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REAL-TIME DISTRIBUTION SYSTEM ANALYSIS AND LOAD MANAGEMENT ALGORITHM FOR MINIMIZING HARMONICS

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This paper presents a detailed analysis of the selected distribution network consisting of fifty-five 200 kVA transformers and thirty 100 kVA transformers. These units are observed five times during the period of one year based on balanced and unbalanced conditions. Detailed power loss analysis has been discussed with an innovative switching algorithm of phase balancing. The switching algorithm is applied on the experimental test bench. This solution provides ease of complete switching between the phases along with that it monitors the real-time data and keeps a record of current flowing on each phase of the transformer.

1. INTRODUCTION

The increasing demand for electricity in developed countries indoctrinated mankind to find several new methods to full fill their energy demands. On the other hand, underdeveloped countries are facing many problems like theft, line losses, lack of technological advancement that ultimately results in power shortage and disturbance in the balance of payment between the distribution company and consumer.

The power distribution networks have been extensively engaged to distribute power to industrial units, residential and commercial buildings. Many residential loads are operated on a single-phase that contributes a major share in phase unbalancing because single-phase loads are equally distributed to the different consumers but due to different operating times of loads it is very difficult to balance the loads on three phases equally, therefore due to unbalanced phases current start flowing through the neutral conductor that results in power loss [1–3].

Power quality plays the most vital part in the power distribution system. Unbalance loads on 3-phase, 4-wire system distribution network cause harmonics in distribution network occur due to the following reasons.

- Load escalating gradually on one phase.
- Switching of phases from one phase to another arbitrarily.
- Inadequate allotment of single phases to the domestic consumer.
- Excessive burden of load during peak hours.

Unbalance loads on a 3-phase 4-wire system distribution network cause the unnecessary flow of neutral current that results in an adverse effect on the whole distribution network [4–8]. Some of the problems related to unwanted excessive neutral current are transformer overloading, common-mode noise, excessive heating in wires, frequent power outages, increase in line losses, voltage swings.

The harmonics on the distribution transformer set adverse effects on the health of a transformer. Harmonics can affect distribution transformers in two folds. Firstly, voltage harmonics cause extra losses in the transformer core, as the higher frequency harmonic voltages set up hysteresis loops, which overlap the fundamental loop. Secondly, harmonics in the distribution network dissipate excessive heating in the transformer winding. Other major components of distribution networks like ac motors, capacitor banks, cables, and protective devices also suffer from harmonics which results in financial and energy loss [9–13].

In this paper, a load balancing methodology is proposed on a prototype that will balance the load automatically by using modern tools and programming techniques. Along with that this paper also examines the effect of unbalance current on the transformers and analyzes the total loss in the selected distribution network.

2. LITERATURE REVIEW

Many techniques are adopted for balancing a three-phase distribution network. The major predicament behind phase balancing is to minimize the losses and improve the power quality by reducing harmonics. The basic technique used for load balancing is "Scott transformers", but it is not cost-effective [1]. Four-leg active filters are used for phase balancing, but this method has the disadvantage of controlling the four-leg inverter [4]. Zigzag transformers are used to reduce the neutral current in a three-phase four-wire system [14]. Star-delta transformers are used for compensation of neutral current in a three-phase four-wire system. The major drawback of using star-delta transformers is relying too much on the impedance of the transformer for compensation characteristics [15].

3-leg voltage source converter with a zigzag transformer act as a DSTATCOM for load compensation in a three-phase four wire distribution system using rapid symmetrical component theory-based controller procedure which is adapted for the voltage regulation and used with indirect current control technique [16]. Similarly, using the synchronous machine for instantaneous absorption of all the zero-sequence harmonic currents of the neutral conductor is discussed in detail. [17–24].

3. EXAMINED DISTRIBUTION NETWORK

The distribution transformers having a power rating of 200 kVA and 100 kVA are examined. There are a total of eighty-five transformers examined in which fifty-five transformers are of 200 kVA power rating and thirty are of 100 kVA power rating. All transformers are examined five times during the whole year. This technique increases the reliability of the data collected from the distribution system. To have fair analysis transformers that are selected for

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examination are of residential, small industrial, and commercial units. The transformers that are selected is bearing highly unbalanced loads that result in maximum financial and energy loss.

3.1. POWER LOSS CALCULATION DUE TO HARMONICS

In this section, a detailed analysis is performed to calculate the power loss due to harmonics. The major cause behind power loss is the flow of current in a neutral conductor that is due to harmonics in three phases [25–28]. The power loss is calculated by using a measured neutral current having a measured power factor of 0.8 of the distribution transformers. Furthermore, manual balancing has been done to shift the load between phases. Table 1 shows the data of the neutral conductor and three phases of 200 kVA transformers at different time instances. Figure 1 shows the average neutral current of fifty-five 200 kVA transformers in unbalance and balanced phase conditions. Same as Table 2 shows the data of the average neutral current of 100 kVA transformers. Whereas Fig. 2 shows the average neutral current of thirty 100 kVA transformers in unbalance and balanced phase conditions. From the set of a total of eight-five transformers only two transformers' data are depicted in Tables 1 and 2.

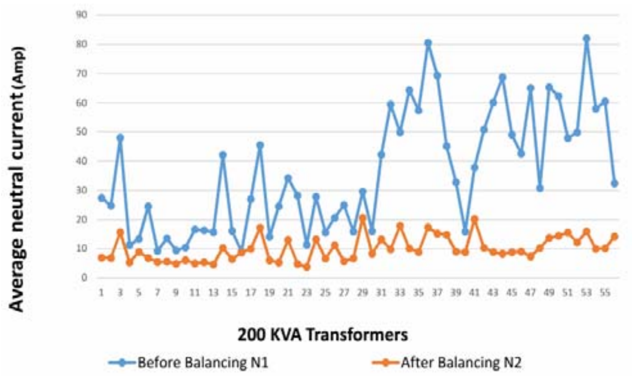

Fig. 1– Average neutral current before balancing and after balancing of 200 kVA.

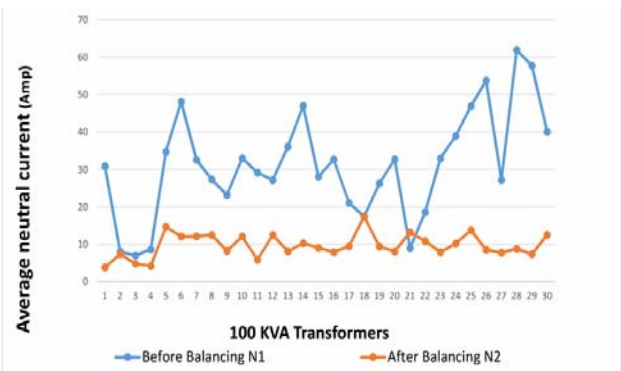

Fig. 2– Average neutral current before balancing and after balancing of 100 kVA.

3.2. COST ANALYSIS DUE TO POWER LOSS

The economics of the whole distribution network is mainly disturbed by the harmonics. Economic loss due to harmonics in 200 kVA and 100 kVA is depicted in Table 3 and Table 4, respectively, of two transformers on different time instances. The loss evaluation of the whole distribution network is based on consumer tariff.

- Peak hour tariff = 15.5 rupees per unit
- Off-peak hour tariff = 9.5 rupees per unit
- Peak hours cost calculation = (kWh×15.5×24)
- Peak hour cost calculation per year = (kWh×15.5×24×365)
- Off-Peak hours cost calculation = (kWh×9.5×24)
- Off-Peak hour cost calculation per year = (kWh×9.5×24×365)
- Total = Peak + Off-peak.

4. COMPARATIVE ANALYSIS

The comparative analysis between unbalanced and balanced phases of neutral current, power loss, and economic loss has been done. Details of comparative analysis are discussed below.

4.1. AVERAGE NEUTRAL CURRENT IN A BALANCED AND UNBALANCED CONDITION

The comparative analysis of the average neutral current in the balanced and unbalanced conditions of 200 kVA and 100 kVA is depicted in Figs. 1 and 2. Fifty-five transformers of 200 kVA rating and thirty transformers of 100 kVA rating are analyzed in both unbalanced and balanced conditions. The graph clearly shows that after balancing the transformers neutral current becomes less.

4.2 AVERAGE POWER LOSS IN A BALANCED AND UNBALANCED CONDITION

The comparative analysis of average power loss in the balanced and unbalanced conditions of 200 kVA and 100 kVA is depicted in Figs. 3 and 4. Fifty-five transformers of 200 kVA rating and thirty transformers of 100 kVA rating are analyzed in both unbalanced and balanced conditions. The power loss directly affects the economics of the whole distribution network. Eventually, lowers the power loss and reduces the stress on transformers and the whole distribution network.

4.3. ECONOMIC LOSS IN A BALANCED AND UNBALANCED CONDITION

The production cost of electricity is one of the major factors of an efficient distribution network. Harmonics in the distribution network eventually results in line losses that directly affect the consumers and distribution company. Figure 5 shows the economic losses of the 200 kVA transformers in a balanced and unbalanced condition. Whereas Fig. 6 shows the economic loss of thirty 100 kVA transformers.

4.4. ADVERSE EFFECTS OF UNBALANCING

Permanent damaged caused by the unbalancing in the 3-phase 4-wire system put adverse effects on the economics of the whole distribution company. Table 5 shows the data of damaged transformers due to (overloading, stress, and unbalanced phases). The total cost for damage transformers of different ratings in selected distribution companies for the year 2017–2018. Furthermore, Table 6 shows the financial loss due to transformer damaged (unbalanced loading).

Table 1
200 kVA current data before and after balancing

Area	Before balancing					After balancing				
	R	Y	B	N	kW	R	Y	B	N	kW
	Amp					Amp				
Time 1										
A	70	50	32	40	7.04	65	50	48	17	3.14
B	17	7	5	12	2.11	11	10	14	5	0.94
Time 2										
A	71	46	29	38	6.74	62	52	47	14	2.63
B	25	9	8	18	3.21	12	10	9	4	0.77
Time 3										
A	50	70	29	37	6.55	50	62	48	14	2.61
B	12	17	8	9	1.68	10	12	7	6	1.07
Time 4										
A	32	45	29	16	2.90	48	62	62	15	2.77
B	5	4	8	5	0.94	7	12	12	6	1.18
Time 5										
A	29	50	70	37	6.55	50	48	62	14	2.61
B	8	7	17	11	1.98	10	7	12	6	1.07

Table 2
100 kVA current data before and after balancing

Area	Before balancing					After balancing				
	R	Y	B	N	kW	R	Y	B	N	kW
	Amp					Amp				
Time 1										
C	50	76	62	26	4.57	60	63	64	11	1.93
D	91	73	60	30	5.28	80	73	78	18	3.16
Time 2										
C	65	35	78	39	7.03	65	63	64	3	0.61
D	75	60	45	27	4.88	85	73	78	12	2.14
Time 3										
C	62	35	50	25	4.43	64	60	63	5	0.94
D	60	60	91	32	5.76	78	80	73	7	1.40
Time 4										
C	50	76	62	24	4.27	60	63	65	6	1.07
D	91	73	60	28	5.05	80	73	85	12	2.14
Time 5										
C	35	65	62	30	5.34	65	64	63	3	0.61
D	60	75	60	16	2.94	85	78	73	12	2.14

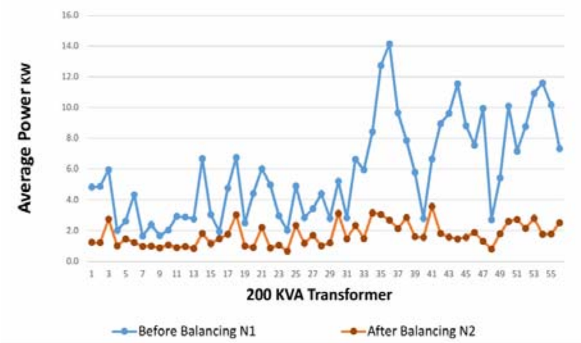

Fig. 3 – Average power loss before and after balancing of 200 kVA.

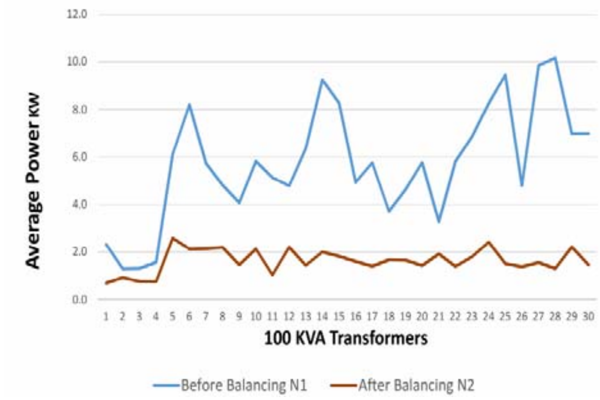

Fig. 4 – Average power loss before and after balancing of 100 kVA.

Table 3
200 kVA Unbalanced cost calculation

Area	kW	kWh/day	kWh/year	Peak hrs PKR Million	Off-Peak hrs PKR Million	Total PKR Million
Time 1						
A	7.04	168.96	61670.4	0.157	0.473	0.630
B	2.12	50.904	18579.96	0.047	0.142	0.190
Time 2						
A	6.47	155.328	56694.72	0.144	0.435	0.579
B	3.21	77.184	28172.16	0.071	0.216	0.288
Time 3						
A	6.55	157.368	57439.32	0.146	0.440	0.587
B	1.68	40.368	14734.32	0.037	0.113	0.150
Time 4						
A	2.90	156	56940	0.145	0.437	0.582
B	0.94	47.664	17397.36	0.044	0.133	0.177
Time 5						
A	6.50	156	56940	0.145	0.437	0.582
B	1.98	47.664	17334	0.044	0.133	0.177

Table 4
100 kVA unbalanced cost calculation

Area	kW	kWh/day	kWh/year	Peak hrs PKR Million	Off-Peak hrs PKR Million	Total PKR Million
Time 1						
C	4.57	109.68	40033.2	0.102	0.307	0.409
D	5.28	126.72	46252.8	0.117	0.355	0.473
Time 2						
C	7.03	168.72	61582.8	0.157	0.472	0.629
D	4.88	117.12	42748.8	0.109	0.328	0.437
Time 3						
C	4.431	106.344	38815.5	0.098	0.298	0.396
D	5.76	138.24	50457.6	0.128	0.387	0.516
Time 4						
C	4.27	102.48	37405.2	0.095	0.287	0.382
D	5.053	121.272	44264.2	0.112	0.339	0.452
Time 5						
C	5.334	128.016	46725.8	0.119	0.358	0.477
D	2.942	70.608	25771.9	0.065	0.197	0.463

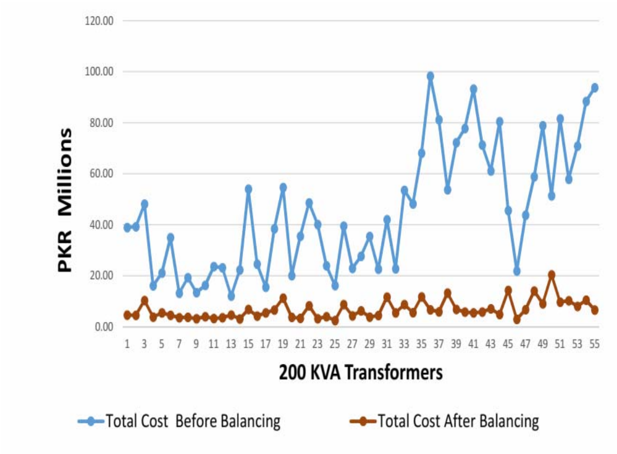

Fig. 5 – Cost analysis (balanced and unbalanced condition of 200 kVA).

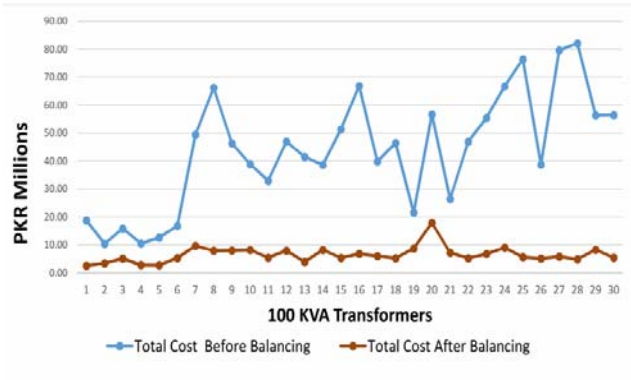

Fig. 6 – Cost analysis (balanced and unbalanced condition of 100 kVA).

Table 5

Transformer damaged data (2017–2018)

S.No	kVA	No. of T/F	Per unit cost	Total cost (Rs. millions)
1	10	13	85000	1.10
2	15	23	96700	2.20
3	25	123	115400	14.19
4	50	300	171600	51.48
5	100	300	266000	79.80
6	200	400	441100	176.44

Table 6

Loss data for one year (2017–2018)

S.No	Loss	PKR million
1	Total loss (2017 – 2018)	325.71
2	Damage loss (caused by unbalancing loading of the transformer)	162.34

The loss analysis was done of the selected distribution network that consists of thirty 100 kVA and fifty five 200 kVA transformers. The analysis of the distribution network was done for the whole year in different five time instances. Figure 7 shows the comparison of average power per year from 200 kVA and 100 kVA transformers of the selected distribution network. It depicts that an unbalanced network produced an adverse effect on the economic system.

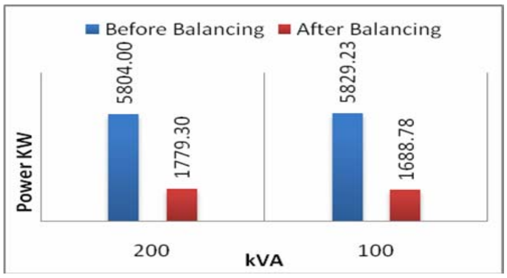

Fig. 7- Power loss comparison between unbalance and balanced phase

5. METHODOLOGY

5.1 BLOCK DIAGRAM OF THE SWITCHING MECHANISM

A load balancing mechanism is proposed for three phase-four wire distribution system. The basic structure of the load balancing mechanism is shown in Fig. 8. The proposed methodology will be able to reduce loss due to harmonics. The whole system comprises of the different subsections. Each subsection is discussed in detail.

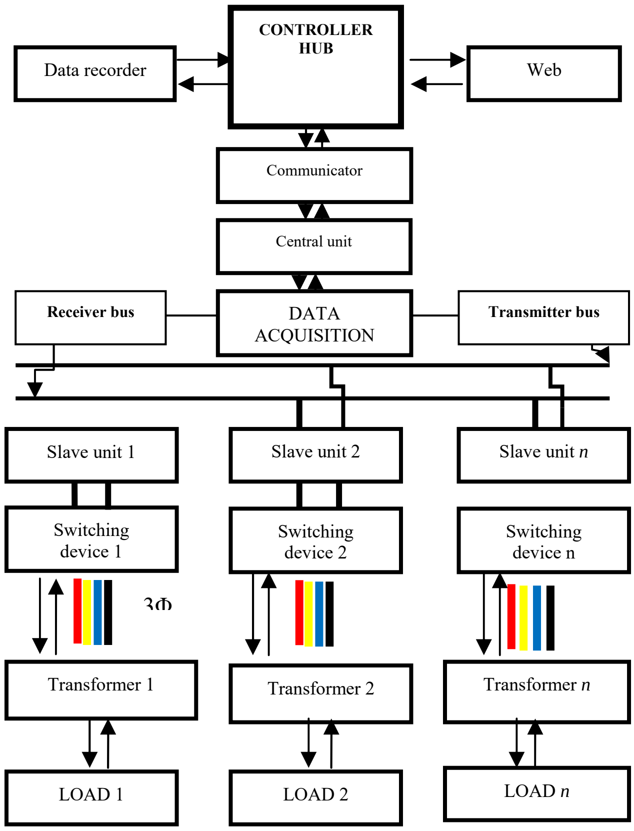

Fig. 8 – Block diagram of switching algorithm.

5.1.1. DATA ACQUISITION

Current sensors are used for data acquisition. It collects information of each phase and neutral conductor and transfer all the data to the central unit.

5.1.2. CONTROLLER HUB

The controller hub is responsible for all the calculating procedures. It monitors all the switching activities and manages all the records.

5.1.3. DATA RECORDER

A data recorder is used to record all the switching activities. The switching logger records all the on/off times of each relay connected with the system. The user can retrieve any switching activities.

5.1.4. WEB

The controller hub is directly linked with a database that can be accessed through a web portal. The access is allowed to only concern authorities for system monitoring.

5.1.5. CENTRAL UNIT

Arduino Mega is the central unit that switches the load between the phases. It receives input from the current sensor that monitors the current in real-time. When the load changes in any phase then the current also changes for that phase, and it shifts the load to another phase for balanced operation. The controller gives a signal to the relay to switch the load when the system is unbalanced.

5.1.6. COMMUNICATOR

It is used to provide a link between the controller hub and the central unit.

5.1.7. SWITCHING DEVICE

The relay module is used for switching the loads. The loads are connected at the common terminal of the relay and the phase is supplied at the normally closed terminal. The normally open terminal is connected to remaining empty loads so when the relay is active because of unbalancing; it shifts the loads to the phase which is free at that moment.

5.2. SWITCHING ALGORITHM

Switching between phases of transformers is supported by the algorithm, "ϕ" represents the phase of the distribution system.

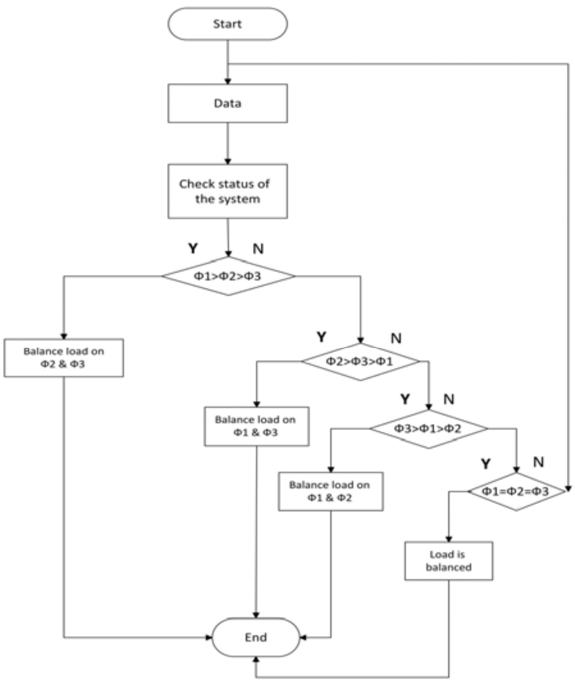

Fig. 9 – Flow mechanism for switching.

5.2.1. CASE A

The phases are connected to their respective loads. The central unit will be controlling the switching of loads. The algorithm will compare current on ϕ_1, ϕ_2, and ϕ_3, and shift the load on another phase if an unbalance occurs. The phases cannot be balanced completely practically so, there is a safe limit 10 % or 0.95 that is to be set by the distribution company. The algorithm will repeat itself until it can achieve a balanced load up to a safe limit.

$$\text{Safe limit} = 0.95 \times \text{Balanced Phase}.$$

5.2.2. CASE B

In case of any fault occur in the distribution system that can be (three-phase fault, double line fault, single line fault, and line to ground fault). All three phases get disconnected from load unless fault mitigation by the distribution company starts on it.

5.3. EXPERIMENTAL SETUP

A three-phase supply has been given as input. There are 18 relays (5 modules) used for switching purposes as shown in Fig. 10. A 200 W load is connected on each phase that depicts a balanced load connected load. Unbalancing of the load was done manually by shifting load on another phase. When any of the phases are unbalanced due to excessive load then the relay unit operates, and normally open contact shift the load on another phase by following the algorithm.

Current sensors are connected in series that automatically records and measures the current continuously. Arduino mega board is used for receiving the analog output from the current sensor and gives digital input to each relay at pins IN1, IN2, IN3, IN4. These input pins provide the input signal to the main control center. The monitoring unit will check the current levels based on a defined algorithm and provide the signal to operate a specific relay to balance the load among three phases. The experiment was done on a real-time small-scale system that successfully balanced the load up to a safe limit of ±10 % on each phase. The complete experimental setup of the phase mechanism is shown in Fig. 10.

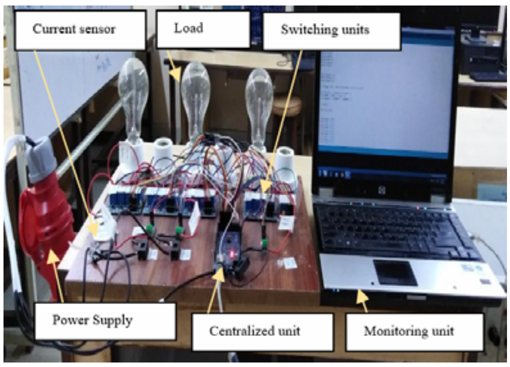

Fig. 10 – Experimental setup with workstation.

7. **CONCLUSION**

To balance the load on the distribution network transformers switching algorithm along with its experimental prototype has been introduced, which balances the three-phase system through which excessive current flow in the neutral conductor can be minimized. The analysis comparative analysis shows that a huge amount of power is wasted due to unbalanced phases. The experimental setup presented is capable to record all the switching activities and current data on different phases. However, for a large distribution setup, the switching can be done with high-performance thyristors. Along with that, it is suggested that phase balancing can be done more accurately by predictive analysis or by using metaheuristic algorithms like (cuckoo search algorithm, particle swarm optimization, and genetic fuzzy system) by implementing these genetic algorithms, it opens a new horizon for phase balancing.

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