Educational Interface of Load Flow Methods Using Matlab Graphic User's Interface Software

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*Abstract—***this paper introduces a new created program application built based on MATLAB programing language to solve power system networks at steady state problems, which include power flow studies with significant approach. The load flow solution uses iterative techniques that are namely, Newton-Raphson, Gauss-Seidel and Fast Decouple. After obtaining their results, line changes like line switching, tap changer and bus changing such as bus deletion or any specific information at the same bus can be easily achieved. Moreover, the users can enter their own system, and save it to apply the pervious analysis. This friendly interactive program designed to be simple for the users with accurate results and it can be applied for any network.**

I. INTRODUCTION

Power systems analysis using MATLAB programing language has been modified to be easier than it can be accomplished by just dealing with windows of Graphic User's Interface. These windows simulate Graphic User's Interface (GUI) and have made the electric power networks calculation much easier than using MATLAB codes, the main window of the Graphic User's Interface can be used to analyze any power systems with the ability of saving it, so its data can be retrieved frequently or simply the user can enter new data.

II. LOAD FLOW STUDIES

The important part of power system analysis is Load flow studies. Load flow studies can give deep insight about the power system, so it helps to understand the fault currents and voltages after knowing its location. This information can be used for planning strong and stable system to face the worst operation cases [3].

Furthermore, in each line, load flow studies solving for magnitudes and phase angles of voltages at each bus can be allowed for voltage control by using under load tap changers, capacitor banks, and generator voltages. On the other hand, the real power control also can include line switching and generator real power inputs [1, 3, 5].

In the interconnected system which is assumed to operate under normal operation conditions, it can be represented by a single-phase network. The voltage nodes method, that is the most appropriate form for many power system analyses, is commonly used. The formulation of the network equations in the nodal admittance form results in complex linear at same time algebraic equations in terms of node currents. When node currents are specified, the set of linear equations can be solved for the node voltages. Nevertheless, in a power system, powers are known instead of currents. Therefore, the resulting equations in terms of power should be solved by iterative techniques because they are nonlinear and will be known as power flow equation [1, 2, 3].

The currents in each bus of the power system shown in Figure. 1 will be calculated by using Kirchhoff's Current Law (KCL) [1], so the currents can be obtained from this form

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=0}^{n} y_{ij} V_j , \, j \neq i \tag{1}$$

Also the real and reactive power at each bus can be given by [1, 2, 4, 6]

$$P_i + jQ_i = V_i \, I_i^* \tag{2}$$

Therefore, form equations (1) and (2) we obtain [1]

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_i , \, j \neq i \tag{3}$$

These equations of power flow problems are easy to solve by iterative techniques (Newton-Raphson, Gauss-Seidel, or Fast Decoupled) because most equations are mathematical formulated in a system of algebraic nonlinear equations.
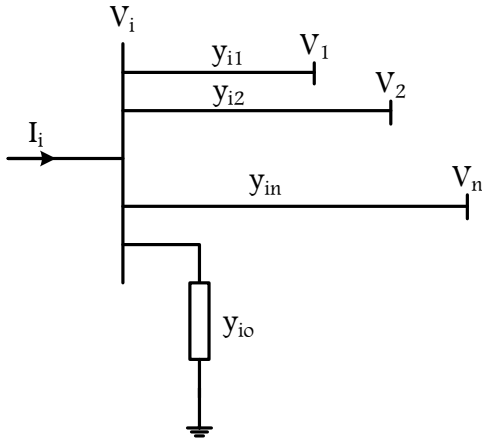
Figure. 1.A Typical Bus of the Power System

A. Newton-Raphson Power Flow Solution

The Newton-Raphson method is the most efficient method and practical for solving nonlinear equations; because of its quadratic convergence. From Figure. 1 the current entering bus *i* for the typical bus of the power system, is given by (1), and it can be rewritten in the form of the bus admittance matrix to be in the following form [1, 2, 3, 4, 6]

$$I_{bus} = Y_{bus}V_{bus} \qquad (4)$$

$$\Rightarrow \quad I_i = \sum_{j=1}^{n} Y_{ij}V_j \qquad (5)$$

Where I_{bus} is the injected bus currents, V_{bus} is the bus voltages, Y_{bus} is the bus admittance matrix. Respectively, diagonal elements and off diagonal elements of the bus admittance matrix are given by the following equations [1, 3]

$$Y_{ii} = \sum_{j=0}^{n} y_{ij} \qquad j \neq i \qquad (6)$$

$$Y_{ij} = Y_{ij} = -y_{ij} \qquad (7)$$

From (2) we can separate the real and imaginary parts, so the new terms can be obtained [1, 2, 3, 4]

$$P_i = \sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\cos(\theta_{ij} - \delta_i + \delta_j) \qquad (8)$$

$$Q_i = -\sum_{j=1}^{n} |V_i||V_j||Y_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \qquad (9)$$

Where δ_i, δ_j, θ_{ij}, indicate bus *i* voltage angle, bus *j* voltage angle and the admittance matrix angle respectively. Then, after neglecting higher order terms, using Taylor series expansion, the final form of the non-linear system

set of equations will be as followed [1, 2, 3, 4, 5, 6]

$$
\begin{bmatrix}
\Delta P_2^{(k)} \\
\cdot \\
\cdot \\
\cdot \\
\Delta P_n^{(k)} \\
\Delta Q_2^{(k)} \\
\cdot \\
\cdot \\
\cdot \\
\Delta Q_n^{(k)}
\end{bmatrix}
=
\begin{bmatrix}
\frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdot & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdot & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\
\cdot & & \cdot & \cdot & & \cdot \\
\frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdot & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdot & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\
\frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdot & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdot & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\
\cdot & & \cdot & \cdot & & \cdot \\
\frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdot & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdot & \frac{\partial Q_n^{(k)}}{\partial |V_n|}
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_2^{(k)} \\
\cdot \\
\cdot \\
\cdot \\
\Delta \delta_n^{(k)} \\
\Delta |V_2^{(k)}| \\
\cdot \\
\cdot \\
\cdot \\
\Delta |V_n^{(k)}|
\end{bmatrix}
\qquad (10)
$$

The left side of (10) is called the power residuals, and it's elements are given by equations [1, 2]

$$\Delta P_i^{(k)} = P_i^{Sch} - P_i^{(k)} \qquad (11)$$

$$\Delta Q_i^{(k)} = Q_i^{Sch} - Q_i^{(k)} \qquad (12)$$

The new values of the bus voltage are calculated by

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \qquad (13)$$

$$|V_i^{(k+1)}| = |V_i^{(k)}| + \Delta |V_i^{(k)}| \qquad (14)$$

The load buses (PQ buses), P_i^{sch} and Q_i^{sch} are specified, $P_i^{(k)}$ and $Q_i^{(k)}$ are calculated using (8) and (9), and $\Delta P_i^{(k)}$, $\Delta Q_i^{(k)}$ are calculated using (11) and (12), voltage magnitude and phase angle are set equal to 1.0 and $\angle 0.0^o$. The voltage-controlled buses (PV buses), $P_i^{(k)}$ and $\Delta P_i^{(k)}$ are calculated using (8) and (11), where P_i^{sch} and $|V_i|$ are specified from the power flow solution, phase angles are set equal to $\angle 0.0^o$. The process is continued until the power residuals $\Delta P_i^{(k)}$, $\Delta Q_i^{(k)}$ are less than the specified tolerance. The Jacobian matrix is calculated, and the linear simultaneous equation (10) is solved directly by optimally ordered triangular factorization and Gaussian elimination. Finally, the new voltage magnitudes and phase angles are computed using (13) and (14) [1, 2].

B. Gauss-Seidel Power Flow Solution

This method is less mathematically popular than Newton-Raphson method and is more exposed to divergence with ill-conditioned problems. It is used to solve non-linear equation; therefore this method will be used to solve (3) for V_i [1, 2, 3, 4, 5, 6].

The steps for the iterative algorithm are as follows [1, 2, 3, 4, 5, 6]

$$V_i^{(k+1)} = \frac{\dfrac{P_i^{sch} - jQ_i^{sch}}{V_i^{*(k)}} + \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}V_j^{(k)}}{Y_{ii}} \quad (15)$$

and

$$P_i^{(k+1)} = \Re\left\{ V_i^{*(k)}\left[V_i^{(k)}Y_{ii} + \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}V_j^{(k)} \right] \right\}, j \neq i \quad (16)$$

$$Q_i^{(k+1)} = -\Im\left\{ V_i^{*(k)}\left[V_i^{(k)}Y_{ii} + \sum\limits_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij}V_j^{(k)} \right] \right\}, j \neq i \quad (17)$$

The load buses, real powers P_i^{sch} and reactive powers Q_i^{sch} are known and expressed in per unit ($p.u$). For unknown voltages, an initial estimation of $1.0 + j0.0\ p.u$ should be used, so (14) can be solved for the real and imaginary components. For the voltage-controlled buses, where P_i^{sch} and $|V_i|$ are specified, reactive power $Q_i^{(k+1)}$ should be found by solving (17), and then use the result in (14) to solve for $V_i^{(k+1)}$. However, since $|V_i|$ is specified, only the imaginary part of $V_i^{(k+1)}$ is retained, and its real part is selected in order to satisfy the following equations [1]

$$(e_i^{(k+1)})^2 + (f_i^{(k+1)})^2 = |V_i|^2 \quad (18)$$

$$e_i^{(k+1)} = \sqrt{|V_i|^2 - \left(f_i^{(k+1)}\right)^2} \quad (19)$$

Where $e_i^{(k+1)}$, $f_i^{(k+1)}$ are real and imaginary components of $V_i^{(k+1)}$ in the iterative sequence.

The new values which represent the updated voltages, immediately substitute the previous values in the solution of the next equations. The process is continued until changes in the real and imaginary components of bus voltages between successive iterations are within a specified accuracy, i.e., [1]

$$\left| e_i^{(k+1)} - e_i^{(k)} \right| \leq \varepsilon \quad (20)$$

$$\left| f_i^{(k+1)} - f_i^{(k)} \right| \leq \varepsilon \quad (21)$$

The method of determining the completion of a solution is based on the accuracy index set up on the power mismatch. The iterative algorithm continues until the magnitude of the largest element in ΔP, ΔQ columns is less than the specified value [1, 2].

C. *Fast Decoupled Power Flow Solution*

This method is the approximate version of the Newton-Raphson method, but it needs less time and reduced storage memory [1, 2, 3, 4, 5].

To describe this method let's first simplify (9) to be:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (22)$$

However, based on the following two reasons, J_2 and J_3 can be neglected [1, 2, 3]:

- It can be noted that, the angle voltage δ of bus affects the real power P and doesn't affect the reactive power Q .

- It can be also noted that, the magnitude $|V|$ of the bus affects the reactive power Q and doesn't affect the real power P .

Applying these observations into the Eq. (22) will yield the fast decoupled power flow equation [1, 2, 3, 4, 5]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & 0 \\ 0 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (23)$$

III. PROGRAM APPLICATION

This program is similar to any program, it has many files related to each other, and they should stay together in the same folder whether the user intend to run the program from the hard disk or from an external storage device. Since the load flow and short circuit program creates temporary files to be used later, the directory in MATLAB software should be changed to indicated to the program's folder. To start the program the user should run the LoadFlow_Program file first within the MATLAB software main window. A suitable GUI window will appear to work with, as shown in Figure. 2. Other windows such as Show Results window can be run from the previous window. From LoadFlow_Program's window the user can easily start the studies on any network or system, regardless the size of the system. This program is provided by several systems' data, two of them are clearly standing on the window and the others are stored in under the stored networks' button. Moreover, the users can enter their own system parameters through the right side of the window and save it as well.

A. Load Flow Studies

The left side of the main window shown in Fig. 2 is used for the load flow studies. Firstly, all the network input data should be uploaded whether if it was stored previously or it was just a new entered data.

NETWORK INPUT DATA consist of:
- System stored data which can be uploaded when

the user clicks the corresponding system button.
- Base MVA of the system.
- Acceleration factor in order to reach the results faster.
- Desirable accuracy for the solution.
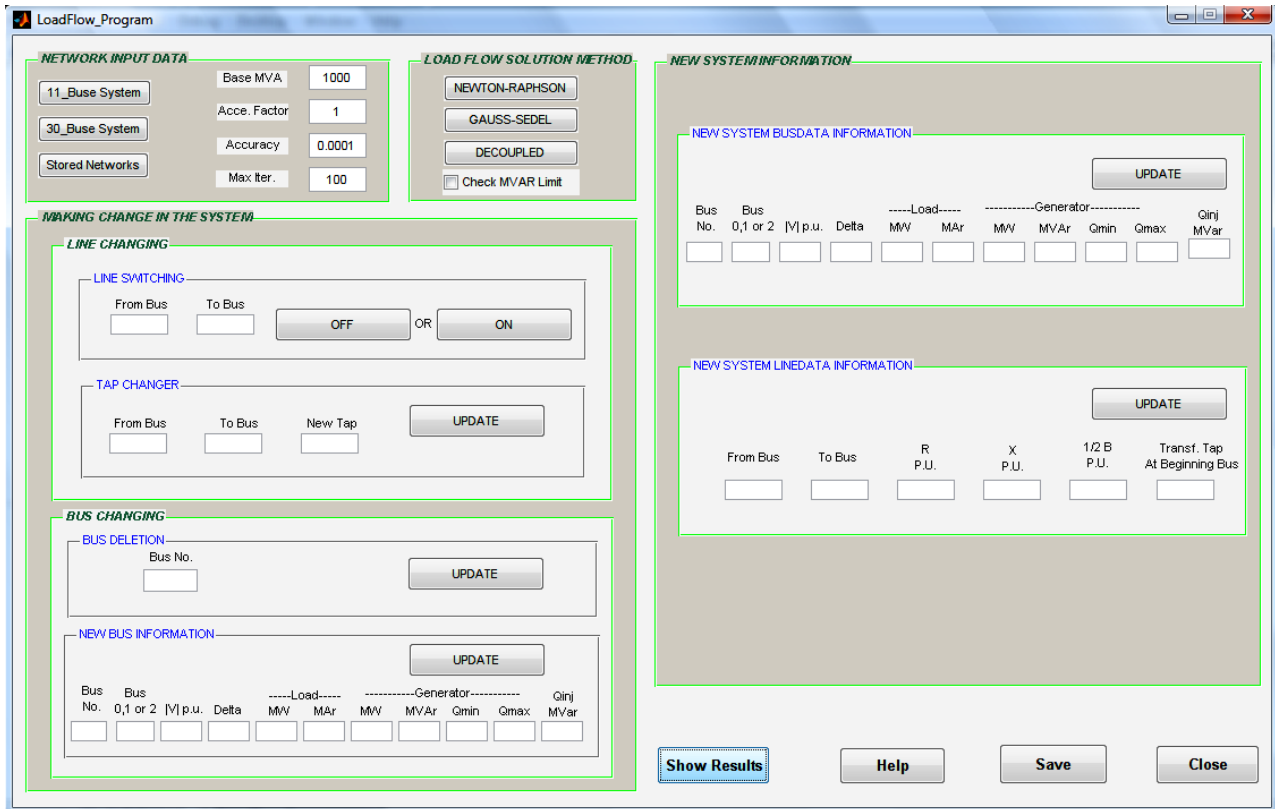- Maximum iteration to terminate the iterations process once the solution does not converge.

Figure. 2. The Main Window of Load Flow Program

Next, the user can choose either the iterative solution methods that appear on the LOAD FLOW SOLUTION METHOD panel. Then the results can be displayed from the show results button which will be explained later.

If more studies are needed, then the user can go forward to make any changes in the system from the MAKING CHANGE IN THE SYSTEM panel. This panel has the following information:
- Two bus numbers have to be given to switch a line OFF or ON in the system. If the line does not exist, the program will notify the user by warning window saying "Either the line is already OFF or not exist in this network".
- To change the tap of the transformer, first specify the winding position of the transformer, and then enter the desired tap value. If supposed that the user made a mistake to change none-exiting tap, the program will show an error window that says "This Tap Changer is not available to change".

BUS CHANGING panel which is useful feature if the

users intend either to completely delete the bus or just change any of its information such as:
- Delete any existing bus from the system if supposed there is an outage in the network.
- To switch a bus from PV bus to PQ bus or vice versa. Bus number 1 indicates the slack bus, bus number 2 indicates the voltage controller bus and bus number 0 indicates the load bus.
- Also, to add or cancel the capacitor bank at the bus bar as a total value of the compensation.
- To change the value of the power either for the load or the source of the system.

All the output results from Load Flow Studies can be displayed on the Display_Resluts' window as shown in the Figure. 3, and they are saved in the temporary files to be used in the future. Moreover, the window contains other buttons as (Ybus) and (Zbus) as well as Bus data and Line data.
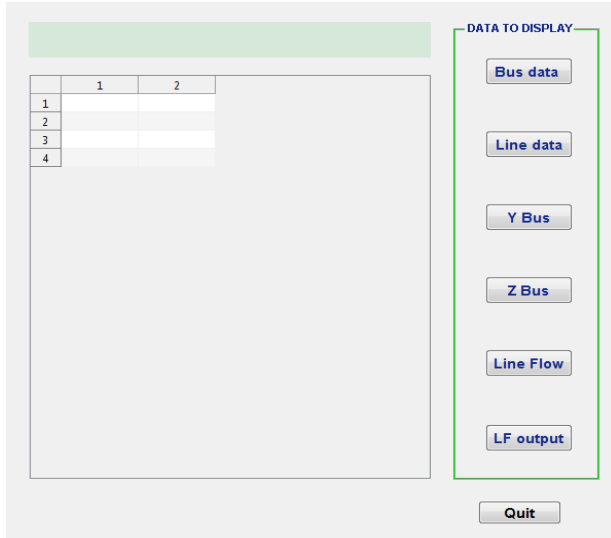
Figure. 3. Display Window Which Can Be Used along with the Program to Show the Results.

The right side of the main window shown in Fig. 2 is used mainly for entering new system information in the same format that is appropriate for the program to work correctly. The user should enter the whole row information each time. If any information is missing, the user should enter zero (0) value for the load and angle and one (1) value for the voltage. Finally, the user can save the data as MATLAB file. The right side of the main window also has other buttons as Help button which helps the user to work correctly with the program.

IV. TEST RESULTS

The 11-bus system in Figure. 4 will be used to illustrate the work of the program. The network data is already stored in the program, and it can be displayed by clicking on Show Results button [1].
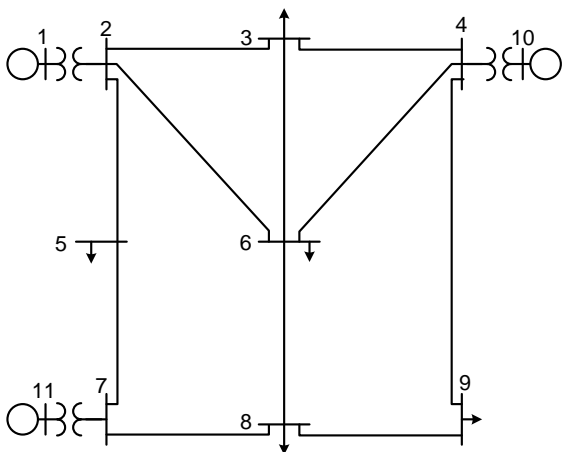

Figure. 4. One-Line Diagram for 11-Bus Power System Network.

After choosing the network, all the information as MVA, accuracy, Maximum iterations and acceleration factor should be entered. Applying Newton-Raphson Power Flow Solution and go to Show Result's Window to review all the network data. Figure. 5 has been taken

from the Display Window and shows bus input data for the 11-bus network as given in the considered system [1].

Bus Input Data

Bus No.	Bus Code	Voltage Mag.	Angle deg.	Load MW	Load MVAR	Gen MW	Gen MVAR	Q Min	QMax	ING MVAR
1	1	1.0400	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	0	0	0	0
3	0	1	0	150	120	0	0	0	0	0
4	0	1	0	0	0	0	0	0	0	0
5	0	1	0	120	60	0	0	0	0	0
6	0	1	0	140	90	0	0	0	0	0
7	0	1	0	0	0	0	0	0	0	0
8	0	1	0	110	90	0	0	0	0	0
9	0	1	0	80	50	0	0	0	0	0
10	2	1.0350	0	0	0	200	0	0	180	0
11	2	1.0300	0	0	0	160	0	0	120	0

Figure. 5. Bus Input Data for 11-Bus System as Shown in the Display Window [1].

Figure. 6 has been taken from the Display Window and shows line input data for the 11-bus network shown in Figure. 4, as given in 11-bus system [1].

Line Input Data

	From Bus	To Bus	R (pu)	X (pu)	1/2 B (pu)	Trans Tap
1	1	2	0	0.0600	0	1
2	2	3	0.0800	0.3000	4.0000e-04	1
3	2	5	0.0400	0.1500	2.0000e-04	1
4	2	6	0.1200	0.4500	5.0000e-04	1
5	3	4	0.1000	0.4000	5.0000e-04	1
6	3	6	0.0400	0.4000	5.0000e-04	1
7	4	6	0.1500	0.6000	8.0000e-04	1
8	4	9	0.1800	0.7000	9.0000e-04	1
9	4	10	0	0.0800	0	1
10	5	7	0.0500	0.4300	3.0000e-04	1
11	6	8	0.0600	0.4800	0	1
12	7	8	0.0600	0.3500	4.0000e-04	1
13	7	11	0	0.1000	0	1
14	8	9	0.0520	0.4800	0	1

Figure. 6. Line Input Data for 11-Bus System as Shown in the Display Window [1]

By clicking LF output button on the display screen the user will obtain the power flow solution for the 11-bus power system network as in the Figure. 7. When comparing the results with the results in the reference, it can be said that the produced results were found conforming with that in [1].

Power Flow Solution

	Bus No.	Voltage Mag.	Angle deg.	Load MW	Load MVAR	Gen MW	Gen MVAR	ING MVAR
1	1	1.0400	0	0	0	246.6425	206.4007	0
2	2	1.0282	-0.7930	0	0	0	0	0
3	3	0.9969	-1.9701	150	120	0	0	0
4	4	1.0242	-0.6081	0	0	0	0	0
5	5	1.0169	-1.3183	120	60	0	0	0
6	6	0.9926	-2.2765	140	90	0	0	0
7	7	1.0209	-0.3482	0	0	0	0	0
8	8	0.9845	-2.4143	110	90	0	0	0
9	9	0.9807	-2.7979	80	50	0	0	0
10	10	1.0350	0.2567	0	0	200	141.4705	0
11	11	1.0300	0.5237	0	0	160	95.0567	0

Figure. 7. The results of the Load Flow Solution for Standard 11- Bus System [1]

V. CONCLUSION

As discussed in this paper, the Graphic User's Interface (GIU) in the MATLAB program can be used to simplify the load flow studies. By using this methodology, changing in the situation of the network can be studied more easily from the same window. The results obtained from the 11-bus system show that the GIU works well. The future work may include fault analysis and stability studies using the results from the load flow studies in this paper.

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BIOGRAPHIES

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