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Comparison of TCSC and Fuel Cell with Optimal Placement of PMU for Voltage Stability Analysis

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Abstract

The present scenario, the power demand has been increased so; it requires the power system to operate within limits. As the load is varying continuously, the voltage stability problems will arise. The foremost cause of voltage instability is deficiency of reactive power. The voltage stability and power transfer capability can be enhanced by compensation of reactive power. By placing Flexible AC Transmission System (FACTS) devices the performance of power system can be improved but these devices are expensive so it has to be placed at optimal location. This paper deals with the optimal placement of TCSC and Fuel cell with PMU in IEEE-14 bus system using PSAT to analyze and enrich the voltage stability margin of a power system network in real time monitoring. In real time the measurement of power system parameters such as current and voltage phasors, frequency can be effectively carried out by synchronized PMU.

Keywords: Flexible AC Transmission System (FACTS); Phasor Measurement Unit (PMU); Simulated Annealing (SA); Power System Analysis Toolbox (PSAT)

1. Introduction

Last twenty years across worldwide most of the power system blackouts were occurred due to the stressed power system. The major factors of stressed power system are due to load variations, over voltage and shortage of reactive power . As the demand of Electrical power is increasing the generation is pacing to match but, the transmission sector is not expanding at the same rate. Concurrently, the burden on transmission system had been increased due to the deregulation and privatization of the power system network. Due to this the power system is exposed to its limits so the voltage instability problems are arising. As the load is varying continuously the voltage at the buses will be low, the losses will be increased simultaneously. To balance the voltage at the buses the network is needed to provide compensating devices with high response speed in the field of power electronics. Currently, without using of capacitors and gate turn off thyristors (GTO) the emerging technology like FACTS had used to generate reactive power [1]. The extensive use of these devices is flexibility and increase security, increases the power transfer capability, and controls the electrical parameters like voltage, impedance, and phase angle, current and damped of oscillations. FACTS devices are used to eliminate voltage instability problems. The utility of a power station is to satisfy the customer needs. This need the setup of a power system should be complex . A constant monitoring of the system is required to control the FACTS devices. To estimate and monitor the voltage and power flow at each bus Phasor measurement Unit (PMU) along with state estimator and Supervisory Control and Data Acquisition (SCADA) is needed. In order to find any abnormalities had take place in the system PMU required less instance. The revelation of power system has increased by combining the PMU and FACTS devices. By manual operation using FACTS devices will be delayed so real time monitoring by PMU can overcome it. To synchronize the measurement at isolated areas the PMU are installed at large number of buses [2]. From PMU the synchro-phsasors is acquired which is large data, through Wide Area Network (WAN) communication the data is transferred to Phasor Data Concentrator (PDC) using standards and protocols. By using different algorithms the operator can be analyzed the synchrophasor data. In this the Distributed Generation is considered, it act as a back-up protection. The type-1 Dg is considered which delivers only real power or active power the best example is solid oxide fuel cell (SO C).

Voltage stability is a critical aspect of electrical power systems, and maintaining stable voltage levels is essential for the reliable operation of various electrical devices. Here are some methods used to improve voltage stability [3]:

In reactive Power Compensation, the power factor of the system can be enhanced by introducing reactive power compensation devices such as capacitors and inductors. These devices aid in voltage regulation by delivering or absorbing reactive power, lowering the load on the gearbox system.

In voltage Regulation at the Generation Level, the voltage stability is greatly influenced by generators. Installed voltage regulators at the generator terminals can alter the output voltage to keep it within an acceptable range. This guarantees that voltage fluctuations in the system are kept to a minimum.

In Transformer Tap Changers, the transformers are critical voltage transformation and distribution components. Tap changers allow for the changing of the transformer turns ratio, allowing for voltage control. Voltage levels can be adjusted or decreased to maintain stability by altering the tap settings.

The Automatic Voltage Regulators (AVRs) are devices that are positioned at the synchronous generator terminals to control the excitation system. They constantly monitor the system voltage and modify the field excitation to keep the

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generator output voltage stable. This contributes to system voltage stability under a variety of operating circumstances.

The Static Var Compensators (SVCs) are power electronic devices that provide fast and precise reactive power compensation. They are typically connected in shunt configuration and can inject or absorb reactive power to maintain voltage stability.

With Load Shedding and Load Control, in situations where voltage stability is compromised, load shedding schemes can be implemented. These schemes prioritize the disconnection of certain loads to relieve the system and prevent voltage collapse. Additionally, load control techniques, such as demand response programs, can be employed to dynamically adjust the power consumption of specific loads.

In Voltage Stability Monitoring and Control Systems, the Advanced monitoring systems equipped with real-time measurements and data analysis capabilities can help identify potential voltage stability issues. Based on the information gathered, control algorithms can be applied to take corrective actions, such as adjusting generator set points or activating reactive power compensators [4].

In Planning and Expansion of the Power System, the Adequate planning and expansion of the power system infrastructure are crucial for voltage stability improvement [5]. This includes considering factors like load growth, transmission capacity, and reactive power requirements to ensure a well-balanced system.

It's important to note that voltage stability improvement is a complex and dynamic process that requires a comprehensive analysis of the power system. Different methods may be applied depending on the specific characteristics and requirements of the system under consideration.

Enriching the voltage stability margin of a power system network in real-time monitoring involves implementing various measures to enhance the network's ability to maintain stable voltage levels. Here are some strategies commonly used to achieve this:

In Reactive Power Control, the Real-time monitoring enables the identification of reactive power imbalances within the network. By dynamically adjusting reactive power sources such as capacitors and inductors, the voltage stability margin can be improved. Automatic Voltage Regulators (AVRs) in generators can also be utilized to control reactive power output.

Load Shedding and Load Balancing: Real-time monitoring helps identify areas with excessive load demand. Load shedding techniques can be employed to reduce the demand in these areas, thus alleviating voltage instability. Load balancing techniques distribute the load across the network more evenly, minimizing voltage fluctuations.

Voltage Control Devices: Utilizing devices like Static VAR Compensators (SVCs) and Static Synchronous Compensators (STATCOMs) can regulate the voltage at specific points in the network, enhancing stability. These devices inject or absorb reactive power to maintain voltage levels within acceptable limits.

Voltage Stability Analysis: Real-time monitoring allows continuous assessment of the network's voltage stability. Advanced analysis techniques, such as dynamic stability simulations and voltage stability indices, can provide insights into potential stability issues. Early detection enables proactive measures to be taken to mitigate voltage instability.

Wide-Area Monitoring Systems (WAMS): Implementing WAMS enhances real-time monitoring capabilities by incorporating synchronized measurements from multiple locations. WAMS can provide a comprehensive view of the network's voltage stability status, enabling timely decision-making and control actions [6].

Enhanced Control and Protection Systems: Real-time monitoring facilitates the integration of advanced control and protection systems. These systems can automatically respond to voltage instability events by adjusting control parameters, activating protection schemes, or implementing corrective actions like coordinated generator tripping or load shedding.

Data Analytics and Machine Learning: Real-time monitoring data can be leveraged for data analytics and machine learning algorithms. By analyzing historical and real-time data, patterns and trends related to voltage stability can be identified. This knowledge can be utilized to develop predictive models for early warning of voltage instability and to optimize control strategies.

It's important to note that the specific strategies employed for voltage stability margin enrichment depend on the characteristics and requirements of the power system network in question. Different networks may have unique challenges and may require tailored approaches to address voltage stability concerns.

2. Phasor Measurement Unit (PMU)

```
START

Step 1: Initialize the system parameters
Step 2: Initialize the PMU placement configuration
Step 3: Set the initial temperature
Step 4: Set the cooling rate
Step 5: Set the maximum number of iterations
Step 6: Set the current solution as the initial
Step 7: PMU placement configuration
Step 8: Set the current objective function value as the
        objective function value of the initial configuration
Step 9: Repeat until the stopping condition is met: Generate a
        new neighboring PMU placement configuration.
Step 10: Calculate the objective function value for the new
         configuration
Step 11: If the new configuration improves the Objective
         Function value:

    Step 12: Accept the new configuration as the current
    solution Update the current objective function value

    else:

    Step 13: Calculate the acceptance probability based on the
    current temperature and the difference between the new
    and current objective. Function values generate a random
    number between 0 and 1

Step 14: If the random number is less than the
acceptance probability:

    Step 15: Accept the new configuration as the current
    solution. Update the current objective function value.

    else:

    Step 16: Reject the new configuration. Reduce the
    temperature based on the cooling rate.

END.
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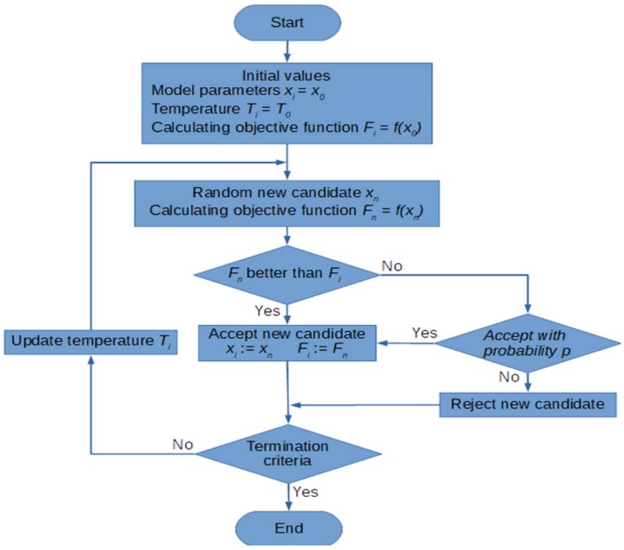

Fig. 1. SA Flow chart.

In this updated flowchart, the SA algorithm for PMU placement optimization is illustrated. The algorithm begins by initializing the system parameters and the PMU placement configuration.

The initial temperature, cooling rate, and maximum number of iterations are set to control the annealing process.

The current solution is initially set as the initial PMU placement configuration, and the current objective function value is set as the objective function value of the initial configuration.

The algorithm then enters the main loop, which continues until a stopping condition is met. Within each iteration, a new neighboring PMU placement configuration is generated.

The objective function value is calculated for the new configuration. If the new configuration improves the objective function value, it is accepted as the current solution, and the current objective function value is updated accordingly. Otherwise, an acceptance probability is calculated based on the current temperature and the difference between the new and current objective function values. A random number between 0 and 1 is generated, and if the random number is less than the acceptance probability, the new configuration is accepted as the current solution, and the current objective function value is updated. Otherwise, the new configuration is rejected.

After evaluating the new configuration, the temperature is reduced based on the cooling rate. The algorithm repeats this process until the stopping condition is met.

Please note that this flowchart provides a general outline of the SA algorithm for PMU placement optimization. The specific implementation details, such as the neighborhood generation, acceptance probability calculation, stopping condition, and objective function formulation, may vary based on the problem requirements and constraints.In the word PMU the phasor represents a sinusoidal signal and the phase angle can be defined as the distance between the sinusoidal peak of signal and reference as time.

Table1. Represents the components of PMU and its functions and the basic block representation of PMU are shown in below Figure 1.

Table 1. Foremost components of PMU.

S.no	Components	Function
1	Analog signal	The input to the PMU are current and voltage from potential transformer and current transformer
2	Anti-aliasing filter	Which is low pass filter it eliminates the frequencies ≥ half of nyquist rate
3	Phase locked oscillator	Stabilize the input signal
4	GPS receiver	Satellite based system provides positioning and time synchronization.
5	A/D converter	Converts analog signals to digital signals
6	Micro-processor	Using Discrete Fourier Transforms (DFT) analysis, it calculates positive sequence of estimated voltage and current.
7	Modem	A signal is produced and decoded to make a copy of unique digital information.

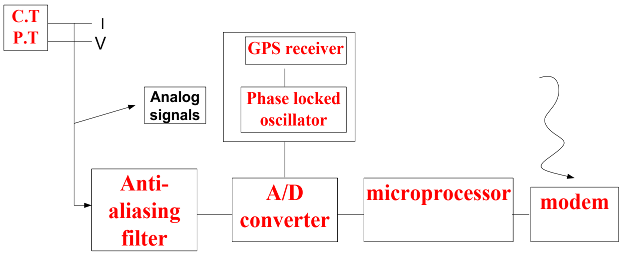

Fig. 2. Pictorial representation of PMU.

If any blackouts or any major fault had occurred in the power system network, through PMU the status of the system can be known and also the sequential events can be recorded without any time delay. Based on this the power system is protected to provide time synchronizing pulse; the Global Positioning System (GPS) is used and it provides one-pulse-per-second (pps). One of the advantage of this system is the installation time has been reduced and turns out to be portable, user friendly.

3. Mathematical Representation of PMU

AC waveform can be represented as:

$$X\,(t) \;=\; X_m\, cos(\omega t + \emptyset) \qquad (1)$$

Where X_m is the magnitude of the waveform, $\emptyset$: is the angle,

$$\omega \;=\; 2\pi f \qquad (2)$$

And 'f' is the frequency. The phasor representation:

$$X = \frac{Xm}{\sqrt{2}}\, e^{j\emptyset} = \frac{Xm}{\sqrt{2}} cos\emptyset + jsin\emptyset \qquad (3)$$

Where $\frac{Xm}{\sqrt{2}}$ is the RMS value of the waveform. The $\emptyset$ value depends on the time scale that is at t=0.

4. Facts Controllers

In past most of the controllers were mechanical in nature. In mechanical there are in-built problems. To overcome this

FACTS controllers are designed which has more possibilities increase the power of existing line with huge conductors. FACTS devices are the new devices emerging from innovative technologies which are capable to change impedance, phase angle at particular points in the power systems. The FACTS devices have high potential to enhance the power system stability [2]. FACTS controllers are categorized in to 4:

1. Shunt device
2. Series device
3. Series-shunt device
4. Shunt-shunt device

5. Thyristor Controlled Series Compensator (TCSC)

TCSC is a series type of compensator. From Figure 3. It has a series capacitor bank connected paralleling by a thyristor controlled reactor to provide a capacitive reactance in a smooth variable form [10].

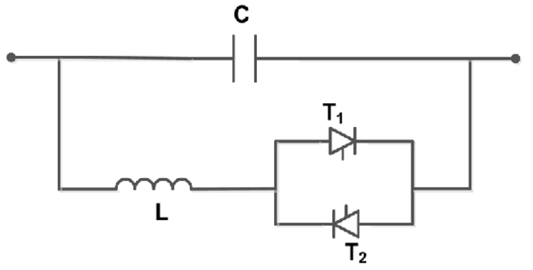

Fig. 3. schematic diagram of TCSC.

The operating principle of TCSC is to compensate the transmission line and improve the voltage profile. TCSC can be used as a capacitive mode at normal operating range at the same time it can be used as inductive mode. The impedance of the line is controlled by varying the firing angle of thyristor. For over voltage protection a Metal Oxide Varistor (MOV) with bypass breaker is connected in shunted to the capacitor.

6. Mathematical Analysis of TCSC

When the thyristor is in full conduction mode the current will be maximum and when the thyristor is in blocking mode the current will be zero. Impedance of TCSC is:

$$Z_{TCSC} = \frac{-jX_C}{\left(1-\frac{X_C}{X_{TCR}}\right)} \tag{4}$$

Current flowing through the reactor

$$I_{TCSC} = \frac{I_L}{\left(1-\frac{X_{TCR}}{X_C}\right)} \tag{5}$$

When $X_c<X_{TCR}$ it is capacitive, $X_{TCR} = \infty$ it acts as a blocked region. When $X_c>X_{TCR}$ it is inductive region.

7. Fuel Cell

Fuel cell modeling involves capturing the complex electrochemical and thermodynamic processes that occur within the cell. While fuel cells offer several advantages, such as high energy efficiency and environmental friendliness, their modeling presents various challenges. Here are some key modeling issues associated with fuel cells [11]:

In Multi-Physics Coupling, the fuel cells involve the interaction of multiple physical phenomena, including fluid flow, heat transfer, electrochemistry, and mass transport. Integrating these different processes into a comprehensive model can be challenging due to their strong interdependencies and non-linear behavior.

In Electrochemical Kinetics, the accurately modeling the electrochemical reactions that take place at the electrodes is crucial for understanding fuel cell performance. The kinetics of electrode reactions, including the anode hydrogen oxidation and cathode oxygen reduction, is complex and influenced by factors like catalyst activity, reactant concentrations, temperature, and electrode structure. Developing accurate and computationally efficient models for these reactions is a significant challenge.

In Mass Transport Phenomena, the effective mass transport of reactants (fuel and oxidant) and products (water and heat) within the fuel cell is critical for its performance. Modeling the transport of species across the various layers of the cell, including the gas diffusion layer, catalyst layer, and electrolyte membrane, requires consideration of diffusion, convection, and migration. Capturing these transport phenomena accurately and accounting for their interactions with other processes is a modeling challenge.

In Water Management, the fuel cell operation produces water as a byproduct, and managing its distribution within the cell is crucial for optimal performance. Excessive water accumulation can lead to flooding, limiting reactant diffusion and impeding the electrochemical reactions. Conversely, insufficient water content can cause dehydration and hinder proton conduction. Modeling the water management dynamics and ensuring a proper balance of water content throughout the cell poses a modeling challenge.

In Thermal Management, the fuel cell operation generates heat, and maintaining appropriate temperature levels is essential for performance and durability. Thermal modeling involves accounting for heat generation from electrochemical reactions, heat transfer through the cell components, and heat dissipation mechanisms. Capturing the thermal dynamics accurately and developing effective cooling strategies to prevent overheating require sophisticated modeling techniques.

Scale and Complexity: Fuel cells exhibit a hierarchical structure, with various layers and components, such as gas channels, flow fields, electrodes, and membranes. Modeling the cell at different scales, from the micro scale of electrode kinetics to the macro scale of stack performance, while considering the interactions between these scales, presents a challenge. Balancing computational complexity with accuracy is crucial for practical fuel cell modeling.

In Parameterization and Validation, the Developing reliable models require accurate determination of model parameters, such as material properties, reaction kinetics, and transport coefficients. However, obtaining precise parameter values experimentally can be challenging, and uncertainty in these parameters can affect model accuracy. Ensuring accurate parameterization and validating the model against experimental data is essential but can be a complex task.

Addressing these modeling issues requires a multidisciplinary approach, involving expertise in electrochemistry, fluid dynamics, heat transfer, and numerical modeling techniques. Continual advancements in experimental techniques, computational methods, and understanding of fuel cell behavior contribute to improving fuel cell models and their predictive capabilities

The modeling equations for fuel cells typically involve a combination of electrochemical kinetics, mass transport, and conservation laws. Here, I'll provide a simplified representation of the modeling equations for a proton exchange membrane (PEM) fuel cell, which is one of the most commonly, used fuel cell types. This model is known as the "1D isothermal model" and assumes steady-state operation.

Conservation of Species (Gases):

The conservation equations for hydrogen (H2) and oxygen (O2) gases can be written as:

$$\nabla\bullet(\rho\_H2u\_H2) = 0 \qquad (6)$$

$$\nabla\bullet(\rho\_O2u\_O2) = 0 \qquad (7)$$

Where ρ_H2 and ρ_O2 are the densities of H2 and O2, respectively, and u_H2 and u_O2 are the velocities of the gases.

The conservation equation for water vapor (H2O) is given by:

$$\nabla\bullet(\rho\_H2O*u\_H2O) = J\_H2O \qquad (8)$$

where ρ_H2O is the density of H2O, u_H2O is the velocity of water vapor, and J_H2O represents the water vapor flux.

The conservation equation for charge can be expressed as:

$$\nabla\bullet(\sigma\nabla\Phi) = 0$$

where σ is the electrolyte conductivity and Φ is the electric potential.

The conservation equation for heat transfer in the fuel cell is given by:

$$\nabla\bullet(\lambda\nabla T) = Q + I^2R + 2\nabla\bullet(k*\nabla T) \qquad (9)$$

where λ is the thermal conductivity, T is the temperature, Q is the heat generation rate from electrochemical reactions, I is the current density, R is the resistance, and k is the convective heat transfer coefficient.

The electrochemical reactions at the anode and cathode can be represented as follows:

$$\text{Anode: } H2 \rightarrow 2H+ + 2e- \qquad (10)$$

$$\text{Cathode: } O2 + 4H+ + 4e- \rightarrow 2H2O \qquad (11)$$

These reactions are typically described using Butler-Volmer kinetics or Tafel equations, which relate the reaction rate to the electrode potential and exchange current density.

These equations need to be supplemented with appropriate boundary conditions and material properties. Additionally, some simplifications may be made depending on the specific assumptions and level of detail desired in the model.

It's important to note that the above equations represent a simplified version of the fuel cell model, and more comprehensive models can include additional phenomena and complexities. The actual modeling equations used in practice can vary based on the specific fuel cell type, operating conditions, and desired level of accuracy. The Distributed generation is a source of electricity; it is connected to connect directly to the customer side of the meter. DG is also called as on-site generation [12].The basic operation of a fuel cell, which converts chemical energy in to electrical energy and heat by chemical reaction. Figure 4 represents the fuel cell diagram. It consists of anode; cathode and middle chamber is electrolyte. The chemical reaction takes place as two parts that is oxidation and reduction. From oxidation reaction the molecules of hydrogen is disassociated at anode to form protons and electrons. Whenever there will be a reducing in the load current the voltage stack will be reduced.

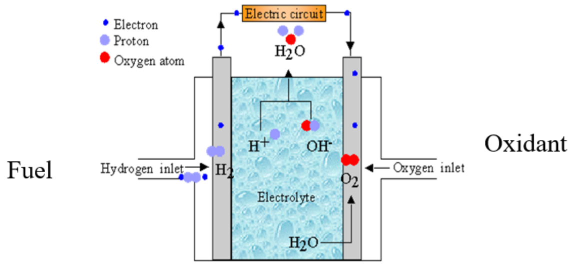

Fig. 4. Fuel cell structure.

Oxidation reaction:

$$2H_2 \Rightarrow 4H^+ + 4e \qquad (12)$$

Cathode Reduction reaction:

$$O_2 + 4H^+ + 4e \Rightarrow 2H_2o \qquad (13)$$

The principle of fuel cell is same as battery operation, but when fuel and oxidant are supplied as long as there is no need of recharging as battery. Based on temperature, and electrolytes and charge carrier the fuel cell can be distinct. The different fuel cells are Alkaline fuel cell (AFC), Phosphoric acid fuel cell (PAFC), polymer electrolyte membrane (PEMFC) and Molten carbonate fuel cell (MCFC), Solid oxide Fuel cell(SOFC)[8]. At low temperature the PEFC, PAFC and AFC are operated. At high temperature that is 800-1000 degree centigrade, MCFC, SOFC will operate. The main assumptions are taken as the losses should be Ohmic and the Nernst equation is applicable in this type of fuel cell. The parameters which are taken as valve molar constants of oxygen, hydrogen and oxygen and its response time. Here the numbers of cells are taken as 450 and its electric potential will be 1.18 volts. These parameters are taken from Nernst equation. Based on the output power the number of cells is designed [9].

8. Optimal Placement of Facts And PMU

Optimal placement of FACTS[13,14] device can be decided by the identification of weak bus. Based on the disturbance type the voltage stability can be classified as small and large disturbance. Voltage stability can be analysed by static and dynamic method. Static method involves P-V curves and Q-V curves and Continuation Power flow Analysis and modal analysis. Dynamic Analysis has time domain simulation approach, and bifurcation analysis like saddle node bifurcation, limit induced bifurcation. P-V curve estimates the critical point when the real power is enhanced the load flow equations fail to converge [4]. One of the proficient and simple methods of static analysis is the modal analysis. By using Modal analysis the critical bus is identified. The voltage magnitude of a particular bus which leads to voltage instability state is known as critical bus. The optimal placement of PMU can be decided by simulated Annealing (SA) algorithm.

9. Simulated Annealing (SA)

Depth first search and simulated annealing are the heuristics method. To deal the complex non-linear problems Kirkpatrick proposed the Simulated Annealing algorithm in 1983. SA algorithm is used for global optimization. In SA the optimization process is annealing of molten metal. In order to maintain the system from melting, the annealing was cooled down slowly and sufficiently. The solid atoms will be ordered at the time of cooling. As cooling increased beyond normal state, the system will become too cold state. The temperature should not be low because to keep away the system from meta-stable state. The objective of SA algorithm is to locate global minimum and try to avoid local minimum. The SA algorithms proceed with minimum and maximum voltage and angle values, and from the load bus the maximum power is removed

10. Results

From the analysis of IEEE 14 bus system the weakest bus is identified and the TCSC has been placed at that bus. The IEEE 14 bus system includes 9 load buses with voltage limits, 4 generator buses with reactive power limits and voltage limits, 1 slack bus, and 4 transformers. By using PSAT software the voltage stability is analyzed. From table 2 the base case voltage magnitude is represented by power flow analysis using Newton Raphson (N.R) method for 4 iterations it was converged.

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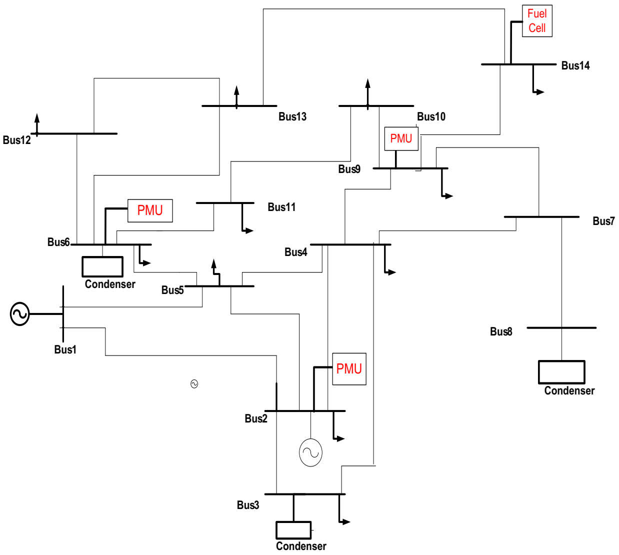

Fig. 5. IEEE 14 bus test system with PMU and Fuel cell.

Table 2. Voltage magnitude for IEEE 14 bus system.

Bus Number	**Voltage Magnitude (P.u)**
1	1.060
2	1.045
3	1.010
4	1.010
5	1.014
6	1.070
7	1.048
8	1.090
9	1.032
10	1.031
11	1.046
12	1.053
13	1.046
14	1.020

As there is a load variation in a system there is seducement in voltage values. The load has been increased to 70% and 80% and respective voltage values taken as shown in Table 3. To compensate this FACTS device are placed at appropriate location. By considering 80% loading the weak bus is identified using Eigen values and its participation factor by modal analysis. By Eigen analysis the Q-V sensitivity, the reduced jacobian matrix is calculated and it's participation factor also. From table 4 the least Eigen value is at bus number 14 and the participation factor is calculated for this critical bus. It can be analyzed that the highest participation factor is the weakest bus that is bus number 14 as shown in Table 4. The red line of P.F indicates the weak bus.

Table 3. Increment of loading with 70% and 80%.

	Voltage Magnitude (P.u)	
Bus Number	**70% Loading**	**80% Loading**
1	1.060	1.060
2	1.045	1.045
3	1.010	1.010
4	0.983	0.979
5	0.989	0.985
6	1.070	1.070
7	1.024	1.019
8	1.090	1.090
9	0.995	0.989
10	0.995	0.989
11	1.026	1.022
12	1.040	1.038
13	1.028	1.025
14	0.977	0.970

Eigenvalue and participation factor calculations are commonly used in power system analysis to assess the dynamic behavior and contribution of individual components (such as generators or loads) in the system. Here are the equations and steps involved in calculating eigenvalues and participation factors: The first step is to develop a linearized state-space model of the power system, which describes the dynamic behavior of the system around a specific operating point. This model typically consists of a set of first-order differential equations in matrix form:

$$dx/dt = Ax + Bu$$

where x represents the state variables (e.g., generator rotor angles and speeds), t is time, A is the system matrix, B is the input matrix, and u is the input vector (e.g., electrical power or disturbance). To find the eigenvalues of the system matrix A, the characteristic equation is formulated as:

det(A - λI) = 0

where det() denotes the determinant, λ is the eigenvalue, and I is the identity matrix. By solving this equation, you can obtain the eigenvalues of the system. The eigenvalues represent the natural frequencies of the system oscillations, and their values determine the stability and dynamic response.

The participation factor measures the contribution of each state variable to a specific mode of oscillation represented by an eigenvalue. It helps identify the most influential components in the system during dynamic events. The participation factor for a specific state variable i and eigenvalue j is calculated using the formula:

$$PF(i,j) = |\varphi(i,j)|^2 \,/\, \sum(|\varphi(k,j)|^2)$$

where PF(i, j) is the participation factor for state variable i and eigenvalue j, φ(i, j) is the corresponding element of the eigenvector matrix representing the participation of state variable i in eigenvalue j, and the sum is taken over all state variables.

Table 4. Eigen values and its participation factors.

Bus Number	Eigen value	Participation Factor
4	63.0928	0.00867
9	37.8522	0.20123
7	21.0536	0.06901
13	18.4584	0.03117
5	15.6315	0.00434
11	10.858	0.10577
10	7.3804	0.23912
12	5.3464	0.01735
14	2.5257	0.32334

The participation factor is usually normalized so that the sum of squared participation factors for a specific eigenvalue equals 1. This normalization allows for a comparison of the relative contributions of different state variables to a particular mode. The eigenvector matrix contains the eigenvectors corresponding to the eigenvalues of the system matrix A. Each column of the eigenvector matrix represents the eigenvector associated with a specific eigenvalue. The eigenvectors provide information about the direction and magnitude of the state variables' response during system oscillations. The eigenvalue and participation factor calculations are typically performed for each eigenvalue of interest, which may include the dominant oscillation modes or critical stability points. By analyzing the eigenvalues and corresponding participation factors, power system engineers gain insights into system stability, mode shapes, and the influence of individual components on system dynamics. These analyses help in identifying potential issues and designing appropriate control strategies to enhance system stability and performance. Table 5 shows the comparison of voltage magnitude of with TCSC and without TCSC

Table 5. Comparison of voltage magnitude of with TCSC and without TCSC.

Voltage Magnitude (P.u)		
Bus Number	**Placing TCSC**	**Placing Fuel Cell**
1	1.060	1.060
2	1.045	1.045
3	1.010	1.010
4	0.984	0.988
5	0.989	0.992
6	1.070	1.070
7	1.025	1.039
8	1.090	1.090
9	0.999	1.025
10	0.984	1.020
11	1.027	1.038
12	1.038	1.051
13	1.025	1.049
14	0.988	1.070

From table 8 the voltage magnitude has been improved PMU with DG than PMU with TCSC. From Figure 6, 7 the voltage profile have been observed.

Table 6. Comparison of voltage magnitudes of TCSC and Fuel cell.

Voltage Magnitude (P.u)		
Bus Number	**Without placing TCSC Device**	**Placing TCSC**
1	1.060	1.060
2	1.045	1.045
3	1.010	1.010
4	0.983	0.984
5	0.989	0.989
6	1.070	1.070
7	1.024	1.025
8	1.090	1.090
9	0.995	0.999
10	0.995	0.984
11	1.026	1.027
12	1.040	1.038
13	1.028	1.025
14	0.977	0.988

From table 6 the voltage profile has been improved from 0.9881 P.u to 1.07 P.u after placing fuel cell at bus number 14.

Table 7. Location of PMU by SA method.

PMU location	Estimated voltage	Estimated θ
2	1.015	-0.279
6	1.031	-0.421
9	1.040	-0.407

Table 8. Comparison of voltage magnitude of PMU with TCSC and PMU with Fuel cell.

Voltage Magnitude (P.u)		
Bus Number	**PMU with TCSC**	**PMU with Fuel cell**
1	1.060	1.060
2	1.045	1.045
3	1.010	1.010
4	1.000	1.007
5	1.002	1.010
6	1.070	1.070
7	1.052	1.054
8	1.090	1.090
9	1.045	1.045
10	1.036	1.037
11	1.047	1.047
12	1.043	1.046
13	1.034	1.045

14	1.013	1.045

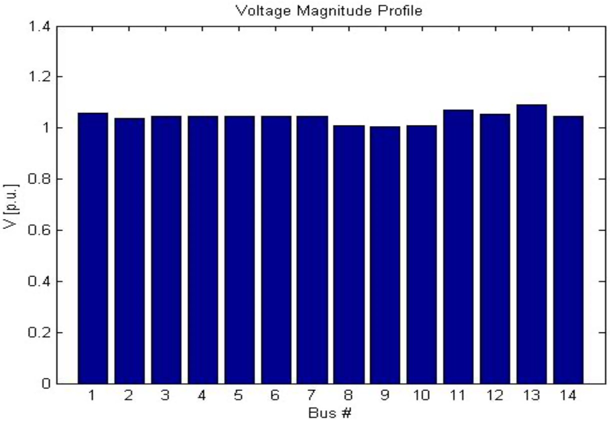

Fig. 6. Representation of voltage magnitudes of PMU with fuel cell in Bar graph.

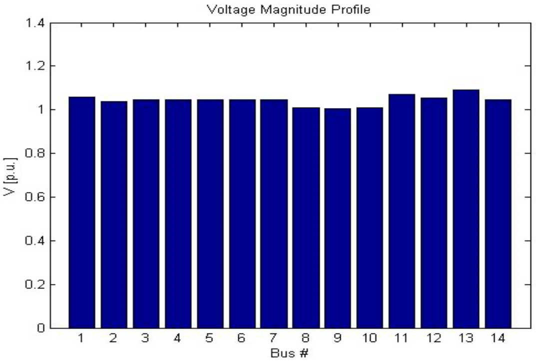

Fig. 7. Representation of voltage magnitudes of PMU with TCSC in Bar graph.

11. Conclusion

Power system blackouts in the past twenty years were mainly caused by stressed power systems, which resulted from load variations, overvoltage, and reactive power shortages. The demand for electrical power is increasing, but the expansion of the transmission sector is not keeping pace, leading to increased burden on the system and voltage instability issues. Flexible AC transmission system (FACTS) devices, such as capacitors and gate turn off thyristors (GTO), are used to provide reactive power and improve system stability. They offer flexibility, increased security, enhanced power transfer capability, and control over electrical parameters. Phasor Measurement Units (PMUs) are essential for monitoring the power system, estimating voltage and power flow, and detecting abnormalities. They provide real-time monitoring and synchronization of measurements. The combination of PMUs and FACTS devices has improved power system reliability and stability by enabling faster response and real-time control. TCSC (Thyristor Controlled Series Compensator) is a type of FACTS device used for series compensation, which can improve voltage profile and control line impedance. Fuel cells, such as solid oxide fuel cells (SOFC), are considered as distributed generation (DG) sources and can act as backup protection. They convert chemical energy into electrical energy and heat through chemical reactions. Optimal placement of FACTS devices and PMUs is crucial for improving system performance. Weak buses can be identified using modal analysis, and simulated annealing (SA) algorithms can be employed for optimal placement. The analysis of an IEEE 14-bus system showed improved voltage stability when TCSC and fuel cells were implemented. The voltage magnitudes were compared for different loading conditions and placement scenarios. The results demonstrated that PMUs, FACTS devices, and fuel cells can enhance the voltage profile, improve system stability, and mitigate the risk of blackouts.

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