

Neutral Current and Neutral Voltage in a Three Phase Four Wire Distribution System of a Technical Institution

Nandita Dey

Lecturer, Electrical Engineer
Department, Tripura University
Suryamaninagar, Agartala, India

A.K.Chakraborty, Ph.D

Associate Professor, Electrical
Engineering Department, NITA,
Jirania, Tripura, PIN 799055, India

ABSTRACT

Neutral current and neutral voltage in three-phase four-wire distribution system is a big concern in power system. Various non-linear loads specially the switch mode power supply types loads inject harmonic current in neutral. The variations of neutral current and neutral voltage are analysed. Measurements taken from Electrical Machine lab of National Institute of Technology, Agartala are presented to determine the extent of neutral current and neutral voltage problem. The results show the effect of harmonic distortion in neutral conductor.

Keywords

Neutral voltage, neutral current, non-linear loads, harmonic distortion, power quality, technical institution, variable power supply.

1. INTRODUCTION

. In a modern Technical institute, there are so many sophisticated and sensitive equipments in various Laboratories such as Laser lab, Control lab etc. This type of modern lab demands high quality power with zero neutral voltage and neutral current.. In this type of institute, the usage of non-linear loads has increased day by day resulting in high level of harmonic distortion in the neutral of power supplied to that institute. Harmonic deteriorates the quality of power and creates high level of distortion in neutral conductor. The 3rd harmonic and other triplen harmonics add in neutral producing excessive neutral current. It results in overheating of neutral wire and can cause fire. This can be dangerous in an technical institute having many non-linear loads and where the neutral conductor is designed to handle only small neutral currents originating mainly from small phase imbalance. As a result, student cannot get exact results while doing experiments in labs. So the necessity of detailed study about the status of neutral voltage and neutral current has become more important for selection and design of mitigating equipments for harmonic reduction.

In a technical institution there are so many sensitive and sophisticated labs. These kinds of labs require quality power with zero neutral voltage and neutral current. In this type of technical institution various non-linear loads are used everywhere in the institution. Review of previous published harmonics and power quality survey indicate that no

significant work has been done on neutral voltage and neutral current in technical institution. Work has been done to identify the effects of harmonics in educational institution [1]-[4]. A few researchers have done work only taking individual or various non-linear loads in an office building or in a industrial plant or in a residential campus [5]-[19]. Some have done only the survey giving only general recommended remedies. Moreover this type of previous studies did not give any information regarding the neutral conductor behavior due to various non-linear loads and the effect of variable power supply on neutral conductor of both the input supply and the load.

The project is one such attempt to identify the level and type of the harmonic distortion in neutral voltage and neutral current waveform caused by certain typical loads which are both non-linear and sensitive to power quality. The paper also reflects the effect of varying power supply on neutral conductor, analysis of neutral current and neutral voltage and their distortion level due to various non-linear loads. Each and every data are analyzed thoroughly in this project. Several conclusions are given which will necessary for designing and installation of the exact mitigating device. It has done by doing a survey in the National Institute of Technology, Agartala to analyze the collected data and give the necessary information based on the analysis. Random sampling at different places of NITA has been carried out to stress the severity of the problem and out of it Electrical Machine laboratory has been taken the place of study for its criticalities.

In three phases four wire distribution system neutral current is the vector sum of the three line-to-neutral currents [20]. In a linear, balanced, three phase system consisting of sine waves spaced 120 electrical degrees apart, the sum at any time instant is zero and so there is no neutral current [21]. In most three phase power system supplying single phase loads there will be some phase current imbalance. As a result there is always some neutral current. Small neutral current due to slightly unbalanced load do not cause problem in the distribution system. The neutral wire supplying non-linear loads is now considered a current carrying conductor [22]. There are single phase loads that are not even perfectly balanced can result in significant neutral current. Non-linear

loads such as rectifiers, switched mode power supply have phase currents that are not sinusoidal.

In three phases, four wire system electrical loads are connected from line to the neutral of the three phases. In an ideal balanced sinusoidal three-phase power system, the neutral current is the vector sum of the three phase currents, should be equal to zero. Under normal operating condition, some phase unbalance occurs resulting in a small neutral current. Non-linear loads draw highly distorted phase current. In non-linear circuits, the triplen harmonic current add arithmetically in the neutral line resulting in high harmonic distortion [23] [24] in neutral. The 3rd harmonic is the main contributor of harmonic current [25] [21].

2. EFFECTS OF HIGH NEUTRAL CURRENT

There are two major problems caused by 3rd harmonic currents flowing in the electrical distribution system. All switchgear, wires are r.m.s current rated. Harmonic currents provide nothing to the load. Therefore, any system capacity carrying harmonic currents is not available to supply useful fundamental current. The second problem caused by 3rd harmonic current flow is production of heat through out the distribution system. The 3rd harmonic current returns to the transformer connection and reflect into the primary winding where they are trapped and circulate within the delta. They are finally dissipated as heat. Waste heat generated by 3rd harmonic currents not only can cause equipment failure, but also increases electrical bills due to wasted energy [26]. With the growing use of non-linear loads such as adjustable speed drives and computer equipment, the pollution in distribution system increases. These equipments draw distorted currents from distribution feeders and from distribution transformers. Because of the load unbalance, the zero sequence triplen harmonics accumulate in neutral conductor resulting in overloading of neutral conductor and the distribution transformer [22].

In a three phase power system having SMPS type non-linear loads, the third harmonic current add in the neutral conductor resulting in a very high r.m.s neutral current. Excessive neutral current can cause high voltage drop in neutral conductor [27]. High neutral current can generate potential difference between neutral and earth. The high voltage drop along the neutral conductor can cause the neutral terminal at the equipment to float at potential of a few volts above earth [22].when the neutral conductor carries harmonic current, additional heat is generated and the capacity of neutral conductor is reduced [28].High neutral current causes overheating of neutral conductor. In worst case, it may lead to burn out of the neutral wire in a cable where the neutral was not fully rated.

3. NEUTRAL VOLTAGE AND NEUTRAL CURRENT: A COMPLAINT OF COMPUTER SUPPLIERS

There is always a complaint of computer suppliers that due to the poor ear thing neutral voltage occurs. Due to which computers do the malfunction. The acceptable neutral to ground voltage is less than 0.5v-3 V. However, during the data collection neutral voltage is found 7 V for a single computer.

Common knowledge is if the earth is not proper, i.e. if the ear thing resistance is large a significant amount of voltage appears in the neutral of a distribution system. Actual fact is due to high harmonic neutral current through the impedance of the neutral conductor a significant neutral voltage drops occurs. People say that computers do the mal operation due to the poor ear thing. However, they do not know that SMPS used in computers itself is the major source of harmonic current generator, which causes high neutral current.

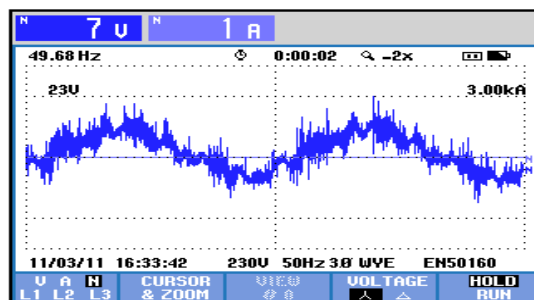


Figure 1: Neutral voltage waveform for a single computer during data collection

In a Technical institute with large number of computer loads the r.m.s neutral current can actually exceed the r.m.s line current due to the presence of zero sequence harmonic specially the 3rd harmonic. Computer load creates high harmonic distortion in neutral current.

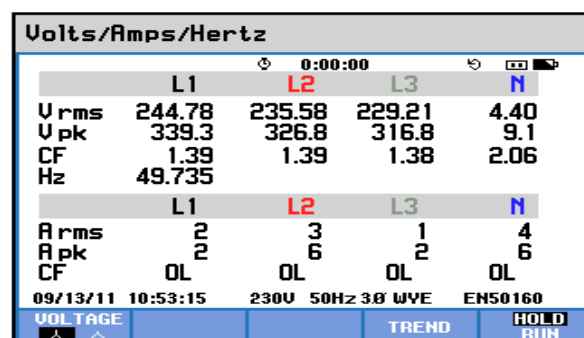


Figure 2: Effect of computer load (8 no) on voltage and current

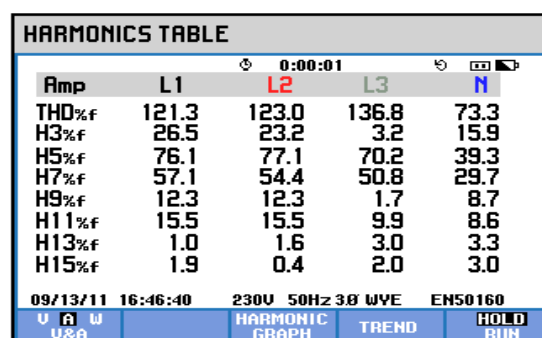


Figure 3: Total harmonic current distortion of computer load (8 no) in phase and neutral

4. NEUTRAL VOLTAGE AND NEUTRAL CURRENT SURVEY IN AN ELECTRICAL MACHINE LAB

The result for the current through the neutral conductor is a combination of the unbalanced loading effects and the non-linear characteristics of the load connected through the UPS. Data are taken to see the variations of Phase-Neutral voltage and Neutral current. Neutral current is related to the zero sequence current components. This current and the ground impedance determine the level of neutral to ground voltage [29].

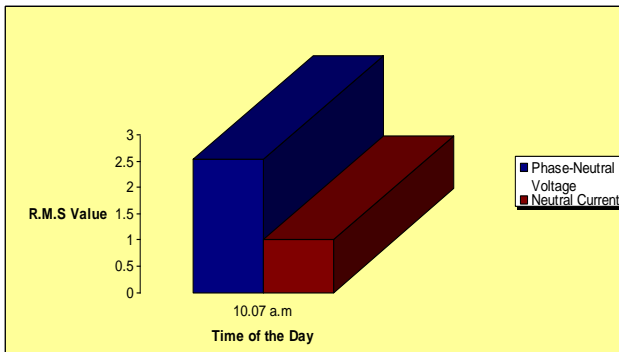


Figure 4: Neutral voltage and Neutral current of the supply system under no loading condition

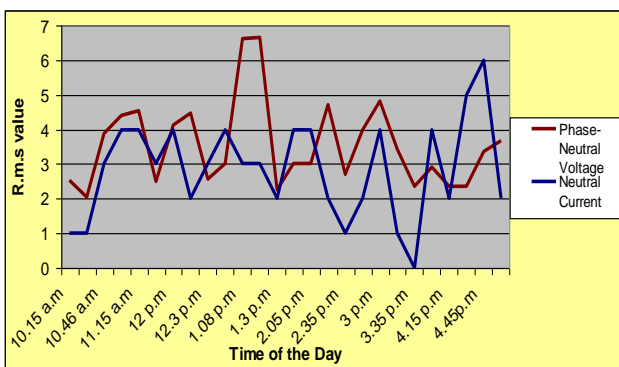


Figure 5: Phase-Neutral Voltage and Neutral Current variations on a working day

An analysis of the graph shows a strong relationship between the phase-neutral voltage and neutral current indicating that the current increased is associated to the voltage increment on the distribution system.

4.1 Neutral voltage waveform analysis

It is observed that neutral voltage is about 6.64 V. The high neutral voltage is caused by the flow of high neutral current in the neutral conductor and ground impedance.

High neutral voltage can quickly destroy the system productivity, cause system lockups, communication errors and unreliable test data, fragmented hard driver and operational problems that cannot be explained or duplicated. High neutral voltage cause significant disruption to the operation of microprocessor based equipment.

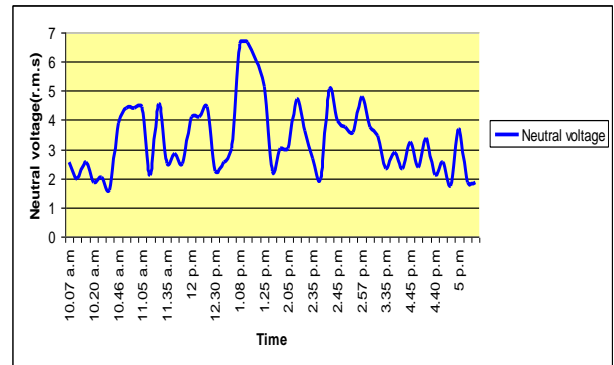


Figure 6: Neutral Voltage Waveform in a working day

4.2 Total harmonic distortion in neutral voltage

The college starts activity at 9.30 a.m and the harmonic level becomes in increasing rate from this time. The college work activity provides the largest pollution levels at mid afternoon while during the morning harmonic pollution is lower. Since the measurements shown are performed in summer, this is likely to be addressed to the incidence of air conditioner actuation between 9.30 a.m to 5.39 p.m and the lack of lighting loads in the morning.

However, the percentage compatibility limit for that harmonic order according to IEEE-519 standard is violated. It is seen that the largest pollution level is at mid afternoon while during the morning the harmonic pollution is lower. High voltage distortion causes the computers locking up and other operational malfunctions that are unexplainable. For this reason, several times we have experienced the no problem found syndrome with our computers.

During data collection at various loading conditions during peak and off-peak period, it was seen that the voltage harmonic level was relatively high. The total Harmonic Distortion in line to neutral voltage was measured at Electrical machine Lab is shown in Figure 7. The THD varies from 12.9% to 237.4%.The maximum THVD occurs at mid noon contributed by the combination loading of Rectifier, UPS and single Induction motor. The excessive distortion in voltage exacerbates the triplen harmonics giving rise to high r.m.s neutral currents.

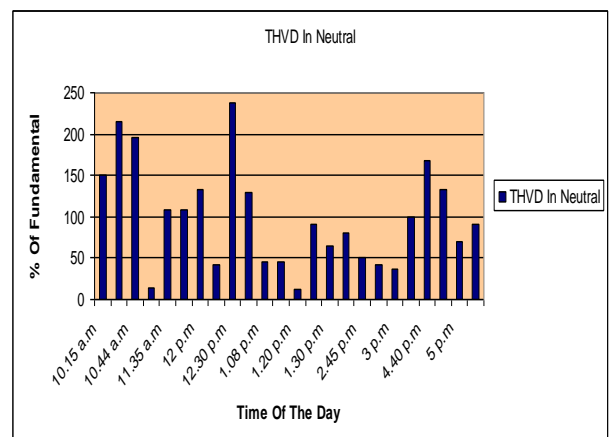


Figure 7: Total Harmonic distortion in neutral voltage

4.5 Neutral voltage harmonics analysis

Harmonic voltage are present at the distribution system due to the interaction of harmonic currents drawn by non-linear loads with the impedance of the line .They have detrimental effects on power system equipments such as overheating of transformers and induction motors etc.

The most prominent harmonic is 9th harmonic having maximum value 148% followed by 7th harmonic having distortion 123.7%Harmonic. The combination of UPS, Rectifier and Induction motor loading gives highest order of 7th harmonic. However, in neutral conductor all the orders of harmonics (3rd-15th) are present

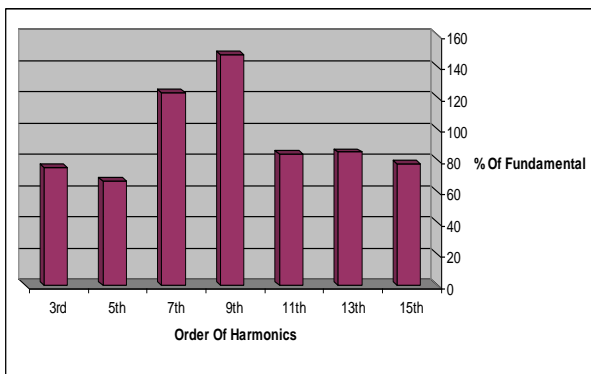


Figure 8: Voltage harmonic spectrum of neutral voltage in Electrical machine lab

The daytime is the most usual period that most electronic equipments are in use in the lab. Compatibility limit for total harmonic distortion for current should not be more than 20%. The building has many electronic types of equipment, which are the main source of harmonic distortion especially the 3rd, 5th and the 7th harmonic levels. These are many computers, printer, rectifier etc. Switch mode power supply produce a lot of harmonics due to many computers.

4.4 Total harmonic distortion in neutral current

Current THD in phase is very much higher than voltage THD. The highest total harmonic distortion for current in neutral is 153.2% (in Figure 9) which is greater than 20%. Therefore, this value has transgressed the standard of 20%.

In electrical Machine Lab there are 9 no of computers supplied through UPS are using continuously. Computers give maximum current distortion in phase of this lab. No loads are used at the same time so that distortion changes from time to time. The THID is always above the acceptable limit through out the working day.

The THID is varying with time. The maximum THID occurs at mid noon. The Figure 9 shows that the maximum total neutral current harmonic distortion is high-about 152.3% and minimum is 9%. UPS fan loading gives highest distortions in neutral current. There are two reasons for this kind of high current distortion in neutral. First due to unbalanced load in the lab. Second, the load draws non-linear current which is distorted from sinusoidal voltage. This distorted current ads in the neutral conductor causing high current distortion in neutral.

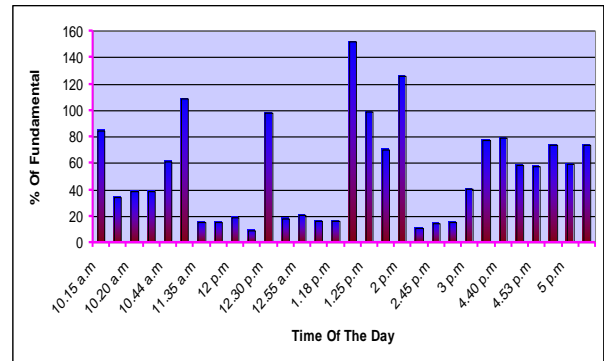


Figure 9: Total Harmonic Distortion of current in neutral

4.5 Current harmonics in neutral current

The increased use of non-linear loads like switched mode power supplies in computers, electronic ballasts for fluorescent lighting, UPS are responsible to make current harmonics to exceed allowable limits in the distribution system. Hence, it is necessary to evaluate the harmonic distortion existing in the system so that suitable harmonic filters can be installed to reduce the distortion within standards limits. The increase in current distortion in phase current is directly correlated to the increase in 5th harmonic current distortion.

The measured results show that the maximum neutral current is 6 amps. The increased use of non-linear loads such as switched mode power supplies in computers, un-interrupted power supplies etc. have caused current harmonics to exceed allowable limits in the distribution system.

From the pie chart it is clear that 3rd, 5th and 7th harmonics are higher in neutral current. The Total Harmonic Distortion in neutral current is 153.2%.5th harmonic is maximum (90.7%) which covers 40% of current distortion in neutral current. The 3rd (46.8%) and 7th (53.3%) cover 20% and 23% respectively. The other harmonics are below the stipulated limit.In Electrical Machine Lab fan, light and computer loads are always supplied power through UPS. This type of load combination gives noticeable amount of harmonic injection into the neutral current (Figure 10).UPS when loaded with fan gives maximum distortion (5th harmonic) in neutral.

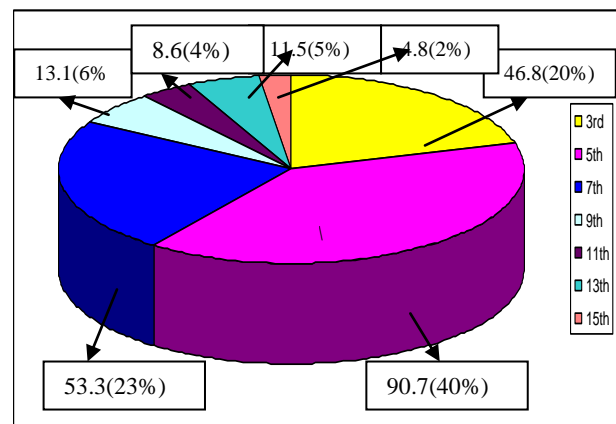


Figure 10: Maximum harmonic contribution in neutral current

5. EFFECT OF UNBALANCE ON NEUTRAL CURRENT

The factors i.e. load and supply have an important effect on the neutral conductor current .Unbalance in any of the two factors greatly effect the value of neutral conductor current. An electrical power system is supposed to operate in a balanced three-phase condition. However unbalance is a common fact in the distribution system supplying three-phase or single phase asymmetric loads. As a result electrical networks are normally unbalanced and a certain degree of imbalance is there. In such a situation when non-linear loads are connected line to neutral, the neutral conductor carry surprising level of current, even the loads are balanced on the three phases[30][31].

Volts/Amps/Hertz				
	L1	L2	L3	N
Vrms	243.58	240.51	234.78	3.21
Vpk	336.5	336.0	328.9	8.9
CF	1.38	1.40	1.40	2.77
Hz	49.631			
02/02/12 11:55:39 230V 50Hz 3Ø WYE ENS0160				
VOLTAGE			TREND	HOLD RUN

Figure 11: Effect of unbalanced power system on neutral conductor current

The load conditions on the other hand have high influence on the neutral conductor current [32]. In three phase four wire distribution system severe unbalance occur due to unbalance grouping of single-phase loads, unequal line impedance, neutral conductor impedance etc. Unbalance current produces increased neutral-ground voltage and neutral current in the neutral conductor. An unbalance in load conditions increases the neutral conductor current up to 15 amp.

The neutral conductor current increases with the increase in load unbalance. The lowest neutral current is obtained with the balance load. Figure 13 shows harmonic content of neutral conductor current for different unbalanced load conditions. Almost all the order of harmonics increase with increasing load unbalance.

Volts/Amps/Hertz				
	L1	L2	L3	N
Vrms	247.91	243.12	235.30	3.98
Vpk	347.4	340.8	332.3	10.1
CF	1.40	1.40	1.41	2.53
Hz	49.683			
02/02/12 10:15:57 230V 50Hz 3Ø WYE ENS0160				
VOLTAGE			TREND	HOLD RUN

Figure 12: Effect of unbalanced load condition on neutral conductor current

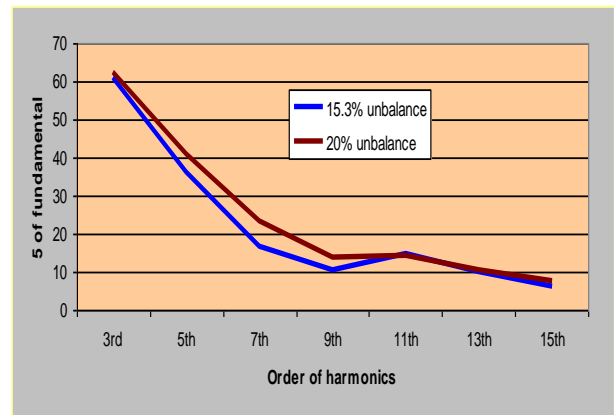


Figure 13: Influence of load unbalance on the neutral conductor current

6. EFFECT OF VARYING POWER SUPPLY ON NEUTRAL CONDUCTOR

We had examined the impact of variations in the input voltage on neutral conductor voltage and current of load. Three tests have been done to assess the impact of variations in input voltage on load neutral voltage and current behavior. Among three measurements the upper range of r.m.s value of voltage is 247.42 V and lower range is 245.25 V. We had collected data on a working day into three times keeping power quality analyzer at the input of the load. In every timing first the input supply voltage conditions are observed and then its effect on load neutral voltage and current are examined. All loads are supplied through UPS. During this investigation UPS is loaded with fan, light, A.C and computers (3 no).The connection diagrams of power quality analyzer with supply mains and UPS are shown in Figures 14(a) and 14(b).

At the beginning of the day, the college just starts activity. Classes just start. So the use of loads is not so high which increases at noon time. The pollution injected by the use of loads in the institution at mid noon reflects in the power supply of Electrical machine lab. At afternoon it again becomes low because the classes are closed.

In case of source and load the neutral voltage has higher level of harmonics than neutral current. Load neutral voltage has highest 3rd harmonic level (51.7%) followed by 6th harmonic (18.1%) and 9th (43.2%).The 3rd harmonic is the dominating harmonics in supply neutral voltage(27.9%) and neutral current(33.6%). Triplen harmonics are the main contributor of source and load neutral voltage and neutral current. The above investigations indicate that due to the variations in power supply the harmonic level in neutral voltage and neutral current of both the input supply and the load are increased. If the supply voltage variations are not checked on proper time then the harmonic level may increase day by day. This will impact on load performance as well as quality of power. The power supply which supply power to different load itself is polluted by harmonics and unbalanced. So a constant monitoring of power supply should require as loads are increasing day by day.

Table 1. Harmonics in input supply and load neutral conductor due to supply voltage variations

	Input1	Load1	Input2	Load2	Input3	Load3
Vh3	27.9	23.8	25.5	21.3	33.6	51.7
Ih3	2.8	4.7	3.7	4	16.1	6
Vh5	1.9	6	13.4	14.2	15.1	18.1
Ih5	5.9	9.9	3.2	3.6	5.8	6.9
Vh7	7	9	15.4	12.4	12.5	22
Ih7	2.2	3.7	0.4	0.4	1.5	7
Vh9	13.1	24.6	17.2	24	30.3	43.2
Ih9	1.43	2.4	0.5	0.5	7.2	2.4
Vh11	1.7	1.4	1.5	2	1.4	1.9
Ih11	0.66	1.1	0.5	0.5	4.5	4.5
Vh13	1.6	1.3	1.7	1.7	1.6	1.4
Ih13	0.54	0.9	0.2	0.2	4.2	2.4
Vh15	0.8	1	0.7	0.8	0.4	0.7
Ih15	1.25	2.1	0.2	0.2	7.4	5



(b)

Figure 14: Connection diagram of power quality analyzer with (a) supply mains (b) UPS

7. CONCLUSIONS

Observations of Electrical machine lab have indicated that due to high harmonic distortion, the neutral voltage and current have significant amount of harmonics. The paper investigates the effect of supply voltage variations on power input and load in a technical institute which the earlier published works did not do. In this paper it also reflects that unbalances in supply as well as load greatly affect the neutral conductor current. High neutral current and voltage are also found out. In a modern Technical institute, many sophisticated and sensitive equipments are constantly using in various Laboratories. This type of modern lab demands zero neutral voltage and neutral current. Harmonics pollute the neutral. As a result, students cannot get exact results while doing experiments. If necessary actions would not be taken then these types of problems become more common in near future. It is because non-linear loads are constantly an ever-increasing portion of the total load in this type of engineering institute. The paper gives the useful information to take steps to mitigate harmonics from the neutral conductor.

8 ACKNOWLEDGEMENTS

Our thanks to the management of National Institute of Technology, Agartala, India for providing necessary facilities to carry out this work.

9 REFERENCES

- [1] Rajesh M Holmukhe and Mrs.J.V.Satre, "Harmonic Measurement And Analysis, A Case study of Electrical and Machine Lab", Bharati Vidyapeeth University college of Engineering, Pune, India, 2007.
- [2] V.Suresh Kumar, P.S. Kannan, T.D.Sudhakar & B.Anand Kumar, "Harmonics & interharmonics in the Distribution System of an Educational Institution-A Case Study", IEEE, 2004.
- [3] N.Karthikeyan, Sasitharan S., Srinivas Bhaskar K., Mahesh K.Mishra and Kalyan Kumar B, "Power Quality Survey in a Technological Institute", 3rd International Conference on Power Systems, Karagpur, 2009.



(a)

- [4] Gerhard P Hancke and Wlodzimierz Koczara, "Pollution Effects caused by office and laboratory equipment in university buildings", IEEE, 1998.
- [5] B.E.Kushare, A.A.Ghatol and Mrs. T.N.Date, "Power Quality survey of 33KV Indian Industrial Supply System: Results and Remedial Actions", 2007.
- [6] A thesis presented by Abraham Olatoke, "Investigation of power quality problem in modern buildings", 2011(Brunel university).
- [7] Karl Johnson and Robert Zavadil, "Assessing the Impacts of Nonlinear Loads on Power Quality In commercial Buildings-An Overview", IEEE, 1991.
- [8] Leon M. Tolbert, Harold D.Hollis and Peyton S.Hale, Jr., "Survey of Harmonic Measurement in Electrical Distribution System", IEEE IAS Annual Meeting, Oct6-10, 1996.
- [9] Antonio Fabio M.M.de Lima, "Discussion of Harmonic Analysis of Industrial Power Systems", IEEE, 1996.
- [10] Robert E.Fuhr, "Save Energy and Improve Power Quality, A case study-75 kVA Transformer", P.E., 2001.
- [11] Emmanuel.E.m, Root C.E, "The Effects of Modern Compact Fluorescent Lights on Voltage Distortion", IEEE, 1992.
- [12] Mohsen Ghafari, Ali Razi Kazemi, Payman Dehghanian and Mehdi Vakilian, "Investigation of the Effects of Compact Fluorescent Lamps in Power Distribution Systems", IEEE, 2011.
- [13] Christopher May and E.Randolph Collins, "An Investigation of the Response of Incandescent Lamps and Compact Fluorescent Lamps to Voltage Fluctuations", IEEE, 2010.
- [14] H.O.Aintablian and H.W.Hill, Jr., "Harmonics Currents Generated by Personal Computers and their effects on the Distribution System Neutral Current", IEEE, 1993.
- [15] B.Justus Rabi, V.Vivek and R.Arumugam, "Harmonics, A Recent Entrant To Power Quality Problem In Uninterruptible Power Supply", IEEE, 2002.
- [16] Don O.Koval, "Power Quality Characteristics of Computer Loads", IEEE, 1997.
- [17] S.N.Govindarajan, m.D.Cox, F.C.Berry, "Survey of harmonic levels on the southwestern Electric power company system", IEEE, 1991.
- [18] Wang Kui, Guan Shuhua, Hou Qian, Hou Yuan Hong, Wu Qinfang, "Investigation of Harmonic Distortion and Losses in Distribution Systems with Non-linear Loads", CIGRE, 2008.
- [19] D C Bhonsle and N K Zaver, "Harmonic Survey of Typical Non-linear Loads", The International Conference on Electrical Engineering, 2008.
- [20] T.Gruzs, "A Survey of Neutral Current in 3 phase computer Power System", IEEE Trans.Ind.Appl.,Vol.26 ,No.4,pp 719-725,July/Aug 1990.
- [21] AH-CHOY LIEW, "Excessive Neutral Currents in 3 phases Fluorescent Lightings Circuits", IEEE Trans. On Industrial Appl., Vol .25, no.4, pp 776-782, July/Aug.1989.
- [22] D.Maheswaran, A.Kalyanasundaarm and S.Kameshwaran, "Power Quality Issues in a Distribution Network Impact of Neutral Current due to Nonlinear Loads", Proceeding for India International Conferences on Power Electronics, 2006.
- [23] Rosli Omar,Azhar Ahmad and Marizan Sulaiman," Triplen Harmonics Mitigation 3 Phase Four-wire Electrical Distribution System Using Wye-Zigzag Transformers", Journal of Emerging Trends in Engineering and Applied Sciences, Vol. 1,p-72-78,2010.
- [24] Gianfranco Chiccoa, Petru Postolaheb and Cornel Toaden, "Triplen Harmonics: Myths and reality" Electric Power Systems Research, Science Direct, Vol.81, page 1541-1549, 2011.
- [25] H.O.Aintablian & H.W.Hill, "Harmonic Currents Generated by personal Computers & their effects on the Distribution System Neutral Current", IEEE, 1993.
- [26] J.Leramati Zadeh and E.Farjah, "New Control Technique for Compensation of Neutral Current Harmonics in Three- Phase Four-Wire Systems", Bucharest Power Tech Conference, IEEE, 2009.
- [27] Alexander E.Emanuel and John A. Orr, "The Effect of Neutral Path Impedance on Voltage and Current Distortion Part-II Imbalanced Three-Phase Systems", 11th International Conference on Harmonics and Quality of Power, 2004.
- [28] R.Christiansen, "Effects of High Levels of harmonics from Lighting Equipment and Systems", IEEE, 1991.
- [29] Jan J.M.Desmet, Isabel Sweetvaegher, Greet Vanalme Kurt Stockman and Ronnie J.M.Belmans, "Analysis of the Neutral Conductor Current in a Three-Phase Supplied Network with Nonlinear Single -Phase Loads", IEEE, 2003.
- [30] Chindris M., "Symmetrical Systems for Single-Phase High-Power Receivers." Socrates Course. April 2001, University of Zaragoza, Spain.
- [31] Zheng, T. et al., "Evaluating Power System Unbalance in the Presence of Harmonic Distortion "IEEE Trans. On Power Delivery.vol.18, No.2, pp.393-397, April 2003.
- [32] Jessica Laverne Williams," Effect of Unbalance on Power System Components in the presence of Harmonics", MS Thesis, Clemson University, Clemson, August 1996.