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Observability & Controllability of a power system by optimizing the performance of PMUs & FACTS controller

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ABSTRACT: The principle objective is to investigate the best method for determining an optimal location for PMUs and FACTS devices, so that the entire power system can be completely observable and controllable. This paper presents a simple and effective method for optimal placement of PMUs and FACTS devices. A voltage stability based weak bus screening method has been utilized to select critical buses for determining power system stability. An algorithm is used for the PMU placement to determine optimal PMU locations for the system observability.
This paper deals with simulation of IEEE 14-bus power system using Statcom & UPFC to improve the power quality. The UPFC is also capable of improving transient stability in a power system. The real and reactive powers can be easily controlled in a power system using a UPFC system. The circuit model for UPFC is developed using rectifier and inverter circuits.
The Matlab simulation results are presented to validate the model. The proposed method is tested on the IEEE 14-bus system & 8-bus system for observability & controllability analysis.

Keywords: Phasor measurement unit (PMU), observability, controllability, voltage stability, FACTS.

I. Introduction

The electric transmission grids operate as a hugely complex machine. Recent history shows that minor instability in one part of the grid can lead to catastrophic failure of large parts of the system. For that and many other reasons, efforts are underway to create a new, Smart Grid. The new grid will be modernized and intelligent, utilizing a number of advanced computing, networking and measurement technologies. It will enable efficient energy usage, increased reliability, and integration of alternative energy sources such as wind and solar.

One of those new technologies is a measurement device known as a Phasor Measurement Unit (PMU). PMUs will play a critical role in monitoring stability throughout the Smart Grid. They will provide the precision knowledge necessary to minimize and control power outages and avoid problems such as cascading blackouts.

In the present day scenario, power generations are increasing rapidly to meet the increase in demand due to heavily loaded customers. Consequently, the transmission system become more stressed, which in turn makes the system more vulnerable to stability and security problems. In this process, the voltage at different load buses may violate their limits and lead to voltage collapse. Hence maintaining voltages at all load buses within the specified limits and also maintaining voltage stability through proper reactive power allocation is a critical problem in power system operation.

Further, in a power system, the power generation and load must balance at all times. If the voltage is increased up with increase in load, then there will be consequent drop in frequency and which may result in system collapse. Alternatively, if there is inadequate reactive power, the system may have voltage collapse. Hence, to control reactive power flow the voltage regulation devices or compensation devices are used such as FACTS controllers to obtain desired voltage through proper reactive power support.

Identification of the weakest bus in a transmission network that is more prone to voltage collapse is of great important in voltage stability studies.

With the increased loading and exploitation of the power transmission system, the problem of voltage stability and voltage collapse attracts more and more attention. A voltage collapse can take place in systems or sub systems and can appear quite abruptly which requires the improved continuous monitoring of the system state and this can be done by PMUs.

The principle objective is to investigate the best method for determining an optimal location for PMUs and FACTS devices, so that the entire power system can be completely observable and controllable.

Voltage stability is a problem in power system which are heavily loaded, faulted or have a shortage of reactive power. The nature of voltage stability can be analysed by examining the production, transmission and consumption of

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reactive power. The problem of voltage stability concerns the whole power system, although it usually has a large involvement in one critical area of the power system.

The above task can only be accomplished when there is proper fast control over power flow in transmission system. With the emergence of high power semiconductor switches, a number of control devices under the generic name of flexible ac transmission system (FACTS) have come under active consideration to achieve the above objectives. In FACTS controllers, by virtue of their fast controllability, are expected to maintain the stability and security margin of highly stressed power systems. However, to achieve the good performance of these controllers, proper placement of the controlling devices in the grid is as important as an effective control strategy.

II. OBSERVABILITY ANALYSIS USING PMUS

Topological observability uses the graph theoretical concepts to find the locations for the measurement placement and thus, to make the system topologically observable. A brief background of PMU based topological observability is given as follows.

PMU based Topological Observability:

For making the system topologically observable using PMUs, following simple rules are used,

1. If voltage phasor and current phasor at one end of a branch are known, voltage phasor at the other end of the branch can be calculated using Ohm's law.
2. If voltage phasors at both the ends of a branch are known, branch current can be calculated.
3. If there is zero injection bus without a PMU, whose outgoing currents are known except for one, then the unknown outgoing current can be calculated using Kirchhoff's Current Law (KCL).

Based on these rules, two types of measurements can be obtained from PMUs. The PMU bus voltage phasor and outgoing currents from PMU bus are defined as direct measurements and measurements obtained by utilizing the rules (1-3) are defined as pseudo measurements. Using this concept, many graph theoretical methods e.g. depth first search, spanning tree based methods, integer linear programming based method [3-6] have been suggested to place PMUs in the system for ensuring the full topological observability of the system. In this work, these methods have been modified to determine optimal PMU locations. The proposed method is explained in the section IV.

III. PROXIMITY INDICATOR FOR VOLTAGE COLLAPSE PREDICTION

The voltage stability index or proximity is the device used to indicate the voltage stability condition formulated based on a line or a bus [2]. The proposed method builds on recent advanced in the areas of real-time voltage stability monitoring and control. The maximum threshold is set at unity as the maximum value beyond which this limit system bifurcation will be experienced. The VSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system. The general two-bus representation is illustrated in Figure 1.

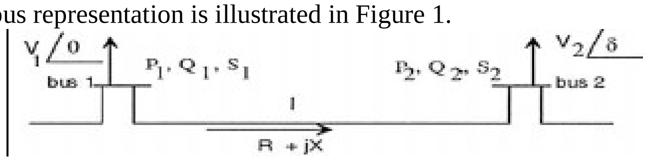

Fig. 1 Two-bus power system model

The mathematical equation for VSI was formulated from a line model as follows: Taking the symbols 'i' as the sending bus and 'j' as the receiving bus. Hence, the fast voltage stability index, VSI can be defined by $VSI_{ij} = \frac{4Z_{ij}^2 Q_j}{V_i X_{ij}}$

where Zij is the line impedance and Xij is the line reactance connecting bus 'i' and bus` j' while, Vi is the voltage at the sending bus and Qj is the reactive power at the receiving bus. The value of VSI that is evaluated close to 1.00 indicates that the particular line is closed to its instability point. Therefore VSI has to be maintained less than 1.00 in order to maintain a stable system. By using this Stability Index, the Voltage stability analysis is conducted and identifies the critical area in the power system for stability enhancements.

The Proposed algorithm was implemented in MATLAB 7 and executed on Pentium 4 machine. The assumption of this procedure for the implementation of this index methodology as follows

• Load buses are selected one at a time
• Voltage Stability Index is computed with an increase in reactive power gradually at chosen load bus until the load flow solution fails to give results when keeping the real power remain constant.
• Voltage Stability Index of every line in the system is computed with an assumption that the real and reactive power loading of all other buses remains constant.

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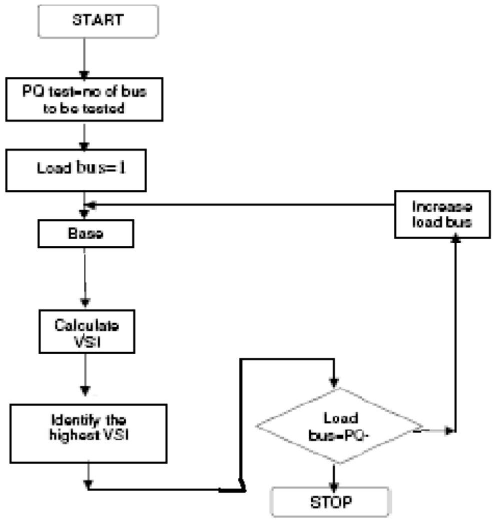

Fig 2: Procedure for Voltage Collapse Prediction

IV PROPOSED PMU PLACEMENT METHOD

In order to illustrate topological observability and optimal placement of PMUs to ensure the full observability, a path finding algorithm has been used in this work to determine optimal PMU location. A brief description of the algorithm is given below.

The blacksmith algorithm observes the bus data. Blacksmith algorithm then searches through every vertex and determines an associated cost in following that path. Once all costs have been determined, the maximum value of the ratio of h(x) and g(x) is selected and that path is explored. If full coverage hasn't been achieved, the vertices will be searched again including the path that has been previously explored and their associated costs will be computed. The maximum value of the ratios will be selected and that path will be explored. This process continues until a solution is found. The flowchart of the proposed method is shown in Fig. 3.

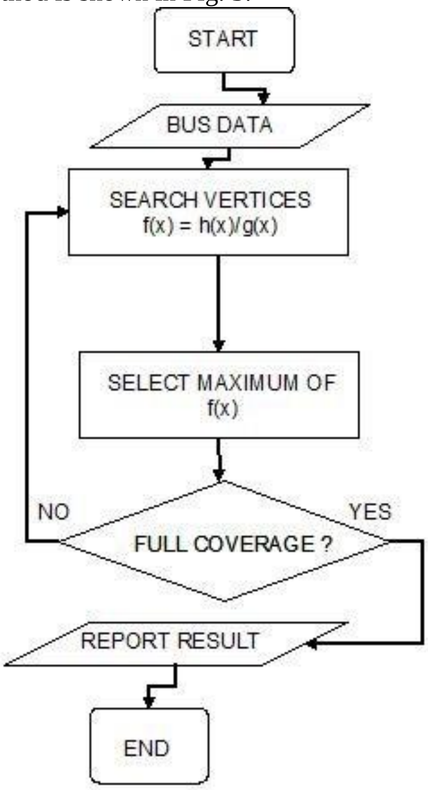

Figure 3: Procedure for optimal placement of PMUs to ensure the full observability

The final optimal solution so obtained ensures the complete Observability.

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V. STATIC SYNCHRONOUS COMPENSATOR AND VOLTAGE SOURCE INVERTER

The Static Synchronous Compensator (STATCOM) is shunt connected reactive compensation equipment, which is capable of generating and /or absorbing reactive power whose output can be varied so as to maintain control of specific parameters of the electric power system. The STATCOM provides operating characteristics similar to a rotating synchronous compensator without the mechanical inertia .The STATCOM employ solid state power switching devices and provide rapid controllability of the three phase voltages, both in magnitude and phase angle.

The STATCOM basically consists of a step-down transformer with a leakage reactance, a three phase GTO/IGBT voltage source inverter (VSI), and a DC capacitor. The AC voltage difference across the leakage reactance produces reactive power exchange between the STATCOM and the power system, such that the AC voltage at the bus bar can be regulated to improve the voltage profile of the power system, which is the primary duty of the STATCOM.

However a secondary damping function can be added into the STATCOM for enhancing power system oscillation stability. The basic objective of a VSI is to produce a sinusoidal AC voltage with minimal harmonic distortion from a DC voltage.

The principle of STATCOM operation is as follows: The voltage is compared with the AC bus voltage system. When the AC bus voltage magnitude is above that of the VSI magnitude; the AC system sees the STATCOM as inductance connected to its terminals. Otherwise if the VSI voltage magnitude is above that of the AC bus voltage magnitude, the AC system sees the STATCOM as capacitance to its terminals. If the voltage magnitudes are equal, the reactive power exchange is zero. If the STATCOM has a DC source or energy storage device on its DC side, it can supply real power to the power system. This can be achieved by adjusting the phase angle of the STATCOM terminals and the phase angle of the AC power system. When phase angle of the AC power system leads the

VSI phase angle, the STATCOM absorbs the real power from the AC system, if the phase angle of the AC power system lags the VSI phase angle, the STATCOM supplies real power to AC system. The real and reactive powers in STATCOM are given by the following equations 1 and 2.

$P_{12} = (V_1 V_2 / X_{12}) \sin(\delta_1 - \delta_2)$ -------- (1)

$Q_{12} = (V_2 / X)(V_1 - V_2)$ -------- (2)

System Bus V_{AC}

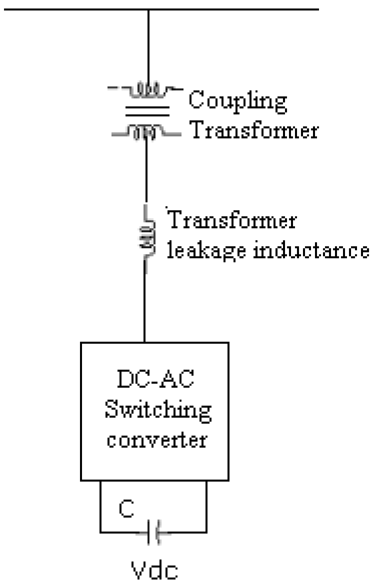

Fig.4. Single - line diagram of a STATCOM.

The Voltage Source Converter or Inverter (VSC or VSI) is the building block of a STATCOM and other FACTS devices. A very simple inverter produces a square voltage waveform as it switches the direct voltage source on and off. The basic objective of a VSI is to produce a sinusoidal AC voltage with minimal harmonic distortion from a DC voltage.

In the last decade commercial availability of Gate Turn off thyristor (GTO) devices with high power handling capability, and the advancement of other types of power semiconductor devices such as IGBT's have led to the development of controllable reactive power sources utilizing electronic switching converter technology [7]. These technologies additionally offer considerable advantage over the existing ones in terms of space reduction and

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performance. The GTO thyristor enable the design of solid-state shunt reactive compensation equipment based upon switching converter technology.

This concept was used to create a flexible shunt reactive compensation device named Static Synchronous Compensator (STATCOM) due to similar operating characteristics to that of a synchronous compensator but without the mechanical inertia. Single-line diagram of STATCOM is shown in Fig4.

The advent of Flexible AC Transmission systems (FACTS) is giving rise to a new family of power electronics equipment emerging for controlling and optimizing the performance of power system, e.g. STATCOM, SSSC and UPFC. The use of voltage source inverter (VSI) has been widely accepted as the next generation of the reactive power controllers of the power system to replace the conventional VAR compensator, Such as the thyristor-switched capacitors (TSC) and thyristor controlled reactors (TCR).

New type of STATCOM based on VSI with phase shifted SPWM is given by Liang[8], Modeling and simulation of DSTATCOM is dealt by Giroux[9]. Dynamically voltage restoration with injection is given by [10]. Compensation of voltage sag by [11]. Power Electronic solution to power quality is given by [12].Analysis of thyristor based STATCOM is given by Song[13].overview of STATCOM technologies is given by Liu[14].Transfer capability improvement using FACTS is given by Arun[15].

The above literature does not deal with simulation of eight bus system using SIMULINK. This work deals with modeling and simulation of eight bus system using STATCOM. The present work uses a voltage source inverter circuit comprising a transformer with a power output end coupled to a load. A power driver unit is connected between the two power output ends. Circuit diagram of voltage source inverter is shown in Fig 5. .T1, T2 and T3, T4 conducts alternatively to produce the AC output.

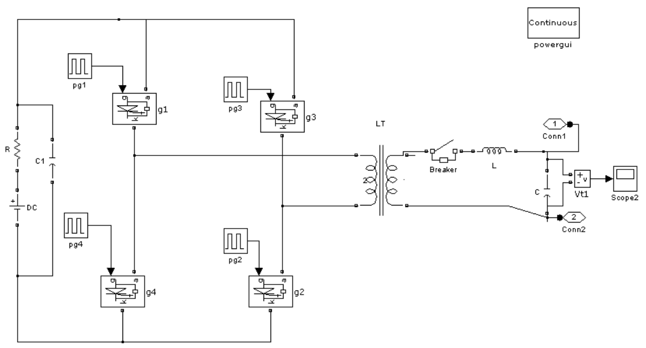

Fig.5 Voltage Source Inverter based STATCOM

PRINCIPLE OF UPFC

The basic components of the UPFC are two voltage source inverters (VSIs) sharing a common dc storage capacitor, and connected to the power system through coupling transformers. One VSI is connected to in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer.

A basic UPFC functional scheme is shown in fig.5a.

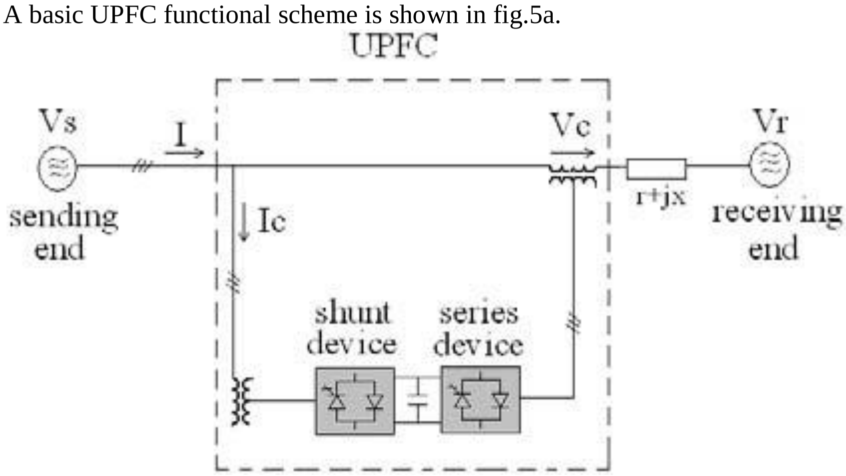

Fig.5a Basic functional scheme of UPFC

The series inverter is controlled to inject a symmetrical three phase voltage system (Vse), of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this

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inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor Vdc constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

The two VSI's can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power flows on the transmission line.

The UPFC has many possible operating modes. In particular, the shunt inverter is operating in such a way to inject a controllable current, ish into the transmission line. The shunt inverter can be controlled in two different modes:

VAR Control Mode: The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the var reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage, Vdc, is also required.

Automatic Voltage Control Mode: The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt coupling transformer.

The series inverter controls the magnitude and angle of the voltage injected in series with the line to influence the power flow on the line. The actual
value of the injected voltage can be obtained in several ways.

Direct Voltage Injection Mode: The reference inputs are directly the magnitude and phase angle of the series voltage.

Phase Angle Shifter Emulation mode: The reference input is phase displacement between the sending end voltage and the receiving end voltage.

Line Impedance Emulation mode: The reference input is an impedance value to insert in series with the line impedance.

Automatic Power Flow Control Mode: The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

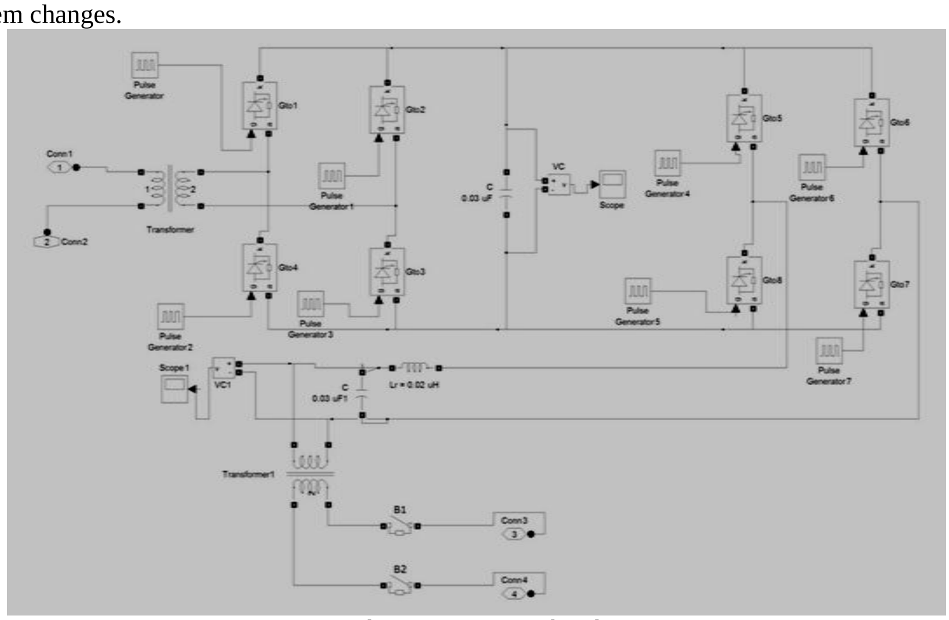

Fig.5 Voltage Source Inverter based UPFC

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VI. SIMULATION RESULTS

A. ObservabilityAnalysis

The proposed method for optimal PMU placement has been tested on the IEEE 14-bus system.

Optimal pmu placement for ieee 14-bus system

Case	*Optimal Locations*	*No. of locations*
IEEE 14 bus system	*1 6 8 9*	*4*

B. Voltage Stability Analysis

To validate the performance of the indicator for voltage stability analysis, 8-bus test system is used. From the analysis, buses 1and 2 are more prone to voltage collapse.

A eight bus system is considered for simulation studies. The circuit model of eight bus system is shown in Fig 6a. Each line is represented by series impedance model. Shunt capacitance of the line is neglected. Additional load is added in parallel with load-1 by closing the breaker in series with the load. Scopes are connected to display the voltages across the two loads. At t = 0.25sec, additional load is connected. Voltage across the load-1 decreases as shown in Fig 6b.This fall is due to the increased voltage drop.

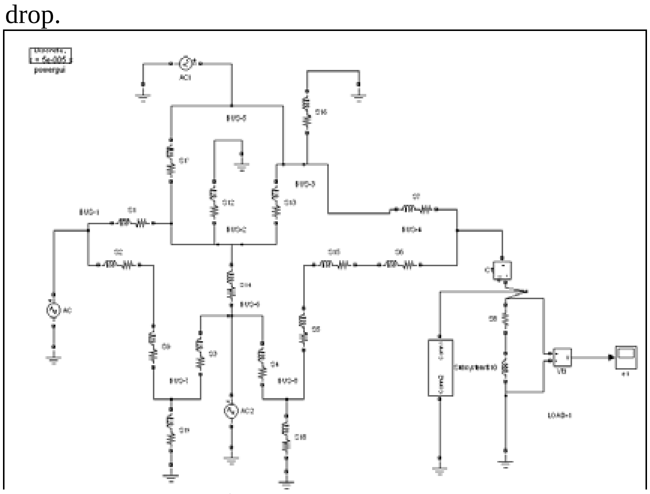

Fig.6a Model of 8-bus system without FACTS Device

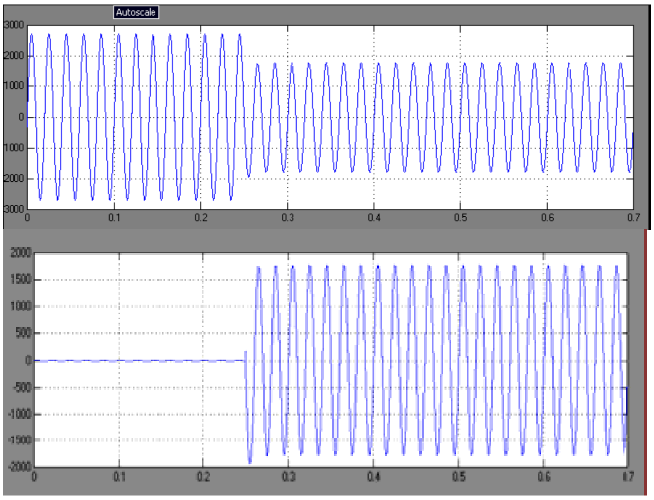

Fig.6b Voltage across Load-1 and Load-2

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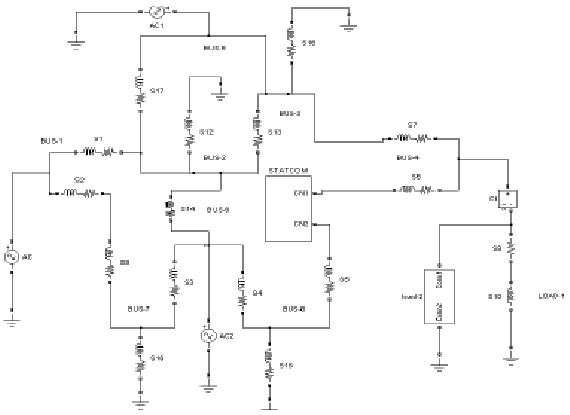

Fig.7a Model of 8-bus system with STATCOM

Eight bus system with STATCOM is shown in Fig.7a.STATCOM is connected in the line between buses 4 & 8. The voltages across Load-1 and Load-2 are shown in Fig.7b. It can be seen that the voltage across load-1 decreases and resumes to the rated value due to the injection of voltage by the STATCOM. Thus the STATCOM is able to mitigate the voltage sag produced by the additional load. Power quality is improved since the voltage reaches normal value.

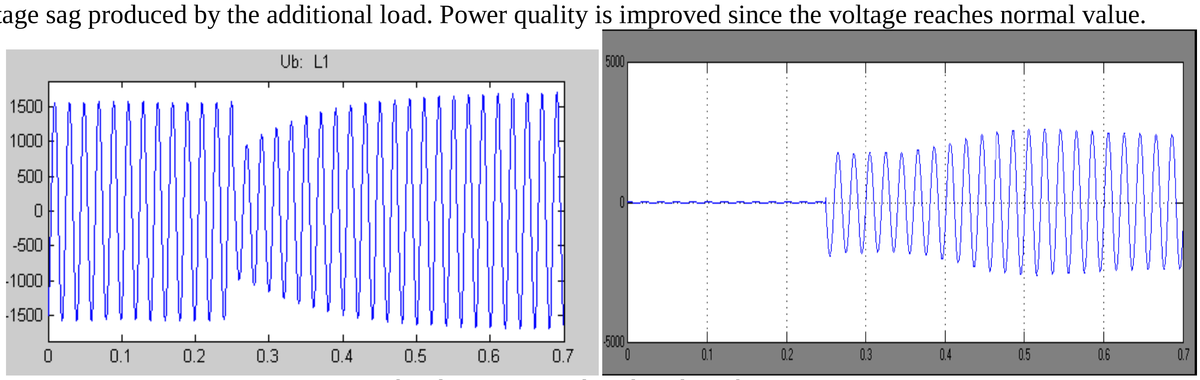

Fig.7.b Voltage across Load-1and Load-2 with STATCOM

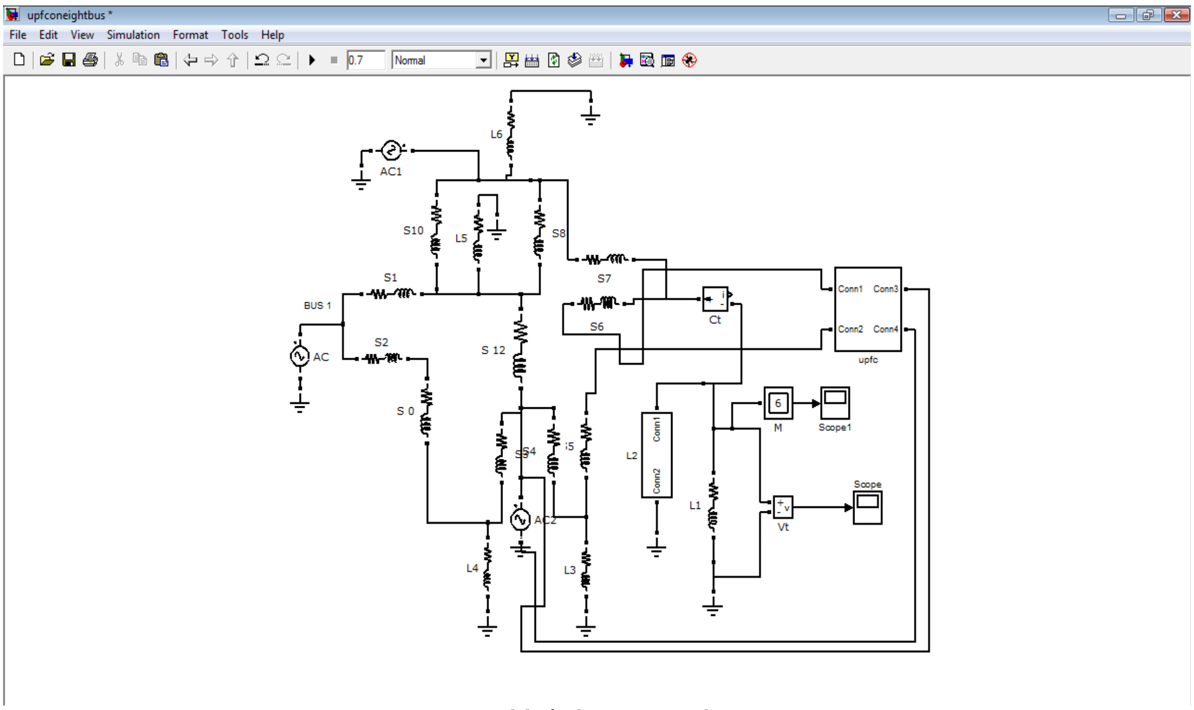

Fig.8a Model of 8-bus system with UPFC

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Eight bus system with UPFC is shown in Fig.8a.UPFC is connected in the line between buses 4 & 8. The voltages across all the Loads are shown in Fig.8b. It can be seen that the voltage across load-1 decreases and resumes to the rated value due to the injection of voltage by the UPFC. Thus even UPFC is able to mitigate the voltage sag produced by the additional load. Power quality is improved since the voltage reaches normal value.

When the transmission line is without UPFC, the real and reactive power flow cannot be controlled. Fig. 9a shows the active power through the line without UPFC. Fig. 9b shows the active power flow through line which is controlled by UPFC. Transmission capability of the existing transmission line is highly improved with the presence of UPFC. But the difference between the sending-end real power and receiving end real power is high in the transmission line with UPFC. This is due to the increase in transmission losses, which include losses in the both converters and coupling transformers. The reactive power flow through the transmission line with and without UPFC is shown in fig. 10. The raise in the transmission capability is noticed from the simulation results.

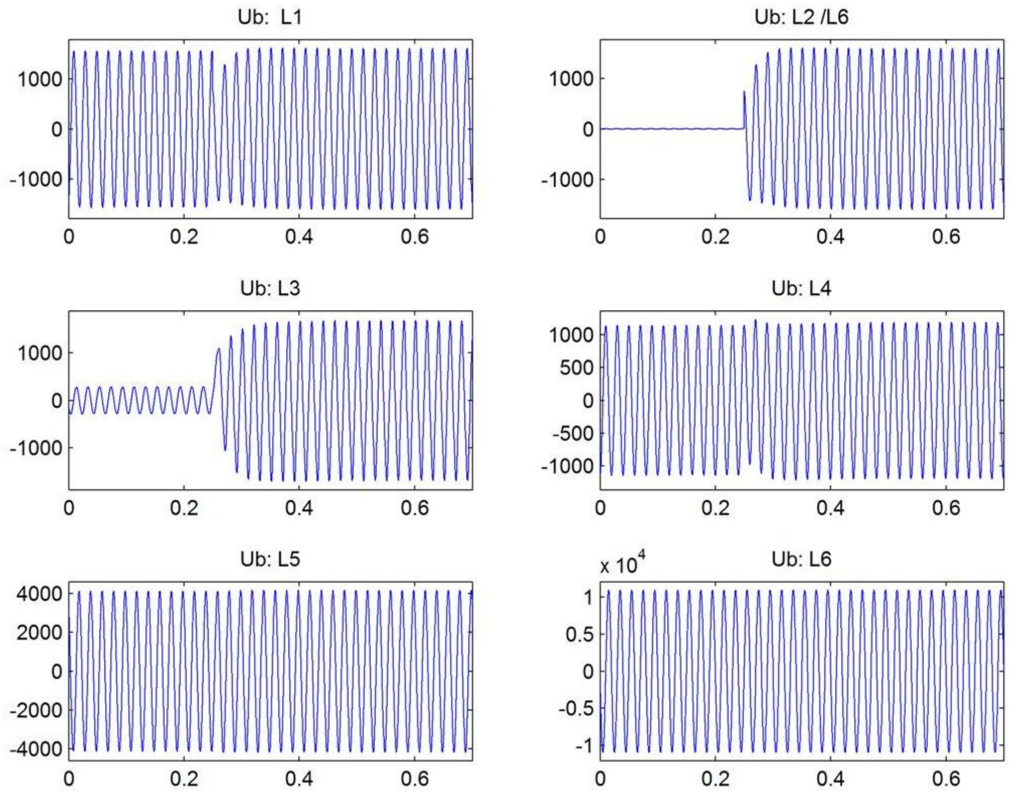

Fig.8.b Voltage across Loads with UPFC

IV. CONCLUSION

This paper has suggested a simple Programming based method for the optimal placement of PMUs to ensure complete topological observability of the system. The paper uses voltage stability index to determine weak bus in the system. The proposed observability and controllability analysis has been tested on the IEEE 14-bus system and 8 bus system respectively. The proposed method is quite effective and simple to adopt.

This paper uses STATCOM & UPFC to improve the voltage stability in a multi-bus system. The load voltage reaches rated value with in 0.25sec. The simulation results of eight bus system with and without STATCOM & UPFC are presented. The simulation studies indicate the usefulness of STATCOM & UPFC to mitigate the voltage sag. Transmission capability of the existing transmission line is highly improved with the presence of UPFC. The raise in the transmission capability is noticed from the simulation results.

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