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Power System Load Flow Analysis using Microsoft Excel

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Keywords

Microsoft Excel, Power System Analysis, Load Flow Studies, Visual Basic

Cover Page Footnote

We acknowledge the support of Department of Electrical Engineering, University of West Indies for carrying out this work.

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1. Introduction

1.1. Power System Analysis

The Load flow (also known as power flow) solution of an electrical power system provides voltages at all the buses, power flows and losses in the lines at specific levels of power generation and loads. The results of load flow analysis are used in load forecasting, system planning and operation. Practically, system engineers carryout load flows on a daily basis with varying system configurations, load patterns and generating conditions to understand the behaviour of the system at different operating conditions. Hence, computation of a load flow solution is a basic requirement and at present there are many tools and software packages available.

Well-known commercial products such as Power System Simulator for Engineering (PSS, 2012) and PowerWorld (PowerWorld, 2012) are already available for power system studies, which can be customized according to requirements. These propriety software packages provide only end results but not the intermediate calculations. However, procurement of such products, training the users, product customization for specific requirements, maintenance over a long time etc. are proved to be quite expensive and yet, the product is not owned by the organization. Most commercial applications are designed for general purposes and hence a high degree of customization is required at the student level for simple studies, especially to match

with textbook illustrations. The licensing system of known and popular commercial products may appear competitive initially; however it would be expensive over a long time. In such cases, universities or even the practicing engineers have to be at the mercy of the product vendors for operation, maintenance and any additional add-on features. Whenever there is replacement of existing hardware, there may be compatibility issues with the new hardware and existing/ old power system analysis software. Also, the software companies and suppliers offering such solutions may not be able to support their own older installations due to technological developments, intentions of phasing out older versions, competition in the market, ease of management and their own survival etc.

On the other hand, spreadsheet based applications assume a greater importance as such applications provide alternative, sustainable and economical solution. In many existing packages, the results of the power flow study are exported into spreadsheet software for the generation of reports. A spreadsheet implementation for power flow studies should therefore prove to be a natural extension. As a result of years of continual improvements, spreadsheet programs have achieved well-acknowledged user friendliness and functionality. Indeed, several programs have been developed to provide application-specific functions while maintaining superior features of the spreadsheet programs. (Xu et al. 1999). Spreadsheet based tools can be effectively used in industries and universities to avoid the above mentioned problems. One of the biggest advantage of spreadsheet based solutions and tools is portability between the machines without much hassle. Lau and Kuruganty (2008) provided a lucid treatment of theory, algorithms and even spreadsheet implementation. Their implementation used cell formulae and only two methods – Gauss-Seidel and N-R methods have been presented. A single spreadsheet based solution for different popular iterative and non-iterative (DC) load flow methods is not presented till date. Keeping in view of the above, a spreadsheet implementation of four commonly used load flow methods along with a comparative analysis has been undertaken in this work.

The content of this paper is divided into seven sections. Section 2 presents basics of load flow algorithms, component modelling of system components etc. Details on features of the tool, overall design, data input and output are presented in section 3. Section 4 presents detailed information on how the design is implemented in a modular fashion, details of VBA programming, some of the modules. Section 5 presents the process of benchmarking of the developed application with the standard software and also comparative analysis of different load flow algorithms within the application. Section 6 provides an effective strategy for using the tool in a typical university classroom. Finally Section 7 presents concluding remarks.

2. Load Flow Algorithms

There are several algorithms for carrying out load flow analysis of power systems and many research papers are available as well. In this paper, we deal with four important algorithms – Gauss-Seidel (G-S) Method, Newton-Raphson (N-R) Method, Fast Decoupled (FDC) Method and DC Load Flow Analysis. These four algorithms are taught to all Power Engineering students and hence are popular. Even utility engineers mostly use these methods and choose a particular algorithm based on the nature of the power system. For instance, if a quick static solution is needed, then engineers choose DC load flow method; as it requires only one iteration and offers approximate solution. In fact this solution can be safely used as an initial operating point when N-R method is chosen. If the system is ill-conditioned, FDC method provides a better solution than others. Hence, it is important to provide a tool which provides an option for the users to select the method of analysis. Even comparative performance of these methods is of great interest to students (Gutierrez et al, 2011), teachers and engineers. Keeping these aspects in mind, we have incorporated these four algorithms in this implementation. Exhaustive theoretical treatment of the algorithms is avoided in this paper, as many resources (Kothari, 2008) provide this information. Specifically the work of Lau and Kuruganty (2008) provides a lucid treatment of theory, G-S and N-R algorithms and even spreadsheet implementation using cell formulae.

2.1. Outlines of the four algorithms

The power system load flow problem is non-linear in nature and hence requires iterative mathematical techniques. DC load flow problem is an approximation to full non-linear problem and hence is linear.

The Gauss-Seidel method is one of the simplest iterative methods in the solution of non-linear equations. The method is based on the Gauss iterative method and a flat voltage profile is considered initially (Kothari, 2008). This method needs more iterations than other methods; however the time taken per iteration is less than other iterative methods. This method works well for systems with light loading conditions and hence is not recommended for heavily loaded systems.

N-R method is a very popular and faster solution for load flows analysis. This method requires an initial condition and works well for heavily loaded systems, when compared to other methods. FDC method is derived from N-R method. It essentially decouples the effect of reactive power on the angles of complex bus voltage; and also the effect of real power on magnitudes of complex bus voltages.

DC load flow algorithm is a simplification of a full AC power flow and ignores reactive power flow (Purchala et al. 2005). It becomes very handy when only approximated solution or real power analysis is required; as original AC modelling

version of non-linear equations are reduced to a set of linear equations. This method is extremely fast, being a non- iterative technique.

2.2. Modelling of Power System Components

Generators on the system are considered as constant voltage sources. The largest generator is treated as the swing bus which will take care of the power mismatch in the system. All loads are treated as constant power sinks. Medium length model is considered for all transmission line sections. Transformers are modelled with tertiary winding and are operating with an on-line tap changer (Vismor, 2012; Peterson and Meyer, 1971).

3. Design Features and data management

We tried to give higher importance to user-friendliness and IEEE data standards in the design and development of this tool. VBA is used to implement the algorithms. The details of GUI, data input and output; design and developmental platforms are provided in the sections below.

3.1. User-friendly Interface

The MS Excel is designed in such a way to provide information on different sheets to minimize the burden of understanding and also to provide clarity in presentation of the information. The first worksheet provides a single menu wherein users can make necessary choices on what is required. Based on the selection, user is taken automatically to a separate sheet for that specific selected task and then user can come back to the front sheet with the help of a hyperlink. A screen shot of the first sheet is provided below.



Figure 1: CoverPage GUI

As can be seen in the figure 1, users can choose to create a new system manually using an interactive interface or can import from an existing file. Once the data is ready, user can select a specific study either AC or DC load flow. When AC load flow is selected, the user is presented with another menu as shown below. If the user wants all the studies to be done automatically, then 'Compare AC Method' can be chosen to so that the application does all the studies and then provides exhaustive information on all studies that includes both numerical data and graphical information with comparison. Figure 2 shows the user screen for setting up study parameters for the iterative methods.

The image shows a software dialog box titled "AC Loadflow". It has a close button (X) in the top right corner. The dialog is divided into two main sections. The left section, titled "Select Loadflow Method", contains three radio button options: "Gauss-Seidel", "NR-Polar" (which is selected), and "NR-FDC". The right section, titled "Solution Constraints", contains four input fields: "Max. No. of Iterations" (empty), "dP Tolerance" (0.0001), "dQ Tolerance" (0.0001), and "GS-Acceleration Factor" (1.6). To the right of these input fields are three buttons: "OK", "Clear", and "Cancel".

Figure 2: AC Load Flow Form

3.2. Data input and output

As stated earlier, the system data can be provided manually or from an existing file. The application is designed to be fully compliant with IEEE Common Format for Exchange of Solved Load Flow Data, which makes the data transfers from one standard source to another. The input data consists of bus data, data and study parameters etc. For the implementation of logic, a specific set of numerical codes are provided to different types of buses as per the IEEE standards. Table 1 provides the details of bus codes and types.

Table 1: Bus Types and Codes

Bus Code	Bus Type Description
0	Load Bus
1	Generator Bus
2	Regulated Generator Bus
3	Slack/Swing Bus

For manual entry of the bus data, users are provided with an easy interface as shown in figure 3.

Figure 3: Bus Record Form

When the user completes the entering of the bus data, then the application presents the same in a separate sheet named 'Bus_Data'. The input bus data for IEEE 14 bus is shown in figure 4.

Bus Id.	Bus Name	Nominal kV	Bus Area	Bus Zone	Bus Type	V (p.u.)	δ (deg.)	P_Load (MW)	Q_Load (MVAR)	P_Gen (MW)	Q_Gen (MVAR)
1	Bus1	HV	1	1	3	1.06	0	0	0	232.4	-16.9
2	Bus2	HV	1	1	2	1.045	-4.98	21.7	12.7	40	42.4
3	Bus3	HV	1	1	2	1.01	-12.72	94.2	19	0	23.4
4	Bus4	HV	1	1	0	1.019	-10.33	47.8	-3.9	0	0
5	Bus5	HV	1	1	0	1.02	-8.78	7.6	1.6	0	0
6	Bus6	LV	1	1	2	1.07	-14.22	11.2	7.5	0	12.2

Figure 4: Bus Data for the IEEE 14-Bus Test Case

Similarly the numerical codes are attached to different types of sections. A complete list of different section codes and types is provided in Table 2. It can be seen that power transformers are modelled with all their control elements and configurations. Even the single and double lines are represented by circuit numbers as per the IEEE specification. Figure 5 shows the user interface screen for collecting the branch information.

Figure 5: Branch Record Form

Table 2: Section Types and Codes

Section Code	Section Type Description
0	Transmission Line
Transformer	
1	Fixed Voltage Ratio and/or Fixed Phase Angle
2	Fixed Phase Angle and Variable Voltage Ratio with Voltage Control
3	Fixed Phase Angle and Variable Voltage Ratio with MVAR Control
4	Fixed Voltage Ratio and Variable Phase Angle with MW Control
Side No.	Description
0	The controlled bus is one of the t/f terminals
1	The remote controlled bus is near the tap side
2	The remote controlled bus is near the impedance side
Circuit #	Description
1	Single Line
2 to 9	Used for Numbering of Parallel Lines

When the user completes the entering of the branch data, then the application presents the same in a separate sheet named 'Branch_Data'.

3.3. Technologies and Platforms

This application is developed using Microsoft Excel 2010. The essential system requirements to use this application (Microsoft 2012) are: a 500 MHz or higher Computer and Processor with Windows XP (with Service Pack 3) operating system or higher, a memory of 256 MB RAM or higher, a hard disk space of 2 GB or more with a display resolution of 1024 x 576 or higher.

4. Design Implementation and Programming

The design of the application is implemented using VBA with interactive GUI for data manipulation and to undertake computation of the load flow problem with the four different methods. The following sections provide information on the implementation of the design process.

4.1. GUI and Form Design

The built-in 'Microsoft Visual Basic Editor' of the MS Excel is used to develop the forms for the users to input data and make selections. To reduce the complexity in operating this application only five forms are designed. Figure 6 shows a screen shot of the built-in editor along with one of the forms that was designed.

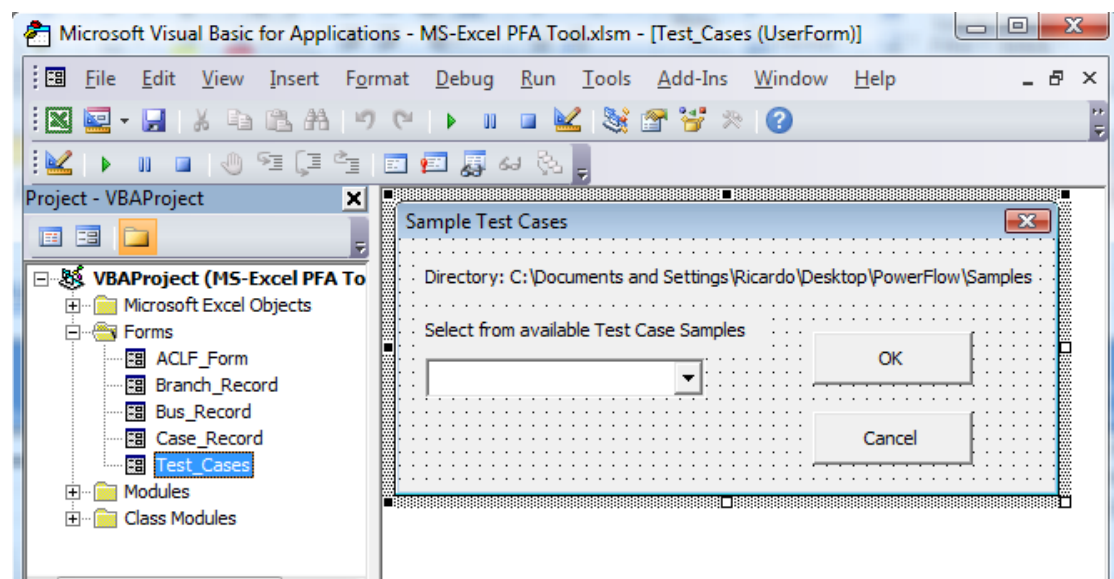


Figure 6: Typical VBA UserForm

4.2. Modular Coding

The source code is divided into several modules, functions and macros. A VBA module consists of different functions and macros. Then a macro is a set of commands and functions to do a specific task and can be called, repeatedly, whenever required to perform that specific task. This ensures the modularity of the source code and thus source code becomes re-usable resulting in higher productivity in developmental process. The data flow through different major modules in this application is shown in the figure 7.

4.3. Source code development

As stated already, the source code consists of eleven modules and a single class module. Table 3 provides information of a few selected modules. A special module is

dedicated to contain all the smaller (auxillary) functions that were common to the powerflow methods as well as those used for unit testing. These functions include subroutines - print_Array (A, lngt); print_Matrix(M, nrow, ncol); clear_results; to_rect; flat_start; GS_soln_cond; NR_soln_cond; calc_mismatch; acf_usrfrm. For instance, the function 'flat_start' is used to set initial estimates prior to a powerflow study employing any one the methods. Where given, voltage magnitudes are set to those specified else they set to 1. All voltage angles are set to zero. The function 'NR_soln_cond' reads the solution conditions for the NewtonRaphson and FastDecoupled methods from their corresponding results worksheet. If no conditions are provided, defaults values are set. The defaults are the same as those stated for the GS_soln_cond. (less an acceleration factor).

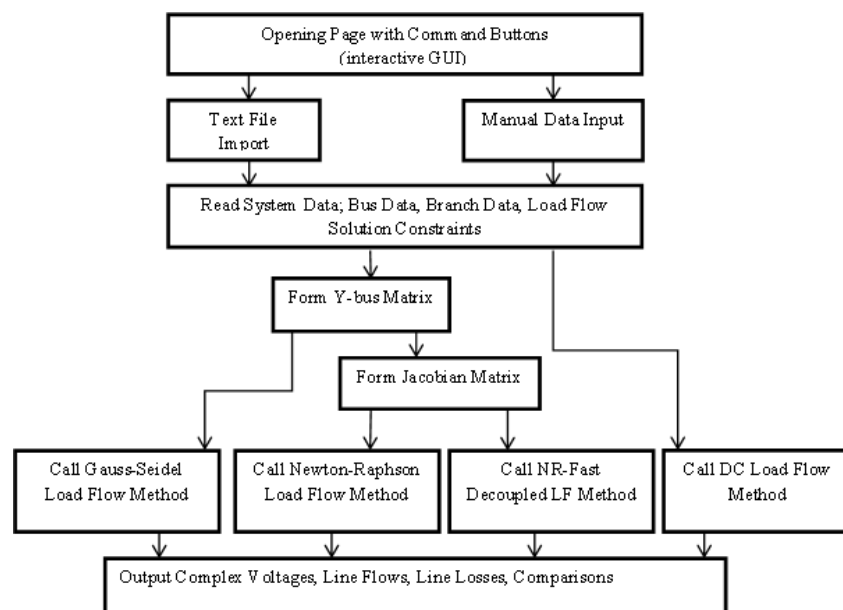


Figure 7: Data Flow Diagram

The function 'calc_mismatch' computes the differences in real power, for all buses except slack bus, and reactive power, for all load buses, between specified values and values calculated using updated voltages. This routine is also used to perform convergence checks.

CTimer Class Module

For the purpose of comparisons, it was necessary to include within each implemented powerflow algorithm provision for timing. With reference to the chosen criteria, the required measurements were the time taken per iteration and that of the total time for the solution, regardless of whether convergence was attained or not.

Since the time taken per iteration to perform a load-flow, on relatively smaller power systems is in the order of milliseconds, the resolution of the built-in vba code timer

was insufficient. Instead, a class module was implemented using the QueryPerformanceCounter and used to determine the time taken for computations.

Table 3: Modules, Subroutines and their descriptions

Module Name and Subroutines	Description
ImportCaseData Subroutines: Import_CaseData; Enter_CaseData	This module consists of two functions to facilitate data input. First function allows importing from IEEE common data format. The implementation of the method is centered on MS-Excel's OpenText workbook function. The second function accepts bus and branch records entered using GUI and transfers into the respective worksheets of Bus_Data and Branch_Data.
BusData Subroutine: get_BusData; clear_BusData	This module reads data from Bus_Data worksheet by parsing each record in turn and enters them into arrays for use by other modules.
GaussSeidel; Subroutines: PF_gs; print_GS_Results;	This module performs a Gauss-Seidel Loadflow, using rectangular coordinates. Output along with numerical results at different intermediate stages is transferred to GS_Results worksheet.
LineFlows Subroutines: calc_lineflows	This module calculates the real and reactive power flows through lines and transformers, using the complex voltages from the results of the different load flow methods.

The four different load flow algorithms have been implemented using the pattern of implementation design. At the end, the application based on the choice of the user, prints the calculated complex bus voltages, complex bus powers, generator reactive power outputs, real and reactive line and transformer power flows, individual and total transmission losses, maximum power mismatches in final iteration, average time per iteration as well as the total solution time to the results to the respective output sheets meant for each study. Further, the application presents detailed information on comparative analysis of all four algorithms in terms of time, numerical output with the help of lucid graphs and tables in the sheets named 'Bar_Plots', 'Line_Plots'.

5. Benchmarking and Performance Analysis

5.1. Benchmarking

To test both the effectiveness and accuracy of the source code, the application is tested thoroughly and numerical results are compared with standard software. InterPSS and MATPOWER are used for benchmarking purpose. For accomplishing this task, same systems are simulated in MSEBPSLF and InterPSS and MATPOWER. Then the output of MSEBPSLF is found to be the same as that of InterPSS or MATPOWER. Table 4 provides the details of benchmarking of MSEBPSLF with InterPSS, in which a comparison of complex voltages at all buses of the standard IEEE-14 bus system, using N-R method.

Table 4: Complex Bus Voltage comparison for IEEE-14 Bus System using N-R method

	InterPSS		MSEBPSLF		Differences	
Bus No.	$ V $	δ	$ V $	δ	$\Delta V $	$\Delta\delta$
1	1.06	0	1.06	0	0	0
2	1.045	-4.98	1.045	-4.98	0	0
3	1.01	-12.73	1.01	-12.73	0	0
4	1.0177	-10.31	1.0177	-10.31	0	0
5	1.0195	-8.77	1.0195	-8.77	0	0
6	1.07	-14.22	1.07	-14.22	0	0
7	1.0615	-13.36	1.0615	-13.36	0	0
8	1.09	-13.36	1.09	-13.36	0	0
9	1.0559	-14.94	1.0559	-14.94	0	0
10	1.051	-15.1	1.051	-15.1	0	0
11	1.0569	-14.79	1.0569	-14.79	0	0
12	1.0552	-15.08	1.0552	-15.08	0	0
13	1.0504	-15.16	1.0504	-15.16	0	0
14	1.0355	-16.03	1.0355	-16.03	0	0

Table 5 provides the details of benchmarking of MSEBPSLF with InterPSS, in which a comparison of complex powers at all buses of the standard IEEE-14 bus system, using N-R method.

Table 5: Complex Bus Power comparison for the N-R method

Bus No.	InterPSS		MSEBPSLF		Differences	
	P	Q	P	Q	ΔP	ΔQ
1	2.3239	-0.1655	2.3239	-0.1655	0	0
2	0.183	0.3086	0.183	0.3086	0	0
3	-0.942	0.0608	-0.942	0.0608	0	0
4	-0.478	0.039	-0.478	0.039	0	0
5	-0.076	-0.016	-0.076	-0.016	0	0
6	-0.112	0.0524	-0.112	0.0523	0	0.0001
7	0	0	0	0	0	0
8	0	0.1762	0	0.1762	0	0
9	-0.295	-0.166	-0.295	-0.166	0	0
10	-0.09	-0.058	-0.09	-0.058	0	0
11	-0.035	-0.018	-0.035	-0.018	0	0
12	-0.061	-0.016	-0.061	-0.016	0	0
13	-0.135	-0.058	-0.135	-0.058	0	0
14	-0.149	-0.05	-0.149	-0.05	0	0

Table 6 provides the details of benchmarking of MSEBPSLF with InterPSS, in which a comparison of reactive power at voltage controlled buses of the standard IEEE-14 bus system, using N-R method.

Table 6: PV Bus Limit Adjustment comparison for the N-R method.

Bus No.	Q(pu)		Difference
	InterPSS	MSEBPSLF	
2	0.44	0.44	0
3	0.25	0.25	0
6	0.13	0.13	0
8	0.18	0.18	0

5.2. Performance Analysis

To illustrate the effectiveness of each of the implemented algorithms, several tests have been conducted on the application. For this, IEEE-14 bus system is considered

and all the methods have been applied and then the final results are compared. Figures 8 & 9 show the voltage magnitudes and angles of all buses, respectively, as compared by all the methods.

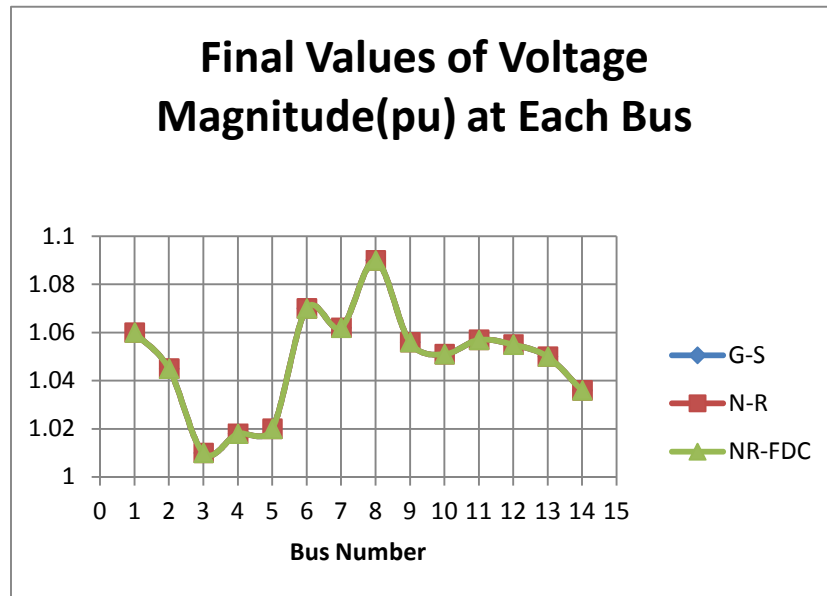


Figure 8: Bus Voltage Magnitudes produced by each method

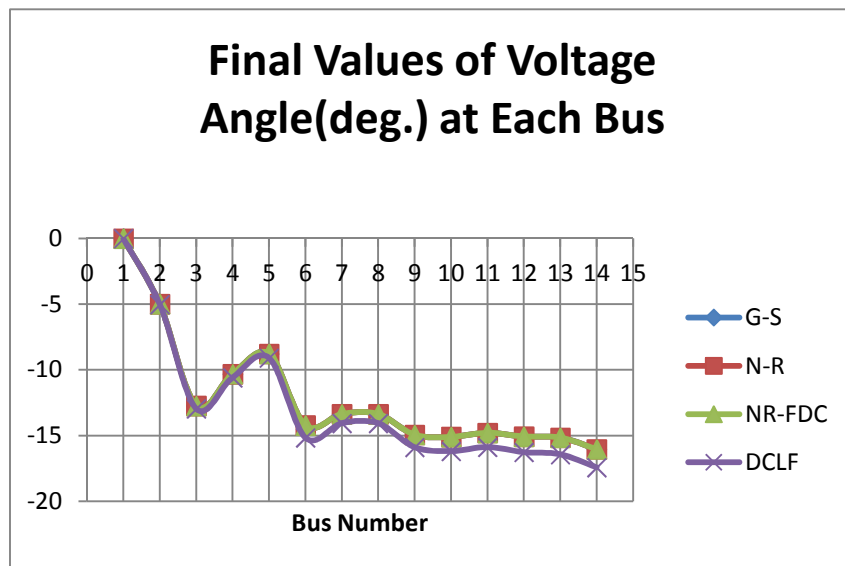


Figure 9: Bus Voltage Angles produced by each method

The MW flows in each line are determined using all the different methods. This plot provides a measure of the degree of accuracy of MW flows as determined by the DC approximation method. Figure 10 shows the comparison of MW flows and it can be clearly seen that all methods do provide the same results including the DC approximated method.

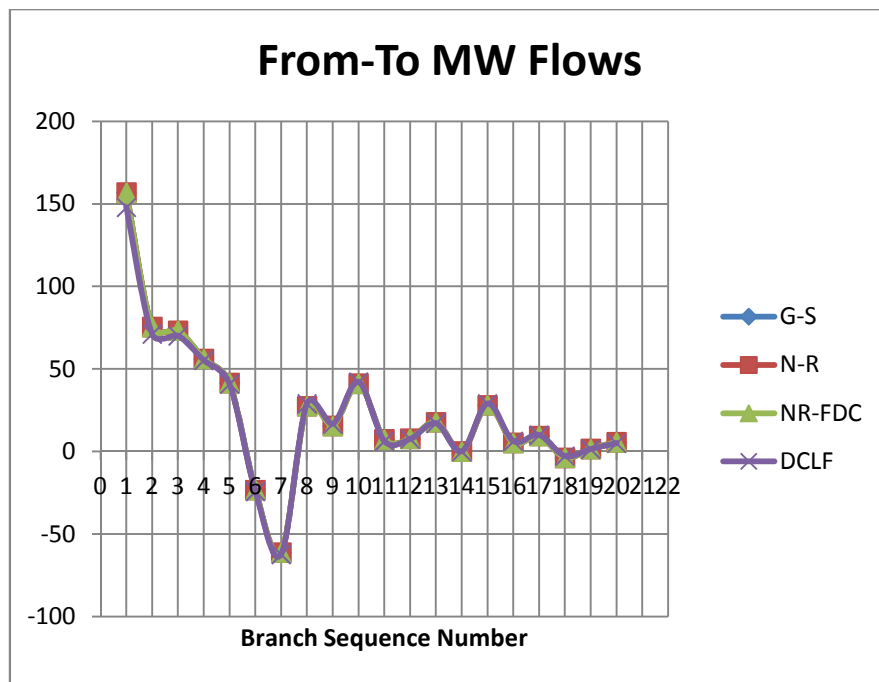


Figure 10: MW flows as calculated by each method

Then the application is used determine number of iterations required to complete the study, time per iteration, total time taken of execution to complete the solution on the standard IEEE-14 bus system. This information is very useful for students when they first learn about effectiveness of the different algorithms. Table 7 provides detailed information on comparison of the algorithms for IEEE-14 bus system.

Table 7: Computational Performance Data of the load flow methods

METHOD	Number of Iterations	Time Per Iteration (ms)	Total Solution Time (ms)
G-S	51	8.1771	421.6368
N-R	3	2.2976	6.8928
NR-FDC	15	1.8909	28.4207
DC	1	0.5353	0.5353

Further, the application is used to study the relative accuracy of results among the iterative methods. Table 8 provides a comparison of the MW and MVAR losses as determined by the three methods. To determine the effectiveness of the application for larger systems with higher number of buses, the three standard systems IEEE-14, IEEE-30, IEEE-57 bus systems have been studied and number of iterations have been determined. One major finding is that the built-in function for matrix inversion 'MINVERSE' of Microsoft Excel can handle matrices only up to size of 52x52.

Table 8: Data used to show Relative Accuracy of the results of each method

METHOD	Total MW Loss	Total MVAR Loss
G-S	13.39	31.51
N-R	13.39	31.52
NR-FDC	13.39	31.51

This limits this application for using larger systems for obvious reasons. To overcome this limitation, a user-defined function for inverse is written in this application development, which is found to be very effective. Figure 11 shows the number of iterations taken by different methods, as number of buses increase.

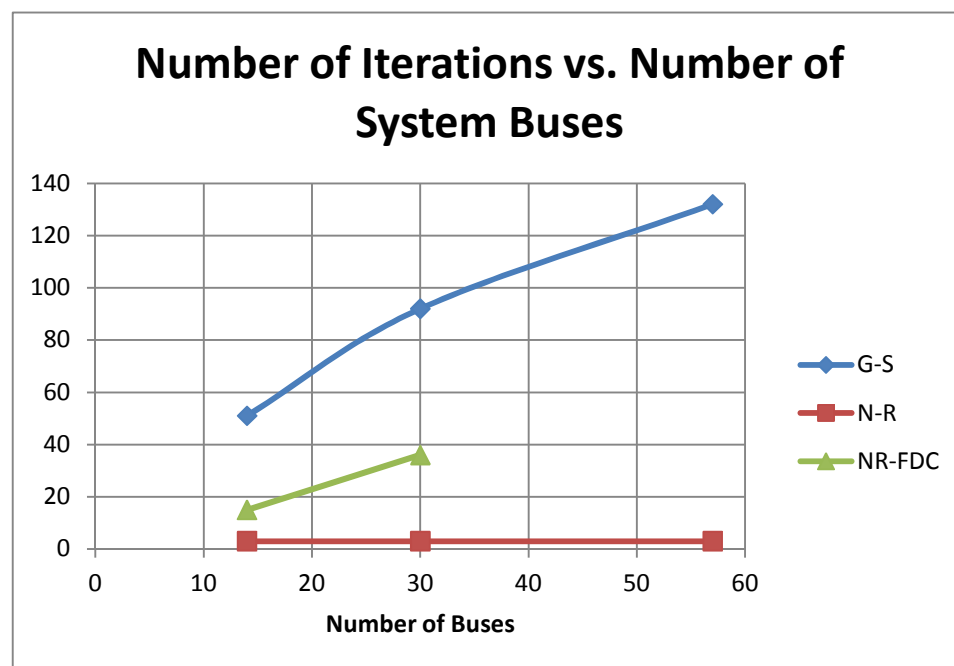


Figure 11: Number of Iterations with System Size

6. Usage of the Application and Effective Classroom Strategy

6.1. Usage of the Application

On opening the implemented spreadsheet application, the user should first enable editing if prompted and then enable macros. If the macro security settings dialog box does not appear on opening and clicking of the command buttons does not run their attached macros, then the user will have to enable macros in the Excel Trust Center. To navigate to the Trust Center, click the MS Office Button and then click Access Options. Go to the Trust Center and click Trust Center Settings and finally, Macro Settings. Select the "Enable all macros" radio button. Now all the macros in the workbook can be executed as normal. It should be noted however, that a spreadsheet

implementation by MS-Excel, might take longer time for larger buses on machines with lesser processing and memory resources. To provide a quick understanding of the application, input data for the standard IEEE-14 bus network is provided with the spreadsheet as default.

6.2. Effective Classroom Strategy

Every electrical engineering student with a major in Power Systems, will study the aspects of load flows in depth. Students need to understand different algorithms, intermediate calculations, selection of algorithm based on network types, loading conditions, convergence criteria, overall system losses, effect of control devices such as tap changing transformer etc. It is recommended that students should prepare the input data first from the diagrams of the systems that need to be studied. This requires selection of base quantities, transformation of actual parameters to per unit quantities, setting up of study parameters etc. Then they should carry out the load flow study up to one iteration using manual approach. Then this developed spreadsheet based application is passed on to the students to verify their own calculations with those generated by the application. With this approach students can understand the complete process of load flow analysis. The reasons being a) in real life, data is presented in diagrams, tables etc., and students need to understand the system, connectivity and required information to conduct a load flow. b) the information is classified into bus data, section data, generator limits etc. Students need to know how to treat each power system component and its modelling aspects and then prepare input properly. As opposed to this strategy, if the data is provided to the students in a text file and then they are asked to use this application; then students need to make only few clicks to get the final results; and this prevents them from understanding intermediate results and other required aspects of load flow studies.

Teachers can use this application differently. Several networks with different loading patterns can be created and studies can be carried out. The results can be shown in tables or charts since the application provides a lucid output instantly. Comparative analysis of four algorithms can also be demonstrated to students easily, as the application supports the same. Studies like capacitor placement, voltage stability or load forecast can be carried out and the system response can be demonstrated. However, it should be noted that this spreadsheet application supports common power system components only and the largest system that was tested is standard IEEE 57 bus network. System elements such HVDC links or polyphase systems or unbalanced conditions are not modelled or incorporated in this

work. Hence, this spreadsheet may not be used for any network that has advanced or modern components or components that require special treatment.

7. Conclusion

A successful case of design, development and implementation of Microsoft Excel based Power System Load Flow tool has been presented. Four popular load flow algorithms have been implemented. The accuracy and effectiveness of tool is verified and benchmarked with existing standard software. This tool can significantly enhance classroom teaching experience and also learning experience; and hence provides an economical and alternative solution for power system load flow analysis.

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