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REAL AND REACTIVE POWER FLOW USING UNIFIED POWER FLOW CONTROLLER

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Abstract— *The focus of this thesis is a FACTS device known as the Unified Power Flow Controller (UPFC). With its unique capability to control simultaneously real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it is connected, this device creates a tremendous quality impact on power system stability. These features become even more significant knowing that the UPFC can allow loading of the transmission lines close to their thermal limits, forcing the power to flow through the desired paths. This will give the power system operators much needed flexibility in order to satisfy the demands that the deregulated power system will impose.The most cost-effective way to estimate the effect the UPFC has on a specific power System operation is to simulate that system together with the UPFC by using one of the existing simulations packages. Specifically, the objective of this thesis is to (1) develop a UPFC model that can be incorporated into existing MATLAB based Power System analysis Toolbox (PSAT), (2) design basic UPFC controllers to enhance power system stability. The proposed tools will be tested on the two-area-four-generator system to prove their effectiveness.*

Keywords— FACTS,UPFC,PSAT,

I.INTRODUCTION

1.1BACKGROUND

The power system is an interconnection of generating units to load centers through high voltage electric transmission lines and in general is mechanically controlled. It can be divided into three subsystems: generation, transmission and distribution subsystems. Until recently all three subsystems were under supervision of one body within a certain geographical area providing power at regulated rates. In order to provide cheaper electricity the deregulation of power system, which will produce separate generation, transmission and distribution companies, is already being performed. At the same time electric power demand continues to grow and also building of the new generating units and transmission circuits is becoming more difficult because of economic and environmental reasons. Therefore, power utilities are forced to relay on utilization of existing generating units and to load existing transmission lines close to their thermal limits. However, stability has to be maintained at all times. Hence, in order to operate power system effectively, without reduction in the system security and quality of supply, even in the case of contingency conditions such as loss of transmission lines and/or generating units, which occur frequently, and will most probably occur at a higher frequency under deregulation, a new control strategies need to be implemented.

In the late 1980s the Electric Power Research Institute (EPRI) has introduced a new technology program known as Flexible AC Transmission System (FATCS). The main idea behind this program is to increase controllability and optimize the utilization of the existing power system capacities by replacing mechanical controllers by reliable and high speed power electronic devices.

The latest generation of FACTS controllers is based on the concept of the solid state synchronous voltage sources (SVSs) introduced by L. Gyugyi in the late 1980s. The SVS behaves as an ideal synchronous machine, i.e. generates fundamental frequency three-phase balanced sinusoidal voltages of controllable amplitude and phase angle. It can internally generate both inductive and capacitive reactive power. If coupled with an appropriate energy storage device, i.e. dc storage capacitor, battery, etc, SVS is able to exchange real power with the ac system. The SVS can be implemented by the use of the voltage sourced converters (VSC).

The SVS can be used as shunt or series compensator. If operated as a reactive shunt compensator it is called static compensator (STATCOM), operated as a reactive series compensator it is called static synchronous series compensator (SSSC).

A special arrangement of two SVSs, one connected in series with the ac system and the other one connected in shunt, with common dc terminals is called Unified Power Flow Controller (UPFC). It represents series - shunt type of controller. The Interline Power Flow Controller (IPFC) is recently introduced series-series type of controller. It consists of two or more SSSCs coupled through a common DC link. IPFC provides independently controllable reactive series compensation of each selected line as well as transfer of real power between the compensated lines.

The advantages of SVS based compensators over mechanical and conventional thyristor compensators are
• Improved operating and performance characteristics
• Uniform use of same power electronic device in different compensation and control
Applications
• Reduced equipment size and installation cost.

2. LITERATURE SURVEY

A literature survey of topics related to UPFC operation, modeling and control will be given here.

The UPFC, which was proposed by L. Gyugyi in 1991, is one of the most complex FACTS devices in a power system today. It is primarily used for independent control of real and reactive power in transmission lines for a flexible, reliable and economic operation and loading of power system. Until recently all four parameters that affect real and reactive power flow on the line, i.e. the line impedance, voltage magnitudes at the terminals of the line or power angle, were controlled separately using either mechanical or other FACTS devices such as a Static Var Compensator (SVC), a Thyristor Controlled Series Capacitor (TCSC), a phase shifter, etc. However, the UPFC allows simultaneous or independent control of these parameters with transfer from one control scheme to another in real time. Also, the UPFC can be used for voltage support, transient stability improvement and damping of low frequency power system oscillations. Because of its attractive features, modeling and controlling an UPFC have come into intensive investigation in the recent years.

Several references in technical literature can be found on development of UPFC steady state, dynamic and linearized models. Steady state model referred as an injection model is described in this thesis. UPFC is modeled as a series reactance together with the dependent loads injected at each end of the series reactance. The model is simple and helpful in understanding the UPFC impact on the power system. However, the amplitude modulation and phase angle control signals of the series voltage source converter have to be adjusted manually in order to find the desired load flow solution.

If a UPFC is operated in the automatic control mode (i.e. to maintain a pre-specified power flow between two power system buses, the sending and the receiving buses, and to regulate the sending end voltage at the specific value) the UPFC sending end is transformed into a PV bus while the receiving end is transformed into a PQ bus, and conventional load flow (LF) program can be performed. This method is simple and easy to implement but it will only work if real and reactive power flows and the sending bus voltage magnitude are controlled simultaneously. It should be also mentioned that there is no need for an iterative procedure used to compute UPFC control parameters. They can be computed directly after the conventional LF solution is found. Due to the advantages that the automatic power flow control mode offers, this mode will be used as the basic operation mode for the most of the practical applications. Therefore, this model will be discussed in the third chapter of this thesis. Series and shunt transformer losses are taken into account.

A Newton-Raphson based algorithm for large power systems with embedded UPFC devices is derived in chapter 5. This algorithm was extended to include UPFC application. It allows simultaneous or independent control of real and reactive powers and voltage magnitude. The algorithm itself is very complicated and hard to implement. It considerably increases the order of the Jacobian matrix in the iterative procedure and is quite sensitive to initial condition settings. Improper selection of initial condition can cause the solution to oscillate or diverge.

2.2 Flexible AC Transmission

Power flow is a function of transmission line impedance, the magnitude of the sending and receiving end voltages, and the phase angle between the voltages. By controlling one or a combination of the power flow arguments, it is possible to control the active, as well as the reactive power flow in the transmission line.

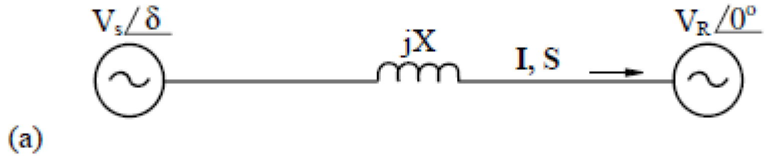
In the past, power systems were simple and designed to be self-sufficient. Active power exchange of nearby power systems was rare as ac transmission systems cannot be controlled fast enough to handle dynamic changes in the system and, therefore, dynamic problems were usually solved by having generous stability margins so that the system could recover from anticipated operating contingencies.

Today, it is possible to increase the system loadability and hence security by using a number of different approaches. It is a usual practice in power systems to install shunt capacitors to support the system voltages at satisfactory levels. Series capacitors are used to reduce transmission line reactance and thereby increase power transfer capability of lines. Phase shifting transformers are applied to control power flows in transmission lines by introducing an additional phase shift between the sending and receiving end voltages.

In past days, all these devices were controlled mechanically and were, therefore, relatively slow. They are very useful in a steady state operation of power systems but from a dynamical point of view, their time response is too slow to effectively damp transient oscillations. If mechanically controlled systems were made to respond faster, power system security would be significantly improved, allowing the full utilization of system capability while maintaining adequate levels of stability. This concept and advances in the field of power electronics led to a new approach introduced by the Electric Power Research Institute (EPRI) in the late 1980. Called Flexible AC Transmission Systems or simply FACTS, it was an answer to a call for a more efficient use of already existing resources in present power systems while maintaining and even improving power system security.

2.3 Basic Principles of Active and Reactive Power Flow Control

Active (real) and reactive power in a transmission line depend on the voltage magnitudes and phase angles at the sending and receiving ends as well as line impedance. To facilitate the understanding of the basic issues in power flow control and to introduce the basic ideas behind VSC-based FACTS controllers, the simple model shown in Figure2.1 is used. The sending and receiving end voltages are assumed to be fixed and can be interpreted as points in large power systems where voltages are "stiff". The sending and receiving ends are connected by an equivalent reactance, assuming that the resistance of high voltage transmission lines is very small. The receiving end is modeled as an infinite bus with a fixed angle of 0^0.



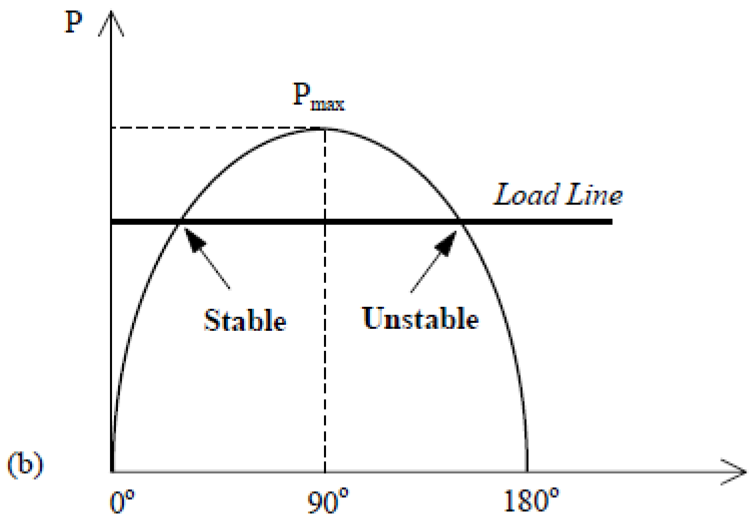


Figure 2.1 – (a) Model for calculation of real and reactive power flow
(b) Power angle curve for (a)

Complex, active and reactive power flows in this transmission system are defined, respectively, as follows:

$$S_R = P_R + jQ_R = V_R I \quad \text{………………(2.1)}$$

$$P_R = \frac{V_S V_R}{X} \sin\delta \quad \text{……………………(2.2)}$$

$$Q_R = \frac{V_S V_R \cos\delta - V_R^2}{X} \quad \text{………………(2.3)}$$

Similarly for the sending end;

$$P_S = \frac{V_S V_R}{X}\sin\delta = P_{max}\sin\delta \quad \text{…………………(2.4)}$$

$$Q_s = \frac{V_s^2 - V_S V_R \cos\delta}{X} \quad \text{…………………..(2.5)}$$

Where V_S and V_R are the magnitudes (in RMS values) of sending and receiving end voltages, respectively, while δ is the phase-shift between sending and receiving end voltages.

The equations for sending and receiving active power flows, P_S and P_R, are equal because the system is assumed to be a lossless system. As it can be seen in Figure2.1.(b), the maximum active power transfer occurs, for the given system, at a power or load angle δ equal to 90^0. Maximum power occurs at a different angle if the transmission losses are included. The system is stable or unstable depending on whether the derivative dP/dδ is positive or negative. The steady state limit is reached when the derivative is zero.

In practice, a transmission system is never allowed to operate close to its steady state limit, as certain margin must be left in power transfer in order for the system to be able to handle disturbances such as load changes, faults, and switching operations. As can be seen in Figure 2.1(b), the intersection between a load line representing sending end mechanical (turbine) power and the electric load demand line defines the steady state value of δ, a small increase in mechanical power at the sending end increases the angle. For an angle above 90^0, increased demand results in less power transfer, which accelerates the generator, and further increases the angle, making the system unstable, on the left side intersection, however, the increased angle δ increases the electric power to match the increased mechanical power. In determining an appropriate margin for the load angle δ, the concepts of dynamic or small signal stability and transient or large signal stability are often used. By the IEEE definition, dynamic stability is the ability of the power system to maintain synchronism under small disturbance, whereas transient stability is the ability of a power system to maintain synchronism when subjected to a severe transient disturbance such as a fault or loss of generation. Typical power transfers correspond to power angles below 30^0 to ensure steady state rotor angle stability, the angles across the transmission system are usually kept below 45^0.

Closer inspection of equations (2.2) and (2.4) shows that the real or active power transfer depends mainly on the power angle; inspection of equations (2.3) and (2.5) shows that the reactive power requirements of the sending and receiving ends are excessive at high angles and high power transfers. It is also possible to conclude that reactive power transfer depends mainly on voltage magnitudes, with flows from the highest voltage to the lowest voltage, while the direction of active power flows depends on the sign of the power angle.

Equations (2.2) to (2.5) show that the power flow in the transmission line depends on the transmission line reactance, the magnitudes of sending and receiving end voltages and the phase angle between the voltages. The concepts behind FACTS a controller is to enable control of these parameters in real-time and, thus, vary the transmitted power according to system conditions. The ability to control power rapidly, within appropriately defined boundaries, can increase transient and dynamic stability, as well as the damping of the system. For example, an increase or decrease of the value of transmission line reactance X, as can be seen from equations (2.2) and (2.4), increases or decreases the value of maximum power transfer P_{max}. For a given power flow, a change of X also changes the angle between the two ends. Regulating the magnitudes of sending and receiving ends voltages, V_S and V_R, respectively, can also control power flow in a transmission line. However, these values are subject to tight control due to load requirements that limit the voltage variations to a range between 0.95 and 1.05 p.u., and hence cannot influence the power flows in a desired range. From the equations of reactive power flow, (2.3) and (2.5), it can be concluded that the regulation of voltage magnitude has much more influence over the reactive power flow than the active power flow.

2.4 FACTS controllers

Of the FACTS controllers of interest here, the STATCOM has the ability to increase/decrease the terminal voltage magnitude and, consequently, to increase/decrease power flows in the transmission line. The SSSC controls power flow by changing the series reactance of the line, whereas the UPFC can control all these parameters simultaneously, i.e., the terminal voltage magnitude, the reactance of the transmission line and the phase angle between the sending and receiving end voltages.

It was shown that FACTS controllers can be used to control steady state active and reactive power flow, but it should be also noted that these fast controllers could have pronounced positive impact on transient and dynamic conditions in a power system if designed properly. By appropriately using these FACTS controllers, it is possible to, for example, increase damping in power system. In damping of power oscillations, caused by a nearby fault, is achieved by using feedback control to efficiently modulate active power flow on the transmission line through a UPFC. It is documented fact that the core of voltage instability is lack of reactive power support in a power system; the STATCOM has the ability to control reactive power absorption/generation, and since its time response is very fast, sometimes even less than one cycle, it can be used to effectively prevent this problem.

2.4.1 Unified Power Flow Controller (UPFC)

The UPFC is the most versatile FACTS controller with capabilities of voltage regulation, series compensation, and phase shifting. The UPFC is a member of the family of compensators and power flow controllers. The latter utilize the synchronous voltage source (SVS) concept to provide a unique comprehensive capability of transmission system control. The UPFC is able to control simultaneously or selectively all the parameters affecting power flow patterns in a transmission network, including voltage magnitudes and phases, and real and reactive powers. These basic capabilities make the UPFC the most powerful device in the present day transmission and control systems.

As illustrated in Fig 2.8, the UPFC is a generalized SVS represented at the fundamental frequency by controllable voltage phasor of magnitude V_{pq} and angle injected in series with the transmission line. Note that the angle ρ can be controlled over the full range from 0 to 2π . For the system shown in Fig 2.8, the SVS exchanges both real and reactive power with the transmission system. In the UPFC, the real power supplied to or absorbed from the system is provided by one of the end buses to which it is connected. This meets the objective of the UPFC to control power flow rather than increasing the generation capacity of the system.

As shown in Fig 2.9, the UPFC consists of two voltage-sourced converters, one in series and one in shunt, both using Gate Turn-Off (GTO) thyristor valves and operated from a common dc storage capacitor. This configuration facilitates free flow of real power between the ac terminals of the two converters in either direction while enabling each converter to independently generate or absorb reactive power at its own ac terminal. The series converter, referred to as Converter 2, injects a voltage with controllable magnitude Vpq and phase ρ in series with the line via an insertion transformer, there by providing the main function of the UPFC. This injected voltage phasor acts as asynchronous ac voltage source that provides real and reactive power exchange between the line and the ac systems. The reactive power exchanged at the terminal of series insertion transformer is generated internally while the real power exchanged is converted into dc power and appears on the dc link as a positive or negative real power demand.

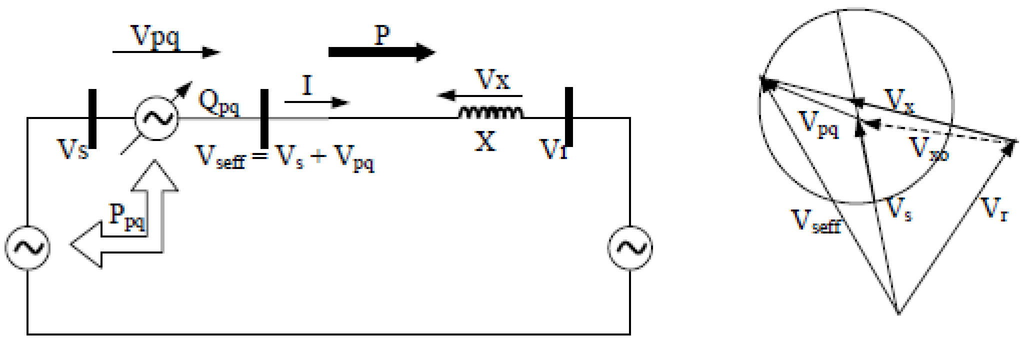


Figure. 2.2. Representation of the UPFC in a two-machine power system.

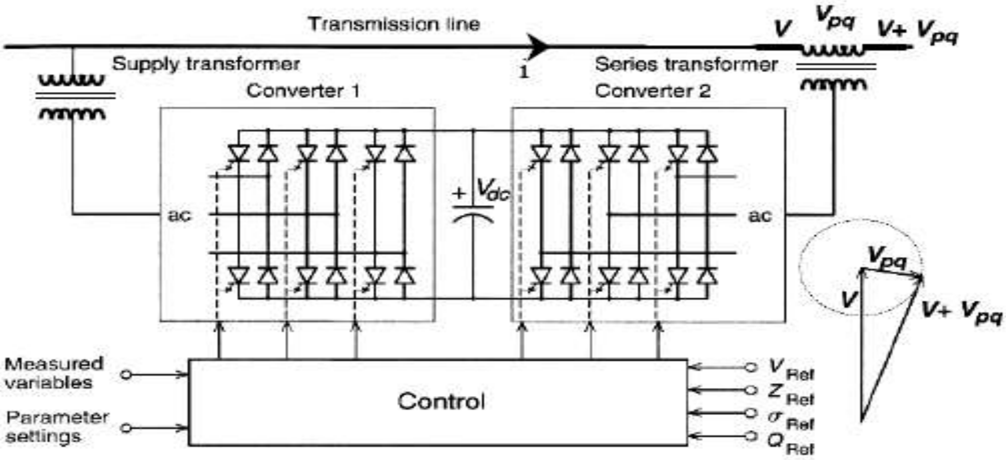


Figure. 2.3. UPFC implemented by two back-to-back voltage source converters

By contrast, the shunt converter, referred to as Converter 1, supplies or absorbs the real power demanded by Converter 2 on the common dc link and supports the real power exchange resulting from the series voltage injection. It converts the dc power demand of Converter 2 into ac and couples it to the transmission line via a shunt connected transformer. Converter 1 can also generate or absorb reactive power in addition to catering to the real power needs of Converter 2; consequently, it provides independent shunt reactive compensation for the line. It is to be noted that the reactive power exchanged is generated locally and hence, does not have to be transmitted by the line. On the other hand, there exists a closed path for the real power exchanged by the series voltage that is injected through the converters back to the line.

Thus, there can be a reactive power exchange between Converter 1 and the line by controlled or unity power factor operation. This exchange is independent of the reactive power exchanged by Converter 2.

2,4.2. Test case with 5-bus system

Standard 5 bus test network is tested with and without UPFC to investigate its behavior. In the analysis bus 1 is taken as slack bus, 2and 3 are voltage control buses and 4, 5are load buses. To include the UPFC in the network an additional bus (bus no 6) is introduced as shown in fig.5.6. The UPFC shunt converter is set to regulate node 3 voltage magnitude at1pu while series converter regulates the power flow between the two nodes. Flat voltage start is assumed for the two UPFC voltage sources.

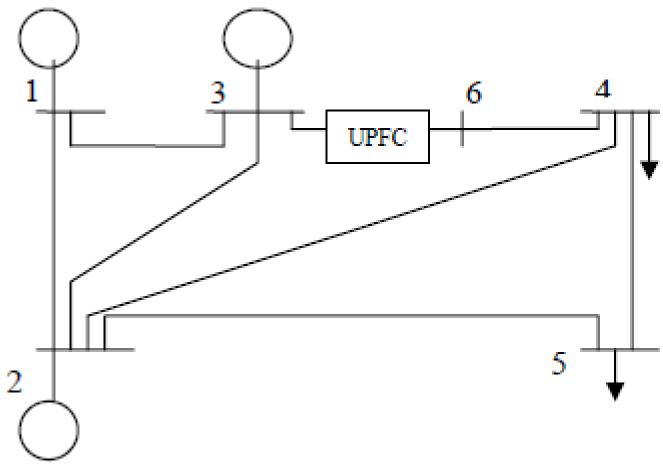


Figure.2.3. Five bus test network

TABLE 1. BUS DATA FOR TEST SYSTEM

Bus no.	Voltage (|v|,Θ)	Load (MW,Mvar)	Generator (MW, Mvar)	Generator Q_{min}, Q_{max}	Injected MAVR
1	1.06,0	0.0,0.0	0.0,0.0	0.0,0.0	0.0

2	1.0,0	20,10	130,85	-5,5	0.0
3	1.0,0	45,15	40,30	-3,3	0.0
4	1.0,0	40,05	0.0,0.0	0.0,0.0	0.0
5	1.0,0	60,10	0.0,0.0	0.0,0.0	0.0
6	--,--	30,02	--, --	--,--	0.0

TABLE, 2. LINE DATA FOR TEST SYSTEM

Sending bus	Receiving bus	Line resistance p.u.	Line reactance p.u.	Line susceptances p.u.
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.12	0.03
3(6)	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

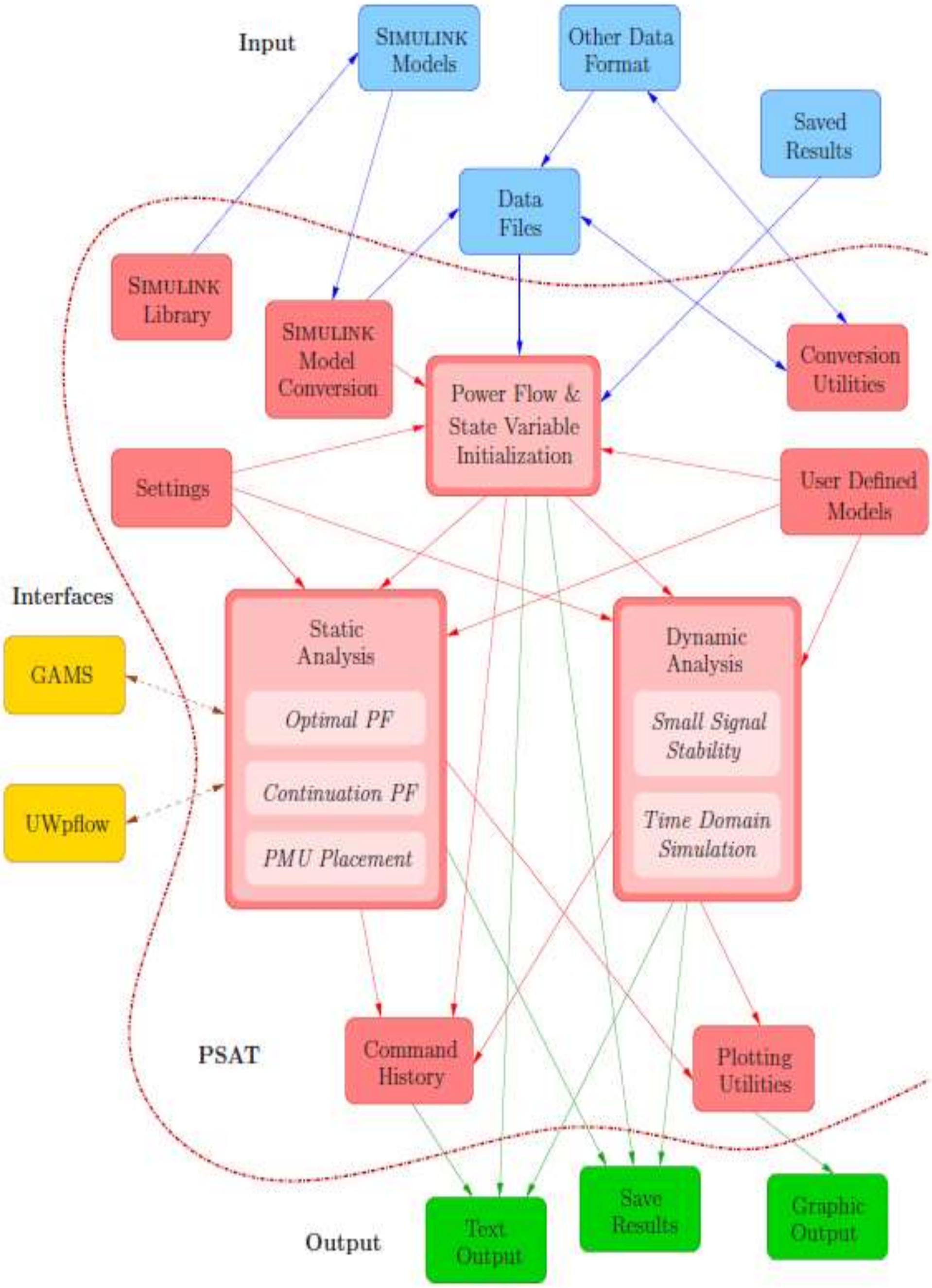


Figure:2.4 PSAT at a glance.

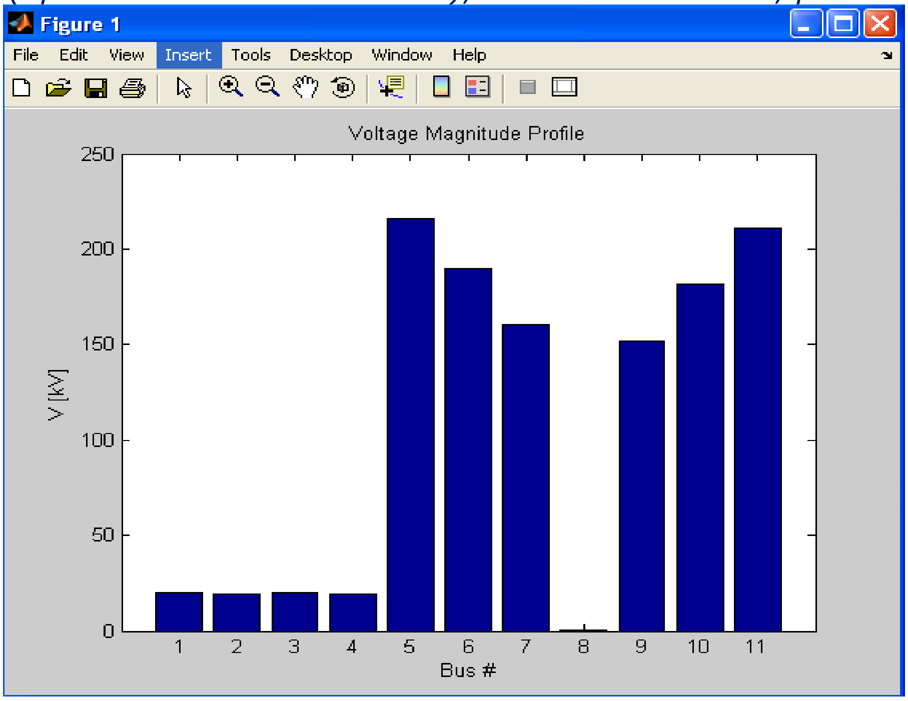


Figure.2,5 Voltage magnitude profile with UPFC

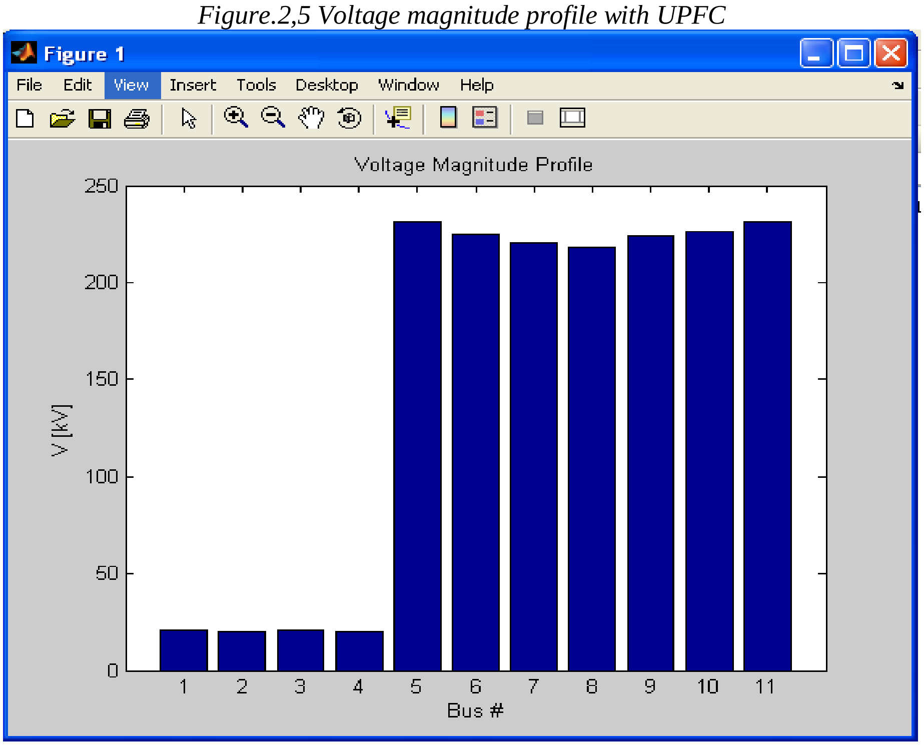


Figure.2.6. Voltage magnitude profile withought UPFC

3. Conclusion

This thesis deals with the FACTS device known as the Unified Power Flow Controller That is used to maintain and improve power system operation and stability. It presents UPFC steady-state models, algorithm for interfacing the UPFC with the power network and UPFC basic controller design. (UPFC). With unique capability of UPFC to control simultaneously real and reactive power flows on a transmission line as well as to regulate voltage at the bus where it is connected, this device creates a tremendous quality impact on power system stability. Here we include the UPFC in standard five bus system and the program has been developed in MATLAB to analyze the power flow in the system. From the result we can conclude that the UPFC controls the power flow in the system as well as improve the stability of the system.

The result of the simulation carried out in power system analysis toolbox indicates that by Employing UPFC in the weakest bus of the system, the voltage profile can be greatly increased with all parameters are kept within limits. The result also shows the effectiveness of UPFC in enhancing the stability as well as reliability of the power system.

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