1.0 Introduction

Power flow analysis (also commonly referred to as *load flow analysis*) is one of the most common studies in power system engineering. We are already aware that the power system is made up of interconnected components that are located at the facilities of utility companies. Thus, the control of generation, transmission and distribution of power are performed from a centralized location. The power flow during normal operation of the power system must be known in order to perform these control functions satisfactorily.

2.0 Problem Definition and Formulation

The power flow problem consists of evaluating the flow of power and voltages of a network for a specified terminal or bus conditions. The results of a power flow solution are used to evaluate *loadability* of lines or transformers and the acceptability of voltage profiles. Additionally, power flow analysis is required for several other analyses such as contingency and transient stability studies.

The mathematical formulation of the power flow problem results in a system of algebraic nonlinear equations that are solved using *Gauss-Siedel* or *Newton-Raphson* techniques. Usually, the nodal analytic technique is used to analyze the power system network. To solve the power flow problem, the power system is assumed to be operating under balanced conditions and a single-phase model is applied.

The ***transmission network*** is modeled as an *admittance* matrix (usually a sparse matrix for large power systems) which we will denote as Y_{bus}. This means that the impedances (resistance and reactance of the lines) will be converted to per unit (p.u) admittances on a common MVA base. The entries on the Y_{BUS} matrix will represent admittances of the transmission lines between buses (i.e. if the admittance of the line between *Bus 1* and *Bus 2* is $0.033 + j0.02$, then the matrix entry $Y_{1,2} = 0.033 + j0.02$; and zero entries would signify no lines between the buses).

3.0 Power Flow Simulation using RPowerLABS

RPowerLABS' power flow simulation virtual laboratory comes preloaded with several IEEE test power systems and a Nigeria 330kV power system; the main technique used for solving the non-linear algebraic equations is the Newton-Raphson technique. RPowerLABS is a web-based virtual lab and is operated through a modern browser (Firefox, Chrome or Internet Explorer)

The following steps are required to startup the lab:

Step 1: On the Home Screen of RPowerLABS, click on "Power Flow", a new tab on the browser is opened to display the power flow lab's interface as seen in Fig. 2. A screenshot showing the Home screen of RPowerLABS is shown in Fig. 1.

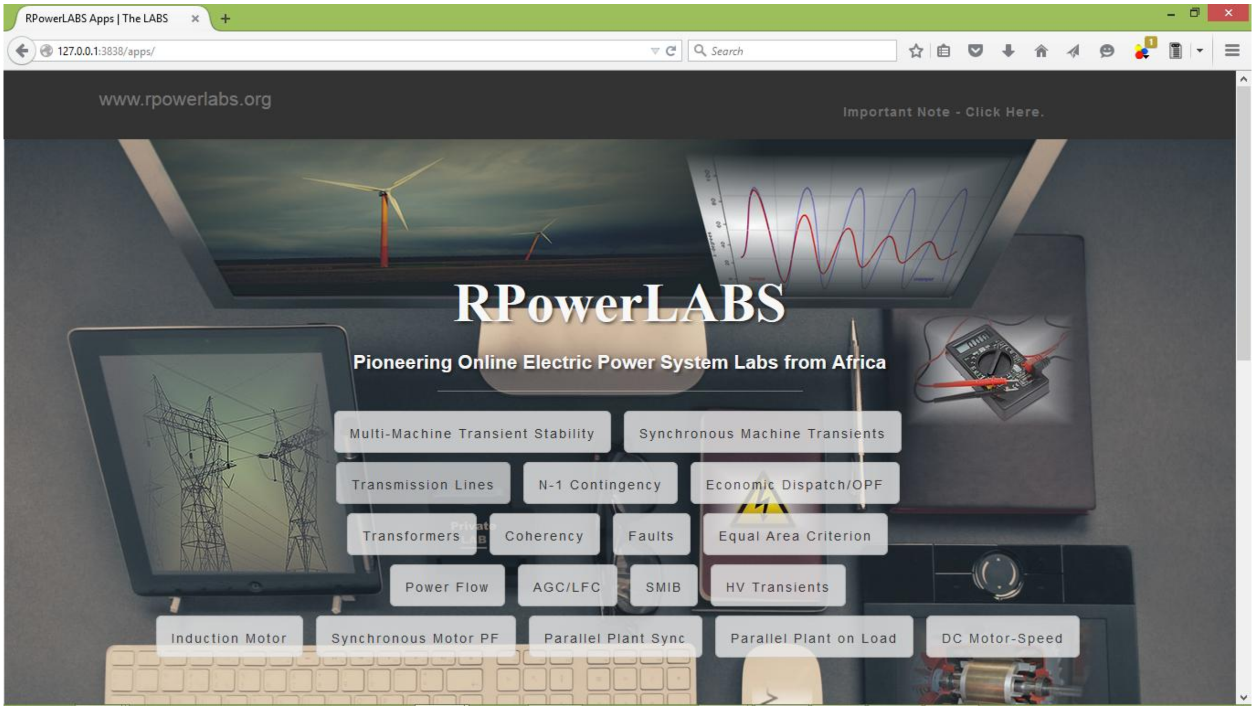


Fig. 1: Home screen of RPowerLABS

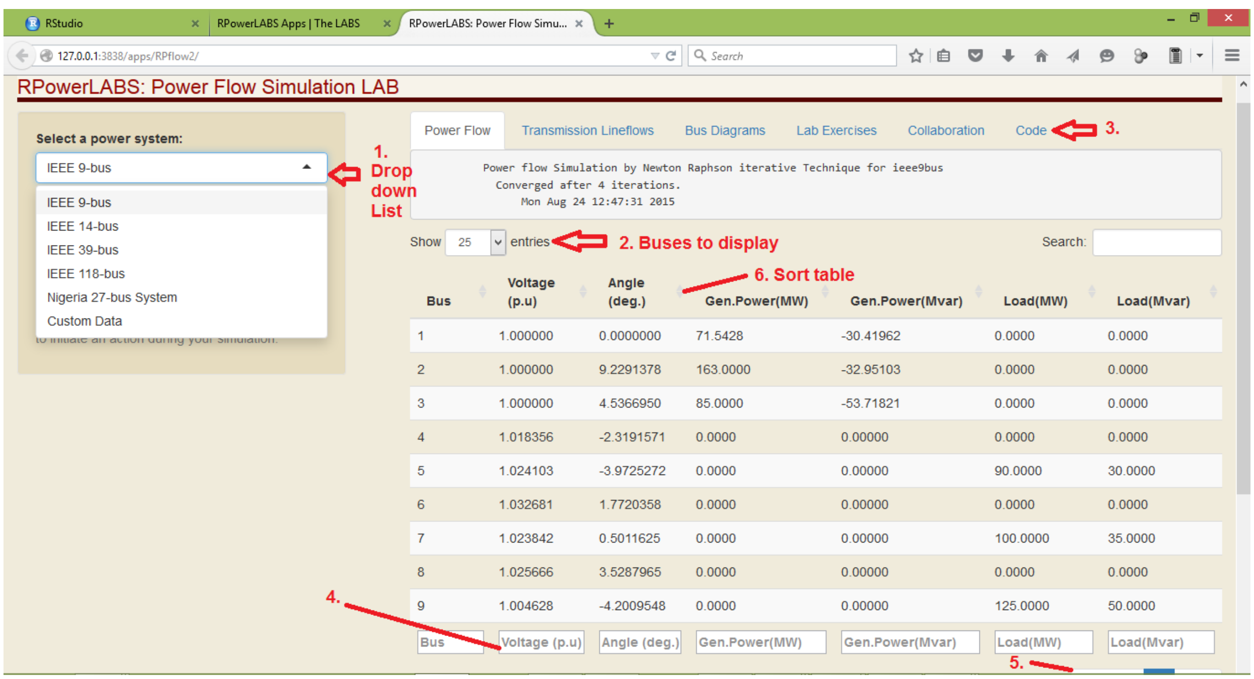


Fig. 2: Screenshot showing Power Flow simulation LAB

3.1 Usage Overview

On the left-hand side of the power flow screen, the user has the option to "***Select a power system***". A power system can be selected by clicking on the drop-down list (***1.***). Once a power system is selected, the power flow simulation for that power system is automatically obtained using Newton-Raphson technique.

To see a selected number of buses at a time, click on ***Buses to display*** (***2.***); to see other buses click on **Previous** or **Next** at the bottom right corner of the table (***5.***). To sort each column click on (***6.***). To search for a particular voltage, type the voltage value into search bar labeled ***4.*** As shown in Figure 2.

The user can scroll down to view the transmission line data and bus data for any power system he has selected. Once the user selects a power system, the line and bus data is selected.

Click on **Transmission Lineflows** to view line flows and losses for all lines in the power system selected.

Click on **Bus Diagrams** to view the bus diagram for the power system you are analyzing. Note: You may not find diagrams for the IEEE-9bus ad IEEE_118bus systems. They have been intentionally omitted.

Click on **Lab Exercises** to view a set of sample laboratory exercises for which you can perform on this lab.

Click on the **Collaboration** tab to chat and learn from other users of RPowerLABS around the world that are online. (This feature is only available to registered users).

Click on the **Code** tab to access a vast amount of functionalities that would enable you modify the parameters of any selected power system. Also, from this **Code** section the user can simulate his own custom power system that is not amongst the list of systems provided by RPowerLABS. See *Appendix*

Note:

The code section allows you to perform several kinds of arithmetic and scientific calculations that permit a nearly direct transition from mathematical expression to simulation. You can also write programs in R language that involve mathematical calculations. Furthermore, the tools the user requires to change the parameters of the preloaded power systems are available within the code section.

LABORATORY CASE STUDY 1:

IEEE 10-machine 39-Bus New England Power System

In this case study we shall consider the IEEE 39-bus New England power system. This power system is made up of *10 generators*, *46 transmission lines*, *39 buses* and *11* active *tap-changing transformers*. You can find the single-line diagram of this power system in Page 2 of the **Bus Diagrams** section of the lab (see Fig. 2).

Aim:

The purpose of this lab is to provide situational learning scenarios that would provide the participant with real-life insights into the planning and operation of electrical power systems especially in the area of power flow studies. If utilized rigorously, this lab can bring deeper insights to practical applications of already acquired theoretical understanding.

Objective:

At the end of this laboratory, the participant should be able to simulate the following:

1. Contingency Analysis (disconnect generators, loads and lines)
2. Vary existing generation and loads & Connect Generators at load buses
3. Inject shunt capacitors at buses*
4. Improvement of voltage profiles at buses by *load shedding*
5. Improvement of transmission capacity *
6. Regulation of voltage profiles at buses using *Tap-changing transformers**
7. Compare Gauss and Newton's solution techniques
8. Vary the slack bus of the system

The participant should also be able to understand the impact of the following simulations on the interconnected power systems and therefore make reasonable decisions as a planner/operator.

Suitability:

This lab is thought to be suitable for the following participants:

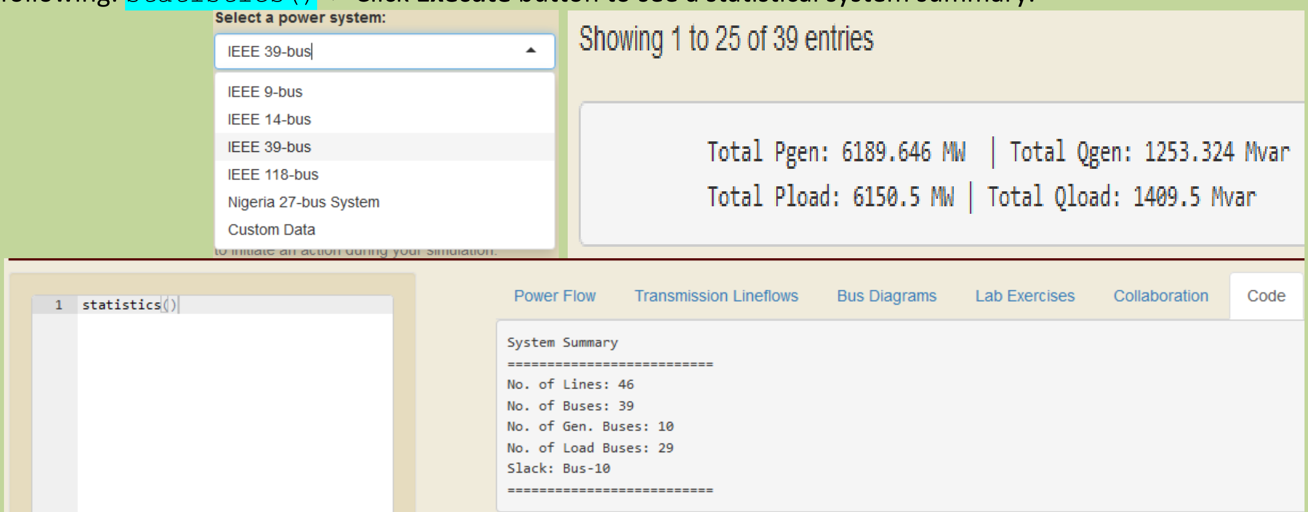
- Final year undergraduates, PgD, and MSc students
- Students studying the courses: Power system analysis, Power system operation and control, etc
- $3^{rd}/4^{th}$ year students that require seeing the application of devices like tap-changing transformers and shunt capacitors.
- Students undertaking related project research (undergraduate and postgraduate)

SCENARIO 1: Understanding and obtaining a summary of the steady state condition of the power system

__Task 1__: As a power system planner you are introduced to the IEEE 39-bus system and you need to know the current state of the system. You need to quickly provide your manager with the following details about the system: *the number of generator buses, load buses, transmission lines, tap transformers, total system load and generation,* and *total system losses*.

ACTIVITIES:

Select the IEEE 39-bus system **>** Scroll down to see Total Generation and Load **>** Click on **Transmission Lineflows** and scroll to the bottom to see the Total system losses **>** Click on **Code** and on the LHS, type the following: `statistics()` **>** Click **Execute** button to see a statistical system summary.



SCENARIO 2: Voltage Improvement through load shedding

__Case 1__: As a power system operator on the IEEE 39-bus system, you observe that the voltages on some buses are below the 1.0 p.u. threshold and you need to test the effect of shedding a large amount of load on voltage profiles of some buses and the buses that are electrically closest to them.

Task 1: Change the slack bus of the power system to Bus-2.
Task 2: Note the Voltages at the following Buses: 10, 30, 31, 38, 36 and 38.
Task 3: Then shed 50% of the load (both real and reactive) at Bus-10.
Task 4: Re-check the Voltages at the following Buses: 10, 30, 31, 38, 36 and 38.
Task 5: View the IEEE 39-bus diagram to see that these buses are electrically closest to Bus-10 where load was shed.

***ACTIVITIES**:

Select the IEEE 39-bus system **>** Click on **Code** and on the LHS, type the following:
Activity 1: `busdata=changeSlack(2)` **>** Click **Execute** button and Click again on **Power Flow** to do *Task 2*.
Activity 3: Find out the load (PL and QL) at Bus-10 by clicking on **Bus Data Input >** Then at the **Code** section type: `busdata=changeLoad(10, 1104/2, 250/2)` **>** Click **Execute**. *Note: PL=1104, QL=250 at Bus-10*
Activity 4: Click on the **Power Flow** tab again to re-check the voltages. Change **Show Entries to 50** to see all buses at a glance.

*Activities correspond to Tasks

SCENARIO 3: Improvement of transmission capacity

Case 1: As a power system planner on the IEEE 39-bus system, you have received reports indicating significant losses on the transmission line connecting Bus-29 and Bus-9 recording the highest in the system. Your duty is to simulate the addition of a second parallel line connecting Bus-29 and Bus-9 to ascertain the effect on the reduction of these losses.

Pre-requisite task: Reset the power system to default.
Task 1: Obtain the initial power flow and losses through the line connecting Bus-29 & Bus-9
Task 2: Improve transmission by adding an extra parallel line to connect Bus-29 & Bus-9.
Task 3: Re-check the power flow and losses through the line connecting Bus-29 & Bus-9
Task 4: Comment on your findings by checking the **Power Flow** and **Transmission Lineflows**

*ACTIVITIES:

Pre-Task: Select the IEEE 39-bus **>** Confirm that the **Code** section is clear of any commands and click **Execute** to reset.
Activity 1: Click on the **Transmission Lineflows** tab and from the first two columns trace the line From 9 – To – 29
Activity 2: Go to the **Code** section type: `linedata=addLine(29,9,0.0008,0.0156,0.000,1.025)` **>** Click **Execute**. *Note: You can get the line parameters used here by clicking on* ***Line Data Input*** *and scroll down to Line-45.*
Activity 3: Click on the **Transmission Lineflows** tab again to re-check.
Activity 4: Observe the second added line equally shares the power flowing out of the bus and losses are reduced. Click on **Power Flow** and see that the *Total Qgen* also reduced

*Activities correspond to Tasks

From Bus	To Bus	-From Bus Injections- MW	Mvar	MVA	-Tx Line losses- MW	Mvar	Percentage loading	Transformer tap
1	31	250.000	110.383	273.285	0.000	12.331	0.000	
2	35	565.080	189.325	595.953	0.000	92.075	0.000	
3	39	650.000	186.704	676.283	0.000	94.663	0.000	
4	19	632.000	90.787	638.488	2.871	58.238	0.000	
5	20	508.000	158.250	532.078	2.488	49.758	0.000	
6	22	650.000	189.352	677.019	0.000	59.564	0.000	
7	23	560.000	90.784	567.311	1.421	77.326	0.000	
8	25	540.000	23.687	540.519	1.659	64.139	0.000	
9	29	830.000	20.838	830.262	5.239	102.155	0.000	

From Bus	To Bus	-From Bus Injections- MW	Mvar	MVA	-Tx Line losses- MW	Mvar	Percentage loading	Tra
1	31	250.000	109.931	273.102	0.000	12.315	0.000	
2	35	565.080	198.531	598.941	-0.000	93.000	0.000	
3	39	650.000	200.397	680.190	0.000	95.760	0.000	
4	19	632.000	103.776	640.464	2.889	58.599	0.000	
5	20	508.000	164.268	533.899	2.505	50.099	0.000	
6	22	650.000	203.929	681.239	0.000	60.309	0.000	
7	23	560.000	99.056	568.693	1.428	77.704	0.000	
8	25	540.000	18.648	540.322	1.658	64.092	0.000	
9	29	415.000	4.420	415.024	1.259	24.559	0.000	
9	29	415.000	4.420	415.024	1.259	24.559	0.000	

SCENARIO 4: Contingency Analysis

Case 1: As a research and development personnel on the IEEE 39-bus system, you hope to ascertain the effects of losing some generation and lines on the steady state performance of the system.

Pre-requisite task: Reset the power system to default.
Task 1: Note the pre-contingency *power flow* and *line flow* parameters esp. at Buses: 10,3,39,11,12,9,29,26,etc. These buses are the closest to the area of contingency.
Task 2: Simulate the loss of two lines (Line-33 and Line-16) due to an unexpected event
Task 3: Record your observations on the **Power Flow** and **Transmission Lineflows** at the buses specified in *Task 1*
Task 4: Reset the power system to default
Task 5: Simulate the loss the generator at Bus-3
Task 6: Record your observations on the **Power Flow** and **Transmission Lineflows**

*

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SCENARIO 1: Comparing Accelerated Gaussian and Newton-Raphson Solution Techniques

Case 1: As a power system researcher on the IEEE 14-bus system, you hope to compare the Accelerated Gauss-Siedel (AGS) and Newton-Raphson iterative techniques.

Pre-requisite task: Reset the power system to default.
Task 1: On the IEEE 14-bus system, run the accelerated Gauss-Siedel power flow
Task 2: Search for the best acceleration factor that gives the fastest convergence for **Task 1**
Task 3: Run the Newton-Raphson power flow
Task 4: Compare both solutions based on their rate of convergence
Task 5: Obtain the Admittance Matrix (Y_{BUS}) of the system
Task 6: From the Y_{BUS}, obtain the Impedance Matrix (Z_{BUS})

***ACTIVITIES**:
Pre-Task: Select the IEEE 14-bus
Activity 1: Click on Code type `gauss()` on the LHS. **>** Click **Execute**

Activity 2: At the **Code** section type: `accel=1.3; gauss()` **>** Click **Execute**. Note the number of iterations
Change the value of `accel` to `1.4, 1.5, 1.6,1.7,1.8` and record the value of `accel` which gives the least number of iterations.

Activity 3: Clear the Code section and type: `newton()` **>** Click **Execute**

Activity 4: From Activity 2 and 3, record which method provides faster results between ***gauss()*** and ***newton()***
Activity 5: Type: `Ybus` > Click **Execute**. The Ybus is shown in complex values.
To round up the values to a specific decimal point (e.g 3 decimal place) type: `round(Ybus, 3)`
To obtain the absolute values of the Ybus elements, type: `abs(Ybus)`
Also you can type: `round(abs(Ybus), 3)`
To access a specific Ybus element, e.g. type: `Ybus [2,1]` **>** Click **Execute.** This returns the element at the second row of the first column of the Ybus matrix.

Activity 6: To obtain the impedance matrix, type: `solve(Ybus)` **>** Click **Execute**
.
*Activities correspond to Tasks

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*ACTIVITIES:

Pre-Task:

Activity 1: Go to the Home Screen of RPowerLABS (see Fig. 1) > Click on **N-1 Contingency**

Activity 2: Clear the **Code Interface**, then type: `runContingency('ieee14bus')` **>** Click **Execute**

Activity 3: Find the power flow simulation and N-1 Contingency analysis report following below.
Automatically, each line in the power system is disconnected and the power flow is performed while the losses and limit violations are computed. For example, the first row of the report is interpreted as:

- ***When the line connecting Bus 1 – Bus2 was disconnected, there were reactive power (Qgen) violations on 5 buses, 0 voltage violations, 0 line limit violations, total real loss was 43.03MW, total reactive loss was 145.03MW and the power flow iterative solution converged (Feasible).***

*Activities correspond to Tasks

APPENDIX

Other commands that could be performed on the **Code** section of the Power Flow Simulation Lab of Fig. 2 are:

1. `connectGen()` – connects a gen to a load bus
2. `changeGen()` – changes the generation at a bus
3. `removeLine()` – removes only one line from the power system
4. `addBus()` – adds a bus to the existing power system
5. `newtonpf()` – Newton-Raphson power flow on your own custom power system
6. `gausspf()` – Gauss-Siedel power flow on your own custom power system
7. `adjustTap()` – add/adjust tap settings of tap-changing transformer
8. `injectMVAR()` – inject a shunt capacitor for reactive power compensation
9. `connectSC()` – connect a synchronous condenser to a bus
10. `createYbus()` – create an admittance matrix for your custom power system data
11. `Qlimits()` – vary the reactive power limits of your generator buses
12. `changeLine()` – change the line impedance values of your transmission network
13. `removeBus()` – disconnect a bus from the power system.

These commands and many more are utilized in our internship/industrial experience program. You may request for a more robust copy of this manual in which some of these commands have been utilized in other scenarios not mentioned here.