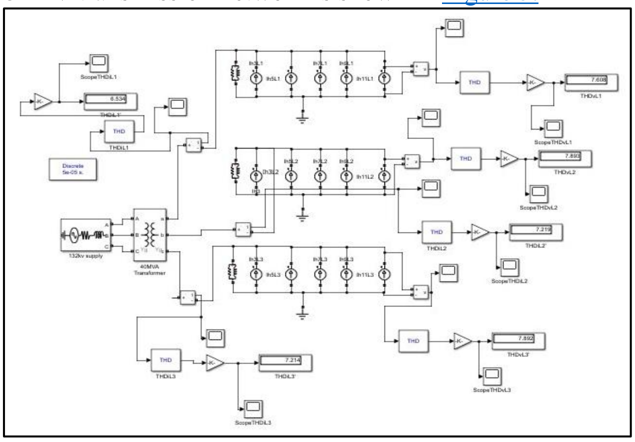
B. Model Flowchart



[Fig.1: Model Flowchart]

C. Application of the Harmonic Penalty Model

Three steel companies along the Ikorodu-Shagamu Road between Lagos and Ogun State, Nigeria, were used as a case study. The companies are African Foundries Limited (AFL), Phoenix Steel Mills Limited, and Quantum Steels Nigeria Limited (Real Steel). An AR6 power analyser was used to measure the load data for these companies, which were then used to simulate each company's non-linear loads in MATLAB/Simulink, as shown in Figures 2 - 4. The 132 kV transmission networks feeding the three companies were then simulated using the Sub-system of each company's non-linear loads, as shown in Figure 6. The single-line diagram of the 132 kV transmission network is shown in Figure 5.



[Fig.2: African Foundries Limited (AFL) Load Simulation]

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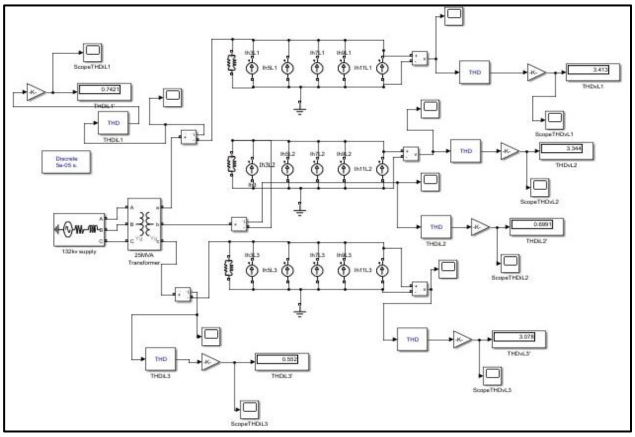
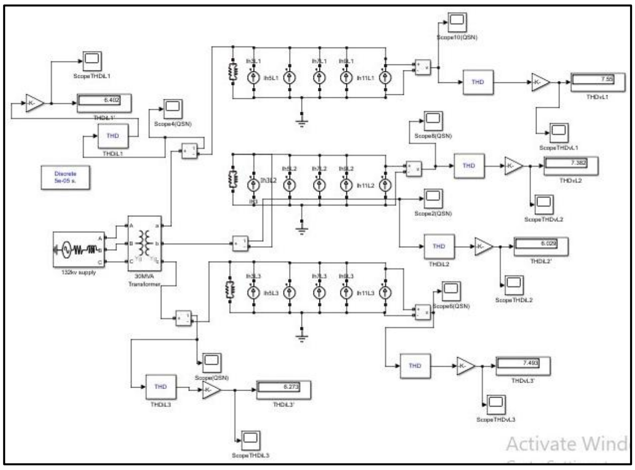
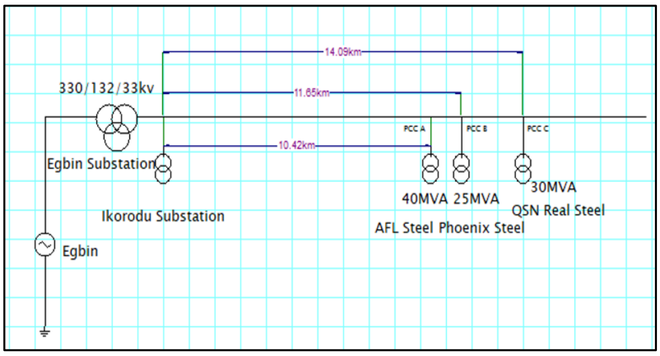


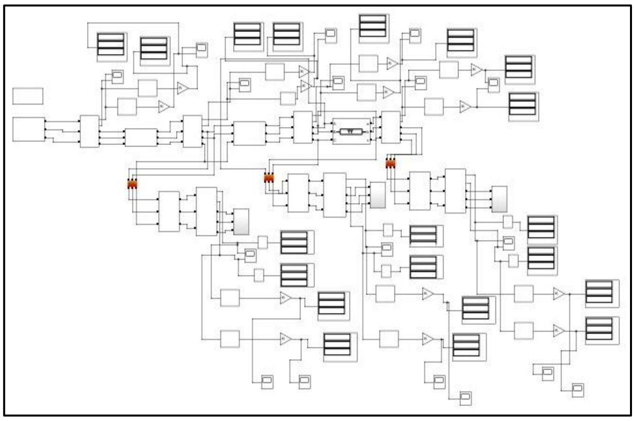
[Fig.3: Phoenix Steel Mills Limited Load Simulation]



[Fig.4: Quantum Steels Nigeria Limited (Real Steel) Load Simulation]



[Fig.5: Single Line Diagram of the 132kv Transmission Network]



[Fig.6: Simulation of the 132kv Transmission Network Feeding Three Steel Companies]

III. RESULTS AND DISCUSSIONS

A. Simulation Results

The results of the simulations for each load of the three companies and the 132 kV transmission networks were shown in Tables 1 and 2, respectively. The Total Harmonic Distortion voltage of each company (THDvc) and the corresponding Total Harmonic Distortion voltage from the utility (THDvu) were used to test the harmonic penalty model

Table I: THDv of the Three Companies (Simulation Result)

	SIMULATION RESULT		
THDvc	**$THDvc_1$(%)**	**$THDvc_2$(%)**	**$THDvc_3$(%)**
AFL Steel	7.57	7.88	7.90
Phoenix Steel	10.30	10.09	10.09
QSN	8.58	8.58	8.58

Table II: THDv From the Utility at PCC of Each Company (Simulation result)

	SIMULATION RESULT		
THDvu	**$THDvu_1$(%)**	**$THDvu_2$(%)**	**$THDvu_3$(%)**
AFL Steel	0.30	1.43	0.29
Phoenix Steel	0.28	1.43	0.30
QSN	1.57	1.42	0.28

B. Testing of the Penalty Model

After obtaining the necessary data for evaluating the electrical bills of the three companies. The penalty model was tested on these companies as follows;

i. Testing of the Model on African Foundries Limited (AFL)

Energy consumption (E) = 71,942 kWh, C1 = ₦100
Maximum demand (S) = 6,000 kW, C2 = ₦65
THDvc = 7.24, Phc = ₦100,000
THDvu = 1.43 (Less than THDv limit of 2.5), Chu = ₦24,000
The harmonic penalty is applied as follows;
Energy charge Me = EC1 = 71942*100 = ₦7,194,200
Demand charge Md = C2S = 65*6000 = ₦390,000
Penalty charge Mhc = Phc*THDvc = 100000*7.24 = ₦720,000
Compensation Mhu = Chu*THDvu = 24000*0 = 0 (No compensation as THDv is less than the limit)
From Eq. (1)
Mb = Me + Md + Mhc - Mhu
Mb = ₦7194200 + ₦390000 + ₦720000 - 0
Mb = ₦8,308,200.00
The electricity bill of the company is ₦8,308,200.00

ii. Testing of the Model on Phoenix Steel Mills Limited

Energy consumption (E) = 9,081.9 kWh, C1 = ₦100
Maximum demand (S) = 7,100 kW, C2 = ₦65
THDvc = 10.30, Phc = ₦100,000
THDvu = 1.43 (Less than THDv limit of 2.5), Chu = ₦24,000
The harmonic penalty is applied as follows;
Energy charge Me = EC1 = 9081.9*100 = ₦908,190
Demand charge Md = C2S = 65*7100 = ₦461,500
Penalty charge Mhc = Phc*THDvc = 100000*10.30 = ₦1,030,000
Compensation Mhu = Chu*THDvu = 24000*0 = 0 (No compensation as THDv is less than the limit)
From Eq. (1)
Mb = Me + Md + Mhc - Mhu
Mb = ₦908190 + ₦461500 + ₦1030000 - 0
Mb = ₦2,399,690.00

The electricity bill of the company is ₦2,399,690.00

iii. Testing of the Model on Quantum Steels Nigeria Limited (Real Steel)

Energy consumption (E) = 205,654.9 kWh, C1 = ₦100
Maximum demand (S) = 18000 kW, C2 = ₦65
THDvc = 8.58, Phc = ₦100,000
THDvu = 1.57 (Less than THDv limit of 2.5), Chu = ₦24,000
The harmonic penalty is applied as follows;
Energy charge Me = EC1 = 205654.9*100 = ₦20563490
Demand charge Md = C2S = 65*18000 = ₦1170000
Penalty charge Mhc = Phc*THDvc = 100000*8.58 = ₦858000
Compensation Mhu = Chu*THDvu = 24000*0 = 0 (No compensation as THDv is less than the limit)
From Eq. (1)
Mb = Me + Md + Mhc - Mhu
Mb = ₦20563490 + ₦1170000 + ₦858000 - 0
Mb = ₦22,591,490.00
The electricity bill of the company is ₦22,591,490.00

C. MATLAB Code for the Harmonic Penalty Model

MATLAB program was developed for easy application of the penalty model as follows;

```
% Program to evaluate the electricity bill of a company with the proposed model
% This section of the script clears the workspace
clear
clc
%
% This section of the script calculates the energy bill using the penalty and % compensation due to harmonics
V = input ('Voltage level (132kv or 33kW)');
E = input ('Emergy consumption kWh);
C1 = input ('Energy rate #');
S = input ('Maximum Demand kW');
C2 = input ('Demand rate #');
Phc = input ('Penalty rate #');
Chu = input ('Compensation rate #');
THDvc = input ('Customer Total Harmonic Distortion %');
THDvu = input ('Utility Total Harmonic Distortion %');
if (V==33)
   R = 5.0;
else
   R = 2.5;
end
if (THDvc<R)
   THDvc = 0
else
end
if (THDvu<R)
   THDvu = 0
else
end
Mb = E*C1+C2*S+(Phc*THDvc)-(Chu*THDvu);
disp('The Electricity bill of the company is #'); disp(Mb);
```

IV. CONCLUSION

The harmonic penalty model presented in this research offers a substantial improvement over existing methods for penalising customers that generate harmonics in the power system. The application of the penalty model will ensure that customers who generate significant harmonics in the power system are appropriately penalised, and that the utility will also take responsibility for harmonics generated by its network by compensating customers. It is recommended that the utility use this harmonic penalty model to reduce harmonic distortion in the power system. Further study on the inclusion of the power factor in the harmonic penalty model can be carried out in the future.

DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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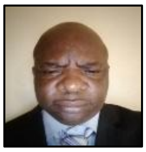

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