POWER NETWORK ADEQUACY EVALUATION USING PV CURVE NOSE POINT

By

CHUNG YIN JIE

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

Assoc. Prof. R. N. Mukerjee
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

December 2006

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Chung Yin Jie

ABSTRACT

The main objective of this project is to determine adequate network configuration for a specific practical power network system. Power network adequacy is a measure of its ability to supply the aggregate electric power and energy requirements of the customers within component ratings and voltage limits, taking into account planned and unplanned outages of system components. Improper network configuration results in weakness in a power transmission or distribution networks and limits flexibility in network operation. Using load flow analysis, power network adequacy can be evaluated in terms of adequate power network configuration. By utilizing the most adequate network configuration, it will be more economical at the same time maintaining the stability of the entire network system.

ACKNOWLEDGEMENTS

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CHAPTER 1
INTRODUCTION

1.0 BACKGROUND OF STUDY

In power engineering, the conditions are rapidly changing with ongoing deregulation of the industry. Mutually supportive transmission systems are now being viewed as super highways for movement of power. This raises concerns about supply adequacy and transmission reliability. Since 1950s, the demand for electric energy has been growing due to the transformation and innovation in the field of power system engineering. The advent of the semiconductor device has seen widespread and often novel application, notably in system protection, power conversion, system control, and system operation. Initially there was an apparently cautious step from appearance of technology to its application; due to the caution was nothing more than a manifestation of the time scales involved. The load flow problem was first solved using the simplest techniques, soon to be replaced by more sophisticated methods. The search for better techniques began almost as soon as computer applications become available. Today, with the help of high speed computers, the ability to take on modern system planning techniques would provide distribution, transmission and generation utilities with a means of determining the necessity for system expansion as well as reinforcement.

1.1 PROBLEM STATEMENT

Improper network configuration results in weakness in a power transmission or distribution networks and limits flexibility in network operation. Permissible loadability with satisfactory voltage gets limited when the network has inherent weaknesses..

1.2 OBJECTIVES AND SCOPE OF STUDY

The objective of this project is to evaluate power network adequacy using PV curve nose point. The scopes of study are as follows:

1.2.1 Learning how to carry out Load Flow study in a practical power system using a package

The power flow study (also known as load-flow study) is an important tool involving numerical analysis applied to a power system. It usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (ie: reactive, real, and apparent) rather than voltage and current. The primary concern is to match consumer loads with capacity to supply energy in an economical and reliable manner.

1.2.2 Determination of adequate network configuration

Power network adequacy is a measure of the ability of the power system to supply the adequate electric power and energy requirements of the customers within component ratings and voltage limits, taking into account planned and unplanned outages of system components. Adequacy measures the capability of the power system to supply the load in all the steady states in which the power system may exist considering standard conditions.

1.2.3 Practice project management skills

The final year project is also a chance to practice project management skills. This is important and crucial as it determines the success or failure of a certain project. Essential aspects such as time management, communication skills, and others are indeed needed.

CHAPTER 2

LITERATURE REVIEW/THEORY

2.1 LITERATURE REVIEW

The maintenance of voltages on the network busses at their respective rated values is a prime requisite. The voltage occurring mainly depends on the network condition. The network condition is overseen by the exchange of generation over-excitation, under-excitation limits, network configuration, presence of shunt compensation, transformers tap settings and exchange of loading. The diagram below shows the aspects of security of electricity supply [1].

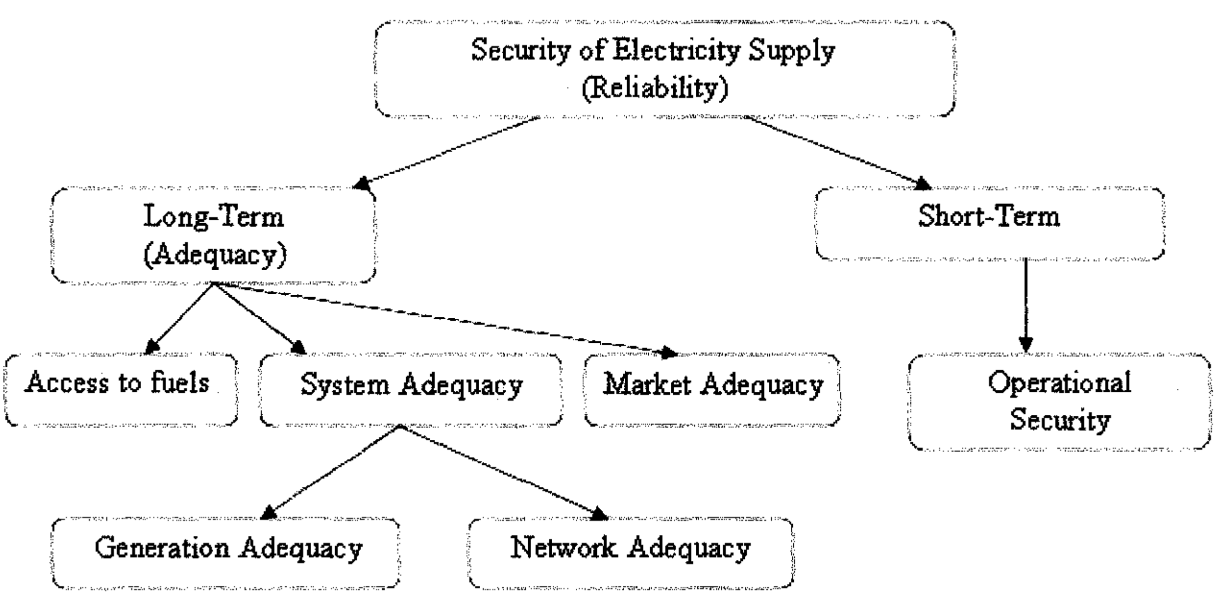


Figure 1 : Aspects of Security of Electricity Supply

In addition to a power flow study itself, sometimes called the base case, many software implementations perform other types of analysis, such as fault analysis and economic analysis. In particular, some programs use linear programming to find the optimal power flow, the conditions which give the lowest cost per kW generated. Advanced algorithms and computational capabilities are required when the issue of stability of the grid is coupled with adequacy and with the impact of dispersed power generation and storage [2].

The electricity system is a critical infrastructure. Its continued and reliable functioning is essential to the nations' economy and citizens' way of life [3]. The interconnection of the networks comprising the critical infrastructure is an ongoing evolutionary process. Demand for electricity (load requirements on the system) fluctuates continuously, based on factors such as time of day, season, and the characteristics of the territory served by the system [4].

> "From an economic point of view, security and adequacy are quite distinct in the sense that the former is a public good while the latter can potentially be treated as a private good."
>
> \- Oren (June 2003)

The significance of this project helps in determining network limitations during design planning and operational planning studies.

2.2 THEORY

2.2.1 Steady-State Stability and Load-Flow Jacobian

Standard Load Flow

Standard load-flow has been the traditional mechanism for computing a proposed steady-state operating point. For this paper, we define standard load-flow as the following algorithm:

(a) Specify bus voltage magnitudes numbered 1 to m.

(b) Specify bus voltage angle number 1 (slack bus).

(c) Specify net injected real power P_i at buses numbered 2 to m.

(d) Specify load powers P_{Li} and Q_{Li} at all buses numbered 1 to n.

The standard load-flow has many variations including the addition of other devices such as tap changing under load (TCUL) transformers, switching var sources and HVDC converters. It can also include inequality constraints on quantities such as Q_i, and be revised to distribute the slack power between all generators. We would like to make one important point about load-flow. Load-flow is normally used to evaluate separation at a specific load level (specified by a given set of powers) [5].

For a specified load and generation schedule, the solution is independent of the actual load model. That is, it is certainly possible to evaluate the voltage at a constant impedance load for a specific case where that impedance load consumes a specific amount of power. Thus the use of '$I_{constant}$ power" in load-flow analysis does not require or even imply that the load is truly a constant power device. It merely gives the voltage at the buses when the loads (any type) consume a specific amount of power.

The load characteristic is important when the analyst wants to study the system in response to a change such as contingency analysis or dynamic analysis. For these purposes, standard load-flow usually provides the "initial conditions".

Angle Reference

In any rotational system, the reference for angles is arbitrary. The dynamic system can be reduced by introducing the new relative angles. The full system remains exactly the same. During a transient, the angle still changes from its initial condition, so that each original can be easily recovered if needed. The angle remains at zero for all time. Amid simulation, the differential equation normally replaced by the algebraic equation. Notice that e is normally arbitrarily selected as zero for the load flow analysis. This means that the initial value is normally not zero.

Instability and Maximum Loadability

When studying a proposed load or interchange level, a load-flow solution is required before steady-state stability can be analyzed. If a load-flow solution cannot be found, then it is normally assumed that the proposed loading exceeded the "maximum power transfer" capability of the system.

This maximum power transfer point is normally assumed to coincide with a zero determinant for the standard load-flow Jacobian. Using this as a criteria, any load level which produces a zero determinant for the standard load-flow Jacobian is an upper bound and hence an optimistic value of the maximum loadability.

This upper bound has been analyzed in the past, and is regaining interest as voltage collapse is associated with it. It is also important to note that non-convergence of load-flows is also a matter of solution technique. Cases have been cited where Gauss-Seidel routines converge when Newton-Raphson routines do not.

If a standard load-flow solution and associated dynamic system equilibrium point are found the stability of the point must be determined. In order to do this, the algebraic equation Jacobian must be nonsingular. Assuming these algebraic equation Jacobians are nonsingular for a given case, steady-state stability must be evaluated from the eigen values of the system dynamic state Jacobian.

A system is at a critical point when the real part of one of its eigen values is zero. If a real eigen value is zero then the determinant is zero. In the general case, the zero eigen value due to the angle reference can easily be removed by using a dynamic model reduced Clearly many cases can be found where an equilibrium point can be critically unstable (at least one eigen value has a zero real part) and the load-flow Jacobian is nonsingular.

A dynamic equilibrium point exists and has a system dynamic state Jacobian which is singular if and only if the load-flow Jacobian is singular.

2.2.2 Steady-state Analysis Method

PV Curves

- Load and generation in selected areas are increased in a predetermined manner to find the distance to voltage instability.
- Full power flow solution is performed at each load level to obtain bus voltages.
- Voltage stability limit is reached when power flow solution failed to converge.

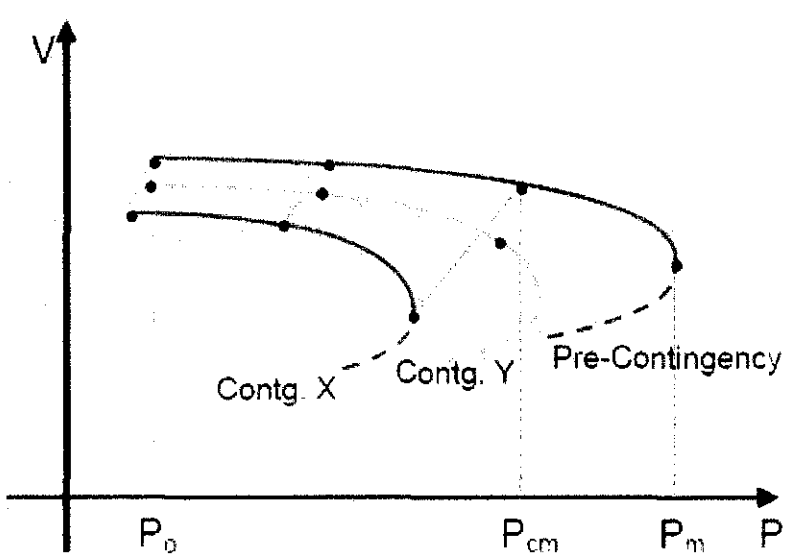


Figure 2 :PV curve

- PV plots show :
  - Variation (sensitivity) of bus voltages (or other variables) with load.
  - Distance to instability
    - $P_m - P_o$: Pre-cont margin
    - $P_{cm} - P_o$: Post-cont margin
  - Voltage/power at which instability occurs ("nose" of PV curve).
- Full power flow solution ensures all system non-linearities are represented as the system is stressed.
- Stressing the system by load/generation increase is the most relevant measure for assessing the voltage stability of the system.
- Computed VS margins are in physical terms (e.g. MW load increase).
- Implementation requires various generation dispatch options to meet the increasing load.
- Concern is that the failure of power flow to converge may be the result of numerical and algorithmic problems rather than the actual instability being reached.
- It is also cautioned that voltage stability may involve complex dynamics from generators, voltage controls, and loads. The PV curve concept captures only some steady-state aspects of voltage stability.
- Experience has shown that the Fast Decoupled method can solve the power flow very close to the instability point (by gradually decreasing the step size).

2.2.3 Operational Problem

A power outage may result from either of two failures: load increases beyond the capability of the transmission lines or a component failure, which leads to an undesirable operating point.

If a system's load were to continue to increase, it is possible for the system to enter an overload situation and "voltage collapse". We will consider this point to be the nose of the PV curve.

A power outage may also begin from a loss of a single component such as with a downed transmission line or transformer failure. This may result in an immediate loss of load and a "blackout".

Another problem that arises with power systems are low voltages. Low system voltages can be a consequence of both overloads and component failures. With respect to overloads, low system voltages can be illustrated with fixed PV curves and abnormally high loads. Regarding a component loss, the operating PV curve changes when the failure occur to a curve which supports a reduced maximum power transfer and, as a result, causes a reduction in system voltage. The term for this low voltage situation is a "brownout"

A voltage problem resulting from a transmission line failure may be corrected by adding shunt capacitance to the power system, which in effect is a change in β and load power factor to PV equation.

$$|V_2|^2 = |V_1|^2/2 - \beta P_D X \pm [|V_1|^4/4 - P_D X (P_D X + \beta|V_1|^2)]^{1/2}$$

CHAPTER 3
METHODOLOGY

The methodology(s) of this project are as below:

- Carry out base case load flow of a given power system network.
- Change in network configuration and monitoring of change in system's stability when stressing the system by increased of load for each of power load flow analysis.
- Network configuration implies numbers of lines connected between the buses and the presence or otherwise of shunt compensation, shunt load at the buses and transformer tap settings.

3.1 PROCEDURE

A few methods are utilized to achieve the objectives of the project. This includes all the stages of development. They are as follows:

- Preliminary research and literature review
- Problem analysis and data gathering
- Tools and equipment identification
- Testing and experimentation
- Implementation and deployment

3.2 TOOLS REQUIRED

- PSAT (Power System Analysis Toolbox)
    - It is a MATLAB toolbox for static and dynamic analysis and control of electric power system.
    - It includes power flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation.
    - Its core is the power flow routine, which also takes care of state variable initialization.

Mainly, the project is started by identifying project specification. Preliminary research and literature review is carried out to understand the theory and gain more knowledge in the field covered.

The problem of this project is analyzed so that data needed in this project can be identified and gathered. This is a crucial stage since the data needed in the simulation stage need to be exact and sufficient enough to run the process. Meanwhile, the PSAT is being studied so that we can familiarize with the tools involved in this project. Test case is then being tested and experimented so that we can expect the outcome of this project when we implement it on a real system network.

A real system network is then applied to the tools. The system is analyzed thoroughly to meet the project's specification. The system is then tested and experimented until we get the best output, to comply with the project's objectives, that is to evaluate power network adequacy of a real system.

As a clearer view of procedure identification of the project, a graphical logic flowchart and brief descriptions of each phase is stated in the diagram.

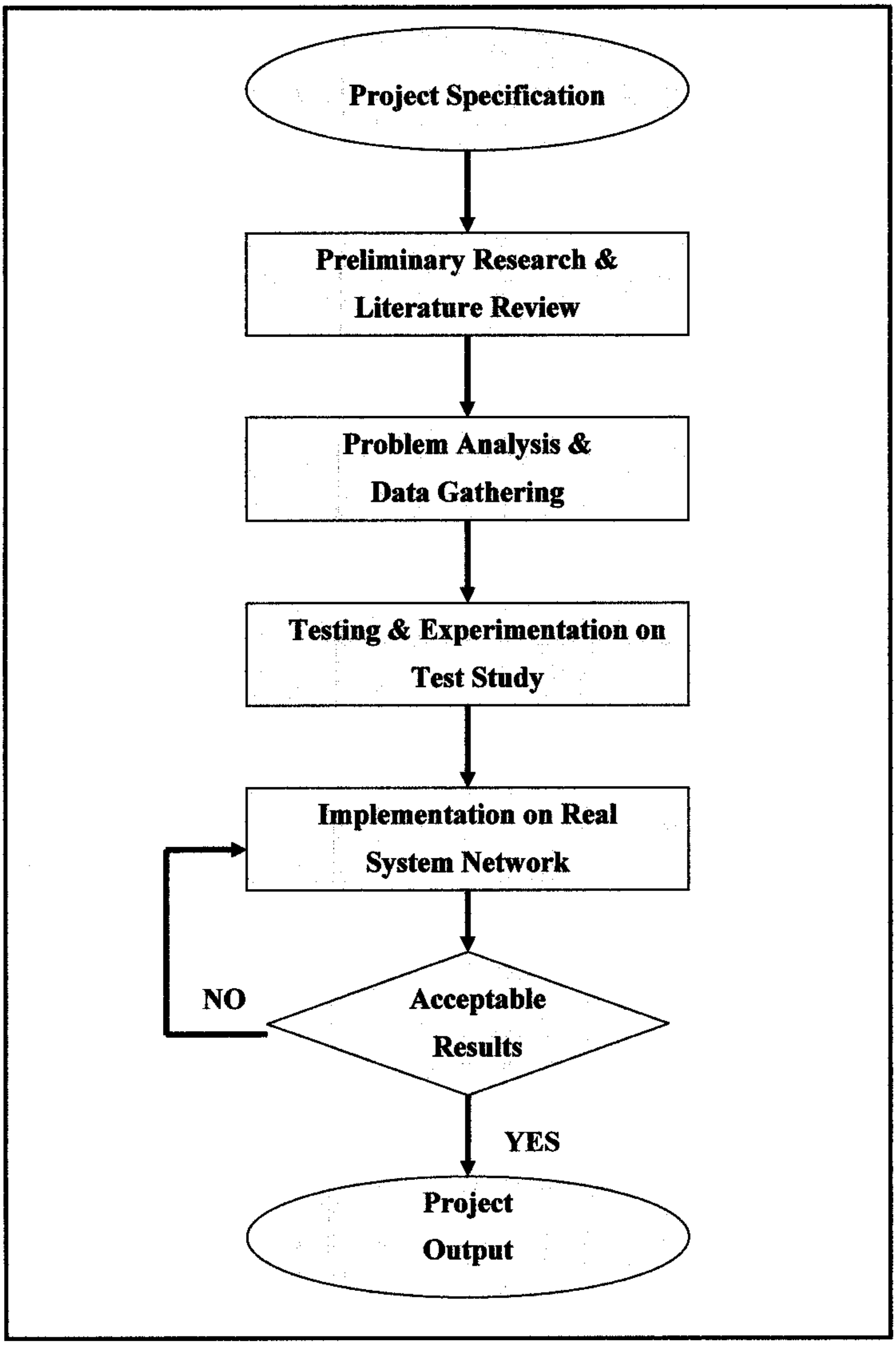


Figure 3 :Logic flowchart for the project

CHAPTER 4
RESULTS AND DISCUSSION

4.1 POWER SYSTEM ANALYSIS TOOLBOX (PSAT) SOFTWARE

PSAT (Power System Analysis Toolbox) is a MATLAB Toolbox for static and dynamic analysis and control of electric power systems. PSAT includes power flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation. All operations can be assessed by means of graphical user interfaces (GUIs) and a SIMULINK-based library provides a user friendly tool for network design.

PSAT core is the power flow routine, which also takes care of state variable initialization. Once the power flow has been solved, further static and/or dynamic analysis can be performed. These routines are:

- Continuation power flow
- Optimal power flow
- Small signal stability analysis
- Time domain simulations
- Phasor measurement unit (PMU) placement

Besides mathematical routines and models, PSAT includes a variety of utilities, as follows:

1. One-line network diagram editor (Simulink library)

2. GUIs for settings system and routine parameters

3. User defined model construction and installation

4. GUI for plotting results

5. Filters for converting data to and from other formats

6. Command logs.

Finally, PSAT includes bridges to GAMS and UWPFLOW programs, which highly extend PSAT ability of performing optimization and continuation power flow analysis. Refer to Appendix A for Test Data and Results.

After some discussion with my supervisor, I decided to use the network system of the New Doha International Airport (NDIA), instead of a substation network and new apartment network. This is because the network of NDIA covers wider range, therefore suits my project's objective.

The data of the network system need to be constructed into Simulink. This is because in order to evaluate the system's adequacy, the Simulink has to be done to be processed by PSAT. The Simulink is being done part by part as the data in the each component in the Simulink is being input.

The entire network system is consists mainly two parts, which is Main Substation North and Main Substation South. I will analyse this two system separately as they are two system which has different incoming source.

4.2 RESULTS ON MAIN SUBSTATION NORTH

In this analysis of power flow, I will determine the adequacy of network configuration for Bus which has been reserve for future demand. This analysis is important because the initial configuration of the network for future demand will be evaluated to make sure the system is stable even though load demand has been increased. Therefore I will examine the adequacy of the particular Bus by decreasing the cable size as well as transmission lines to determine whether the system will maintain stable with the increased of load demand in vaious network configuration.

For Base Case Load Flow analysis, I will first determine the Bus which has been reserved for future demand. Then I will carry out Load Flow analysis of the network. After obtaining the result, the load demand of that particular Bus is increased by 10% and load flow analysis is being carried out again. The process is repeated 10 times to get the ultimate value of the PV Curve (Nose Point).

The cable size of this particular Bus is then being decreased and load flow analysis is carried out again. The process similar to Base Case Load Flow analysis is repeated to get the new ultimate value of nose point for new PV Curve.

Number of transmission line is then decreased so that new power flow analysis can be carried out. The process to obtain new PV Curve is repeated so that I will be able to compare the three results obtained from three different network configurations.

More details of the analysis, results and discussion will be shown in their respective sub topic later.

The next page shows the power system network of Main Substation North.

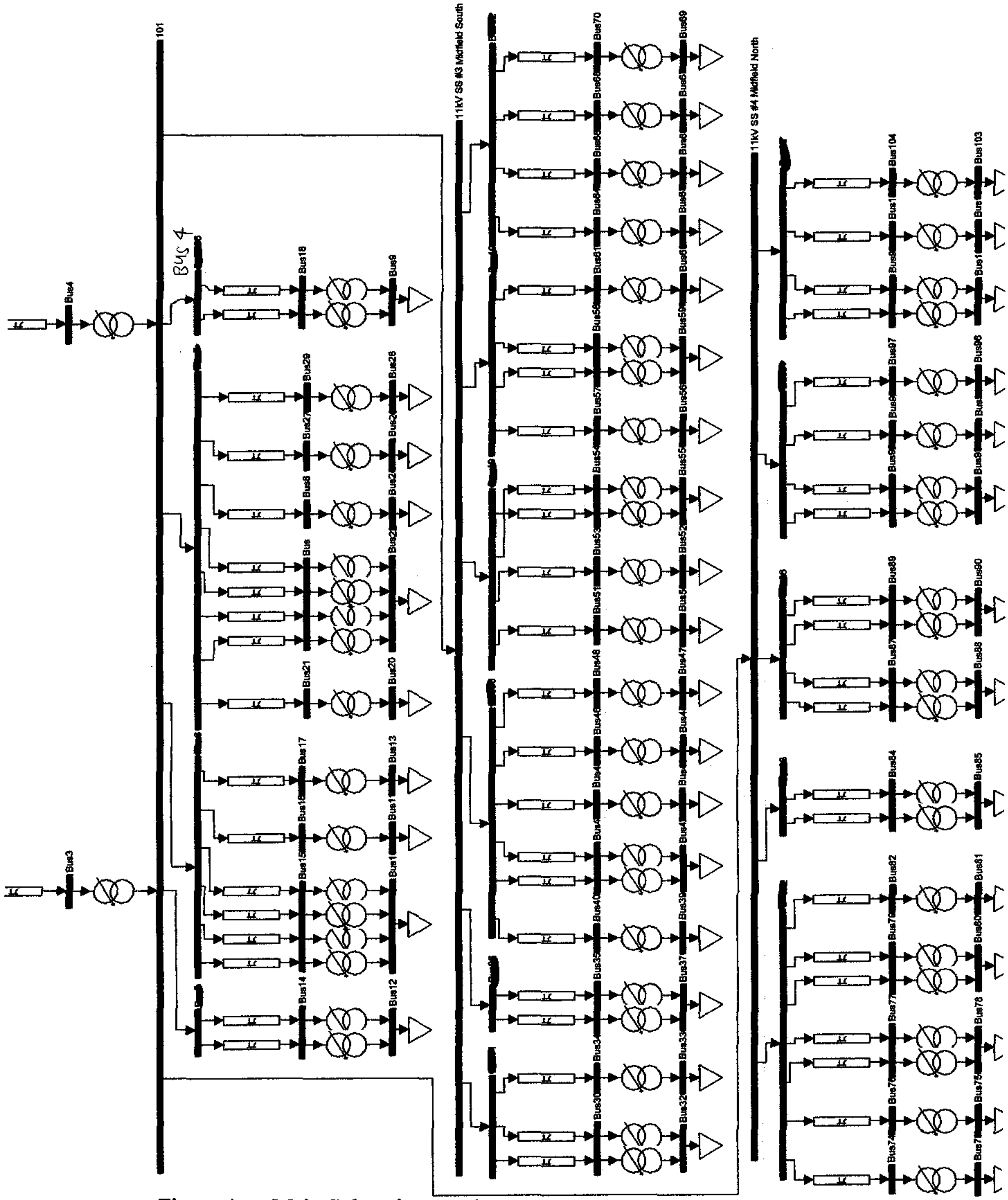


Figure 4 : Main Substation North

The table below shows the Load Bus Number and Load Destination as well as Load Demand.

Load Bus Number	Load Destination	Load Demand (kVA)
1	Free Trade Zone	2609
2	Commercial Area Access Road Lighting Fuel Receiving Station Hotel	3011
3	PW & FW Distribution Pump Station Service Area Lighting Satellite Fire Station Midfield Tunnel West Radar Transmitter Station	1823
4	Business Park Retail Mall Employee Parking Commercial Reserve	7130
5	Cargo Terminal WH-2 Lighting Transformer	2024
6	Cargo Terminal WH-1	1866
7	Facility Maintenance Catering Facility Receiver Station Fuel Farm GSE Maintenance Facility	3709

8	Lighting Transformer Administration Facility Employee Canteen	2158
9	Cargo Agents Building Air Control Tower Airline Operations	1540
10	Midfield Tunnel East Vent Structure GA Maintenance Hangar GA Terminal Lighting Transformer	2183
11	Meteorological Complex North Retention Pond Storm Water Pipe Station East Runway Power System North West Runway Power System North Fire Training Facility	2130
12	Aircraft Maintenance Hangar #2	2355
13	Aircraft Maintenance Hangar #1 Aircraft Maintenance Workshop	2766
14	EMIRI Hangar Check Point Building Radar	1711
15	Midfield Area PW & FW Pump Station Solid Waste Handling Facility Incinerator	3426

Table 1 : Load Demand for Main Substation North

4.2.1 Analysis on the Result of Base Case Load Flow (2x(3/C 300mm²)

In the Base Case Load Flow analysis of Main Substation North, it is known that Bus 4 is reserved for future utilisation which has load demand of 7130 kVA. Bus 4 has two transmission lines and each transmission line uses 3/C 300mm^2 cable. The table below shows the electrical data of the cable.

Cable Size	Current Rating	A.C. Resistance	Star Reactance	Star Capacitance
3/C 300mm^2	540A	0.0798ohm/km	0.0858ohm/km	0.53

Table 2 : Electrical Data of 3/C 300mm^2 Cable

From the result (refer to Appendix A), voltage magnitude of Bus 4 is set to 1 p.u. and Pload of 0.2086. After obtaining the result, the load demand is then increased by 10% and load flow analysis is being carried out again. The process is repeated 10 times to get the ultimate value of the Nose Point. The result is then plotted in PV Curve.

The table below shows the result of Base Case Load Flow Analysis.

Load Demand (kVA)	P load (p.u.)	V (p.u.)
7130	0.2086	1
7843	0.2295	0.9998
8627	0.2524	0.9976
9490	0.2776	0.9945
10439	0.3054	0.9909
11483	0.336	0.9857
12631	0.3695	0.9791
13894	0.4065	0.9725
15284	0.4472	0.9649
16812	0.4919	0.9555

Table 3 : Result of V and Pload of Base Case Load Flow Analysis

From the table above, PV Curve for Base Case Load Flow analysis in plotted.

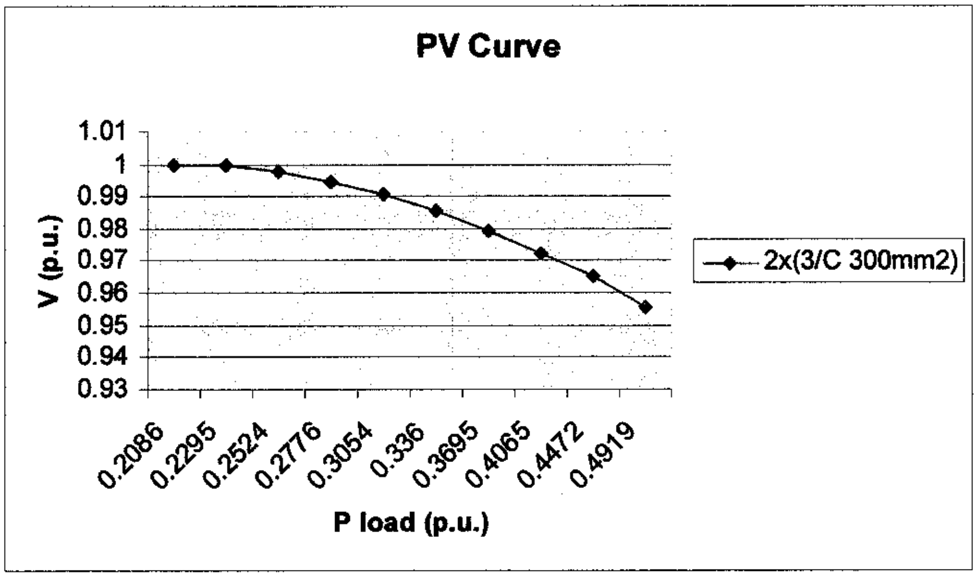


Figure 5 : PV Curve of Base Case Load Flow Analysis.

From the curve above, when Pload is increased, V magnitude is decreased. Besides, losses on real power and reactive power also increased.

4.2.2 Analysis on the Result after Cable Size is Decreased (2x(3/C 150mm²)

The cable size of this Bus 4 is then being decreased and load flow analysis is carried out again. In this analysis, the cable size of 3/C 150mm^2 is used to further testify the adequacy of this network system. The process similar to Base Case Load Flow analysis is repeated to get the new ultimate value of nose point for new PV Curve.

The electrical data of the cable 3/C 150mm^2 is shown in the table below.

Cable Size	Current Rating	A.C. Resistance	Star Reactance	Star Capacitance
3/C 150mm^2	380A	0.159ohm/km	0.0943ohm/km	0.40

Table 4 : Electrical Data of 3/C 150mm^2 Cable

From the result, Bus 4 has the voltage magnitude of 1 p.u. and Pload of 0.2086. After obtaining the result, the load demand is then increased by 10% and load flow analysis is being carried out again. The process is repeated 10 times to get the ultimate value of the new Nose Point. The result is then plotted in PV Curve.

The table below shows the result after the cable size is Changed to 3/C 150mm^2.

Load Demand (kVA)	**P load (p.u.)**	**V (p.u.)**
7130	0.2086	1
7843	0.2295	0.9985
8627	0.2524	0.9947
9490	0.2776	0.9885
10439	0.3054	0.9793
11483	0.336	0.9698
12631	0.3695	0.9578
13894	0.4065	0.9441
15284	0.4472	0.9282
16812	0.4919	0.9106

Table 5 : Result of V and Pload After the Cable Size is Changed to 3/C 150mm^2

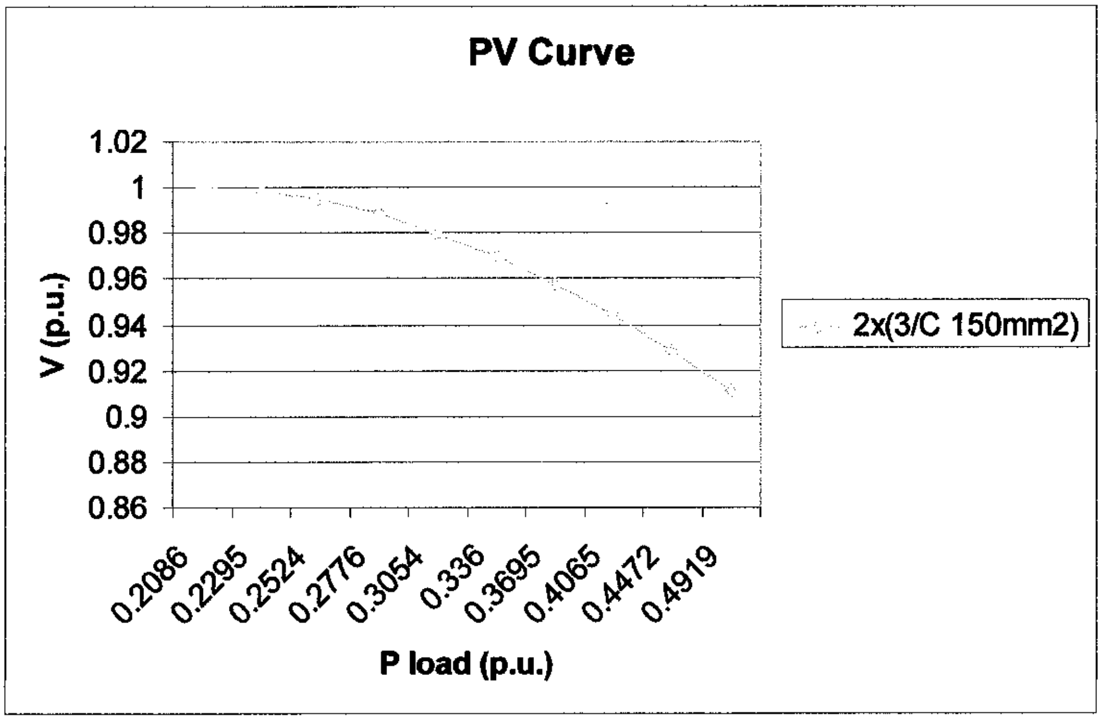


Figure 6 : PV Curve After Cable Size is Changed to 3/C 150mm^2

After the cable size is decreased to 3/C 150mm^2, at the same time maintaining the number of transmission lines, it is clearly shown that it has a smaller PV Curve. This means that the network system using 3/C 150mm^2 cable is more adequate.

4.2.3 Analysis on the Result after Number of Transmission Line is Decreased (1x(3/C 150mm^2)

Number of transmission line is then decreased so that new power flow analysis can be carried out. Through the network system shown, Bus 4 initially has two transmission line. This time around, load demand for Bus 4 is served by using only one transmission line, with 3/C 150mm^2 cable. The process similar to the previous conditions is carried out to obtain new PV Curve.

The table below shows the result after the number of transmission line is decreased.

Load Demand (kVA)	P load (p.u.)	V (p.u.)
7130	0.2086	1
7843	0.2295	0.9972
8627	0.2524	0.9927
9490	0.2776	0.9857
10439	0.3054	0.9752
11483	0.336	0.9652
12631	0.3695	0.9517
13894	0.4065	0.9368
15284	0.4472	0.9172
16812	0.4919	0.8952

Table 6 : Result of V and Pload After the Number of Transmission Line is Decreased

The PV Curve below shows that after number of transmission line is decreased.

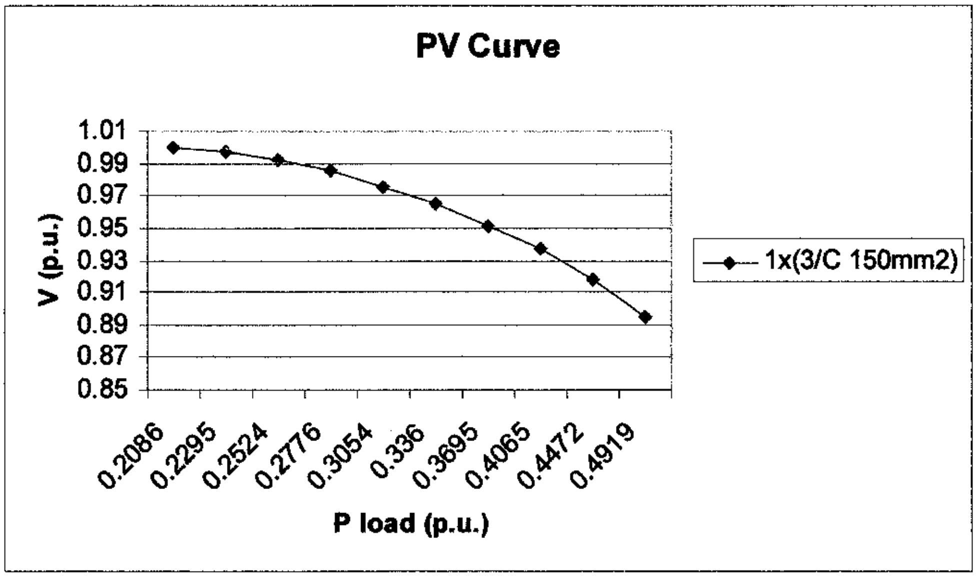


Figure 7 :PV Curve After Number of Transmission Line is Decreased

From the graph, the graph curves in even earlier. This means that with this configuration, the system has the most adequate network.

4.2.4 Comparison of Results of Three Conditions

The three PV Curve obtained from the power flow analysis which has been carried out on Main Substation North network system is shown in the graph below.

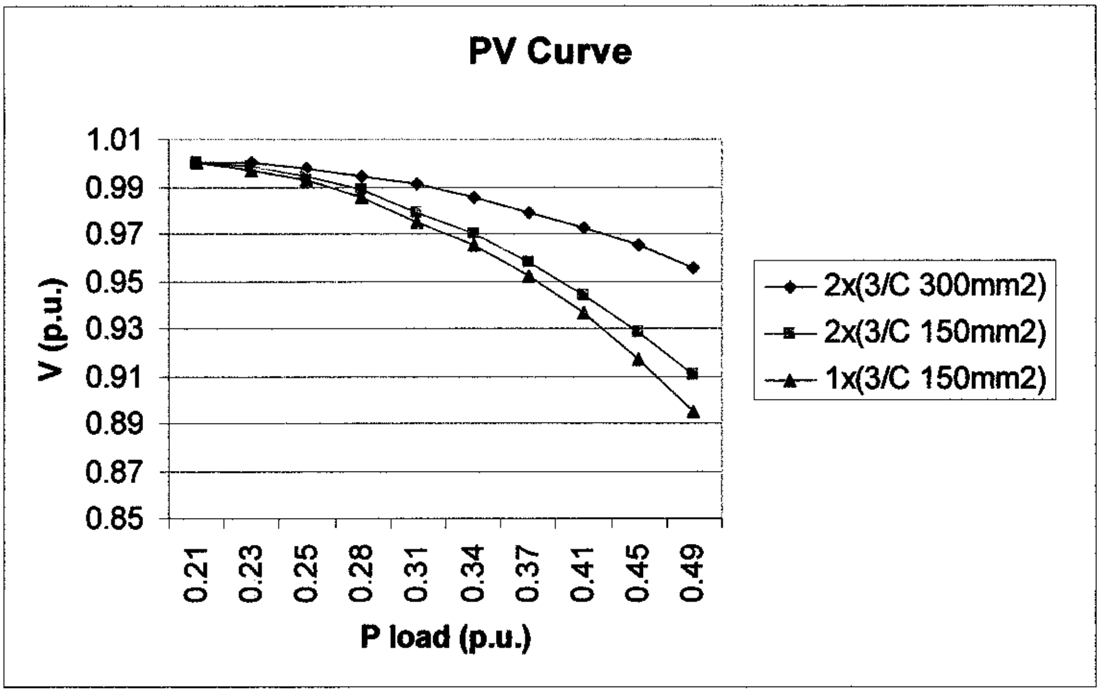


Figure 8 :Comparison of Results of Three Conditions

From the graph shown above, it is very clear that the third case load flow analysis result has the most adequate network configuration. Bus 4 which is reserved for future demand for Main Substation North initially is served through two transmission line using 3/C 300mm^2 cable each.

If the cable size is changed to 3/C 150mm^2, the results shows that the network system has a smaller PV curve. This means that the network is more adequate. When the transmission is decreased to only one transmission line using 3/C 150mm^2 cable, the results are even better as it curves in earlier and has even smaller PV curve. This shows that the network system only needs one transmission line with 3/C 150mm^2 cable to achieve its adequacy.

4.3 RESULTS ON MAIN SUBSTATION SOUTH

For the Main Substation North, I will first determine the Bus which is reserved for future demand. Base Case Load Flow analysis is carried out for the entire network system. After obtaining the result, the load demand is increased by 10% and load flow analysis is being carried out. The process is repeated 10 times to get the ultimate value of the PV Curve (Nose Point).

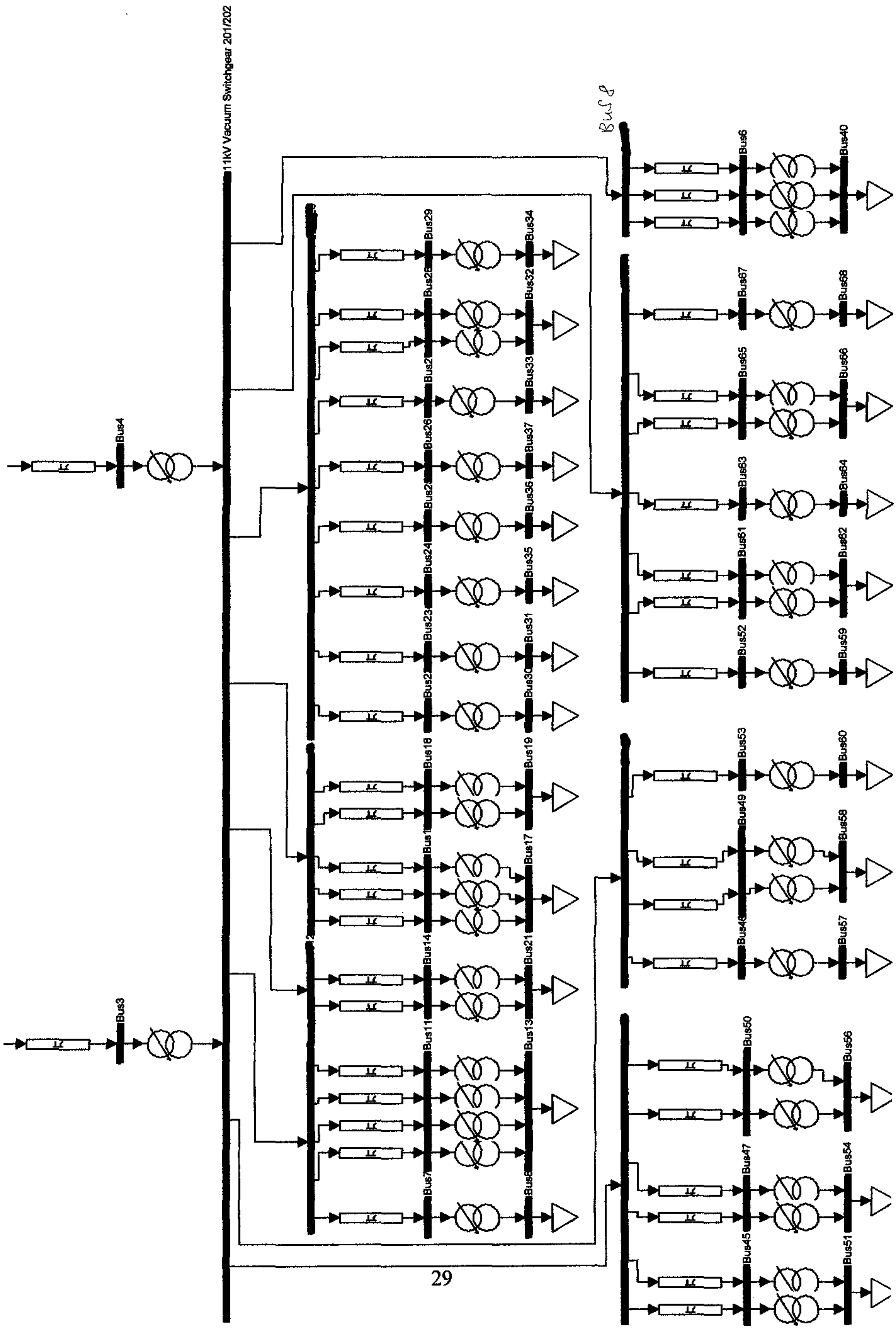
The cable size for the Bus which is reserved for future demand is then being decreased and load flow analysis is carried out again. The process similar to Base Case Load Flow analysis is repeated to get the new ultimate value of nose point for new PV Curve.

Number of transmission line for the particular Bus is then decreased so that new power flow analysis can be carried out. The process to obtain new PV Curve is repeated so that I will be able to compare the three results obtained from three different conditions.

More details of the analysis, results and discussion will be shown in their respective sub topic later.

The next page shows the power system network of Main Substation South

Figure 9 : Main Substation South



The table below shows the Load Bus Number and Load Destination as well as Load Demand for the Main Substation South.

Load Bus Number	Load Destination	Load Demand (kVA)
1	South-West Pond Storm Water Pump Station 300HP Terminal Area Access Road Lighting	2000
2	Waste Water Treatment Plant	2799
3	Passenger Terminal Concourse B	6476
4	Public Mosque Security Fence Triturator Airsite Access c/p & Access Road Lighting Access Road Lighting Car Rental & Parking Lot West Runway Power South Remote Aircraft Cargo & Transfer Area West	2064
5	Central Utility Plant Auxiliaries Central Utility Plant Chillers 1 & 2 Central Utility Plant Chillers 3 & 4	7030
6	Main Fire Station Remote Aircraft Cargo Transfer Area East (UD)	3828
7	Emiri Site Improvement Term Access Emirt Terminal VIP Pavilion Emiri Gate East Runway Power South	2714

	South-East Stormwater Pump & Sea Rescue Station	
8	Passenger Terminal Concourse D Passenger Terminal Concourse E	22598

Table 7 :Load Demand for Main Substation South

4.3.1 Analysis on the Result of Base Case Load Flow (3x(3/C 300mm^2)

In the Base Case Load Flow analysis of Main Substation South, it is shown that Bus 8 is reserved for future demand, whch is 22598 kVA. Bus 8 has three transmission lines and each transmission line uses 15kV 3/C 300mm^2 cable. The table below shows the electrical data of the cable.

Cable Size	Current Rating	A.C. Resistance	Star Reactance	Star Capacitance
3/C 300mm^2	540A	0.0798ohm/km	0.0858ohm/km	0.53

Table 8 : Electrical Data of 3/C 300mm^2 Cable

From the result (refer to Appendix B), Bus 8 has the voltage magnitude of 1 p.u. and Pload of 0.2099. After obtaining the result of Base Case Load Flow Analysis, the load demand is then increased by 10% and load flow analysis is being carried out again. The process is repeated 10 times so that I can get the ultimate value of the Nose Point. The result is then plotted in PV Curve.

The table below shows the result after load demand is increased by 10%. The steps are repeated so that PV curve can be obtained.

Load Demand (kVA)	P load (p.u.)	V (p.u.)
22598	0.2099	1
24858	0.2310	0.9996
27344	0.2540	0.9983
30078	0.2794	0.9964
33086	0.3073	0.9931
36394	0.3380	0.9892
40034	0.3719	0.9847
44037	0.4090	0.9789
48441	0.4499	0.9718
53285	0.4949	0.9636

Table 9 : Result of V and Pload of Base Case Load Flow Analysis

From the table above, PV Curve for Base Case Load Flow analysis can be plotted.

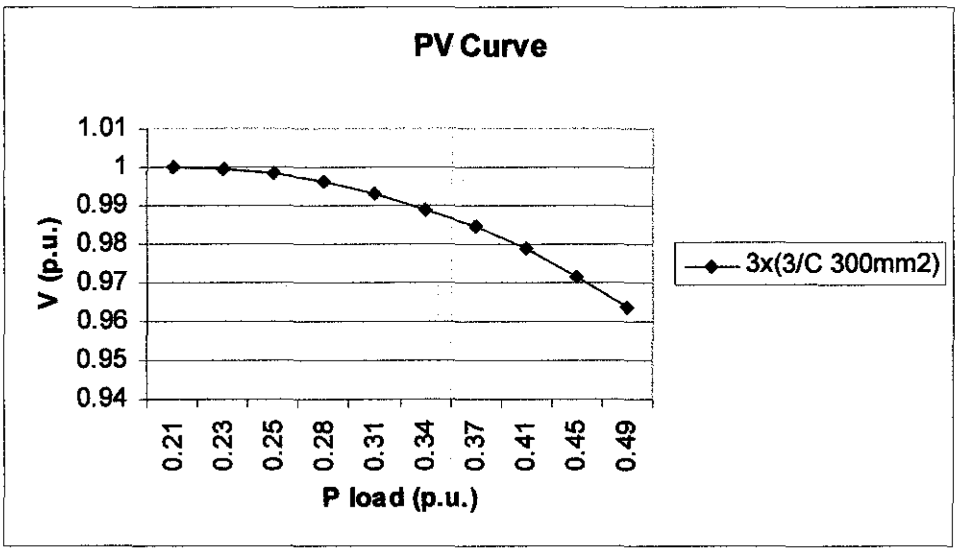


Figure 10 :PV Curve of Base Case Load Flow Analysis

From the table above, when Pload is increased, V magnitude is decreased. Besides, losses on real power and reactive power also increased.

4.3.2 Analysis on the Result After Cable Size is Decreased (3x(3/C 150mm^2)

Next, the cable size for Bus 8 is the decreased from 3/C 300mm^2 to 3/C 150mm^2, at the same time maintaining the number of transmission lines. The load flow analysis is then being carried out again. This is to further testify the adequacy of the network system. The process similar to Base Case Load Flow analysis is repeated to get the new ultimate value of nose point for new PV Curve. The electrical data of the cable 3/C 150mm^2 is shown in the table below.

Cable Size	Current Rating	A.C. Resistance	Star Reactance	Star Capacitance
3/C 150mm^2	380A	0.159ohm/km	0.0943ohm/km	0.40

Table 10 : Electrical Data of 3/C 150mm^2 Cable

From the result obtained, Bus 8 has the voltage magnitude of 1 p.u. and Pload of 0.2099. After obtaining the result, the load demand of Bus 8 is then increased by 10% and load flow analysis is being carried out again. The process is to be repeated 10 times to get the ultimate value of the new Nose Point. The result is then plotted in PV Curve.

The table below shows the result after the cable size is Changed to 3/C 150mm^2.

Load Demand (kVA)	P load (p.u.)	V (p.u.)
22598	0.2099	1
24858	0.2310	0.9991
27344	0.2540	0.9952
30078	0.2794	0.9889
33086	0.3073	0.9808
36394	0.3380	0.9707
40034	0.3719	0.9576
44037	0.4090	0.9427
48441	0.4499	0.9255
53285	0.4949	0.9066

Table 11 :Result of V and Pload After the Cable Size is Changed to 3/C 150mm^2

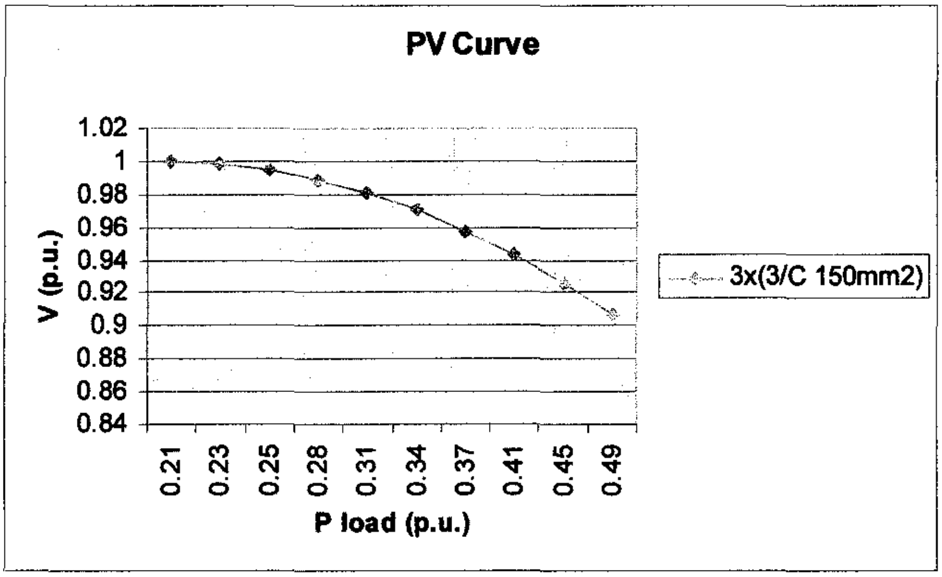


Figure 11 :PV Curve After Cable Size is Changed to 3/C 150mm^2

After the cable size is decreased to 3/C 150mm^2, it is clearly shown that the graph curves in earlier and has a smaller PV Curve. This means that the network system is now more adequate than the base case condition.

4.3.3 Analysis on the Result After Number of Transmission Line is Decreased (2x(3/C 150mm^2)

The number of transmission line is then decreased so that new power flow analysis can be carried out. Through the network system shown, Bus 8 initially has three transmission lines serving its load demand. This time around, load demand for Bus 8 is served by using only two transmission lines, with decreased cable size of 3/C 150mm^2 cable. The process similar to the previous conditions is carried out to obtain new PV Curve.

The table below shows the result after the number of transmission line is decreased.

Load Demand (kVA)	P load (p.u.)	V (p.u.)
22598	0.2099	1
24858	0.2310	0.9982
27344	0.2540	0.9933
30078	0.2794	0.9868
33086	0.3073	0.9755
36394	0.3380	0.9611
40034	0.3719	0.9433
44037	0.4090	0.9225
48441	0.4499	0.8974
53285	0.4949	0.8699

Table 12 : Result of V and Pload After the Number of Transmission Line is Decreased

The PV Curve below shows the result after number of transmission line is decreased from three transmission lines to two transmission lines only.

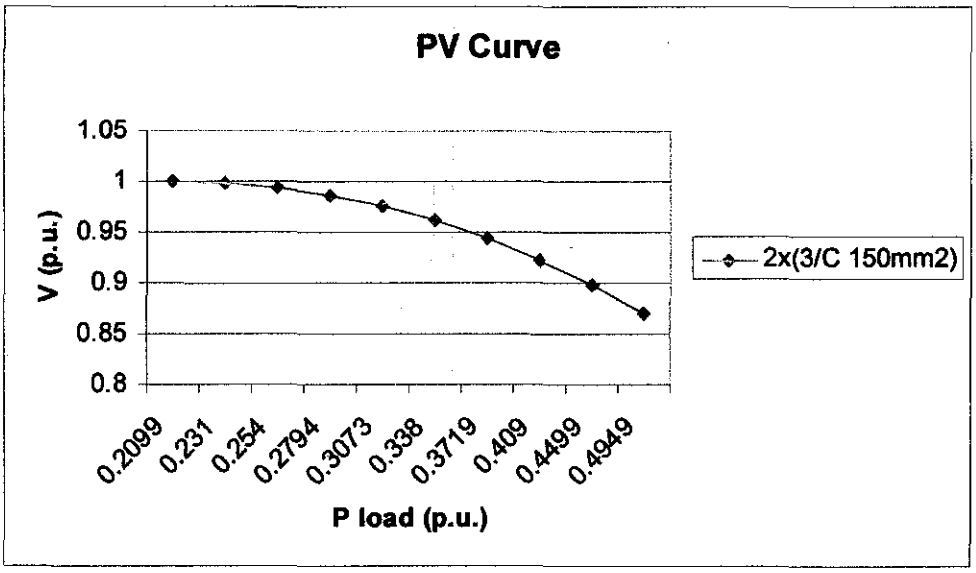


Figure 12 : PV Curve After Number of Transmission Line is Decreased

4.3.4 Comparison of Results of Three Conditions

The three PV Curve obtained from the power flow analysis which has been carried out on Main Substation South network system is shown in the graph below.

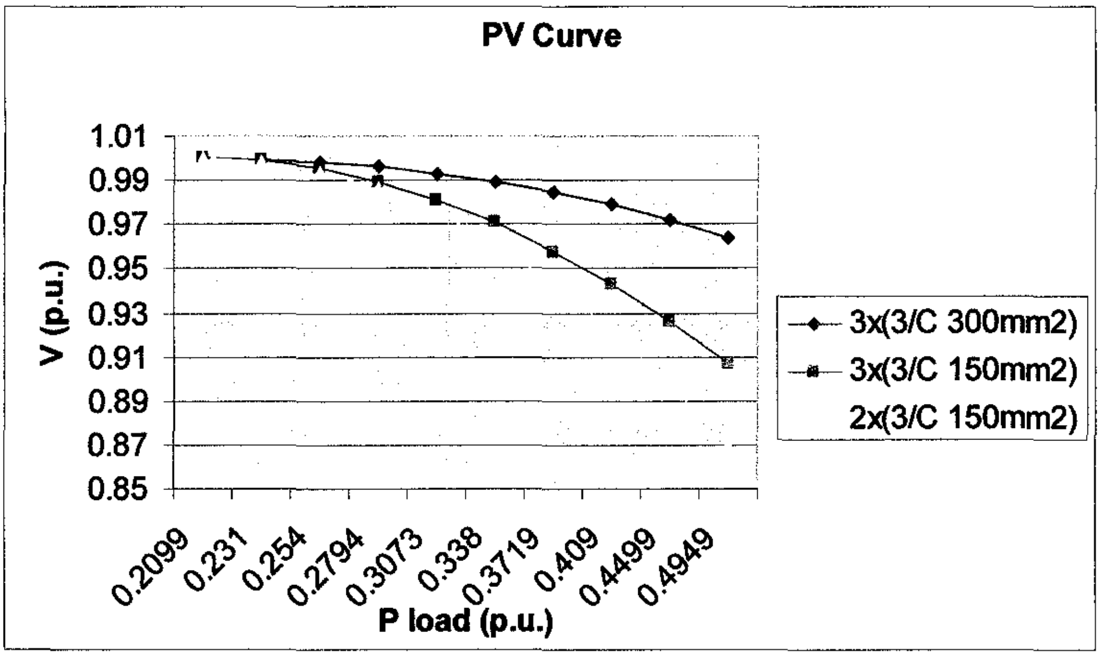


Figure 13 : Comparison of Results of Three Conditions

From the graph shown above, it is clear that the third condition load flow analysis result has the most adequate network configuration. Bus 8 which is reserved for future demand is initially served through three transmission lines using 3/C 300mm^2 cable each. By using third network configuration, the network system is able to operate within the normal operating parameters. This shows that it only need two transmission lines with 3/C 150mm^2 cable to achieve adequacy. Thus with the new configuration, the network system achieve its adequacy, thus results in ability to maintain the stability of the entire network.

When the cable size is changed to 3/C 150mm^2, the results shows that it has smaller curve. This means that it is more adequate than the base case condition. When the transmission is decreased to only two transmission line using 3/C 150mm^2 cable serving the load demand, the results shows that it has even smaller PV curve, thus it is most adequate.

This proves that by decreasing the cable size as well as transmission line, adequacy of the network system can be achieved. Determination of network adequacy evaluation is crucial in a particular system to ensure the system maintain its stability even with increased of load demand.

4.4 DISCUSSION

4.4.1 Power Flow

The power flow problem is formulated as the solution of a nonlinear set of equations in the form:

$$P = 0 = f(x; y) \quad (4.1)$$

$$0 = g(x; y)$$

where y ($y \in R^{2n}$), n being the number of buses in the network, are the algebraic variables, i.e. voltage amplitudes V and phase θ at the network buses, x($x \in R^{m}$) are the state variables, g ($g \in R^{2n}$) are the algebraic equations for the active and the reactive power balances at each bus1 and f ($f \in R^{m}$) are the differential equations.

Differential equations are included in (4.1) since PSAT initializes the state variables of some dynamic components (e.g. induction motors and load tap changers) during power flow computations. Other state variables and control parameters are initialized after solving the power flow solution (e.g. synchronous machines and regulators).

4.4.2 Bus

The network topology is defined by \bus" components, whose data format is depicted in Table 1 Bus numbers, which can be in any order, and voltage ratings Vb are mandatory. Voltage magnitudes V0 and phases Θo can be optionally set if the power flow solution is known or if a custom initial guess is needed. If voltages are not specified, a at start is used (V = 1 at all buses except for the PV and slack generator buses, and Θ = 0). Once the power flow has been solved, voltage values can be saved in the data file using the File/Save/Append Voltages menu in the main window. Data associated with area and region numbers are optional, and will be used in future version of the program. Bus components are defined in the structure Bus, as follows:

4.4.3 Power Flow Results

Column	Variable	Description	Unit
1	-	Bus number	int
2	Vb	Voltage base	kV
3	V0	Voltage amplitude initial guess	p.u.
4	Θo	Voltage phase initial guess	p.u.
5	Ai	Area number	int
6	Ri	Region number	int

Table 13 : Bus Data Format (Bus.con)

1. con: bus data.

2. n: total number of buses.

3. int: bus indexes.

4. Pg: active power injected in the network by generators.

5. Qg: reactive power injected in the network by generators.

6. Pl: active power absorbed from the network by loads.

7. Ql: reactive power absorbed from the network by loads.

8. island: indexes of islanded buses.

The fields Pg, Qg, Pl and Ql are a byproduct of the power flow solution. In the fields Pl and Ql shunt power consumptions are not included, since the shunt admittances are included in the admittance matrix. The field island depends on breaker interventions: if a bus is disconnected from the grid after one or more breaker interventions, the resulting island is properly handled by the time domain simulation routine.

PSAT is component oriented, i.e. standard components can be connected to any bus in any number and type. Only exceptions are slack generators (SW), PV generators (PV) and PQ loads (PQ), which have to be unique for each bus.

4.4.4 Line Flow Results

Transmission lines are defined in the structure Line, which is used also for transformers (see Section 10.3). The user can define data in absolute values or in p.u. In the latter case, the length ` of the line has to be ` = 0. If ` 6= 0, it is assumed that parameters are expressed in unit per km. Table 10.2 depicts the data format of transmission lines. Imax, Pmax and Smax define the limits for currents, active power flows and apparent power flows (S = pP2 + Q2).

PSAT interprets the component as a line, if kT 6= 0, the component is considered a transformer. When kT 6= 0, the line length, l is neglected, even if l, 6= 0. The fixed tap ratio a and the fixed phase shift ratio Φ are optional parameters.

Column	Variable	Description	Unit
1	k	From Bus	int
2	m	To Bus	int
3	Sn	Power rating	MVA
4	Vn	Voltage rating	kV
5	fn	Frequency rating	Hz
6	l	Line length	km
7	-	not used	-
8	r	Resistance	p.u. (/km)
9	x	Reactance	p.u. (H/km)
10	b	Susceptance	p.u. (F/km)
11	-	not used	-
12	-	not used	-
13	Imax	Current limit	p.u.
14	Pmax	Active power limit	p.u.
15	Smax	Apparent power limit	p.u.

Table 14 : Line Data Format (Line.con)

Column	Variable	Description	Unit
1	K	From Bus	int
2	M	To Bus	Int
3	Sn	Power Rating	MVA
4	Vn	Voltage Rating	kV
5	Fn	Frequency Rating	Hz
6	R	Resistance	p.u.
7	X	Reactance	p.u.
8	B	Susceptance	p.u.

Table 15 : Alternative Line Data Format (Lines.con)

CHAPTER 5
CONCLUSION

From the analysis, we can conclude that in order to evaluate the adequacy of a particular network system, we need to stress the system by increasing the load/generation and monitoring the characteristics of the PV curve.

When the cable size is decreased, the results show that it has smaller curve. This means that it is more adequate than the base case condition. When the transmission lines which serve the load demand is decreased, the results shows that it has even smaller PV curve, thus achieve its system's adequacy. Determination of network adequacy evaluation is crucial in a network system to ensure the system maintain its stability even with the increased of load demand

Through this project, I have learnt that the needs of knowledge in advanced algorithms and computational capabilities are required when the issue of stability of the grid is coupled with adequacy and with the impact of dispersed power generation and storage. With the help of today's high speed computers and advanced software, the ability to take on modern system planning techniques would provide distribution, transmission and generation utilities with a means of determining the necessity for system expansion as well as reinforcement.

Hence, the deliverables of this project has been obtained, which is to carry out load flow study in a practical power system using a package. At last, determination of appropriate network configuration for New Doha International Airport has been able to carry out.

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APPENDIX A
POWER FLOW REPORT OF MAIN SUBSTATION NORTH

POWER FLOW REPORT

NETWORK STATISTICS

Buses:	61
Lines:	20
Transformers:	61
Loads:	42

SOLUTION STATISTICS

Number of Iterations:	6
Maximum P mismatch [p.u.]	0
Maximum Q mismatch [p.u.]	0
Power rate [MVA]	100

POWER FLOW RESULTS

Bus	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus 01	1.06	0	4.6203	-0.28197	0	0
Bus 02	1.045	-0.13568	0.7	0.4486	0.1038	0.1778
Bus 03	1.01	-0.33212	0	0.39736	1.1188	0.066
Bus 04	**0.95943**	**-0.26441**	**0**	**0**	**0.1086**	**0.056**
Bus 05	1.0029	-0.22695	0	0	0.0064	0.0224
Bus 06	1.07	-0.36956	0	0.34433	0.0568	0.105
Bus 07	1.036	-0.33938	0	0	0	0
Bus 08	1.09	-0.33938	0	0.13402	0	0
Bus 09	1.0129	-0.37908	0	0	0.0313	0.0324
Bus 10	1.0122	-0.38446	0	0	0.026	0.0812
Bus 11	1.0357	-0.37984	0	0	0.049	0.0252
Bus 12	1.0462	-0.39059	0	0	0.0854	0.0224
Bus 13	1.0366	-0.39147	0	0	0.0189	0.0812
Bus 14	0.99695	-0.41056	0	0	0.0086	0.17
Bus 15	1.022	-0.3797	0	0	0.1067	0.0533

Bus 16	1.041	0	0	0.28397	0	0
Bus 17	1.025	-0.13767	0	0.2463	0.1054	0.0796
Bus 18	1.012	-0.33422	0	0.19556	0.1207	0.064
Bus 19	0.99872	-0.26631	0	0	0.0712	0.053
Bus 20	1.0019	-0.22825	0	0	0.1041	0.0246
Bus 21	0.95	-0.37156	0	0.24623	0.158	0.007
Bus 22	1.034	-0.34138	0	0	0	0
Bus 23	0.98943	-0.43456	0	0	0.1033	0.185
Bus 24	1.09	-0.33947	0	0.03512	0	0
Bus 25	1.0119	-0.37858	0	0	0.0512	0.1344
Bus 26	1.0132	-0.38356	0	0	0.0224	0.0792
Bus 27	1.0343	-0.38124	0	0	0.047	0.0263
Bus 28	1.0462	-0.39059	0	0	0.0854	0.0224
Bus 29	1.0347	-0.39037	0	0	0.0801	0.0823
Bus 30	0.99875	-0.40876	0	0	0.02104	0.0718
Bus 31	1.0223	-0.3794	0	0	0.107	0.0536
Bus 32	1.0412	0	0	0.08417	0	0
Bus 33	1.0252	-0.13747	0	0.2465	0.03056	0.0798
Bus 34	1.0123	-0.33412	0	0.09576	0.0209	0.0642
Bus 35	0.99892	-0.26611	0	0	0.06714	0.0532
Bus 36	1.002	-0.22815	0	0	0.02042	0.0247
Bus 37	1.0521	-0.37126	0	0.24653	0.01621	0.0091
Bus 38	1.0343	-0.34108	0	0	0	0
Bus 39	1.062	0	0	0	0	0
Bus 40	1.0454	-0.13528	0	0.0488	0.0842	0.0782
Bus 41	1.012	-0.33012	0	0.09756	0.319	0.168
Bus 42	0.99784	-0.26439	0	0	0.0596	0.0562
Bus 43	1.0028	-0.22693	0	0	0.0766	0.0226
Bus 44	1.071	-0.36856	0	0.14533	0.0578	0.046
Bus 45	1.037	-0.33838	0	0	0	0
Bus 46	1.092	-0.33738	0	0.23602	0	0
Bus 47	1.0139	-0.37808	0	0	0.114	0.0334
Bus 48	1.0124	-0.38426	0	0	0.0562	0.0814
Bus 49	1.0119	-0.37808	0	0	0.114	0.0334
Bus 50	1.0132	-0.38346	0	0	0.027	0.0822
Bus 51	1.0367	-0.37884	0	0	0.05	0.0262

Bus 52	1.0472	-0.38959	0	0	0.0864	0.0234
Bus 53	1.0376	-0.39047	0	0	0.19	0.0822
Bus 54	0.99795	-0.40956	0	0	0.0096	0.071
Bus 55	1.023	-0.3787	0	0	0.0077	0.0543
Bus 56	1.042	0	0	0.18397	0	0
Bus 57	1.026	-0.13667	0	0.1463	0.0064	0.0806
Bus 58	1.013	-0.33322	0	0.29556	0.1217	0.065
Bus 59	0.99972	-0.26531	0	0	0.0722	0.054
Bus 60	1.1029	-0.22725	0	0	0.1051	0.0256
Bus 61	0.951	-0.37056	0	0	0.059	0.0108

GLOBAL SUMMARY REPORT

TOTAL GENERATION

REAL POWER [p.u.] 5.3203

REACTIVE POWER [p.u.] 4.07602

TOTAL LOAD

REAL POWER [p.u.] 4.3087

REACTIVE POWER [p.u.] 3.1993

TOTAL SHUNT

REAL POWER [p.u.] 0

REACTIVE POWER (IND) [p.u.] 0

REACTIVE POWER (CAP) [p.u.] 0

TOTAL LOSSES

REAL POWER [p.u.] 1.0116

REACTIVE POWER [p.u.] 0.8769

APPENDIX B
POWER FLOW REPORT OF MAIN SUBSTATION SOUTH

NETWORK STATISTICS

Buses:	39
Lines:	13
Transformers:	49
Loads:	28

SOLUTION STATISTICS

Number of Iterations:	4
Maximum P mismatch [p.u.]	0
Maximum Q mismatch [p.u.]	0
Power rate [MVA]	100

POWER FLOW RESULTS

Bus	V [p.u.]	phase [rad]	P gen [p.u.]	Q gen [p.u.]	P load [p.u.]	Q load [p.u.]
Bus 01	1.062	0	4.7193	-0.27227	0	0
Bus 02	1.0443	-0.13578	0.55	0.9474	0.4041	0.1781
Bus 03	1.011	-0.33312	0	0.49836	1.1198	0.267
Bus 04	0.99832	-0.26321	0	0	0.07671	0.0554
Bus 05	1.0019	-0.22675	0	0	0.02053	0.1229
Bus 06	1.068	-0.36846	0	0	0.02579	0.1061
Bus 07	1.043	-0.33858	0	0	0	0
Bus 08	**0.962**	**-0.34238**	**0**	**0**	**0.2099**	**0.1134**
Bus 09	1.0209	-0.38708	0	0	0.0521	0.1404
Bus 10	1.0122	-0.38536	0	0	0.0271	0.0815
Bus 11	1.0427	-0.37284	0	0	0.0953	0.1322
Bus 12	1.0523	-0.38459	0	0	0.0934	0.0285
Bus 13	1.0436	-0.38447	0	0	0.096	0.0883
Bus 14	0.9989	-0.40855	0	0	0.1104	0.172
Bus 15	1.023	-0.3789	0	0	0.0978	0.0547
Bus 16	0.9914	0	0	0	0	0
Bus 17	0.987	-0.1357	0	0	0.1075	0.1815
Bus 18	1.025	-0.33312	0	0	0.0217	0.165
Bus 19	0.9997	-0.26531	0	0	0.03732	0.155
Bus 20	1.0029	-0.22635	0	0	0.0661	0.1266

Bus 21	0.987	-0.36956	0	0	0.2239	0.109
Bus 22	1.0341	-0.34148	0	0	0	0
Bus 23	0.97953	-0.43446	0	0	0.03087	0.0851
Bus 24	0.992	-0.33757	0	0.2498	0	0
Bus 25	1.0108	-0.37958	0	0	0.0311	0.0334
Bus 26	1.0142	-0.38266	0	0	0.0325	0.0802
Bus 27	1.0354	-0.38014	0	0	0.038	0.1272
Bus 28	1.0472	-0.38959	0	0	0.0364	0.1234
Bus 29	1.0452	-0.28927	0	0	0.0314	0.0924
Bus 30	0.99675	-0.31076	0	0	0.0284	0.0698
Bus 31	1.0123	-0.2694	0	0	0.0417	0.0636
Bus 32	1.0522	0	0	0.27317	0	0
Bus 33	0.9992	-0.14347	0	0.9405	0.0366	0.0738
Bus 34	1.0223	-0.32412	0	0.60576	0.0309	0.0742
Bus 35	0.9989	-0.26613	0	0	0.0324	0.0534
Bus 36	1.012	-0.22715	0	0	0.0352	0.0257
Bus 37	1.0611	-0.36226	0	0.45553	0.0211	0.0181
Bus 38	1.0453	-0.33008	0	0	0	0
Bus 39	1.0613	0	0	0.27954	0	0

GLOBAL SUMMARY REPORT

TOTAL GENERATION

REAL POWER [p.u.] 5.2693

REACTIVE POWER [p.u.] 3.9778

TOTAL LOAD

REAL POWER [p.u.] 4.15585

REACTIVE POWER [p.u.] 3.08812

TOTAL SHUNT

REAL POWER [p.u.] 0

REACTIVE POWER (IND) [p.u.] 0

REACTIVE POWER (CAP) [p.u.] 0

TOTAL LOSSES

REAL POWER [p.u.] 1.11345

REACTIVE POWER [p.u.] 0.88968.

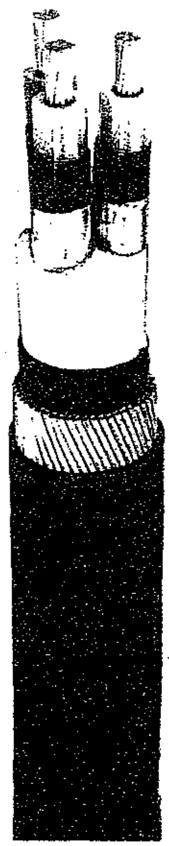
APPENDIX C
ELECTRICAL DATA OF CABLES

CONSTRUCTIONAL DATA (NOMINAL)

NOMINAL CONDUCTOR AREA	DIAMETER UNDER ARMOUR	ARMOUR WIRE DIAMETER	ARMOUR TAPE THICKNESS	OVERALL DIAMETER		CABLE WEIGHT	
				SWA	STA	SWA	STA
mm²	mm	mm	mm	mm	mm	Kg/100m	Kg/100m
25	36.8	2.5	0.5	46.6	43.4	400	3?0
35	39.0	2.5	0.5	49.0	45.8	440	330
50	41.5	2.5	0.5	51.8	48.6	530	370
70	45.1	2.5	0.5	55.5	52.3	590	470
95	49.1	2.5	0.5	59.7	56.5	710	570
120	52.2	2.5	0.5	63.5	60.3	820	690
150	55.4	2.5	0.5	66.6	63.4	920	770
185	59.4	2.5	0.5	70.8	67.6	1070	910
240	65.1	3.15	0.5	76.2	73.7	1380	1110
300	70.1	3.15	0.5	83.6	78.9	1620	1430
400	76.6	3.15	0.8	90.5	87.2	1930	1720

6350/11000V THREE CORE

COPPER CONDUCTORS ARMOURED CABLE



ELECTRICAL DATA (AT 50 HZ)

NOMINAL CONDUCTOR AREA	A.C. RESISTANCE OF CONDUCTOR AT 90°C	STAR REACTANCE	STAR CAPACITANCE
mm2	ohm/Km	ohm/Km	µf/Km
25	0.927	0.126	0.22
35	0.668	0.117	0.24
50	0.494	0.112	0.27
70	0.342	0.106	0.30
95	0.247	0.100	0.34
120	0.196	0.0969	0.37
150	0.159	0.0943	0.40
185	0.128	0.0914	0.43
240	0.0986	0.0882	0.48
300	0.0798	0.0858	0.53
400	0.0641	0.0832	0.59

CURRENT RATINGS (CONTINUOUS)

NOMINAL CONDUCTOR AREA	DIRECT IN GROUND	IN SINGLEWAY DUCTS	IN AIR
mm2	amp	amp	amp
25	140	125	145
35	170	150	175
50	210	180	220
70	255	215	270
95	300	255	330
120	340	290	375
150	380	330	430
185	430	370	490
240	490	425	570
300	540	470	650
400	600	530	740

Current ratings are based on the following conditions:

a) Ground temperature 15°C

b) Ground thermal resistivity 1.2°C m/W

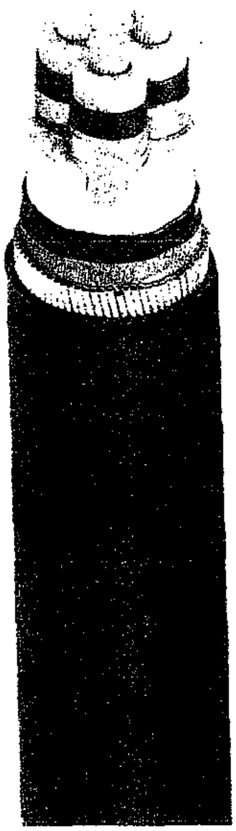
c) Depth of laying 0.8m

d) Ambient air temperature 25°C

e) All cables thermally independent.

19000/33000V THREE CORE

COPPER CONDUCTORS ARMOURED CABLE



CONSTRUCTIONAL DATA (NOMINAL)

NOMINAL CONDUCTOR AREA	DIAMETER UNDER ARMOUR	ARMOUR WIRE DIAMETER	ARMOUR TAPE THICKNESS	OVERALL DIAMETER		CABLE WEIGHT	
				SWA	STA	SWA	STA
mm2	mm	mm	mm	mm	mm	Kg/100m	Kg/100m
70	69.2	3.15	0.5	82.5	77.8	1030	830
95	73.1	3.15	0.5	86.6	82.1	1170	970
120	75.6	3.15	0.8	90.3	87.3	1200	1050
150	79.5	3.15	0.8	93.4	90.1	1410	1190
185	83.5	3.15	0.8	97.8	94.3	1510	1370
240	89.2	4.00	0.8	103.7	100.4	1830	1570
300	94.2	4.00	0.8	108.9	105.8	2150	1830

ELECTRICAL DATA (AT 50 HZ)

NOMINAL CONDUCTOR AREA	A.C. RESISTANCE OF CONDUCTOR AT 90°C	STAR REACTANCE	STAR CAPACITANCE
mm2	ohm/km	ohm/km	μf/km
70	0.342	0.135	0.16
95	0.247	0.127	0.18
120	0.196	0.122	0.19
150	0.159	0.118	0.21
185	0.128	0.114	0.22
240	0.0978	0.109	0.24
300	0.0788	0.105	0.26

CURRENT RATINGS (CONTINUOUS)

NOMINAL CONDUCTOR AREA	DIRECT IN GROUND	IN SINGLEWAY DUCTS	IN AIR
mm2	amp	amp	amp
70	255	225	275
95	295	260	330
120	335	300	380
150	375	335	430
185	420	380	490
240	480	430	570
300	530	480	650

Current ratings are based on the following conditions:

a) Ground temperature 15°C

b) Ground thermal resistivity 1.2°C m/W

c) Depth of laying 0.8m

d) Ambient air temperature 25°C

e) All cables thermally independent.

For variations in these conditions, please refer to page nos. 55 to 57.

Impedance table

Resistance and reactance of XLPE / PVC power cable, Type 600 / 1000V Multi-Core				
Nominal sectional area mm^2	90°C alternating current effective resistance Ω / km		Reactance Ω / km	
	50 Hz	60 Hz	50 Hz	60 Hz
2.5	9.45	9.45	0.0932	0.112
4	5.88	5.88	0.0875	0.105
6	3.93	3.93	0.0837	0.100
10	2.33	2.33	0.0785	0.0942
16	1.47	1.47	0.0761	0.0913
25	0.927	0.927	0.0768	0.0922
35	0.669	0.669	0.0743	0.0892
50	0.494	0.494	0.0739	0.0887
70	0.342	0.343	0.0726	0.0872
95	0.247	0.248	0.0708	0.0850
120	0.196	0.197	0.0705	0.0846
150	0.160	0.160	0.0709	0.0850
185	0.128	0.129	0.0712	0.0854
240	0.0987	0.0998	0.0703	0.0843
300	0.0799	0.0812	0.0697	0.0836
400	0.0640	0.0657	0.0694	0.0833

Resistance and reactance of XLPE / PVC power cable, Type 600 / 1000V Multi-Core (sector-shaped stranded conductor)				
Nominal sectional area mm^2	90°C alternating current effective resistance Ω / km		Reactance Ω / km	
	50 Hz	60 Hz	50 Hz	60 Hz
2.5	0.927	0.927	0.0683	0.0820
35	0.669	0.669	0.0656	0.0787
50	0.494	0.494	0.0651	0.0781
70	0.343	0.343	0.0637	0.0764
95	0.247	0.248	0.0616	0.0739
120	0.197	0.197	0.0613	0.0736
150	0.160	0.161	0.0618	0.0742
185	0.129	0.130	0.0623	0.0747
240	0.0993	0.101	0.0612	0.0734
300	0.0807	0.0824	0.0605	0.0726
400	0.0650	0.0671	0.0603	0.0724

APPENDIX D
POWER SYSTEM ANALYSIS TOOLBOX

\n Open Source Power System Analysis Toolbox

F. Milano, *Member, IEEE*

stract—**This paper describes the Power System Analysis ox (PSAT), an open source Matlab and GNU/Octave- software package for analysis and design of small to ım size electric power systems. PSAT includes power flow, ıuation power flow, optimal power flow, small signal stability sis and time domain simulation as well as several static and nic models, including non-conventional loads, synchronous synchronous machines, regulators and FACTS. PSAT is also ded with a complete set of user-friendly graphical interfaces Simulink-based editor of one-line network diagrams. Basic res, algorithms and a variety of case studies are presented is paper to illustrate the capabilities of the presented tool ts suitability for educational and research purposes.**

lex Terms—**power flow, continuation power flow, optimal r flow, small signal stability analysis, time domain simula- Matlab, GNU/Octave.**

I. INTRODUCTION

)FTWARE packages for power system analysis can be ıasically divided into two classes of tools: commercial 'ares and educational/research-aimed softwares. Commer- ;oftware packages available on the market (e.g. PSS/E, Stag, Simpow, and CYME) follows an "all-in-one" phi- ıhy and are typically well-tested and computationally ent. Despite their completeness, these softwares can result ıersome for educational and research purposes. Even more rtant, commercial softwares are "closed", i.e. do not ' changing the source code or adding new algorithms. 'esearch purposes, the flexibility and the ability of easy typing are often more crucial aspects than computational ency. On the other hand, there is a variety of open source rch tools, which are typically aimed to a specific aspect of :r system analysis. An example is UWPFLOW [1] which des an extremely robust algorithm for continuation power analysis. However, extending and/or modifying this kind ientific tools also requires keen programming skills, in ion to a good knowledge of a low level language (C in ase of UWPFLOW) and of the structure of the program. the last decade, several high level scientific languages, as Matlab, Mathematica and Modelica, have become and more popular for both research and educational ›ses. Any of these languages can lead to good results e field of power system analysis (see for example [2]); :ver Matlab proved to be the best user choice. Key features Iatlab are the matrix-oriented programming, excellent ɪng capabilities and a graphical environment (Simulink) h highly simplifies control scheme design. For these ıns, several Matlab-based commercial, research and ed- onal power system tools have been proposed, such as Power System Toolbox (PST) [3], MatPower [4], Toolbox (VST) [5], MatEMTP [6], SimPowerSystems (SPS) [7], Power Analysis Toolbox (PAT) [8], and the Educational Simulation Tool (EST) [9]. Among these, only MatPower and VST are open source and freely downloadable.

ımitted to the IEEE Transaction on Power Systems, November 2004.
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TABLE I
MATLAB-BASED PACKAGES FOR POWER SYSTEM ANALYSIS

Package	PF	CPF	OPF	SSA	TD	EMT	GUI	GNE
EST	✓			✓	✓			✓
MatEMTP					✓	✓	✓	✓
MatPower	✓		✓					
PAT	✓			✓	✓			✓
PSAT	✓	✓	✓	✓	✓		✓	✓
PST	✓	✓		✓	✓			
SPS	✓			✓	✓	✓	✓	✓
VST	✓	✓		✓	✓		✓	

This paper describes a new Matlab-based power system analysis tool (PSAT) which is freely distributed on line [10]. PSAT includes power flow, continuation power flow, optimal power flow, small signal stability analysis and time domain simulation. The toolbox is also provided with a complete graphical interface and a Simulink-based one-line network editor. Table I depicts a rough comparison of the currently available Matlab-based tools for power system analysis and PSAT. The features illustrated in the table are the power flow (PF), the continuation power flow and/or voltage stability analysis (CPF-VS), the optimal power flow (OPF), the small signal stability analysis (SSA) and the time domain simulation (TD) along with "aesthetic" features such as the graphical user interface (GUI) and the graphical network editor (GNE).

An important but often missed issue is that the Matlab environment is a commercial and "closed" product, thus Matlab kernel and libraries cannot be modified nor freely distributed. To allow exchanging ideas and effectively improving scientific research, both the toolbox and the platform on which the toolbox runs should be free [11]. At this aim, PSAT can run on GNU/Octave [12], which is a free Matlab clone.

The paper is organized as follows. Section II illustrates the main PSAT features while Section III describes the models and the algorithms for power system analysis implemented in PSAT. Section IV presents a variety of case studies based on the IEEE 14-bus test system. Finally Section V presents conclusions and future work directions.

II. PSAT FEATURES

A. *Outlines*

PSAT has been thought to be portable and open source. At this aim, PSAT has been developed using Matlab, which runs on the commonest operating systems, such as Unix, Linux, Windows and Mac OS X. Nevertheless, PSAT would not be letely open source if it run only on Matlab, which is ıprietary software. At this aim PSAT can run also on test GNU/Octave releases [12], which is basically a free ıb clone. In the knowledge of the author, PSAT is actually rst *free software* project in the field of power system sis. PSAT is also the first power system software which on GNU/Octave platforms.

ɜ synoptic scheme of PSAT is depicted in Fig. 1. Observe 'SAT kernel is the power flow algorithm, which also takes of the state variable initialization. Once the power flow ıeen solved, the user can perform further static and/or nic analyses. These are:

Continuation Power Flow (CPF);
Optimal Power Flow (OPF);
Small signal stability analysis;
Time domain simulations.

AT deeply exploits Matlab vectorized computations and ɜ matrix functions in order to optimize performances. ermore PSAT is provided with the most complete set of ithms for static and dynamic analyses among currently ıble Matlab-based power system softwares (see Table I). ` also contains interfaces to UWPFLOW [1] and GAMS which highly extend PSAT ability to solve CPF and OPF ems, respectively. These interfaces are not discussed here, ɜy are beyond the main purpose of this paper.

order to perform accurate and complete power system ses, PSAT supports a variety of static and dynamic ls, as follows:

ver Flow Data: Bus bars, transmission lines and trans- ners, slack buses, PV generators, constant power loads, shunt admittances.
rket Data: Power supply bids and limits, generator 'er reserves, and power demand bids and limits.
'tches: Transmission line faults and breakers.
asurements: Bus frequency measurements.
ıds: Voltage dependent loads, frequency dependent loads, (polynomial) loads, thermostatically controlled loads, exponential recovery loads [14].
chines: Synchronous machines (dynamic order from 2 to nd induction motors (dynamic order from 1 to 5).
ıtrols: Turbine Governors, AVRs, PSSs, Over-excitation ters, and secondary voltage regulation.
;ulating Transformers: Under load tap changers and ɜe shifting transformers.
ƆTS: SVCs, TCSCs, SSSCs, UPFCs.
ıd Turbines: Wind models, constant speed wind turbine ı squirrel cage induction motor, variable speed wind ıine with doubly fed induction generator, and variable ɜd wind turbine with direct drive synchronous generator.
ıer Models: Synchronous machine dynamic shaft, sub- chronous resonance model, solid oxide fuel cell, and sub- smission area equivalents.

sides mathematical algorithms and models, PSAT in- s a variety of additional tools, as follows:

User-friendly graphical user interfaces;
Simulink library for one-line network diagrams;
Data file conversion to and from other formats;

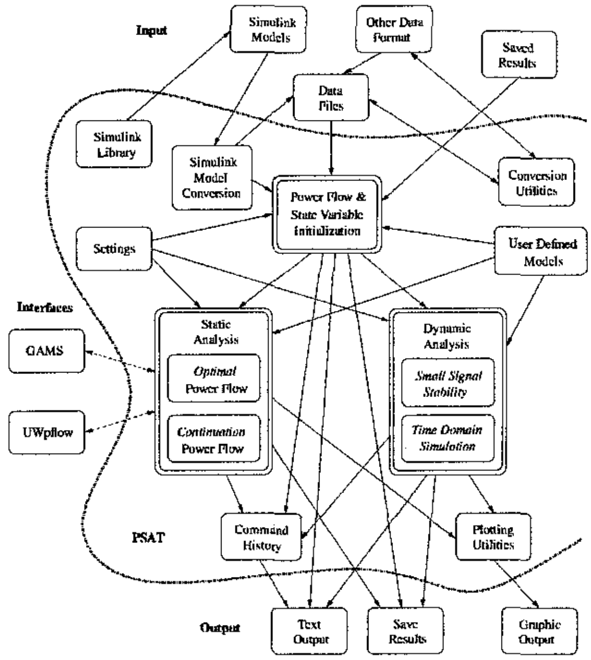


Fig. 1. Synoptic scheme of PSAT.

TABLE II
FUNCTIONS AVAILABLE ON MATLAB AND GNU/OCTAVE PLATFORMS

Function	Matlab	GNU/Octave
Continuation power flow	yes	yes
Optimal power flow	yes	yes
Small signal stability analysis	yes	yes
Time domain simulation	yes	yes
GUIs and Simulink library	yes	no
Data format conversion	yes	yes
User defined models	yes	no
Command line usage	yes	yes

4) User defined model editor and installer;
5) Command line usage.

The following subsections will briefly describe these tools. Observe that, due to GNU/Octave limitations, not all algorithms/tools are available on this platform (see Table II).

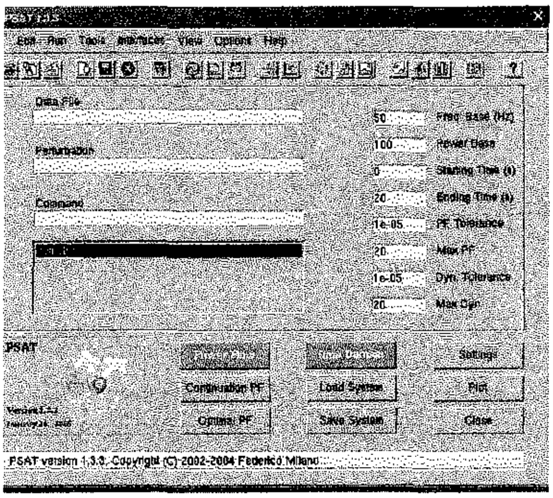
B. Getting Started and Main Graphical User Interface

PSAT is launched by typing at the Matlab prompt:

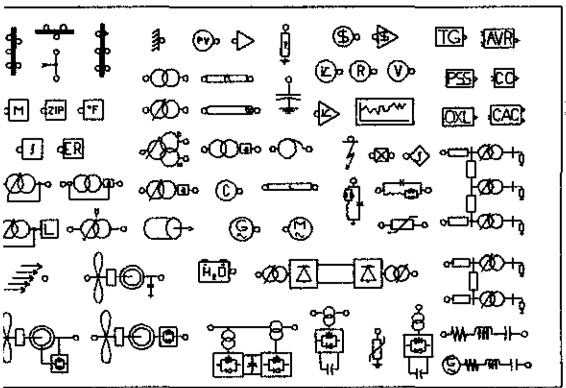
```
>> psat
```

which will create all structures required by the toolbox and open the main GUI (see Fig. 2). All procedures implemented in PSAT can be launched from this window by means of menus, buttons and/or short cuts.

The main settings, such as the system base or the maximum number of iteration of Newton-Raphson methods, are shown in the main window. Other system parameters and specific algorithm settings have dedicated GUIs (see Figs. 8 and 11). Observe that PSAT does not rely on GUIs and makes use of global variables to store both setting parameters and data. This approach allows using PSAT from the command line as needed in many applications (see following Section II-E).



Main graphical user interface of PSAT.



PSAT Simulink library.

mulink Library

AT allows drawing electrical schemes by means of picto-locks. Fig. 3 depicts the complete PSAT-Simulink library ılso Fig. 7 which illustrates the IEEE 14-bus test system). e PSAT computational engine is purely Matlab-based and imulink environment is used only as graphical tool. As a r of fact, Simulink models are read by PSAT to exploit ›rk topology and extract component data. A byproduct of pproach is that PSAT can run on GNU/Octave, which is ntly not providing a Simulink clone.

ıserve that some Simulink-based tools, such as PAT [8] EST [9], use Simulink to simplify the design of new ol schemes. This is not possible in PSAT. However, PAT EST do not allow representing the network topology, thus ing in a lower readability of the whole system.

ata Conversion and User Defined Models

ensure portability and promote contributions, PSAT is ded with a variety of tools, such as a set of Data Format ersion (DFC) functions and the capability of defining Defined Models (UDMs).

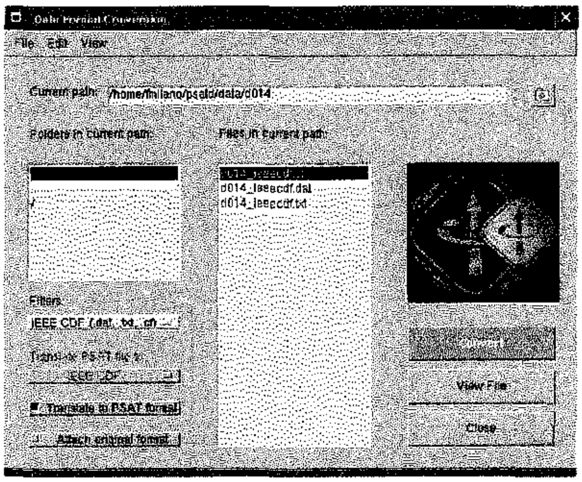


Fig. 4. GUI for data format conversion.

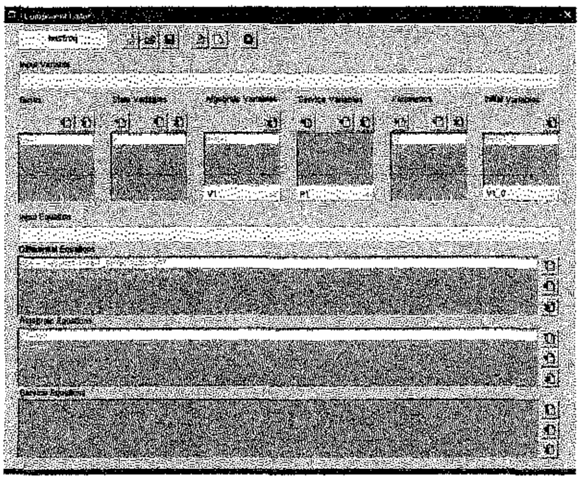


Fig. 5. GUI for user defined models.

The set of DFC functions allows converting data files to and from formats commonly in use in power system analysis. These include: IEEE, EPRI, PTI, PSAP, PSS/E, CYME, MatPower and PST formats. On Matlab platforms, an easy-to-use GUI (see in Fig. 4) handles the DFC.

The UDM tools allow extending the capabilities of PSAT and help end-users to quickly set up their own models. UDMs can be created by means of the GUI depicted in Fig. 5. Once the user has introduced the variables and defined the DAE of the new model in the UDM GUI, PSAT automatically compiles equations, computes symbolic expression of Jacobians matrices (by means of the Symbolic Toolbox) and writes a Matlab function of the new component. Then the user can save the model definition and/or install the model in PSAT. If the component is not needed any longer it can be uninstalled using the UDM installer as well.

E. Command Line Usage

GUIs are useful for education purposes but can in some cases limit the development or the usage of a software. For

eason PSAT is provided with a command line version. feature allows using PSAT in the following conditions:
it is not possible or very slow to visualize the graphical ronment (e.g. Matlab is running on a remote server).
one wants to write scripting of computations or include to PSAT functions within user defined programs.
PSAT runs on the GNU/Octave platform, which currently ıer provides GUI tools nor a Simulink-like environment.

III. Models and Algorithms

ıwer System Model

standard power system model is basically a set of ıear differential algebraic equations, as follows:

$$\begin{aligned} \dot{x} &= f(x,y,p) \\ 0 &= g(x,y,p) \end{aligned} \quad (1)$$

x are the state variables $x \in \mathbb{R}^n$; y are the algebraic ıles $y \in \mathbb{R}^m$; p are the independent variables $p \in \mathbb{R}^\ell$; f e differential equations $f : \mathbb{R}^n \times \mathbb{R}^m \times \mathbb{R}^\ell \mapsto \mathbb{R}^n$; and g ıe algebraic equations $g : \mathbb{R}^m \times \mathbb{R}^m \times \mathbb{R}^\ell \mapsto \mathbb{R}^m$.
AT uses (1) in all algorithms, namely power flow, CPF, small signal stability analysis and time domain simula- as discussed in the following subsections from III-B to The algebraic equations g are obtained as the sum of all and reactive power injections at buses:

$$c,y,p) = \begin{bmatrix} g_p \\ g_q \end{bmatrix} = \begin{bmatrix} g_{pm} \\ g_{qm} \end{bmatrix} - \sum_{c \in \mathcal{C}_m} \begin{bmatrix} g_{pc} \\ g_{qc} \end{bmatrix} \quad \forall m \in \mathcal{M} \quad (2)$$

g_{pm} and g_{qm} are the power flows in transmission lines mmonly defined in the literature [15], $\mathcal{M}$ is the set of ırk buses, $\mathcal{C}_m$ and $[g_{pc}^T, g_{qc}^T]^T$ are the set and the power ions of components connected at bus m, respectively.
AT is component-oriented, i.e. any component is defined endently of the rest of the program as a set of nonlinear ential-algebraic equations, as follows:

$$\begin{aligned} \dot{x}_c &= f_c(x_c, y_c, p_c) \\ P_c &= g_{pc}(x_c, y_c, p_c) \\ Q_c &= g_{qc}(x_c, y_c, p_c) \end{aligned} \quad (3)$$

x_c are the component state variables, y_c the algebraic ıles (i.e. V and θ at the buses to which the component is cted) and p_c are independent variables. Then differential ions f in (1) are built concatenating f_c of all components. uations (3) along with Jacobians matrices are defined function which is used for both static and dynamic ses. In addition to this function, a component is defined eans of a structure, which contains data, parameters and ıterconnection to the grid.
the sake of clarity, let us consider the following exam- amely the exponential recovery load (ERL) [14]. The set ferential-algebraic equations are as follows:

$$\begin{aligned} \dot{x}_{c_1} &= -x_{c_1}/T_P + P_0(V/V_0)^{\alpha_s} - P_0(V/V_0)^{\alpha_t} \\ \dot{x}_{c_2} &= -x_{c_2}/T_Q + Q_0(V/V_0)^{\beta_s} - Q_0(V/V_0)^{\beta_t} \\ P_c &= x_{c_1}/T_P + P_0(V/V_0)^{\alpha_t} \\ Q_c &= x_{c_2}/T_Q + Q_0(V/V_0)^{\beta_t} \end{aligned} \quad (4)$$

TABLE III
EXPONENTIAL RECOVERY LOAD DATA FORMAT (`Erload.con`)

Column	Variable	Description	Unit
1	-	Bus number	int
2	S_n	Power rating	MVA
3	V_n	Active power voltage coefficient	kV
4	f_n	Active power frequency coefficient	Hz
5	T_P	Real power time constant	s
6	T_Q	Reactive power time constant	s
7	α_s	Static real power exponent	-
8	α_t	Dynamic real power exponent	-
9	β_s	Static reactive power exponent	-
10	β_t	Dynamic reactive power exponent	-

where most parameters are defined in Table III and P_0, Q_0 and V_0 are initial powers and voltages, respectively, as given by the power flow solution. Observe that a constant PQ load must be connected at the same bus as the ERL to determine the values of P_0, Q_0 and V_0.

Exponential recovery loads are defined in the structure `Erload`, whose fields are as follows:

1) `con`: exponential recovery load data.
2) `bus`: Indexes of buses to which the ERLs are connected.
3) `dat`: Initial powers and voltages (P_0, Q_0 and V_0).
4) `n`: Total number of ERLs.
5) `xp`: Indexes of the state variable x_{c_1}.
6) `xq`: Indexes of the state variable x_{c_2} .

B. Power Flow

PSAT included the standard Newton-Raphson method [15], the fast decoupled power flow (XB and BX variations [16]), and a power flow with a distributed slack bus model [17]. The latter is a novelty among Matlab-based power system softwares. The power flow problem is formulated as (1) with zero first time derivatives $\dot{x}$:

$$\begin{aligned} 0 &= f(x,y) \\ 0 &= g(x,y) \end{aligned} \quad (5)$$

Differential equations are included in (5) although some dynamic components are initialized after power flow analysis. This is needed if the known input data of the component are not the input parameters of its dynamic model. For example the user does not generally know field voltages and mechanical torques of synchronous machines. However the user does know desired voltages and active powers injected into the network by generators. Thus one can solve the power flow first, using PV buses and then initialize synchronous machine state variables using the power flow solution. Nevertheless, other components can be included in the power flow as one typically knows the input parameters of the dynamic model. For example in the case of load tap changers, it is likely the user knows the regulator reference voltage rather than the transformer tap ratio.

The distributed slack bus model is based on a generalized power center concept and consists in distributing losses among all generators [17]. This is obtained by rewriting active powers P_G of slack and PV generators as:

$$P_G = (1 + k_G\gamma)P_{G_0} \quad (6)$$

: P_{G_0} are the desired generator active powers, k_G is lar variable which distributes power losses among all ators and γ are the participation factors of the generators ; losses. Observe that k_G is an unknown insofar as ; are unknown. Assuming that (6) has been written for nerators, k_G is balanced by the phase reference equation.

ontinuation Power Flow

; Continuation Power Flow (CPF) function included in ' is a novelty among available Matlab-based packages ower system analysis. The CPF algorithm consists in a ctor step which computes a normalized tangent vector corrector step that can be obtained either by means of a parametrization or a perpendicular intersection [18]. The problem is defined based on (1), as follows:

$$\begin{aligned} 0 &= f(x,y,\lambda) \\ 0 &= g(x,y,\lambda) \end{aligned} \tag{7}$$

: $\lambda \in \mathbb{R}$ is the *loading parameter*, which is used to base case generator and load powers, P_{G_0}, P_{L_0} and Q_{L_0} ctively, as follows:

$$\begin{aligned} P_G &= (\lambda + \gamma k_G) P_{G_0} \\ [P_L, Q_L] &= \lambda [P_{L_0}, Q_{L_0}] \end{aligned} \tag{8}$$

ptimal Power Flow

; Optimal Power Flow (OPF) is defined as a nonlinear :ained optimization problem. The Interior Point Method) with a Mehrotra's predictor-corrector method is used ve the OPF problem [19]. Notice that PSAT is the only b-based software which provides an IPM algorithm to the OPF-based market clearing problem. A variety of tive functions are included in PSAT, as follows:

Market Clearing Procedure: The "standard" OPF-based et model is represented in PSAT as follows:

$$\begin{aligned} \text{Minimize}_{(y,p)} \quad & F(p) \\ \text{subject to} \quad & g(y,p) = 0 \\ & h_{\min} \le h(y) \le h_{\max} \\ & p_{\min} \le p \le p_{\max} \end{aligned} \tag{9}$$

: g and y are defined as in (1), the control variables p ie power demand and supply bids P_D and P_S, while $^{\ell} \mapsto \mathbb{R}$ and $h : \mathbb{R}^m \mapsto \mathbb{R}^q$ are the objective function and equality constraints, respectively.

; goal is to maximize the social benefit; thus, the objecunction F is defined as:

$$F = -\Big(\sum_i C_{D_i}(P_{D_i}) - \sum_i C_{S_i}(P_{S_i})\Big) \tag{10}$$

: C_S and C_D are quadratic functions of supply and nd bids in \$/MWh, respectively.

; physical and security limits h included in PSAT are r to what is used in [20], and take into account transmisine thermal limits, transmission line power flow limits, ator reactive power limits, and voltage "security" limits.

2) VSC-OPF Market Clearing Model: The following optimization problem is used for representing an OPF market clearing model with inclusion of voltage stability constraints, based on what was proposed in [21] and [22]:

$$\begin{aligned} \text{Minimize}_{(y,p,\hat{y},\lambda)} \quad & f(p,\lambda) \\ \text{subject to} \quad & g(y,p) = 0 \\ & \hat{g}(\hat{y},p,\lambda) = 0 \\ & \lambda \ge \hat{\lambda} \\ & h_{\min} \le h(y) \le h_{\max} \\ & \hat{h}_{\min} \le h(\hat{y}) \le \hat{h}_{\max} \\ & p_{\min} \le p \le p_{\max} \end{aligned} \tag{11}$$

In (11), a second set of power flow variables $\hat{x} \in \mathbb{R}^m$ and equations $\hat{g} : \mathbb{R}^m \times \mathbb{R}^{\ell} \times \mathbb{R} \mapsto \mathbb{R}^m$, together with the constraints $h(\hat{x}) : \mathbb{R}^m \mapsto \mathbb{R}^q$, are introduced to represent the solution associated with a loading parameter λ, where λ represents an increase in generator and load powers, as follows:

$$\begin{aligned} \hat{P}_G &= (1 + \lambda + \hat{k}_G) P_G \\ \hat{P}_L &= (1 + \lambda) P_L \end{aligned} \tag{12}$$

where P_G and P_L are total generator and load powers for the current market condition.

Two objective functions are available: the maximization of the distance to the maximum loading condition:

$$F = -\lambda \tag{13}$$

and a multi-objective objective function:

$$F = -\omega\Big(\Big(\sum_i C_{D_i}(P_{D_i}) - \sum_i C_{S_i}(P_{S_i})\Big)\Big) - (1-\omega)\lambda \tag{14}$$

where $\omega \in (0,1)$ is a factor which allows weighting the influence of the system security on the market clearing procedure.

E. Small Signal Stability Analysis

PSAT allows computing and plotting the eigenvalues and the participation factors of the system, once the power flow has been solved. The eigenvalues can be computed for the state matrix of the dynamic system, and for the power flow Jacobian matrix (QV sensitivity analysis) [23]. Unlike other softwares, such as PST and Simulink-based tools, eigenvalues are computed using analytical Jacobian matrices, thus ensuring high precision results.

1) Dynamic Analysis: The Jacobian matrix A_C of a dynamic system is defined by linearizing (5), as follows:

$$\begin{bmatrix} \Delta\dot{x} \\ 0 \end{bmatrix} = \begin{bmatrix} F_x & F_y \\ G_x & J_{LFV} \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} = [A_C] \begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix} \tag{15}$$

where $F_x = \nabla_x f$, $F_y = \nabla_y f$, $G_x = \nabla_x g$, and $J_{LFV} = \nabla_y g$. Then the state matrix A_S is obtained by eliminating Δy, and thus implicitly assuming that J_{LFV} is non-singular (i.e. no singularity-induced bifurcations):

$$A_S = F_x - F_y J_{LFV}^{-1} G_x \tag{16}$$

The computation of all eigenvalues can be a lengthy process if the dynamic order of the system is high. At this aim, PSAT

TABLE IV

ɪRMANCE OF PSAT SOLVERS FOR THE IEEE 14-BUS TEST SYSTEM

Simulation	Elapsed Time [s]
Power flow (Newton-Raphson method)	0.0345
Continuation power flow	2.41
Optimal power flow	0.21
Small signal stability analysis	0.16
Time domain simulation ($\Delta t = 0.1$ s)	22.0

s computing a reduced number of eigenvalues based on ɜ matrix properties and eigenvalue relative values (e.g. ;t or smallest magnitude, etc.). PSAT also computes partion factors using right and left eigenvector matrices [15].

QV Sensitivity Analysis: The QV sensitivity analysis is uted on a reduced matrix, as it was proposed in [23]. s assume that the power flow Jacobian matrix J_{LFV} is ɜd in four sub-matrices:

$$J_{LFV} = \begin{bmatrix} J_{P\theta} & J_{PV} \\ J_{Q\theta} & J_{QV} \end{bmatrix} \quad (17)$$

the reduced matrix used for QV sensitivity analysis is ɔd as follows:

$$J_{LFVr} = J_{QV} - J_{Q\theta} J_{P\theta}^{-1} J_{PV} \quad (18)$$

ɜ it is assumed that $J_{P\theta}$ is non-singular [23]. Observe he power flow Jacobian matrix used in PSAT takes into ɪnt all static and dynamic components, e.g. tap changers ls etc.

ne Domain Simulation

Integration Methods: Two integration methods are avail- i.e. backward Euler and trapezoidal rule, which are cit A-stable algorithms and solve (1) together (simulus-implicit method, SI). This method is numerically stable than the partitioned-explicit method, which solves ential and algebraic equations separately [15]. Observe PSAT is currently the only Matlab-based tool which ments a SI method for the numerical integration of (1).

Handling Disturbances: The commonest perturbations ansient stability analysis, i.e. faults and breaker operaare handled by means of embedded functions. Step perːions can be obtained by changing parameter or variable s after completing the power flow. All other disturbances e defined through custom "perturbation" functions, which ɪclude and modify any global structure of the system.

IV. CASE STUDIES

is section illustrates some PSAT features for static and nic stability analysis by means of the IEEE 14-bus test n (authors interested in reproducing the outputs could ve the data from the PSAT web site [10]). All results been obtained on Matlab 7 running on a Intel Pentium 66 GHz. Table IV depicts simulation times for the 14-est system. Results were double-checked by means of software packages, namely PST [3], UWPFLOW [1], ƷAMS [13].

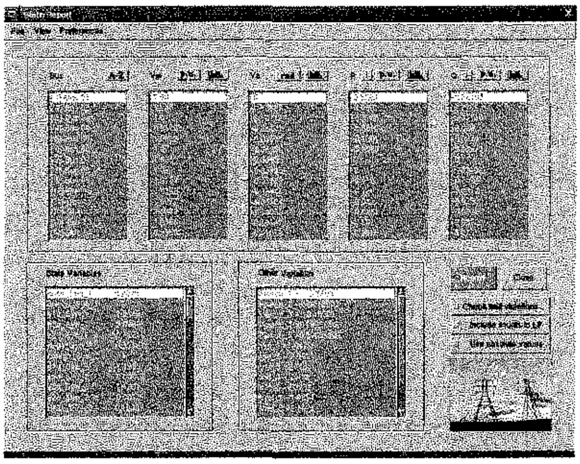


Fig. 6. GUI for power flow reports. The results refer to the IEEE 14-bus test system.

TABLE V

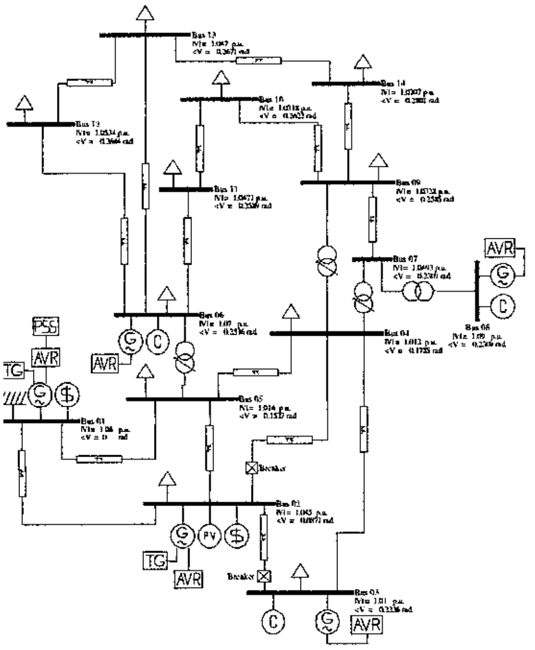
PERFORMANCE OF PSAT POWER FLOW SOLVERS

Network	NR [s]	XB [s]	BX [s]
IEEE 14-bus	0.0345	0.0151	0.0166
IEEE 118-bus	0.0586	0.0197	0.0173
IEEE 300-bus	0.1306	0.0447	0.0423
1228-bus (Italian HV grid)	0.6546	0.1413	0.1798

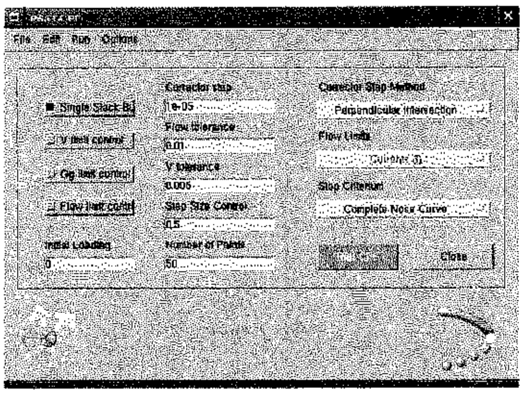
Figure 7 depicts the model of the IEEE 14-bus network built using the PSAT Simulink library. Once defined in the Simulink model, one can load the network in PSAT and solve the power flow. Power flow results can be displayed in a GUI (see Fig. 6) and exported to a file in several formats including Excel and LaTeX. PSAT also allows displaying bus voltages and power flows within the Simulink model of the currently loaded system (e.g. see the bus voltage report in Fig. 7). Notice that PSAT uses vectorized computations and sparse matrix functions provided by Matlab, so that computation times increase slowly as the network size increase. Table V illustrates net power flow computation times for a variety of tests network, with different solvers, namely Newton-Raphson method (NR) and fast decoupled power flows (both XB and BX variations). Results were obtained using the command line version of PSAT (times are about 0.5 s slower if using GUIs).

CPF analysis is handled by a dedicated GUI, as illustrated in Fig. 8. Nose curves can be plotted using the GUI for plotting simulation results, which is depicted in Fig. 9. Figure 10 illustrates the nose curves (V, λ_c) obtained using the CPF algorithm implemented in PSAT. The curves refers to mere static equations, i.e. the differential equations of synchronous machines and controls are ignored during the CPF analysis. Figure 10 depicts three different nose curves considering the base case network and line 2-4 and line 2-3 outages, respectively. Notice that contingencies are simulated by setting the status of breakers as "open" in the Simulink model.

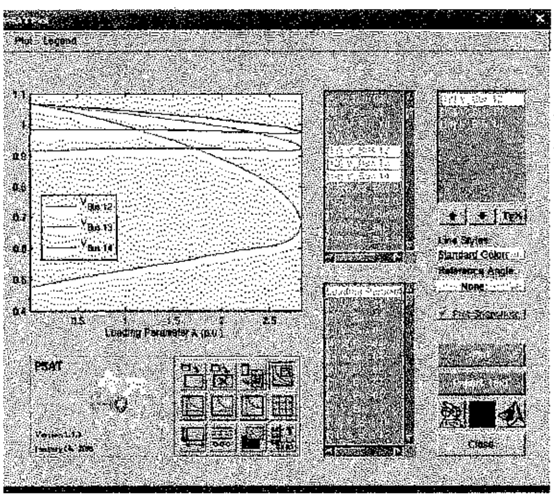
The GUI depicted in Fig. 11 allows adjusting parameters and preferences for OPF analysis. For the sake of comparison with the CPF analysis, Table VI depicts the maximum loading parameter λ^*, the base case power ($BCP = \sum_i P_{L_i}$) the



PSAT-Simulink model of the IEEE 14-bus test system.



GUI for continuation power flow settings.



GUI for plotting CPF results. The plots illustrate voltages at buses and 14 for the IEEE 14-bus test system with no contingency.

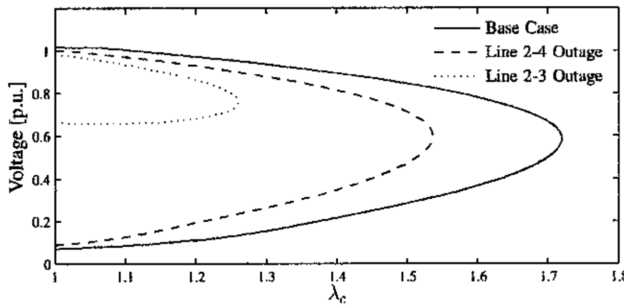


Fig. 10. Nose curves at bus 14 for different contingencies for the IEEE 14-bus test system.

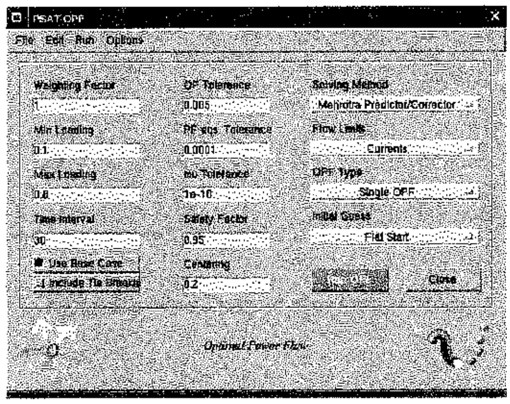


Fig. 11. GUI for OPF settings. Observe that the weighting factor is set to 1 in order to obtain the objective function (13).

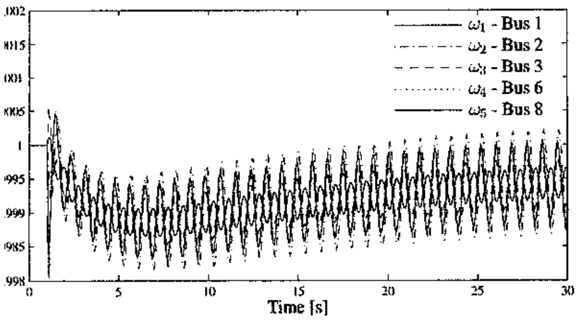
Maximum Loading Condition ($MLC = (1 + \lambda^*)BCP$) and the Available Loading Capability ($ALC = \lambda^* BCP$) for the base case and the lines 2-3 and 2-4 outages. The OPF problem used to compute the MLC is (11) and (13). Notice that, because of the definitions of generator and load powers P_G and P_L given in (8) and (12), one has $\lambda_c = \lambda^* + 1$.

The test case presented in [24] is reproduced here to illustrate small signal stability analysis and time domain simulation available in PSAT. Firstly it has been used the IEEE 14-bus system with a 40% load increase with respect to the base case loading, and no PSS at bus 1. As illustrated by the time domain simulation depicted in Fig. 12, a Hopf bifurcation occurs for the line 2-4 outage resulting in undamped oscillations of generator angles. A similar analysis can be carried on the same system with a 40% load increase but considering the PSS of the generator connected at bus 1. Figure 13 depicts the GUI for eigenvalue analysis and shows that the system is stable.

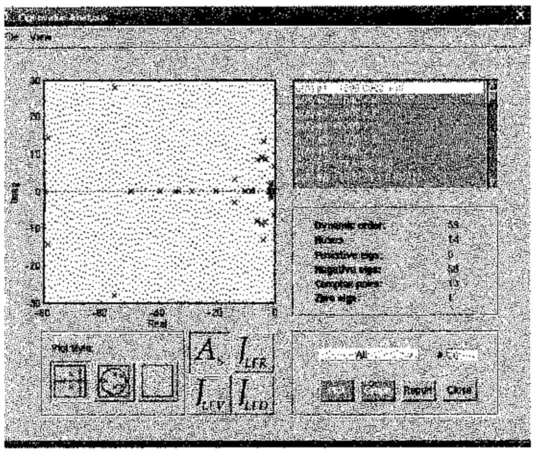
TABLE VI

MAXIMUM LOADING CONDITION OPF FOR THE IEEE 14-BUS NETWORK

Contingency	BCP [MW]	λ^* [p.u.]	MLC [MW]	ALC [MW]
None	259	0.7211	445.8	186.8
Line 2-4 Outage	259	0.5427	399.5	148.6
Line 2-3 Outage	259	0.2852	332.8	73.85



. Generator speed oscillations for the IEEE 14-bus test system due f bifurcation triggered by line outage at 40% overload.



. GUI for eigenvalue analysis. The plot illustrates eigenvalues for the 4-bus test system with PSS, for a line 2-4 outage at 40% overload.

V. Conclusions

s paper has presented a new open-source power sys- ınalysis toolbox (PSAT) which runs on Matlab and 'Octave. PSAT comes with a variety of procedures for and dynamic analysis, several models of standard and ıventional devices, a complete GUI, and a Simulink- network editor. These features make PSAT suited oth educational and research purposes. As a matter :t, PSAT is currently used by several undergraduates, students and researchers, and has an active mailing list '/groups.yahoo.com/groups/psatforum) currently count- ver 290 members. Among future projects, there are ding the CPF algorithm to dynamic bifurcation analysis ncluding new control schemes and renewable energy ator models. Any suggestion and/or bug report are very ıme.

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