ADVANCED DEVELOPMENT AND DESIGN OF MULTIPHASE RADIAL DISTRIBUTION SYSTEM WORKSTATION FOR PERFORMING LOAD FLOW ANALYSIS UNDER NORMAL AND ABNORMAL CONDITIONS

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Abstract: It is understandable that carrying out research work in power system is feasible only with the simulation software as setting up the power system laboratory turn out to be difficult while considering its economical and technical aspects. It creates complexity in understanding power system concepts due to lack of hands on experimentation. This problem has been identified as noteworthy and formulated as the main objective in this work. The focus of this research work is to design and develop a multi phase radial distribution system workstation. This workstation has been equipped with the hardware and software in order to carry out the various distribution system analyses under normal and abnormal conditions, and also under different load conditions. Special attention has been rewarded for development of software package for monitoring and control. The developed software package features Graphical User Interface (GUI) support and compatible with web browsers. It facilitates and encourages the researchers to contribute their research work in the distribution system analyses. Most prominently, it provides a wide opening to the researchers in distribution system optimization and fault analysis. This paper details the set up/hardware equipments of the proposed workstation and its simulation package.

***Index Terms*—Distribution system, fault analysis, laboratory, transmission line simulator**

I. INTRODUCTION

Electric power system educators around the world face the problem of making their students to understand the power system operation experimentally in real time. Since traditional classroom teaching and exercises on the power system alone is not capable for the students to make understandable. Even for power system fundamental studies/analyses, students look difficulty in understanding power transfer between sources, loads and transmission lines. The basic theoretical definitions are understood but they will lack in understanding how the total picture of each component of a system interacts with the other. Always researchers in power system will face complexity physically in understanding how the source, load and transmission line changes will affect the performance of the entire system. To improve the quality of technical education and research involvement, many utilities around the world have developed their distribution automation projects [3].

This paper is focused on the design and implementation of the multiphase radial power distribution laboratory with remote monitoring and data acquisition for the research developers [2]. The reconfigurable power distribution laboratory which is set up for the physical experimentation allow the researchers to perform experiments under: balanced and unbalanced radial multi-phase power flow analysis, radial distribution network reconfiguration for different loading conditions, service restoration to provide reliable service whenever a permanent fault occurs in a power system, capacitor placement in radial distribution system to calculate the real power losses under different types of loading, placement of Distributed Generator (DG) in radial distribution system to minimize the total active power loss and also to improve the voltage profile, radial distribution system phase balancing, analysis of pre and post-fault distribution systems and web-based energy management [1], [4], [10]-[12].

The laboratory is embraced with three sections: input control panel, pi-section panel, and load control panels. The source panel is inbuilt with a Numerical Over Current Relay (NOCR) which is configurable for 1A/5A, a step-down transformer 400/110V, a multifunction meter present on the secondary side of the transformer. The pi-section panel has four pi-section units where each unit is of 2kM length. The load control panel consists of resistive load, capacitive load, inductive load and motor load. Each load panel consists of 8-stages of loading which can be selected through each independent switch. Additionally, a motor load of rating 0.5A, 50 Hz, 1440/2800 r/min, 0.7/1 kW/HP is provided. Also, a Transmission Line Simulator (TLS) for remote monitoring and data acquisition is build with a Graphical User Interface (GUI) [5] – [9].

The principal intention of developing this power distribution laboratory is to perform experimentations physically. Any software package developed on short circuit analysis is to determine circuit breaker capacity and its relay operation for reliable operation of the power system. As such Transmission Line Simulator (TLS) software with data acquisition is developed in power distribution laboratory. The radial distribution fault analysis experimentation can be performed in this laboratory. The laboratory is developed with a fault simulator where the fault can be simulated. Using this simulator we can perform line-to-ground fault, line-to-line fault, double line-to-ground fault, three phase fault and one or two open conductors fault [13]-[15].

Network or feeder reconfiguration is the process of changing the topological structure of the feeders by opening or closing the sectionalizing and tie switches. A reconfigurable experimentation is planned to be conducted in power distribution laboratory in near future [16]-[19]. To maintain reliable power in Distribution System (DS) a small electric power generation can be used either in the distribution system or directly to the customer side. To minimize the total active power loss and also to improve the voltage profile in distributed generation system the optimal placement of Distributed Generation (DG) units is very crucial [20]-[21].

This paper begins with a brief overview of elements used in workstation is described in Section II. Section III delivers the software package used in the system. In section IV the results and their test systems are discussed briefly. Finally it is concluded in the section V.

II. MAIN PANELS OF POWER DISTRIBUTION SYSTEM WORKSTATION (PDSW)

Power Distribution System Workstation is a sophisticated unit developed with the purpose of helping students in their understanding of basic concepts in power systems. With referring the literatures related to distribution system laboratory setup, the scaled down equipments for the proposed workstation has been customized. The workstation has four major modules which are listed below,

1. Input Control Panel (ICP) – to model the source
2. Distribution Line Panel (DLP) – to simulate the effect of transmission line
3. Load Control Panel (LCP) – to model the equivalent load
4. Fault Simulator Panel (FSP)– to introduce the fault in the system

Apart from the above components, the following additional components have been provided to experiment other phenomenon related to distribution system.

- Numerical over current relay – to understand the protection philosophy
- Smart meters – for monitoring various electrical parameters
- Software which interacts with the distribution system experimental setup

The general layout diagram of the distribution system hardware setup along with load panels is shown in Fig. 1.

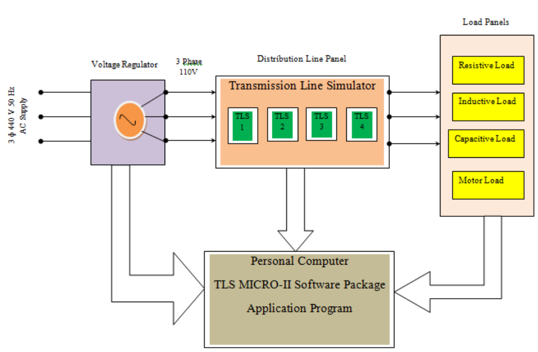

Fig. 1 General layout diagram of the workstation

The laboratory is designed in such a way to enhance the knowledge of researchers for carrying out their research works in distribution system analysis such as:

i. Reconfiguration, [22]
ii. Capacitor Placement, [23]
iii. Distributed Generators placement, [24]
iv. Feeder load balancing, [25]
v. Feeder phase balancing, [26]
vi. Fault analysis (three-phase fault, single line to ground fault, line to line fault and double line to ground fault) [13], [14] and
vii. Service restoration under fault. [27]

A. *Input Control Panel (ICP)*

The Input Control Panel is considered as the heart of the workstation as it feeds the supply to the entire system from the main. The main function of this panel is to step down the main supply voltage to the compatible level. The present ICP setup reduces the supply voltage into 110V. Therefore, the base voltage considered for the distribution system experiments are 110V. The main components of input control panel are as follows

- Step down transformer 400V / 110V
- Auto transformer to adjust the sending end voltage
- Regulator switch to vary secondary voltage
- Three phase LED indication (R-phase, Y-phase, B-phase)
- Fuses for individual phase
- Multifunction digital meter is present on secondary side
- One three phase over current relay
- One MCB for protection

B. *Distribution Line Panel (DLP)*

Distribution system lines are modeled by an equivalent pi-model. The equivalent circuit of the developed pi-model consists of resistance and reactance of the line in series and half of total shunt capacitance lumped on either side of the series element. Most predominantly, in order to get the characteristics of the distribution line, the line parameters are designed with high R/X ratio.

In DLP, each of the pi-section units consist of resistor; inductor and capacitor connected in a way so as to form an equivalent pi network. Each pi-section of DLP has been developed as 3 phase and 4 wire system. It facilitates the user to work with balanced and unbalanced distribution system. Most importantly, the developed DLP permits the students to prepare their own distribution system structure for their analysis. The selector switches are provided to each pi-section to vary the line parameters. The distribution line parameters are adjusted to meet out R>>X.

Furthermore, for each DLP, in order to model transmission line of variable length, 4 pi-section units have been provided with each having total Z = 14.7+j9Ω and Y/2 = 0m℧. The workstation model has a base voltage of 110V and base power = 100 kVA, which corresponds to a base impedance of 63.5Ω and base admittance of 0.01574℧. The z-bus matrix for one pi-model is derived as shown in the equation (1).

$$Zabc = \begin{bmatrix} 14.7 + j9.00 & 0.17 + j4.50 & 0.17 + j4.00 \\ 0.17 + j4.50 & 14.7 + j9.00 & 0.17 + j4.40 \\ 0.17 + j4.00 & 0.17 + j4.40 & 14.7 + j9.00 \end{bmatrix} \Omega/\text{pi-section} \quad (1)$$

C. *Load Control Panel (LCP)*

To have the experience in working with different characteristics of loading, the workstation is equipped with separate Resistive Load Control Panel (RLCP), Inductive Load Control Panel (ILCP), Capacitive Load Control Panel (CLCP) and motor load. The above mentioned loads will provide the students to get the different combination of loading to the distribution system.

i. Resistive Load Control Panel (RLCP)

The developed resistive panel consists of 8 independent selector switches. In RLCP, the load ranges can be reconstructed in steps of 50 Ω + 10*7Ω. The workstation is equipped with one number of RLCP to have the wide range of loading. The main components of RLCP are loading in steps, fuses for individual phase, one multi-function meter, terminals for connecting input panel and other loading panels and an interfacing unit.

Apart from RLCP, the load resistance is employed by making use of multiphase rheostat loadings to the system. The wide usage of various resistive loading facilitates the students to understand the impact of resistive loading in the circuit.

ii. Capacitive Load Control Panel (CLCP)

The capacitive load control panel provides the capacitive loading to the workstation with four stages of loading which can be selected through 8 independent switches. The main components of the associated control panel are same as that of RLCP. Various ranges of capacitive loadings are used as an additional load for experimentation.

iii. Inductive Load Control Panel (ILCP)

This load panel consists of 8 stages of inductive loading, which can be selected through 8 independent switches as discussed in RLCP and CLCP. The ILCP can also be modified with variable ranges of inductive loadings. The main components of the associated control panel are same as mentioned in RLCP.

iv. Motor Load

The workstation has also been equipped with a three-phase Induction Motor (IM) load. The rating of the motor load is 3-phase, 110 V, 0.5A, 1440/2800 r/min, 0.7/1 kW/HP. It facilitates the student to work with the balanced loading. The loading of the motor can be varied with the help of spring balance ranging from 0.1 A to 0.5A.

Thus the combination of different loading panels provides variety of characters and encourages the students to work with the balanced load and unbalanced load. Furthermore, the loads of the individual panels can be varied to get different load patterns.

D. *Fault Simulator Panel (FSP)*

The workstation is facilitated with the fault simulator. The list of various faults created through the fault simulator is,

i. Three phase fault
ii. Single Line to Ground (SLG) fault
iii. Line to Line (LL) fault
iv. Double Line to Ground (DLG) fault

With using this simulator, students can situate the distribution system to any of the above mentioned faults and different analysis can be performed. Additional importance should be taken so that the relay at the source end is set to definite time curve and the time is set at less than 4 sec preferably [11].

III. GRAPHICAL USER INTERFACE (GUI)

As all the equipments are facilitated with data interface provision, all the electrical parameters are acquired by the Personal Computer (PC). Each load panel, Pi-section panel and the substation panel are connected to the computer by a communication port. It is important that the specially developed software package TLS MICRO-II must be installed in the PC. This package has the Graphical User Interface feature for the user interaction and monitoring. It displays all the acquired parameters of the workstation. The TLS MICRO-II workstation resembles the real hardware setup for three phase distribution system [6], [19].

The source panel in TLS MICRO-II is built-in with an Integrated Numerical Over Current Relay (INOCR). The over current relay is used wherever over current protection is required. The features of INOCR are integrated digital technology, configurable for 1A/5A, separate LED indication for each protection and storage capability of last 20 events. The program is invoked by double clicking on the application TLS.exe installed in the “C:/ProgramFiles/”. The screenshot of the main window of the GUI is as shown in Fig.2.

The workstation consists of energy meters, each of which is provided with RS485 communication port. It is possible to read the parameters such as voltage, current, power factor remotely through the RS485 communication. In the GUI, the parameters are displayed against each meter. It is possible to set the communication parameters by clicking on the communication menu. After selecting comports press the “save” button to save the changes made on the window or click on “cancel” to exit without saving. The port setting window is as shown in Fig. 3, which appears by clicking the “COM setting” button. Using this window it is possible to set comport and energy meter id’s.

The user of the application can select the preferred location in PC to store the acquired data through data acquisition program module. The data acquisition window can be obtained by selecting data acquisition menu item from the edit menu which appears in the main window.

The Fig. 4 shows the screenshot of the data acquisition sub window which asks the user to select the destination path for the file, the time interval at which data has to be acquired and the meters for which data acquisition is required.

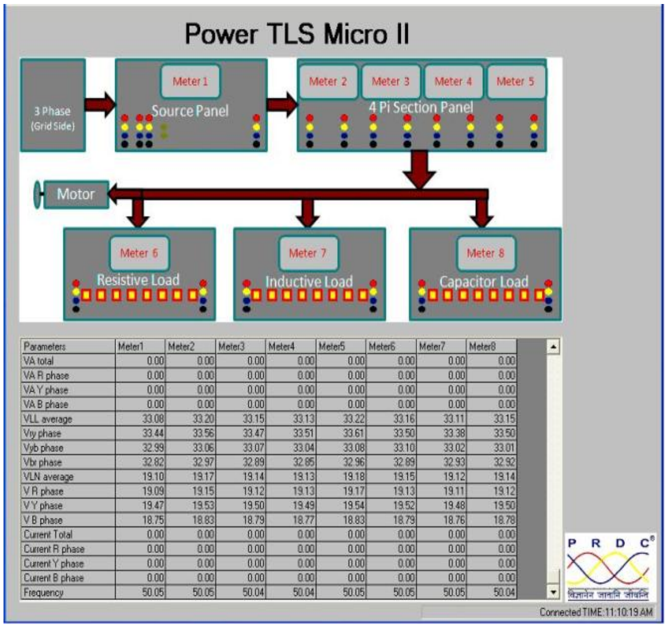

Fig. 2 Main screen of TLS software

The three phase workstation can be operated under normal and abnormal conditions with three phase resistive, capacitive and inductive loads. Performance analysis can be carried out under both single phase and/or three phase mode. Students can do their experimentation by varying the loads as well as by adjusting the distance of the Pi-section. The impact of various loads on the power flow can be viewed by manually by noting down the meter readings from the DLP. This can be cross verified by using the TLS MICRO-II software where readings are stored automatically in a excel sheet for meters. The stored data's are examined for future reference and from this analysis can be prepared for future works.

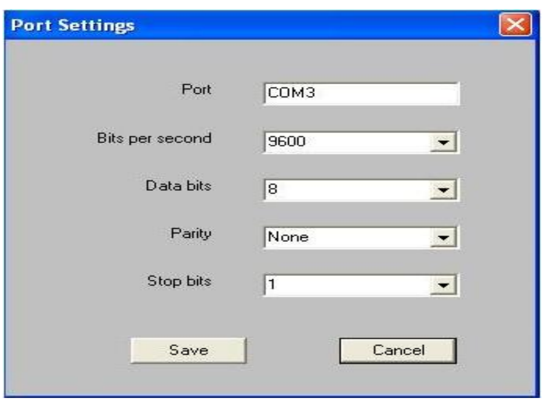

Fig. 3 COM settings

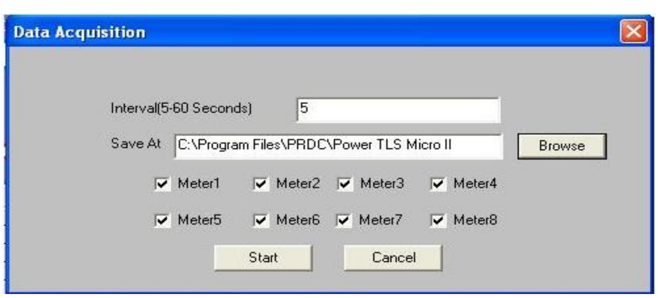

Fig. 4 Data acquisition setting

IV. EXPERIMENTATION AND VALIDATION

The developed workstation has been validated by performing fundamental single phase and three phase load flow analysis. With the available equipments in the workstation, radial distribution system has been structured separately for single phase and multiphase. Under the balanced loading condition, single phase load flow analysis is preferred and vice versa for multiphase.

A. Single Phase System

1. Single Feeder Radial Distribution System

The single phase radial distribution system has been structured with 12 branches and 13 buses. The system has 63.5V base voltage and 100 kVA rating. The single line diagram of an proposed system for experimentation is shown in the Fig. 5. The initial power loss of the system is considered as $5.728E^{-7}$. The characteristic data of the 13 bus RDS is listed in the Table 1.

The specified structure with the proper load setting has been made with the workstation. The supply voltage is fed to the load through the ICP. The meter readings are received through the software package in PC. Simultaneously, for the assumed radial structure, the conventional backward/forward sweep radial load flow is used to calculate the system parameters. The results after conducting the radial load flow analysis by using the simulation is compared with the received parameters from the smart meters during experimentation.

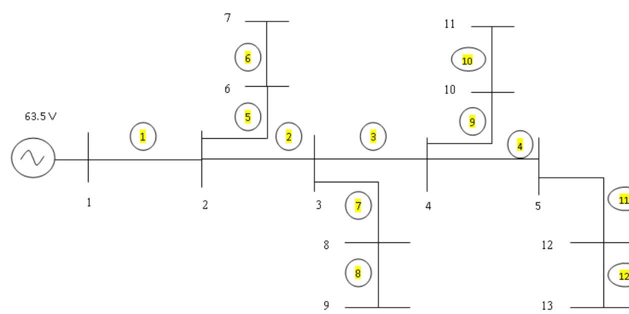

Fig. 5 Single line diagram of assumed single phase distribution system

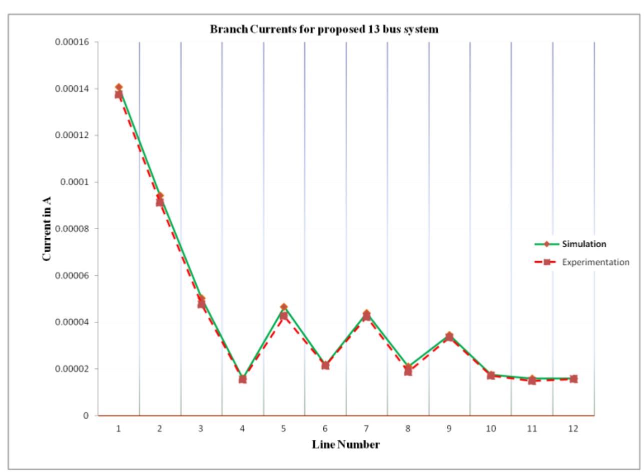

Fig. 6 Branch current for proposed 13-bus system

Table 1 Load data for the proposed 13-bus system

Bus No.	Load	
	Real Power in W	**Reactive Power in VAR**
1	0.0	0.0
2	0.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	1.1947	0.8961
7	1.0406	0.7804
8	1.0753	0.8065
9	0.9775	0.7331
10	0.7868	0.5901
11	0.8065	0.6048
12	0.0000	0.0000
13	0.7331	0.5499

The Table 2 shown below depicts the voltage profile of both experimentation and simulation of the proposed system. From this table, it is observed that experimentation results and simulation results match each other. Fig.6 shows the graphical representation for the proposed 13-bus system with the simulation and experimentation branch currents.

Table 2 Voltage at buses through Simulation and Experimentation

Bus No.	Simulation Result		Experimentation Result		% Error
	|V| in p.u	Voltage in V_{sim}	|V| in p.u	Voltage in V_{exp}	
1	1.0000	63.50	1.0000	63.50	0.00
2	0.9616	61.06	0.9520	60.45	1.00
3	0.9359	59.43	0.9311	59.13	0.51
4	0.9222	58.56	0.9129	57.97	1.01
5	0.9178	58.28	0.9094	57.75	0.92
6	0.9489	60.26	0.9416	59.79	0.78
7	0.9430	59.88	0.9345	59.34	0.90
8	0.9239	58.67	0.9147	58.08	1.00
9	0.9182	58.31	0.9078	57.65	1.14
10	0.9128	57.96	0.9083	57.68	0.48
11	0.9080	57.66	0.9008	57.20	0.80
12	0.9135	58.01	0.9045	57.43	1.00
13	0.9092	57.73	0.9000	57.15	1.01

Where,

$$\% \, Error = \frac{(V_{sim} - V_{\exp})}{V_{sim}} * 100 \quad (2)$$

2. Multi Feeder Radial Distribution System

In order to understand the concept of feeder balancing, multi-feeder RDS has been modeled with the existing workstation. The proposed single phase multi feeder radial distribution system has been structured with 12 branches and 10 buses. The system has 63.5V base voltage and 100 base kVA. The power loss of the proposed system is considered as $1.909E^{-7}$. The single line diagram of an assumed system is shown in the Fig. 7. The characteristic data of the system is given through the Table 3. The voltage profile for single phase multi feeder system is shown in Table 4. The Fig.8 shows the graph plotted for the proposed multiphase RDS.

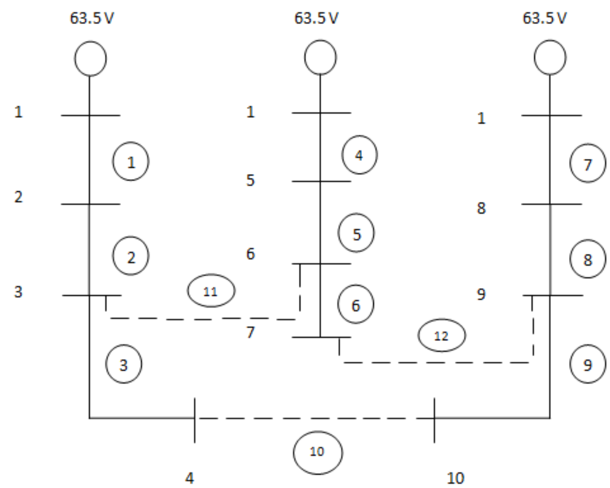

Fig. 7 Single line diagram of assumed single phase Multi distribution system

Table-3 Load data for multi feeder system

Bus No.	Load	
	Real Power in W	**Reactive Power in VAR**
1	0.0	0.0
2	0.0	0.0
3	0.7868	0.5901
4	0.7331	0.5499
5	0.0000	0.0000
6	1.0406	0.7804
7	1.1947	0.8961
8	1.0406	0.7804
9	1.0753	0.8065
10	0.9775	0.7331

Table-4 Summary of Results for single phase multi feeder system

Bus No.	Simulation Result		Experimentation Result		% Error
	|V| in p.u	Voltage in V_{sim}	|V| in p.u	Voltage in V_{exp}	
1	1	63.5	1	63.5	0.00
2	0.9917	62.97	0.9902	62.97	0.15
3	0.9834	62.44	0.9821	62.44	0.13
4	0.9793	62.19	0.9764	62.19	0.30
5	0.9876	62.72	0.9863	62.72	0.13
6	0.9753	61.93	0.9713	61.93	0.41
7	0.9687	61.51	0.9672	61.51	0.15
8	0.9829	62.42	0.9784	62.42	0.46
9	0.9716	61.69	0.9684	61.69	0.33
10	0.9661	61.35	0.9582	61.34	0.82

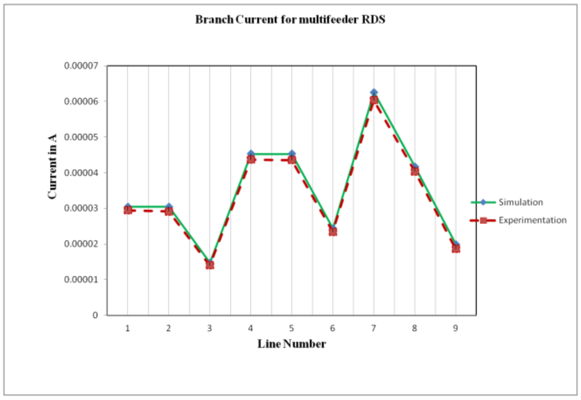

Fig. 8 Branch current for proposed multifeeder RDS

B. Analysis under faulted conditions

1. Single Phase RDS

The purpose of doing any short circuit analysis is to determine the line voltage and branch current in the system. In the developed workstation shunt and series fault analysis can be performed with a fault simulator. Experimentation is carried out by for single phase and multiphase systems with various loads connected at various buses.

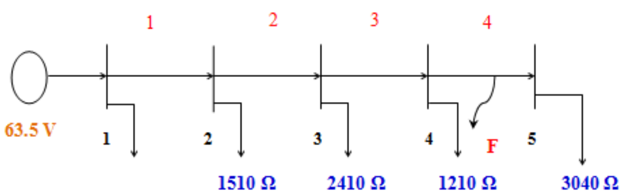

Fig. 9 Single line diagram for fault analysis at different loads

The single line diagram of single phase radial distribution for fault analysis is shown in figure 9. The proposed system is sampled with a 5-bus system radial distribution system of 63.5V as base voltage and 100 kVA as MVA rating. For this test system, the line impedance are considered as R=14.7Ω and X=9Ω. In this system the load is connected at various buses and fault is created at bus-5. Table 5 shows their experimentation results with different loads and faults at various buses.

2. Multi Phase RDS

The multiphase RDS considered here is of 5-bus system with three phase resistive load is connected at bus number 5. The pre-fault and post fault analysis are carried out for this proposed system in the workstation. Figure 10 shows the single line diagram of multi-phase system with 3-phase resistive load is connected at bus 5. The Table 6 shown below illustrates the pre-fault analysis of 3-phase system with resistive load is connected at bus number 5. The analysis is determined for various loads. The voltage and current profile for each node is clearly depicted in the table.

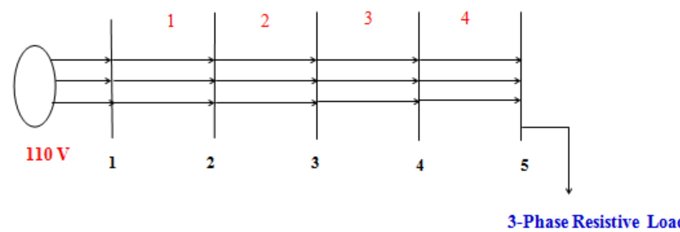

Fig. 10 Single line diagram for multi-phase system

Simultaneously, for the proposed radial structures, the conventional backward/forward sweep radial load flow analysis is used to calculate the system parameters. The results obtained after conducting the radial load flow analysis by using the simulation is compared with the experimentation setup. The result of every panel is collected through the smart energy meters through TLS micro software. Table 7 is intended for experimentation results of short circuit analysis of the proposed 3-phase system under various fault conditions.

The Fig.11 shows the complete setup of the workstation where the experimentation is carried out for normal and abnormal conditions.

Table 5 Load & fault at various buses for single phase RDS

Bus No.	Pre-fault		Fault at Bus No. 5		Fault at Bus No. 4		Fault at Bus No. 3		Fault at Bus No. 2	
	Voltage in V	Current in A	Voltage in V	Current in A	Voltage in V	Current in A	Voltage in V	Current in A	Voltage in V	Current in A
1	63.91	0.132	63.51	0.797	63.11	0.978	62.87	1.216	62.29	1.742
2	58.55	0.132	47.90	0.798	45.42	0.976	41.38	1.218	**33.44**	**1.738**
3	56.79	0.092	35.98	0.767	30.99	0.949	**23.52**	**1.193**	31.62	0.051
4	55.05	0.067	24.48	0.751	**17.24**	**0.933**	22.12	0.027	30.73	0.037
5	55.74	0.021	**0.0**	**0.728**	17.14	0.0	22.43	0.0.	31.10	0.0

Table 6 Three phase pre-fault bus voltage and current at different loads

S. No.	**Phase**	**Pre-fault**										**3ϕ Resistive Load in (Ω)**
		Bus 1		**Bus 2**		**Bus 3**		**Bus 4**		**Bus 5**		
		Voltage in V	**Current in A**	**Voltage in V**	**Current in A**	**Voltage in V**	**Current in A**	**Voltage in V**	**Current in A**	**Voltage in V**	**Current in A**	
1	a	109.5	0.131	108.4	0.132	107.1	0.131	105.5	0.131	104.4	0.131	418
	b	108.1	0.126	104.1	0.126	100.4	0.126	96.84	0.126	92.94	0.126	
	c	107.8	0.125	105.7	0.125	103.4	0.125	102.0	0.125	100.0	0.125	
2	a	107.3	0.308	99.19	0.309	90.86	0.309	82.49	0.309	74.53	0.308	142.3
	b	105.6	0.294	97.24	0.294	89.21	0.294	80.21	0.293	71.99	0.292	
	c	105.3	0.290	97.19	0.290	88.91	0.291	82.41	0.291	74.11	0.290	
3	a	107.6	0.431	96.16	0.431	84.51	0.432	72.86	0.431	61.79	0.430	85
	b	106.1	0.407	94.57	0.408	83.36	0.409	70.96	0.408	59.80	0.406	
	c	105.8	0.409	94.26	0.410	82.63	0.411	73.11	0.410	61.81	0.409	
4	a	106.4	0.658	88.97	0.659	71.38	0.661	53.99	0.659	37.24	0.658	33.8
	b	104.9	0.606	87.79	0.609	71.18	0.610	52.68	0.604	35.99	0.603	
	c	105.5	0.622	87.62	0.624	69.81	0.625	54.98	0.623	37.55	0.623	

Table 7 Three phase post-fault analysis for different faults at various buses

Bus No.	**Phase**	**3-Phase Fault**		**Line-Line Fault**		**Line-Line Ground Fault**		**Single Line-Ground Fault**	
		Voltage in V	**Current in A**	**Voltage in V**	**Current in A**	**Voltage in V**	**Current in A**	**Voltage in V**	**Current in A**
1	a	105	0.771	105.7	0.652	105.1	0.786	107.7	0.743
	b	104.1	0.703	107.3	0.619	105.3	0.681	107.5	0.117
	c	103.8	0.713	106.4	0.124	104.8	0.123	105.5	0.129
2	a	85.16	0.771	85.35	0.652	84.90	0.786	94.75	0.742
	b	84.44	0.704	99.0	0.619	93.49	0.682	103.8	0.117
	c	83.58	0.714	99.25	0.125	92.49	0.124	94.13	0.130
3	a	64.92	0.768	64.76	0.654	64.57	0.786	81.92	0.744
	b	64.70	0.707	91.38	0.621	81.98	0.683	100.4	0.117
	c	62.81	0.716	92.65	0.125	81.48	0.124	83.23	0.129
4	a	44.44	0.768	44.40	0.625	44.35	0.785	69.42	0.741
	b	43.40	0.705	84.23	0.619	70.08	0.681	94.39	0.117
	c	45.63	0.713	87.77	0.124	72.80	0.123	73.01	0.129
5	a	24.98	0.764	24.64	0.651	24.83	0.784	57.43	0.739
	b	24.02	0.702	77.64	0.618	58.56	0.680	90.51	0.117
	c	25.34	0.709	83.51	0.124	63.25	0.124	64.20	0.129

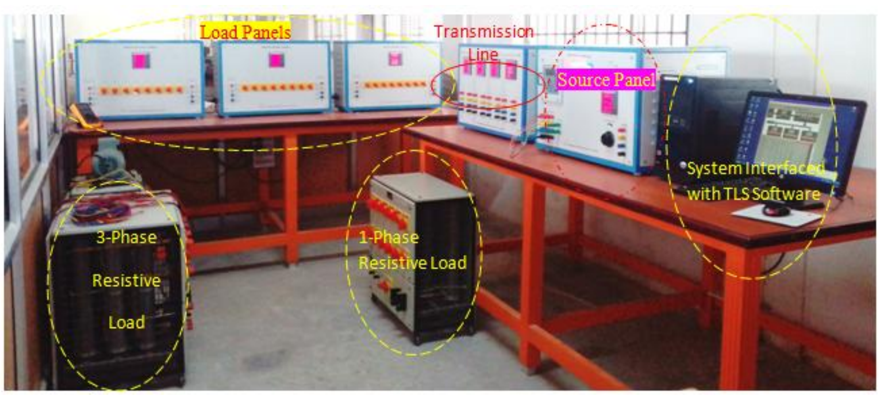

Fig.11 Workstation complete set up

V. CONCLUSION

An understanding of basic power system principles is essential in the operation of electric power systems. This paper mainly focuses on the development and implementation of a distribution system workstation for understanding the basic concepts and to perform various experiments in real time. Also development of this workstation will provide a path way for the researchers to do their research work in distribution system experimentally. The load flow analysis under balanced and unbalanced loading in the distribution system is carried out in the workstation and the analyses are verified with the simulation. In near future, apart from short circuit studies reconfiguration, phase balancing and service restoration will be performed.

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