Cost Evaluation of Ohmic Losses in a Distribution Transformer due to Balanced and Unbalanced Loading (A Case Study of New Idumagbo 2 x 15-MVA, 33/11-kV Injection Substation)

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Abstract
This study shows the evaluation cost of ohmic losses due to balanced and unbalanced loading in a distribution transformer. Load readings were taken from all public and private 11/0.415-kV distribution transformers fed from the New Idumagbo Injection substation, 2 x 15MVA, 33/11-kV. The results showed that cost evaluation due to copper losses for both balanced and unbalanced load for Adeniji Adele feeder was $185,884 and $191,990 respectively for the period (June 2012 to May 2013) under review. For Tokunboh feeder, balanced and unbalanced cost was $91,334 and $95,919 respectively. Also, the cost due to copper losses due to balanced and unbalanced load for Dolphin feeder was $77,774 and $81,995 respectively. The result of the comparison between balanced and unbalanced loads showed that $14,912 would have been saved if the loads were to be balanced. Therefore, cost evaluation of copper losses varies considerably with the degree of load imbalanced.
Keywords: Substation, Transformer, Fault, Feeders.

I INTRODUCTION
Generally, three-phase balance is the ideal situation that any power system utility should achieve. However, single-phase loads, single-phase distributed resources, asymmetrical three-phase equipment and devices (such as three-phase transformers with open wye-open delta connections), unbalanced faults, bad connections to electrical connectors and many other factors cause power system imbalances and reduce power quality [1]. In a limited energy resource, energy efficiency is considered as a source of energy in a distribution system. This is particularly important in a country like Nigeria whose distribution system is faced with many problems, like low voltage drop and losses which vary with the pattern of loading in the distribution network [2]. Since utilities and consumers consider system losses as cost, its evaluation and reduction are necessary for researchers. There are many devices in distribution network responsible for energy losses, these include losses along distribution lines (feeders), losses in transformer windings and losses associated with unbalanced loads connected to distribution transformers.

II AIM OF THE STUDY
Considering the importance of losses in a distribution system, the aim of this research is to evaluate the cost of copper losses in a distribution network due to balanced and unbalanced loading in a transformer.

III MATERIALS AND METHODS
The Idumagbo Injection Substation under review was visited and the following data was collected:
1) Document containing the list of all 11-/0.415-kV transformers connected to the substation, year of manufacture, series number and ratings.
2) Single-line diagram of the substation and its associated feeders.
3) Load readings (red, yellow and blue phase) for each of the 11-/0.415-kV transformers in the network between June 2012 and May 2013.

The average load reading for the period under review and other data collected for the three feeders are presented in Tables 1.1 to 1.3.

Table 1.0: Substation parameters for Adeniji Adele 11-kV feeder

S/N	NAME OF SUBSTATION	Rating of transformer(KVA)	Average load current(A)			Total load current in the three phases
			Red Phase	Yellow Phase	Blue Phase	
1	PHASE 1-DOLPHIN ESTATE	500	343	401	456	1168
2	PHASE 2A-DOLPHIN ESTATE	500	352	394	363	1109
3	PHASE 2B-DOLPHIN ESTATE	500	406	235	295	936
4	PHASE 3-DOLPHIN ESTATE	500	330	298	387	1015
5	PHASE 4-DOLPHIN ESTATE	500	432	247	309	988
6	THOMAS-ADENIJI ADELE	500	179	413	319	911
7	GLOVER I-OSHODI	500	354	268	438	1060
8	GLOVER II-AMUTO	500	301	455	403	1159
9	OKEPOPO II-THOMAS	500	340	295	404	1039
10	GRIFITH-GRIFITH-OKEPOPO	500	213	172	150	535

Table 1.1: Substation parameters for Tokunboh 11-kV feeder

S/N	NAME OF SUBSTATION	Rating of transformer(KVA)	Average load current(A)			Total load current in the three phases
			Red Phase	Yellow Phase	Blue Phase	
1	TOKUNBO-ADAMS	500	236	427	385	1048
2	RICCA I-MACAULAY	500	308	351	459	1118
3	RICCA II-MACAULAY	500	264	370	455	1089
4	OMIDIDUN-EVANS	500	273	335	220	828
5	GRIFFITH-GRIFFITH I	500	221	229	423	873

Table 1.2: Substation parameters for Dolphin 11-kV feeder

S/N	NAME OF SUBSTATION	Rating of transformer(KVA)	Unbalanced Load Condition			
			Red Phase	Yellow Phase	Blue Phase	Total load current in the three phases
1	GRIFFITH II-OKEPOPO	500	237	419	440	1096
2	GLOVER II	500	378	271	406	1055
3	GLOVER I	500	198	311	298	807
4	PHASE III-DOLPHIN ESTATE	500	279	188	224	691
5	PHASE IV-DOLPHIN ESTATE	500	249	208	437	894

Mathematically, copper loss in a transformer is given by
Copper losses $= I^2R$ -----(1.0)

Where I = current (A) and R = resistance of the transformer winding. There is, however, another type of copper loss created as a result of unbalanced currents flowing in a three-phase transformer. For a three- phase transformer, let the secondary load currents flowing in each of the three-phase be I_R, I_Y and I_B.

Thus, total load current $(I_T) = I_R + I_Y + I_B$ ------ (1.1)
Copper losses in each phase = $I_R^2 R$ (Red phase),
$I_Y^2 R$ (Yellow phase) and $I_B^2 R$ (Blue phase).
Where R is the winding resistance of the transformer per phase.

Therefore, Total copper loss (unbalanced load condition)
$= I_R^2 R + I_Y^2 R + I_B^2 R = R(I_R^2 + I_Y^2 + I_B^2)$ ------- (1.2)
If the load on the transformer is balanced, then $I_R + I_Y + I_B = I$
Therefore, equation (1.2) becomes
Total copper loss $= R(I^2+I^2+I^2) = 3I^2R$ -------- (1.3)
Equation (1.3) gives the total copper losses in a transformer under balanced load condition, while equation (1.2) gives the total copper losses for unbalanced load.
Subtracting equation (1.3) from equation (1.2) yields:
$R(I_R^2 + I_Y^2 + I_B^2) - 3I^2R = P_{\text{loss unbalanced load}}$
$\therefore R\left[(I_R^2 + I_Y^2 + I_B^2\right] - 3I^2 = P_{\text{loss unbalanced load}}$ -------- (1.4)
Equation (1.4) shows that the total losses due to unbalanced load in a transformer would be higher as a result of unequal current flowing through the different phases of the transformer compared to when the load is balanced (equal current flowing through the phases). In determining these losses, the winding resistance per phase is assumed to be unity since this value is the same and constant for all phases of the transformer irrespective of the loading.
For the purpose of this research, we assume unit cost of ohmic losses to be \$0.055.

IV RESULTS AND DISCUSSION

The results from the copper losses calculations for both balanced and unbalanced load conditions show that:

i) The total transformer copper loss in the Adeniji Adele feeder is 3379701 units and 3490724 units for balanced and unbalanced load conditions, while the cost due to balanced and unbalanced load is \$185884 and \$191990 respectively.
ii) The total transformer copper loss in the Tokunboh feeder is 1660620 units and 1743982 units for balanced and unbalanced load conditions while the cost due to balanced and unbalanced load is \$91334 and \$95919 respectively.
iii) The total transformer copper loss in the Dolphin feeder is 1414065 units and 1490815 units for balanced and unbalanced load conditions while the cost due to balanced and unbalanced load is \$77774 and \$81995 respectively.
iv) Copper losses in transformer vary considerably with the degree of load unbalance.
v) Unbalanced loading in a transformer will reduce the capacity of the transformer in a distribution system.

Table 1.3: Ohmic losses for Adeniji Adele 11-kV feeder

NAME OF SUBSTATION	Total loss in the three phases due to unbalanced load	Total loss in the three phases due to balanced load	Cost due to unbalanced load	Cost due to balanced load
PHASE 1-DOLPHIN ESTATE	465458	454740	25600	25011
PHASE 2A-DOLPHIN ESTATE	410909	409959	22600	22548
PHASE 2B-DOLPHIN ESTATE	307086	292032	16890	16062
PHASE 3-DOLPHIN ESTATE	347473	343407	19111	18887
PHASE 4-DOLPHIN ESTATE	343114	325380	18871	17896
THOMAS-ADENIJI ADELE	304371	276639	16740	15215
GLOVER I-OSHODI	388984	374532	21394	20599
GLOVER II-AMUTO	460035	447759	25302	24627
OKEPOPO II-THOMAS	365841	359844	20121	19791
GRIFITH-GRIFITH-OKEPOPO	97453	95409	5360	5247

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Fig. 1.0: Graph of cost evaluation of ohmic losses due to balanced and unbalanced load for Adeniji Adele 11-kV feeder

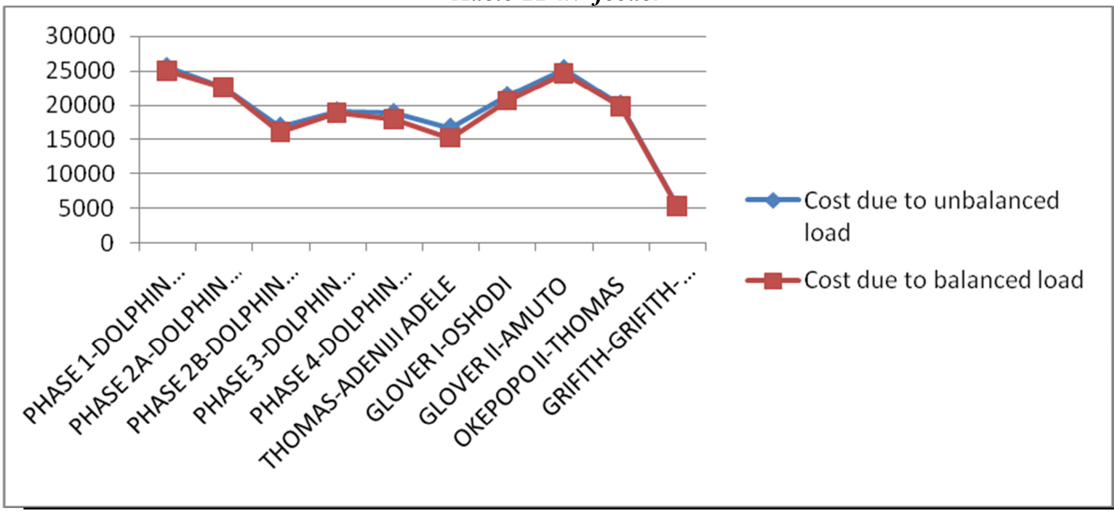

Fig. 1.1: Graph of ohmic losses due to balanced and unbalanced load for Adeniji Adele 11-kV feeder

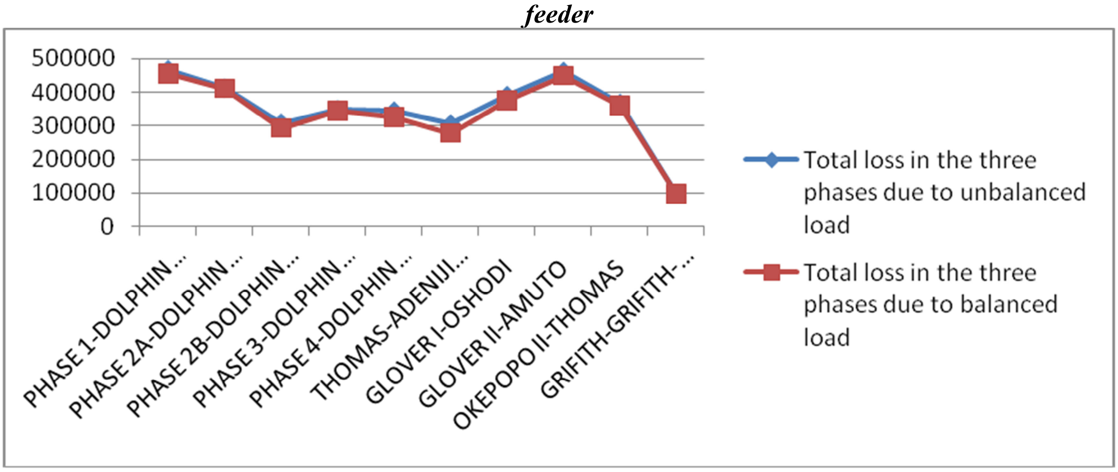

Table 1.4: Ohmic losses for Tokunboh 11-kV feeder

NAME OF SUBSTATION	Total loss in the three phases due to unbalanced load	Total loss in the three phases due to balanced load	Cost due to unbalanced load	Cost due to balanced load
TOKUNBO-ADAMS	386250	366102	21244	20136
RICCA I-MACAULAY	428746	416640	23581	22915
RICCA II-MACAULAY	413621	395307	22749	21742
OMIDIDUN-EVANS	235154	228528	12933	12569
GRIFFITH-GRIFFITH I	280211	254043	15412	13972

Fig. 1.2: Graph of cost evaluation of ohmic losses due to balanced and unbalanced load for Tokunboh 11-kV feeder

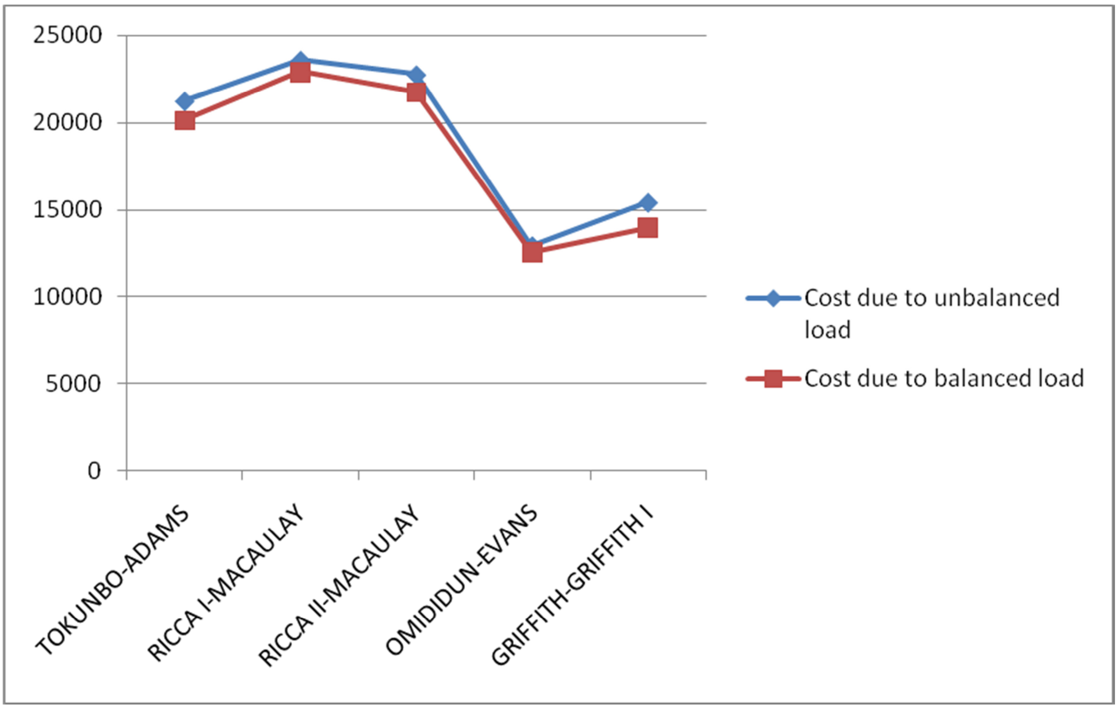

Fig. 1.3: Graph of ohmic losses due to balanced and unbalanced load for Tokunboh 11-kV feeder

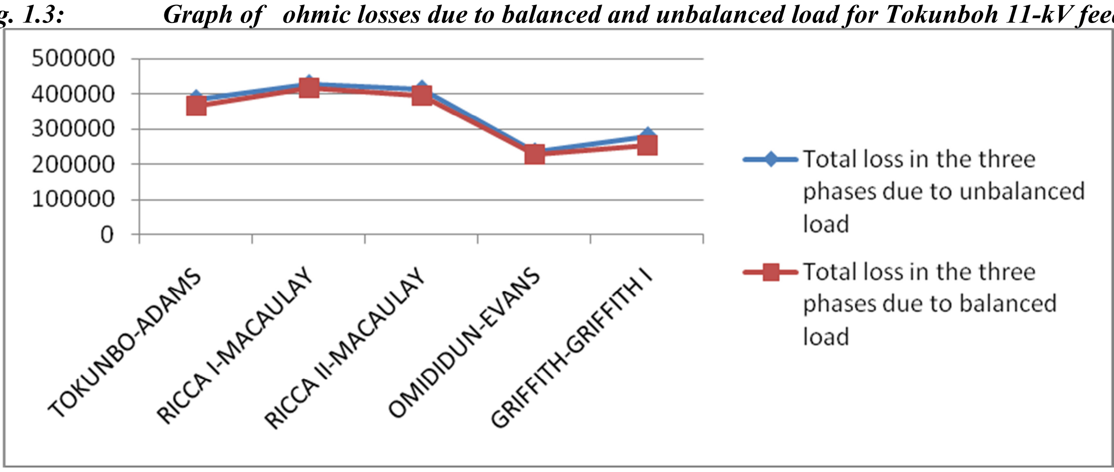

Table 1.5: Ohmic losses for Dolphin11-kV feeder

NAME OF SUBSTATION	Total loss in the three phases due to unbalanced load	Total loss in the three phases due to balanced load	Cost due to unbalanced load	Cost due to balanced load
GRIFFITH II-OKEPOPO	425330	400404	23393	22022
GLOVER II	381161	371007	20964	20405
GLOVER I	224729	217083	12360	11940
PHASE III-DOLPHIN ESTATE	163361	159159	8985	8754
PHASE IV-DOLPHIN ESTATE	296234	266412	16293	14653

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Fig. 1.4: ***Graph of cost evaluation of ohmic losses due to balanced and unbalanced load for Dolphin 11-kV feeder***

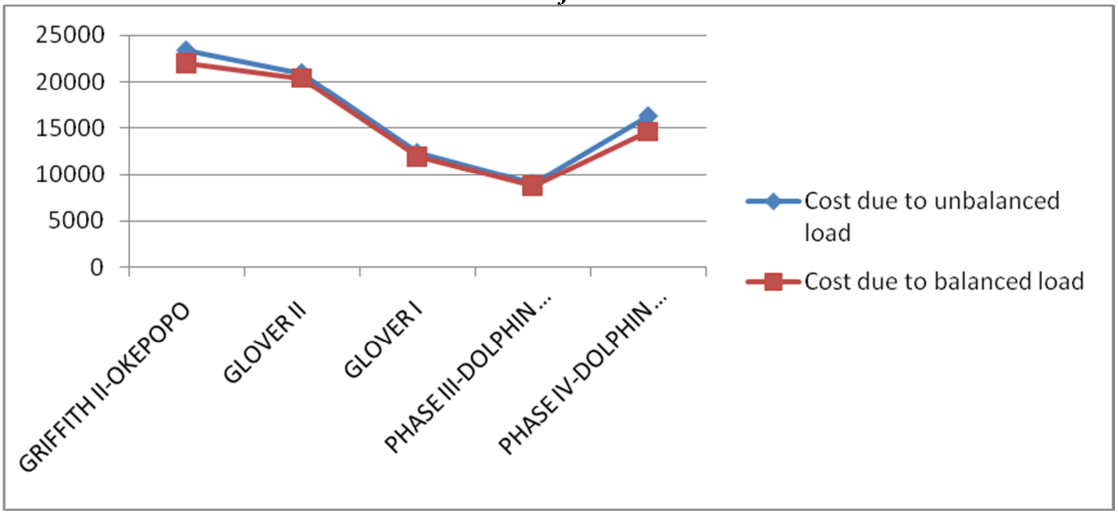
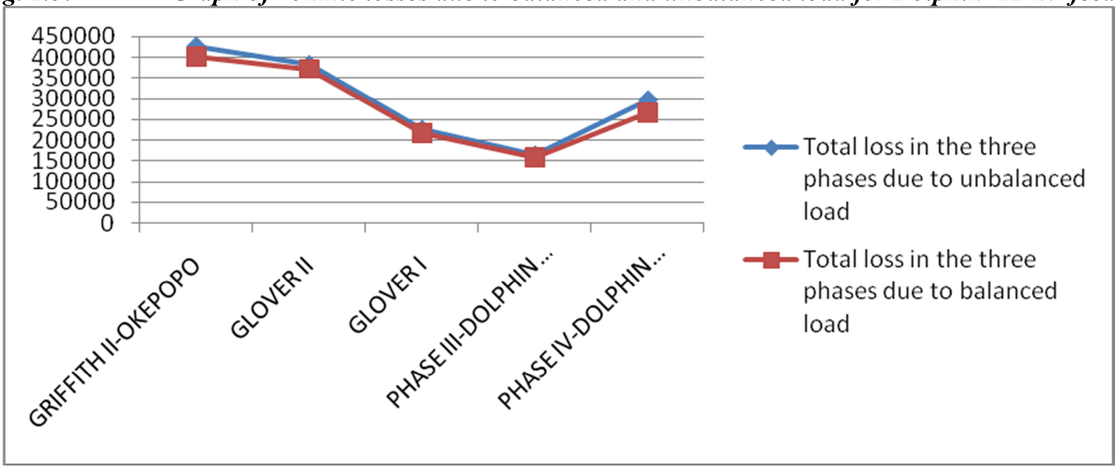


Fig. 1.5: ***Graph of ohmic losses due to balanced and unbalanced load for Dolphin 11-kV feeder***



V CONCLUSION

This study investigate the cost of copper losses due to balanced and unbalanced loading in a distribution transformer. The investigation showed that the average cost for both balanced and unbalanced load for Adeniji Adele feeder was $185,884 and $191,990 respectively. While for Tokunboh feeder, the average cost was $91,334 and $95,919 for both balanced and unbalanced load respectively. Furthermore, $77,774 and $81,995 was evaluated for Dolphin feeder for both balanced and unbalanced load. This means that network reconfiguration considering load balancing is highly necessary in order to reduce the cost of copper losses due to load imbalance.

VI REFERENCES

1) Okakwu K. Ignatius, Abagun K. Saadu and Oluwasogo S. Emmanuel, “Analysis of copper losses due to balanced and unbalanced load in a distribution transformer, “International Journal of Research and Reviewers in Applied Sciences. Vol. 23 Issue 1 (April, 2015).
2) Jawad, F., Ebrahimpour, H., and Pillay, P., “Influence of unbalanced voltage supply on efficiency of three phase, squirrel cage induction motor and economic analysis”, 2006.
3) Meliopoulos, A.P., Kennedy, J.C., Nucci, C.A. Borghetti, A. and Contanies, G., “Power distribution practices in USA and Europe: Impact on power quality”, 1998.
4) Daoud, A. and Kadri, B., “Implementation methods to eliminate overload power system problem”, 2008.
5) Tsai-Hsiang, C., Chwng-Han, Y. and Ting-Yen, H., “Case studies of the impact of voltage imbalance on power distribution systems and equipment”, 2007.
6) Sanjay, A.D. and Laxman, M.W., “Analysis of distribution transformer performance under non-linear

balance load conditions and its remedial", 2011.
7) Gabriel, P., Mircea, C. and Radu, B. "Determination of power losses in transformers working in unbalanced and harmonic polluted network", 2009.
8). Ashfaq Husain Electric Machine, Second Edition, Educational and Technical Publishers, (2006).
9) Sen, P.C., Power Electronics, McGraw-Hill, New Delhi, (1989).
10) Theraja, B.L., A Textbook of Electrical Technology. Seventeenth Edition. Nirja Construction and Development Company, New Delhi, (1980).
11) Agarwal, R.K., Principles of Electrical Machine Design. Fourth Edition, S.K. Kataria & Son Publishers, (2006).
12) B.R. Gupta and V.Singhal, Power Electronics, Fifth Edition, S.K.Kataria & Sons Publishers, (2007).
13) J.C. Ekeh, Electric Power Principles. Amfitop, Books Publishers, (2003).
14) B.R. Gupta, Generation of Electrical Energy, Eurasia Publishing House Ltd, (2006).
15) B.V. Jayawant, Electromagnetic Suspension and Levitation Techniques (London: Edward Arnold, 1981).
16) H. Linacre, J.S. Chanal, G. Cravshaw and B. Rawlinson, 'Birmingham Air-port Maglev propulsion system; IMechE International Conference on Maglev Transport, October 1984, (408/84, pp. 193-201).
17) McGraw-Hill, Electrical Machines, Direct and Alternating Current, 2nd ed. New York, (1984), By Charles S. Siskiod.
18) Electrical Machines Drives and Power Systems. 4th Edition, Theodore Wildi Professor Emeritus Laval University KT 2183 w53, (2000).
19) Computer Methods for Circuit Analysis and Design, 2nd Edition Jiri Vlach, Kishore Singhai Waterloo, Ontario, Canada, (1793).
20) Beemaqn, D. (1995), Industrial Power Systems Handbook. New York: McGraw-Hill.
21) Chapman, S.J. (1999), Electric Machinery Fundamentals. New York: McGraw.