Time Series Regression Modelling Of Transformer Failure Rate For Aba District Electricity Distribution Network

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***Abstract*— In this paper, time series regression modelling of transformer failure rate for Aba district electricity distribution network is presented. The case study data on transformer failure covered a period of five years (2016 to 2020) as observed or recorded in the operational log book from the respective injection substations in the Aba electricity distribution network, which were obtained from the Enugu Electricity Distribution Company (EEDC). From the data, the customer hours, customer frequency due to transformer fault and the feeder wise transformer failure percentage, as well as the yearly total of the relevant power distribution network parameters that pertain to transformer failure were computed. Then, quadratic regression time series model with one period lagged dependent variable was used to model the yearly total of the relevant power distribution network parameters. The modelled parameters are; the total number of transformer or total number of transformers installed, the total number of customers, the total outage due to transformer fault or total number of failed transformers, the total outage duration due to transformer fault and the transformer failure percentage. The time series regression models were also used forecast the modelled parameter value up to the year 2023. The results show that in 2023 the total number of transformer or total number of transformers installed will increase to a value of 1094.668 which is about 32% increase from 2016 base year value), the total number of customers will increase to a value of 144846.174 which is about 12% increase from 2016 base year value), the total outage due to transformer fault or total number of failed transformers will increase to a value of 499.1713 which is about 389 % increase from 2016 base year value), the total outage duration due to transformer fault will increase to a value of 20686.31 which is about 133 % increase from 2016 base year value) and the transformer failure percentage will increase to value of 87.01079 which is about 465 % increase from 2016 base year value). In all, it was observed from the forecast that the transformer failure in the network will continue to increase significantly each year and that is a big concern for management of power distribution in the case study power distribution network.**

Keywords*— *Transformer Fault, Time Series Model, Transformer Failure Rate, Regression Model, Aba District Electricity Distribution Network, Transformer Failure Percentage

1. Introduction

In Nigeria, electric power shortage is a dominant problem [1,2,3,4,5,6,7,8,9,10]. Large population of the Nigerian citizens are not connected to the national grid. Also, the growing dependence of human beings on electric-powered technologies, devices and systems has made electric power supply increasingly important and also made the demand to increase perpetually [11,12,13, 14,15,16,17,18,19,20,21,22,23,24,25,26,27]. Also, the very poor and epileptic power supply from the grid also discourages many households and business entities from relying on the national grid for sustainable power supply [28,29,30,31,32,33]. Rather, many people have resorted to alternative power supply through solar power systems, wind energy system, diesel generators and other readily available and affordable alternative energy supply system [34,35, 36,37,38, 39,40,41, 42,43,44, 45,46, 47,48, 49, 50, 51].

One of the major causes of the poor and epileptic power supply from the national grid is the failure of transformers in the electricity distribution network [42,53,54,55,56,57]. Also, the meagre energy generated when compared to the energy demand leads to load shading approach in the power supply system [58,59,60]. This also causes the epileptic power supply. In any case, the focus of this paper is to analyse the transformer rate in a case study electricity distribution network. Dataset of transformer rate over a period of time (in years) acquired from the power distribution company is used to carry out time series modelling of the transformer failure rate for the case study power network. The essence of the study is to identify the time series trend of the transformer failure and hence extract relevant information for decision making on how to manage the situation for improved electric power supply in the case study area.

2. Methodology

The focus of this paper is to use the available dataset on transformer failure for a case study power distribution to develop time series models and apply the models for forecasting some key parameter of the power network. Specifically, the parameters that are modelled includes;

i. The total number of transformer or total number of transformers installed (denoted as Ntf),
ii. The total number of customers (denoted as Ni),
iii. The total outage due to transformer fault or total number of failed transformers (denoted as λf)
iv. The total outage duration due to transformer fault (denoted as Df)
v. The transformer failure percentage (denoted as λ).

2.1 Description and pre-analysis of the case study dataset

The case study data on transformer failure covered a period of five years (2016 to 2020) as observed or recorded in the operational log book from the respective injection substations in the Aba electricity distribution network, which were obtained from the Enugu Electricity Distribution Company (EEDC).

The data collected include list of all transformers rated 50 KVA – 500 KVA fed from the respective injection substations as well as those directly fed from the 33 kV lines in between the respective injection sub-stations, monthly maximum loadings on the injection stations/ feeders, number of transformer units that failed, cause of failure, the number of outages caused by transformer failures, the outage duration, voltage level etc. covering the period of the study.

The summary of the dataset is as contained in Table 1 for the year 2016. The dataset in Table 1 shows that there are a total of seventeen (17) feeder lines with two (2) operating at 33 kV voltage class while the other fifteen (15) are operating at 11 kV levels. Also, the datesse in table 2016 shows that as at December 2016, there were a total of 830 active transformer units installed to service 129,498 active customers within the Aba distribution network.

Table 1 Feeder Wise Transformer Outage Summary for 2016

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8	Column 9
S/No	**Feeder Name**	**Voltage level**	**No. of Trfs (Ntf)**	**No of Customers (Ni)**	**Outage due to Trf Fault (λf)**	**Outage Duration due to Trf Fault (Df)**	**Customer Hrs due to Trf Fault (Ni*Df)**	**Customer Frequency due to Trf Fault (Ni*λf)**
1	PS FDR-1	11KV	27	5,002	0	0	0	0
2	PS FDR-2	11KV	59	8,814	7	302	2,661,828	61,698
3	PS FDR-3	11KV	27	3,251	6	134	435,634	19,506
4	PS FDR-4	11KV	70	7,530	8	385	2,899,050	60,240
5	PS FDR-5	11KV	62	5,535	7	284	1,571,940	38,745
6	ECN FDR-1	11KV	21	3,300	0	0	0	0
7	ECN FDR-2	11KV	82	16,546	17	1,160	19,193,360	281,282
8	ECN FDR-3	11KV	33	6,204	2	150	930,600	12,408
9	ECN FDR-4	11KV	72	7,656	12	902	6,905,712	91,872
10	ECN FDR-5	11KV	28	5,940	0	0	0	0
11	7UP FDR	11KV	81	8,316	12	1,560	12,972,960	99,792

12	WATERSIDE	11KV	40	7,261	2	198	1,437,678	14,522
13	IGI FDR	33KV	30	13,850	4	128	1,772,800	55,400
14	ABA/UMUAH IA	33KV	104	13,150	9	806	10,598,900	118,350
15	OVOM FDR	11KV	18	8,440	3	900	7,596,000	25,320
16	OMOBA FDR	11KV	18	4,550	0	0	0	0
17	OVUOJI FDR	11KV	58	4,153	13	1,970	8,181,410	53,989
	TOTAL		830	**129,498**	**102**	**8,879**	**77,157,872**	**933,124**

2.2 Customer hours and customer frequency due to transformer fault

In Table 1, the values in column 1 to column 7 are primary data items while the values in column 8 (which is customer hours due to transformer fault) and column 9 (which is customer frequency due to transformer fault) are computed. Accordingly, column 8 content is computed as;

$$\text{Customer Hours Due To Transformer Fault} = \text{Ni (Df)} \quad (1)$$

. Similarly, column 9 content is computed as;

$$\text{Customer frequency due to transformer fault} = \text{Ni} (\lambda f) \quad (2)$$

Where Ni denotes the number of customers, Df denotes the outage duration due transformer fault and λf denotes outage due to transformer fault.

2.3 The feeder wise transformer failure percentage

Based on the data provided in Table 1, the number of transformers in operation, Nf is computed as follows;

$$\text{Nf} = \text{Ntf} - \lambda\text{f} \quad (3)$$

Where Ntf denotes total of transformers installed and λf denotes number of failed transformers. Then, the percentage of failed transformer in each year is denoted as λ and is computed as follows;

$$\lambda = \left(\frac{\lambda f}{Nf}\right) 100\,\% \quad (4)$$

By using the analytical expressions in Equation 3 and Equation 4, the feeder wise transformer failure percentage is computed for each year and a summary for 2016 is presented in Table 2. From the data generated in Table 1 and 2 for the year 2016 as well as similar data generated for the other years (2017 to 2020) considered in the study, the total feeder-wise transformer outage summary and feeder wise transformer failure percentage summary for year 2016 to 2020 are obtained and presented in Table 3.

Table 2 The feeder wise transformer failure percentage summary for 2016

		Ntf	λf	Nf =Ntf - λf	ƛ = (λf /Nf)100%
S/No	Injection Substation/ Feeder	Total of transformers installed, Ntf	Number of failed transformers, λf	Number of transformers in operation, Nf	Transformer failure percentage
1	ECN	236	31	205	15.1
2	Ovom	18	3	15	20.0
3	Power Station	245	28	217	12.9
4	Ogbor Hill	121	14	107	13.1
5	Omoba	76	13	63	20.6
6	33KV (IGI & Aba/Umuahia	134	13	121	10.7
	Total	830	102	728	92.48801146
	Average failure Rate				15.4

Table 3 Total feeder-wise transformer outage summary and feeder wise transformer failure percentage summary for year 2016 to 2020

Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7	Column 8
TOTAL	Total No. of Transformer (Ntf)	Total No of Customers (Ni)	Total Outage due to Transformer Fault (λf)	Total Outage Duration due to Transformer Fault (Df)	Total Transformer failure percentage (%)	Total Customer Hrs due to Transformer Fault (Ni*Df)	Total Customer Frequency due to Transformer Fault (Ni*λf)
2016	**830**	**129,498**	**102**	**8,879**	**15.4**	**77,157,872**	**933,124**
2017	**830**	**130,516**	**101**	**7,798**	15.0	**63,306,989**	**859,568**
2018	**835**	**131,637**	**109**	**8,745**	13.9	**77,197,952**	**1,013,876**
2019	**853**	**134,778**	**123**	**8,889**	19.6	**85,156,308**	**1,140,322**
2020	**885**	**135,098**	**162**	**10,990**	28.3	**96,008,136**	**1,522,318**

Each of the parameters in columns 2 to column 6 are characterised using suitable time series model. The items in column 8 and column 9 are computed from the items in column 1 to column 5. The modelled parameters are;

i. Columns 2: the total number of transformer or total number of transformers installed (denoted as Ntf)
ii. Columns 3: the total number of customers (denoted as Ni)
iii. Columns 4: the total outage due to transformer fault or total number of failed transformers (denoted as λf)
iv. Columns 5: the total outage duration due to transformer fault (denoted as Df)
v. Columns 6: the transformer failure percentage (denoted as λ)

2.4 The model development and evaluation

Each of the parameters is modelled using quadratic regression with one period lagged dependent variable which is expressed given as;

$$P_{a(t)} = a(t^2) + b(t) + c + d(P_{a(t-1)}) \quad (5)$$

Where $P_{a(t)}$ is the parameter value estimated for time t and the $P_{a(t-1)}$ is the parameter value estimated for time t-1 while a, b, c and d are the model constants which in this paper are determined from the available data using Microsoft Excel Solver tool. The model prediction error, $e_{(t)}$ and the mean of the $P_{a(t)}$ for t = 1,2,3,…n are expressed as follows;

$$e_{(t)} = P_{a(t)} - P_{p(t)} \quad (6)$$

$$\overline{P_a} = \left(\frac{1}{n}\right)\left(\sum_{t=1}^{n}(P_{a(t)})\right) \quad (7)$$

The Mean Squared Error (MSE) and Root Mean Squared Error (RMSE) are expressed as follows;

$$MSE = \left(\frac{1}{n}\right)\left(\sum_{t=1}^{n}(e_{(t)})^2\right) \quad (8)$$

$$RMSE = \sqrt[2]{\left[\left(\frac{1}{n}\right)\left(\sum_{t=1}^{n}(e_{(t)})^2\right)\right]} \quad (9)$$

The Mean Absolute Percentage Error (MAPE) and Mean Percentage Error (MPE are expressed as follows;

$$MAPE = \left(\frac{1}{n}\right)\left(\sum_{t=1}^{n}\left(\frac{P_{a(t)} - P_{p(t)}}{P_{a(t)}}\right)\right) \quad (10)$$

$$MPE = \left(\frac{100}{n}\right)\left(\sum_{t=1}^{n}\left(\frac{P_{a(t)} - P_{p(t)}}{P_{a(t)}}\right)\right) \quad (11)$$

The Mean Absolute Deviation (MAD) is expressed as follows;

$$MAD = \left(\frac{1}{n}\right)\left(\sum_{t=1}^{n}\left|P_{a(t)} - \overline{P_a}\right|\right) \quad (12)$$

3. Results and discussion

3.1 The results for the total number of transformer or total number of transformers installed

The quadratic regression with one period lagged dependent variable for the total number of transformer or total number of transformers installed is given as;

$$\text{Ntf}_{p(t)} = a(t^2) + b(t) + c + d(\text{Ntf}_{p(t-1)}) \quad (13)$$

Where $\text{Ntf}_{p(t)}$ at time t is the predicted value and $\text{Ntf}_{p(t)}$ is the actual value at time t, as shown in Table 4. The results of the model development for the total number of transformer or total number of transformers installed are such that the values of the model constants are; a = 1.578026313, b= 0, c =0 and d = 0.990977487. Hence,

$$\mathrm{Ntf}_{p(t)} = 1.578026313t^2 + 0.990977487\left(\mathrm{Ntf}_{p(t-1)}\right) \quad (14)$$

The results of the model prediction and performance evaluation for the total number of transformer or total number of transformers installed are given in Table 4. The graph of the actual and predicted values of the total number of transformers installed, Ntfa and Ntfp is shown in Figure 1. The results show that in 2023 the total number of transformer or total number of transformers installed will increase to a value of 1094.668 which is about 32% increase from 2016 base year value).

Table 4 The total number of transformer or total number of transformers installed (denoted as Ntf)

Year	Year Index, t	The total number of transformers installed, $\mathrm{Ntf}_{a(t)}$	a	b	c	d	$\mathrm{Ntf}_{p(t)}$
			1.578026	**0**	**0**	**0.990977**	
2016	**1**	**830**	1.578026	0	0	0.990977	830
2017	**2**	**830**	1.578026	0	0	0.990977	828.8234
2018	**3**	**835**	1.578026	0	0	0.990977	836.7136
2019	**4**	**853**	1.578026	0	0	0.990977	852.7146
2020	**5**	**885**	1.578026	0	0	0.990977	884.7545
2021	**6**		1.578026	0	0	0.990977	933.824
2022	**7**		1.578026	0	0	0.990977	1002.722
2023	**8**		1.578026	0	0	0.990977	1094.668
	RMSE:	0.944726		MSE:	0.892507	MAD:	0.68422
	MAPE:	0.000816		MPE:	-4.5E-06		

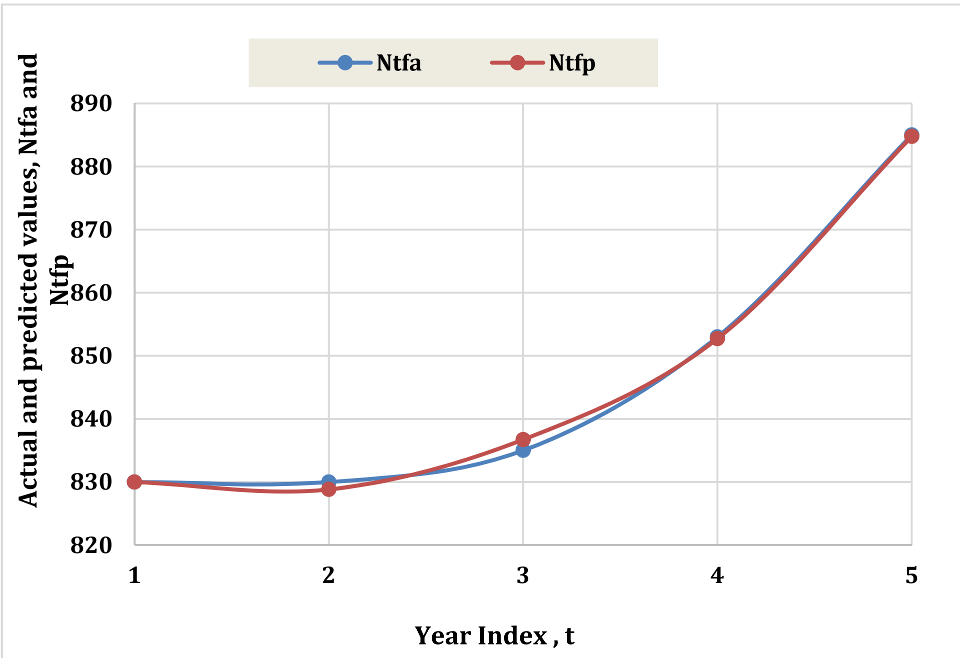

Figure 1 The graph of the actual and predicted values of the total number of transformers installed, Ntfa and Ntfp

3.2 The results for the total number of customers

The quadratic regression with one period lagged dependent variable for the total number of customers, is given as;

$$\mathrm{Ni}_{p(t)} = a(t^2) + b(t) + c + d\left(\mathrm{Ni}_{p(t-1)}\right) \quad (15)$$

Where $\mathrm{Ni}_{p(t)}$ at time t is the predicted value and $\mathrm{Ni}_{p(t)}$ is the actual value at time t, as shown in Table 5. The results of the model development for the total number of customers are such that the values of the model constants are; a = 234.1543, b= 0, c = 129846.2 and d = 0.0001. Hence,

$$Ni_{p(t)} = 234.1543t^2 + 129846.2 + 0.0001(Ni_{p(t-1)}) \quad (16)$$

The results of the model prediction and performance evaluation for the total number of customers are given in Table 5. The graph of the actual and predicted values of the total number of costumers, Nia and Nip is shown in Figure 2. The results show that in 2023 the total number of customers will increase to a value of 144846.174, which is about 12% increase from 2016 base year value).

Table 5 The total number of customers (denoted as Ni)

Year	Year Index, t	The total number of customers, $Ni_{a(t)}$	a	b	c	d	$Ni_{p(t)}$
			234.1543	0	129846.2	0.0001	
2016	1	129,498	234.1543	0	129846.2	0.0001	129498
2017	2	130,516	234.1543	0	129846.2	0.0001	130795.7342
2018	3	131,637	234.1543	0	129846.2	0.0001	131966.6074
2019	4	134,778	234.1543	0	129846.2	0.0001	133605.7994
2020	5	135,098	234.1543	0	129846.2	0.0001	135713.5019
2021	6		234.1543	0	129846.2	0.0001	138289.2309
2022	7		234.1543	0	129846.2	0.0001	141333.5555
2023	8		234.1543	0	129846.2	0.0001	144846.174
	RMSE:	622.8626006		MSE:	387957.8193	MAD:	479.40882
	MAPE:	0.003580088		MPE:	-0.00010118		

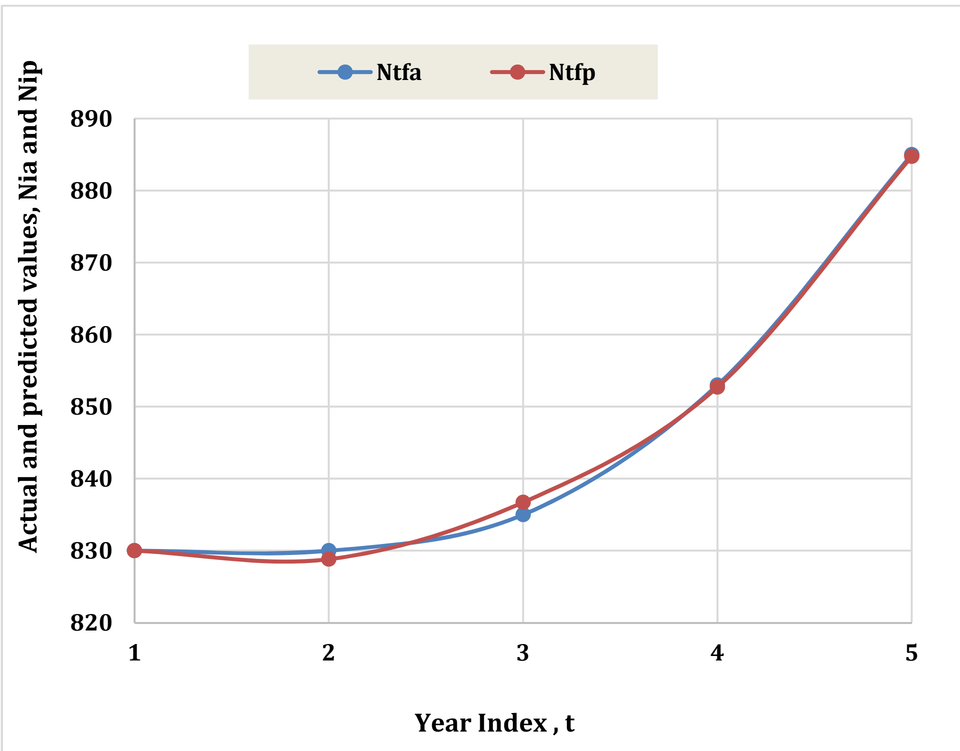

Figure 2 The graph of the actual and predicted values of the total number of customers ($Ni_{a(t)}$ and $Ni_{p(t)}$)

3.3 The results for the total outage due to transformer fault or total number of failed transformers

The quadratic regression with one period lagged dependent variable for the total outage due to transformer fault or total number of failed transformers , is given as;

$$Ʌf_{p(t)} = a(t^2) + b(t) + c + d\left(Ʌf_{p(t-1)}\right) \quad (17)$$

Where $Ʌf_{p(t)}$ at time t is the predicted value and $Ʌf_{p(t)}$ is the actual value at time t, as shown in Table 6. The results of the model development for the total outage due to transformer fault or total number of failed transformers are such that the values of the model constants are; a = 3.506755, b= 12.72452, c = 0.001195 and d = 1.11206. Hence,

$$Ʌf_{p(t)} = 3.506755\, t^2 + 129846.2t + 0.001195 + 1.11206\left(Ʌf_{p(t-1)}\right) \quad (18)$$

The results of the model prediction and performance evaluation for the total outage due to transformer fault or total number of failed transformers are given in Table 6. The graph of the actual and predicted values of the total outage due to transformer fault or total number of failed transformers, Ʌfa and Ʌfp is shown in Figure 3. The results show that in 2023 the total outage due to transformer fault or total number of failed transformers will increase to a value of 499.1713 which is about 389 % increase from 2016 base year value).

Table 6 The total outage due to transformer fault or total number of failed transformers (denoted as Ni)

Year	Year Index, t	The total outage due to transformer fault or total number of failed transformers, $Ʌf_{a(t)}$	a	b	c	d	$Ʌf_{p(t)}$
			3.506755	12.72452	0.001195	1.11206	
2016	1	102	3.506755	12.72452	0.001195	1.11206	102
2017	2	101	3.506755	12.72452	0.001195	1.11206	102.0093
2018	3	109	3.506755	12.72452	0.001195	1.11206	105.7065
2019	4	123	3.506755	12.72452	0.001195	1.11206	126.4258
2020	5	162	3.506755	12.72452	0.001195	1.11206	160.8309
2021	6	230.0511	3.506755	12.72452	0.001195	1.11206	230.0511
2022	7	338.5912	3.506755	12.72452	0.001195	1.11206	338.5912
2023	8	499.1713	3.506755	12.72452	0.001195	1.11206	499.1713
	RMSE:	2.234669067		MSE:	4.993745838	MAD:	1.77954
	MAPE:	0.015055473		MPE:	-8.25678E-05		

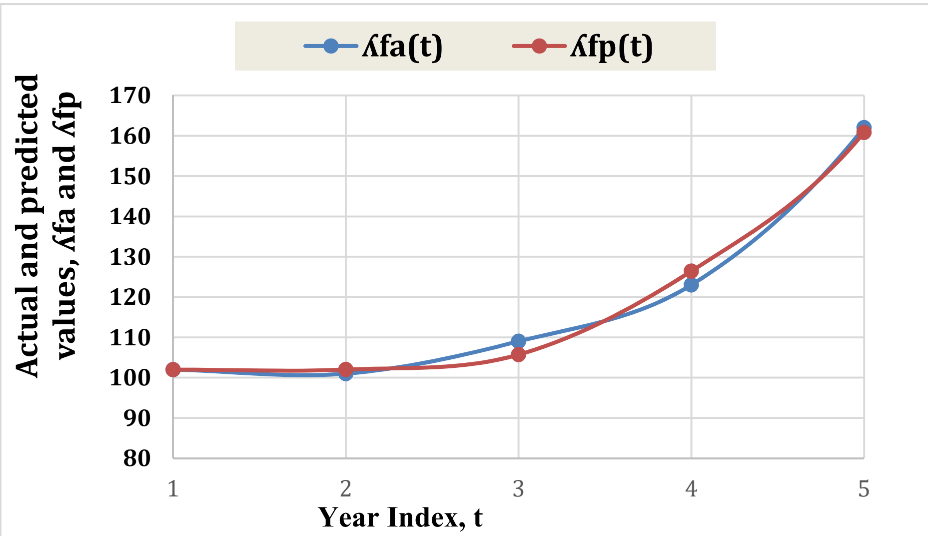

Figure 3 The graph of the actual and predicted values of the total outage due to transformer fault or total number of failed transformers ($Ʌf_{a(t)}$ and $Ʌf_{p(t)}$)

3.4 The results for the total outage duration due to transformer fault

The quadratic regression with one period lagged dependent variable for the total outage duration due to transformer fault , is given as;

$$\mathrm{Df}_{p(t)} = a(t^2) + b(t) + c \ + d\left(\mathrm{Df}_{p(t-1)}\right) \quad (19)$$

Where $\mathrm{Df}_{p(t)}$ at time t is the predicted value and $\mathrm{Df}_{p(t)}$ is the actual value at time t, as shown in Table 7. The results of the model development for the total outage duration due to transformer fault are such that the values of the model constants are; a = 397.21, b= -1852, c = 10247 and d = -0.01. Hence,

$$\mathrm{Df}_{p(t)} = 3.506755\, t^2 - 1852\mathrm{t} + 10247 - 0.01\left(\mathrm{Df}_{p(t-1)}\right) \quad (20)$$

The results of the model prediction and performance evaluation for the total outage duration due to transformer fault are given in Table 7. The graph of the actual and predicted values of the total outage duration due to transformer fault, Dfa and Dfp is shown in Figure 4. The results show that in 2023 the total outage duration due to transformer fault will increase to a value of 20686.31 which is about 133 % increase from 2016 base year value).

Table 7 The total outage duration due to transformer fault (denoted as Df)

Year	Year Index, t	The total outage duration due to transformer fault, $\mathrm{Df}_{a(t)}$	a	b	c	d	$\mathrm{Df}_{p(t)}$
			397.21	-1852	10247	-0.01	
2016	1	8,879	397.21	-1852	10247	-0.01	8879
2017	2	7,798	397.21	-1852	10247	-0.01	8043.05
2018	3	8,745	397.21	-1852	10247	-0.01	8187.91
2019	4	8,889	397.21	-1852	10247	-0.01	9106.91
2020	5	10,990	397.21	-1852	10247	-0.01	10828.36
2021	6		397.21	-1852	10247	-0.01	13324.66
2022	7		397.21	-1852	10247	-0.01	16613.04
2023	8		397.21	-1852	10247	-0.01	20686.31
	RMSE:	297.9969893		MSE:	88802.20566	MAD:	236.338
	MAPE:	0.026870208		MPE:	0.004494491		

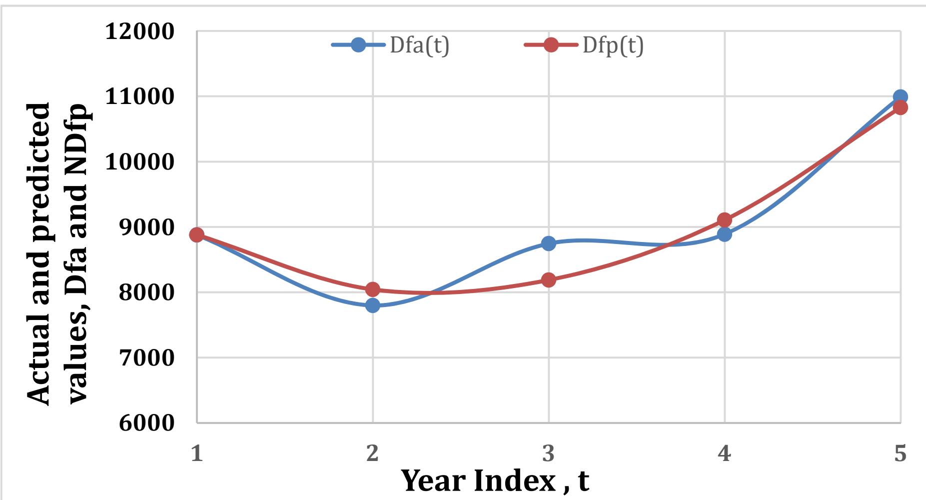

Figure 4 The graph of the actual and predicted values of the total outage duration due to transformer fault ($\mathrm{Df}_{a(t)}$ and $\mathrm{Df}_{p(t)}$)

3.5 The results for the transformer failure percentage

The quadratic regression with one period lagged dependent variable for the transformer failure percentage, is given as;

$$ʎ_{p(t)} = a(t^2) + b(t) + c\ + d(ʎ_{p(t-1)}) \quad (21)$$

Where $ʎ_{p(t)}$ at time t is the predicted value and $ʎ_{p(t)}$ is the actual value at time t, as shown in Table 7. The results of the model development for the transformer failure percentage are such that the values of the model constants are; a = 2.449548034, b= 12.58724132, c = 30.18618492 and d = 0.012. Hence,

$$ʎ_{p(t)} = 2.449548t^2 + 12.58724\text{t} + 30.18618 + 0.012(ʎ_{p(t-1)}) \quad (22)$$

The results of the model prediction and performance evaluation for the transformer failure percentage are given in Table 7. The graph of the actual and predicted values of the transformer failure percentage, $ʎ_{a(t)}$ and $ʎ_{p(t)}$ is shown in Figure 5. The results show that in 2023 the transformer failure percentage will increase to value of 87.01079 which is about 465 % increase from 2016 base year value).

0.012

Table 8 The transformer failure percentage (denoted as ʎ)

Year	**Year Index, t**	**The transformer failure percentage, $ʎ_{a(t)}$**	**a**	**b**	**c**	**d**	$ʎ_{p(t)}$
			2.449548	12.58724	30.18618	0.012	
2016	**1**	**15.4**	2.449548	12.58724	30.18618	0.012	15.4
2017	**2**	**15**	2.449548	12.58724	30.18618	0.012	14.99469
2018	**3**	**13.9**	2.449548	12.58724	30.18618	0.012	14.65039
2019	**4**	**19.6**	2.449548	12.58724	30.18618	0.012	19.19679
2020	**5**	**28.3**	2.449548	12.58724	30.18618	0.012	28.72388
2021	**6**		2.449548	12.58724	30.18618	0.012	43.18607
2022	**7**		2.449548	12.58724	30.18618	0.012	62.62158
2023	**8**		2.449548	12.58724	30.18618	0.012	87.01079
	RMSE:	0.425526945		MSE:	0.181073181	MAD:	0.316558
	MAPE:	0.017977785		MPE:	- 0.009607409		

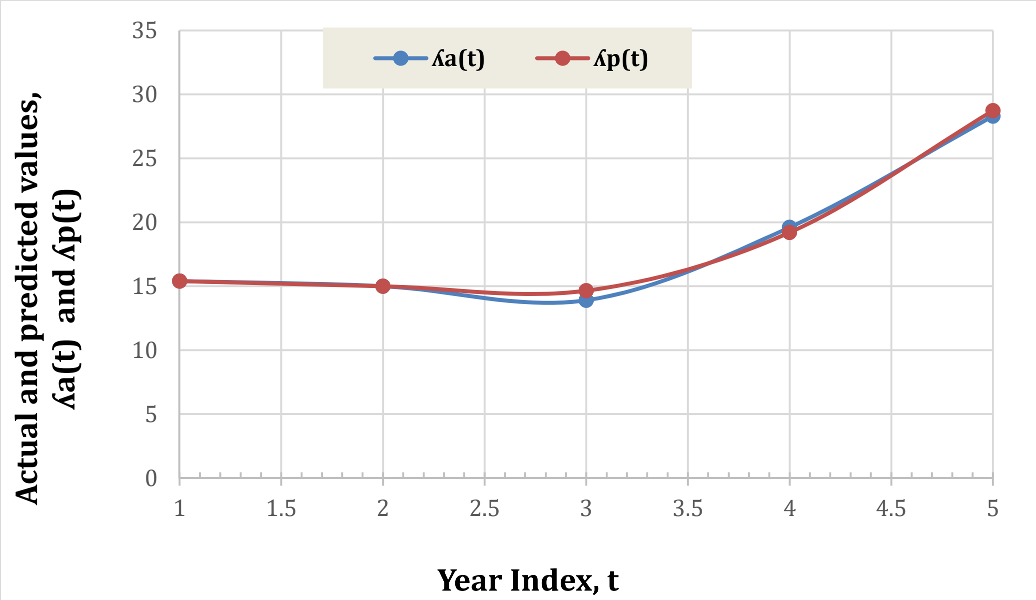

Figure 5 The graph of the actual and predicted values of the transformer failure percentage ($ʎ_{a(t)}$ and $ʎ_{p(t)}$)

4. Conclusion

The paper presents the modelling of key parameters pertaining to the transformer failure rate for a case study Aba district electricity distribution network. Specifically, time series quadratic regression models were developed based on the five years (2016 to 2020) transformer failure dataset obtained for the case study power network. The modelled parameters are; the total number of transformer or total number of transformers installed, the total number of customers, the total outage due to transformer fault or total number of failed transformers, the total outage duration due to transformer fault and the transformer failure percentage.

The time series regression models were used forecast the modelled parameter value up to the year 2023. In all, it was observed from the forecast that the transformer failure in the network will continue to increase significantly each year and that is a big concern for management of power distribution in the network.

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