



DEMOCRATIC AND POPULAR ALGERIAN REPUBLIC  
MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH  
ECHAÏD HAMMA LAKHDAR UNIVERSITY OF EL-OUED  
FACULTY OF TECHNOLOGICAL



## **Master's Thesis**

In order to obtain a diploma of an Academic Master

**In technology**

**Specialty: Electrical Networks**

## **Theme**

**Transient Stability Enhancement in a PV-Integrated  
IEEE 30-Bus System: Comparative Study of SVC,  
STATCOM, and UPFC**

**Presented by:**

MEHRIA Akram

LEKHOUA Rachid

**President**

**Mrs. Elabi Yassine**

**University of El Oued.**

**Examiner**

**Mrs. Nour Eddin Brika**

**University of El Oued.**

**Supervisor**

**Mrs. MAAMRI Oussama**

**University of El Oued**

Academic Year 2025–2026

# *Acknowledgements*

*First and foremost, we would like to express our sincere gratitude to our supervisor, Mrs. MAAMRI Oussama, for her valuable guidance, continuous support, and constructive advice throughout the preparation of this thesis. Her expertise, encouragement, and availability greatly contributed to the successful completion of this work.*

*We would also like to thank all the professors and staff members of the Faculty of Technology, Echahid Hamma Lakhdar University of El-Oued, for the knowledge and skills they have provided during our academic journey.*

*Our appreciation is extended to the members of the jury for accepting to evaluate this work and for their valuable comments and suggestions.*

*We are deeply grateful to our families and friends for their unwavering support, patience, and encouragement throughout our studies.*

*Finally, we would like to thank everyone who directly or indirectly contributed to the realization of this thesis.*

# ***Dedication***

*I dedicate this work to my beloved parents, whose endless love, sacrifices, support, and prayers have always been the source of my strength and inspiration.*

*To my family, for their constant encouragement and confidence in my abilities.*

*To my friends and colleagues, who shared with me the challenges and successes of this academic journey.*

*To all those who supported me and believed in me throughout my studies.*

***Akram Mehria***

# ***Dedication***

*I dedicate this thesis to my dear parents, who have always encouraged me to pursue knowledge and excellence.*

*To my brothers and sisters, whose affection and support have been invaluable.*

*To my friends and all those who contributed to my academic and personal development.*

*May this work be a humble expression of my gratitude and appreciation.*

***Rachid Lekhoua***

## **Abstract**

This paper investigates the influence of fault location on the transient stability of the IEEE 30-bus transmission system under the integration of photovoltaic (PV) sources. The Critical Clearing Time (CCT) is adopted as the primary performance indicator. Several fault scenarios were analyzed, both before and after the integration of a 50 MW PV unit at selected buses. Additionally, the study provides a comparative evaluation of three FACTS devices—Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), and Unified Power Flow Controller (UPFC)—to assess their effectiveness in enhancing system stability. Dynamic simulations were carried out using PSAT in MATLAB. The results demonstrate that fault location has a substantial impact on system behavior, and the incorporation of FACTS devices significantly improves the CCT. Among the three, UPFC consistently delivers superior performance, followed by STATCOM and then SVC.

**Keywords:** Transient Stability, Critical Clearing Time (CCT), Photovoltaic Integration, FACTS, IEEE 30-Bus System

## الملخص

تبحث هذه الورقة تأثير موقع العطل على الاستقرار العابر لنظام نقل الطاقة الكهربائي IEEE 30 عقدة في ظل دمج مصادر الطاقة الكهروضوئية (PV) وقد تم اعتماد زمن الإزالة الحرج (CCT) كمؤشر الأداء الرئيسي. تم تحليل عدة سيناريوهات للأعطال، سواء قبل أو بعد دمج وحدة كهروضوئية بقدرة 50 ميغاواط في عقد مختارة من الشبكة. كما تقدم الدراسة تقييماً مقارناً لثلاثة أجهزة من أنظمة النقل المرنة للتيار المتردد (FACTS)، وهي: المعوض الساكن للقدرة غير الفعالة (SVC)، والمعوض التزامني الساكن (STATCOM)، ومتحكم تدفق القدرة الموحد (UPFC)، وذلك لتقييم مدى فعاليتها في تعزيز استقرار النظام. أُجريت المحاكاة الديناميكية باستخدام برنامج PSAT ضمن بيئة MATLAB. أظهرت النتائج أن موقع العطل له تأثير كبير على سلوك النظام، وأن دمج أجهزة FACTS يحسن بشكل ملحوظ زمن الإزالة الحرج. ومن بين الأجهزة الثلاثة، حقق جهاز UPFC أفضل أداء بصورة مستمرة، يليه STATCOM ثم SVC.

**الكلمات المفتاحية:** الاستقرار العابر، زمن الإزالة الحرج (CCT)، دمج الطاقة الكهروضوئية، أنظمة FACTS، نظام IEEE 30 عقدة.

## Résumé

Cet article étudie l'influence de l'emplacement du défaut sur la stabilité transitoire du système de transport d'énergie IEEE à 30 nœuds intégrant des sources photovoltaïques (PV). Le **temps critique d'élimination du défaut (CCT)** est adopté comme principal indicateur de performance. Plusieurs scénarios de défaut ont été analysés avant et après l'intégration d'une unité photovoltaïque de 50 MW sur certains nœuds sélectionnés. En outre, l'étude présente une évaluation comparative de trois dispositifs FACTS : le **Compensateur Statique de Puissance Réactive (SVC)**, le **Compensateur Statique Synchrone (STATCOM)** et le **Contrôleur Unifié de Flux de Puissance (UPFC)**, afin d'évaluer leur efficacité dans l'amélioration de la stabilité du système. Des simulations dynamiques ont été réalisées à l'aide du logiciel PSAT sous MATLAB. Les résultats montrent que l'emplacement du défaut a un impact significatif sur le comportement du système et que l'intégration des dispositifs FACTS améliore considérablement le CCT. Parmi les trois dispositifs étudiés, l'**UPFC** offre systématiquement les meilleures performances, suivi du **STATCOM**, puis du **SVC**.

**Mots-clés:** Stabilité transitoire, Temps critique d'élimination du défaut (CCT), Intégration photovoltaïque, FACTS, Système IEEE à 30 nœuds.

## List of Figures

|                                                                                   |    |
|-----------------------------------------------------------------------------------|----|
| Figure 1 Typical electric power system single-line diagram [2] .....              | 5  |
| Figure 2 Traditional Transmission line.[1] .....                                  | 6  |
| Figure 3 Classification of buses.....                                             | 7  |
| Figure 4 one line diagram of 6 bus system .....                                   | 8  |
| Figure 7 Electrical Faults [11] .....                                             | 11 |
| Figure 8 The different types of power system fault [12] .....                     | 11 |
| Figure 9 The open circuit fault .....                                             | 12 |
| Figure 10 Short-Circuit Faults .....                                              | 13 |
| Figure 11 Examples of architectures [14].....                                     | 15 |
| Fig1 : types of FACTS Controller .....                                            | 21 |
| Fig2: Static VAR Compensator .....                                                | 21 |
| Fig 3: Thyristor Controlled Series Capacitor .....                                | 22 |
| Fig 4: Static Synchronous Series Compensator .....                                | 22 |
| Fig5: Unified Power Flow Controller .....                                         | 23 |
| Fig. 3. An equivalent solar cell circuit.....                                     | 24 |
| Figure. 1: Equivalent circuit of a photovoltaic cell .....                        | 30 |
| Figure. 2: Three-phase voltage source inverter topology .....                     | 31 |
| Figure 3: Simplified schematic of a Static Var Compensator (SVC) .....            | 32 |
| Figure 4: Simplified schematic of a Static Synchronous Compensator (STATCOM)..... | 32 |
| Figure 5: Basic structure of the UPFC .....                                       | 33 |
| Figure.6 : Diagram of the IEEE 30 Bus System. ....                                | 34 |
| Figure.7. Rotor speed of all generators at $t=20$ ms .....                        | 36 |
| Figure.8: Rotor speed of all generators at $t=21$ ms.....                         | 36 |
| Figure.9: Voltage profile .....                                                   | 36 |
| Fig 10. Rotor speed of all generators at $t=30$ ms .....                          | 37 |
| Figure. 11: Rotor speed of all generators at $t=31$ ms.....                       | 38 |
| Figure. 12: Voltage profile .....                                                 | 38 |
| Figure.13: CCT comparison histogram without PV integration.....                   | 39 |
| Figure.14: Rotor speed of all generators at $T=7$ ms .....                        | 40 |
| Figure.15: Rotor speed of all generators at $T=8$ ms .....                        | 40 |
| Figure.16. Voltage profile.....                                                   | 41 |
| Figure.17: Rotor speed of all generators at $T=3$ ms .....                        | 42 |
| Figure.18: Rotor speed of all generators at $T=4$ ms .....                        | 42 |

---

|                                                                                                     |    |
|-----------------------------------------------------------------------------------------------------|----|
| Figure. 20: CCT comparison histogram with and without PV integration .....                          | 44 |
| Figure 21 . Histogram Comparison of (CCT) for Different FACTS Devices in PV-Integrated System ..... | 46 |

---

## List of Table

|                                                                                                     |    |
|-----------------------------------------------------------------------------------------------------|----|
| Table 1 Description of Jacobian matrix .....                                                        | 10 |
| Table 2 the main characteristics of each architecture for comparison.[14] .....                     | 15 |
| Table 3 Symbols and Units for Transmission Line Parameters .....                                    | 16 |
| Table 1: power flow results .....                                                                   | 34 |
| Table2 – Variation of Critical Clearing Time (CCT) According to Photovoltaic (PV) Penetration ..... | 43 |

## Table of contents

|                             |          |
|-----------------------------|----------|
| Acknowledgements .....      |          |
| Dedication .....            |          |
| Abstract .....              |          |
| Résumé .....                |          |
| List of Figures.....        |          |
| List of Table .....         |          |
| Table of contents .....     |          |
| List of Abbreviations ..... |          |
| General Introduction .....  | <b>1</b> |

### Chapter 1 — Power System Studies

|                                                           |    |
|-----------------------------------------------------------|----|
| 1.1 Power System: .....                                   | 4  |
| 1.2 The structure of the power system: .....              | 5  |
| 1.2.1 Génération Subsystem: .....                         | 5  |
| 1.2.2 Transmission and Sub transmission Subsystem : ..... | 5  |
| 1.2.3 Distribution Subsystem: .....                       | 6  |
| 1.3 Power flow studies: .....                             | 6  |
| 1.3.1 Necessity for power flow studies .....              | 6  |
| 1.3.2 Bus classification: .....                           | 7  |
| 1.3.3 The power flow methods: .....                       | 9  |
| 1.3.3.1 Gauss-Siedel (GS) load flow method: .....         | 9  |
| 1.3.3.2 Newton-Raphson (NR) load flow method: .....       | 9  |
| 1.4 Faults in electrical power systems: .....             | 11 |
| 1.4.1 Types of faults in power system : .....             | 11 |
| 1.5 Power-system architecture: .....                      | 13 |
| 1.5.1. Architectures include the following: .....         | 13 |
| 1.5.1.1 Radial systems: .....                             | 13 |
| 1.5.1.2 Loop systems: .....                               | 13 |
| 1.5.2 Systems with internal power generation: .....       | 14 |
| 1.6 Transmission line parameters: .....                   | 15 |
| 1.6.1 Series resistance : .....                           | 16 |
| 1.6.2 Series inductance : .....                           | 16 |
| 1.6.3 Shunt capacitance : .....                           | 16 |
| 1.6.4 Shunt conductance: .....                            | 17 |
| 1.7 Conclusion: .....                                     | 17 |

---

**Chapter 2 — Transient Stability and CCT Definition**

|                                                          |    |
|----------------------------------------------------------|----|
| 2.1. Introduction .....                                  | 19 |
| 2.2. Generalities on facts devices .....                 | 19 |
| 2.2.1 Static Var Compensator (SVC) .....                 | 21 |
| 2.2.2 Thyristor Controller Series Capacitor (Tcsc) ..... | 21 |
| 2.2.3 Static Synchronous Series Compensator (SSSC) ..... | 22 |
| 2.2.4 Unified Power Flow Controller (UPFC) .....         | 23 |
| 2.3. PV Panel and Boost Converter Modeling .....         | 23 |
| 2.3.1 PV Panel Simulation .....                          | 23 |
| 2.4. CONCLUSION .....                                    | 27 |

**Chapter 3 — DIFFERENT TYPES OF FACTS DEVICE IN POWER SYSTEM**

|                                                                                                          |           |
|----------------------------------------------------------------------------------------------------------|-----------|
| 3.1. Methodology: .....                                                                                  | 29        |
| 3.1.1 Transient Stability and CCT Definition: .....                                                      | 29        |
| 3.1.2 PV System Modeling: .....                                                                          | 30        |
| 3.1.3. Modelling of PV Inverter .....                                                                    | 30        |
| 3.2. Modeling of SVC and STATCOM and UPFC: .....                                                         | 31        |
| 3.2.1. Static Var Compensator (SVC): .....                                                               | 31        |
| 3.2.2. Static Synchronous Compensator (STATCOM): .....                                                   | 32        |
| 3.2.3. UPFC (Unified Power Flow Controller): .....                                                       | 32        |
| 3.3. Power System Description .....                                                                      | 33        |
| 3.4. RESULTS AND DISCUSSION .....                                                                        | 35        |
| 3.4.1. Case 1: Impact of three-phase faults on transient stability (CCT) and before PV integration ..... | 35        |
| a. Influence of three phase fault at bus 12: .....                                                       | 36        |
| b. Influence of three phase fault at bus 18: .....                                                       | 37        |
| 3.5. Improving transient stability using FACTS devices .....                                             | 45        |
| <b>Conclusion .....</b>                                                                                  | <b>48</b> |
| <b>References .....</b>                                                                                  | <b>50</b> |

---

---

## *General Introduction*

---

---

The global transition toward sustainable energy systems has driven the large-scale integration of renewable energy sources, particularly photovoltaic (PV) systems, into modern power grids [1,2]. While this transition contributes significantly to decarbonization objectives and energy autonomy, it also presents notable technical challenges—foremost among them is the preservation of power system stability [3,4].

Within the various dimensions of system stability, transient stability holds critical importance, as it pertains to the system's ability to maintain synchronism among generators in response to severe disturbances such as short-circuit faults [5,6]. The Critical Clearing Time (CCT) is widely employed as a key indicator in this context, signifying the maximum allowable fault duration beyond which system instability becomes inevitable [7,8].

Due to their inverter-based nature and absence of inherent rotational inertia, PV systems often compromise transient stability, especially under conditions of high penetration or in weak grid environments [9,10]. Consequently, enhancing transient stability in PV-integrated power systems has become a pressing concern in both academic and industrial domains [11,12].

To address these challenges, various Flexible AC Transmission Systems (FACTS)—notably the Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), and Unified Power Flow Controller (UPFC)—have been proposed and implemented for their fast dynamic reactive power support and voltage regulation capabilities [13,14]. Each device exhibits distinct structural and operational features that influence its effectiveness under different grid conditions and fault scenarios [15,16].

This study conducts a comparative evaluation of SVC, STATCOM, and UPFC for enhancing the transient stability of the IEEE 30-bus test system incorporating a 50 MW PV unit [17,18]. The analysis focuses on the impact of various fault locations, with CCT serving as the primary performance metric. Time-domain simulations are executed using the Power System Analysis Toolbox (PSAT) within MATLAB to assess the stabilizing contribution of each FACTS device under uniform fault conditions [19,20].

The remainder of this paper is organized as follows: Section 2 describes the system configuration and modeling methodology. Section 3 provides an overview of the power system components. Section 4 presents the base case analysis of transient stability under three-phase faults without PV integration and further examines the impact of incorporating PV on system behavior. Section 5 offers a comparative evaluation of SVC, STATCOM, and UPFC in enhancing transient stability. Finally, Section 6 concludes the study and outlines future research directions.



---

---

# *Chapter 1 — Power System Studies*

---

---

A power system is an interconnected network designed to generate, transmit, distribute, and utilize electrical energy efficiently and reliably. It consists of power generation units, high-voltage transmission lines, substations, and distribution networks that deliver electricity to end users. With the increasing integration of renewable energy sources and the growing demand for electricity, maintaining system stability, power quality, and operational security has become a major challenge. Therefore, advanced control and compensation techniques are increasingly employed to enhance the performance, reliability, and efficiency of modern power systems.

## 1.1 Power System:

Now in developed and developing nations, the availability of electrical power is necessary for economic growth. The many important items cannot be produced without energy. Without electricity, which is a necessary component of modern life, individuals find it challenging to do their tasks.

The generating system, transmission system, and distribution system are the three main parts of the electrical power system. The distribution system delivers electricity to the end user through substations that are connected to the generating units by a high voltage (HV) transmission system. Any breaks in these connecting cables have the potential to stop the system's power supply [1].

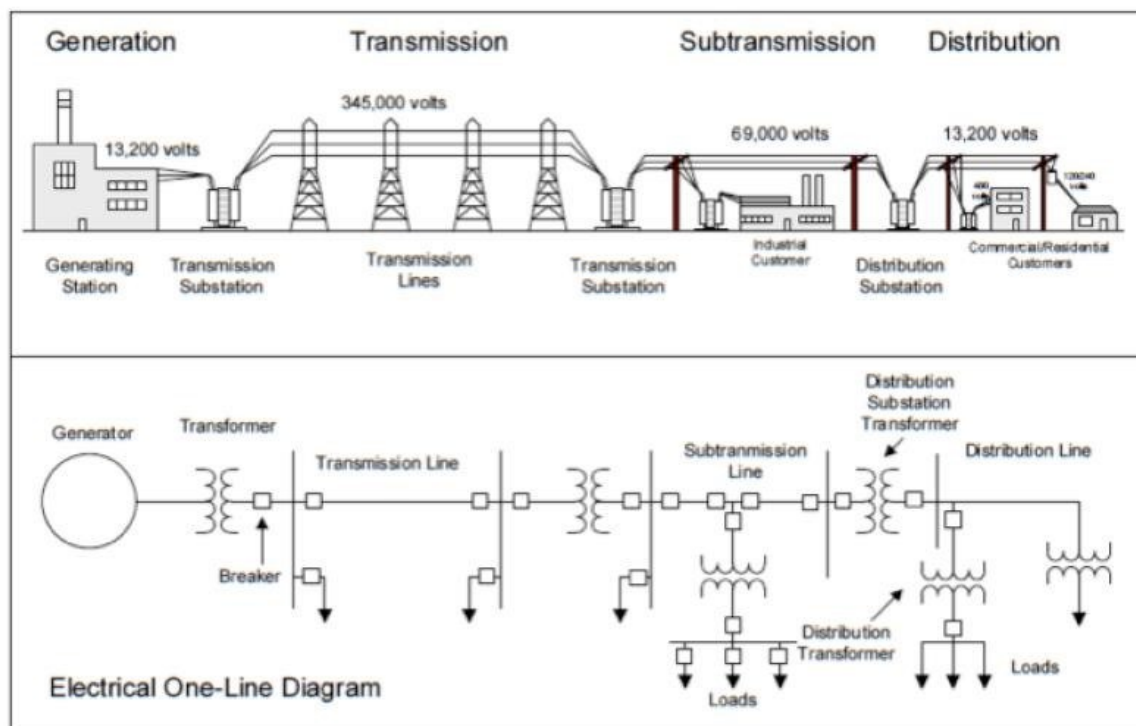


**Figure 1** Typical electric power system single-line diagram [2]

## 1.2 The structure of the power system:

An interconnected power system is a complex enterprise that may be subdivided into the following major subsystems:

- Generation Subsystem
- Transmission and Sub transmission Subsystem
- Distribution Subsystem
- Utilization Subsystem

### 1.2.1 Génération Subsystem:

This includes generators and transformers.

**Generators:** The three-phase ac generator, an alternator or synchronous generator, is a fundamental and essential part of power systems.

Two synchronous rotating fields are included in generators. One field is created by a rotor that is rotated at synchronous speed and activated by dc current. The three-phase armature currents in the stator windings create the other field. Excitation systems provide the rotor windings with dc current. Older machines have dc generators located on the same shaft as the exciters, which excite slip rings. Asynchronous excitation systems, which are now used in systems, utilize ac generators with revolving rectifiers. Generator voltage is maintained and reactive power flow is managed by the excitation system. Ac generators are able to produce high power at high voltage, often 30 kV, since they do not use a commutator [3].

The source of the mechanical power, also known as the prime mover, may be internal combustion engines, gas turbines, steam turbines powered by the combustion of coal, gas, and nuclear fuel, or even hydraulic turbines.

**1.2.1.1 Transformers:** From one voltage level to another, the transformer efficiently transmits electricity. With the exception of losses in the secondary, the power transferred from the primary is extremely similar. transformer Power transmission across long distances is made possible by the use of a step-up transformer, which reduces line losses [3].

"The generation subsystem may be called GENCO"[4], responsible for generating electric power as per the predicted load requirements

### 1.2.2 Transmission and Sub transmission Subsystem :

Electricity from producing units is transferred via an overhead transmission network to the distribution network, which in turn feeds the load. Transmission lines also link nearby

utilities, allowing the dispatch of electricity within regions under natural conditions and the transfer of electricity across areas in times of emergency [3].

The transmission subsystem may be called "TRANSCO" [4].



**Figure 2** Traditional Transmission line.[1]

### 1.2.3 Distribution Subsystem:

The distribution system links the equipment at the consumers' service entrances to the distribution substations. The load is supplied by the primary distribution lines, which have a voltage range of 4 to 34.5 kV and cover a certain geographic region [3].

The distribution subsystem may be called "DISCOM"[4]

## 1.3 Power flow studies:

Power flow studies are conducted to calculate voltages, active and reactive power, etc.

at various locations in the network for different operating possibilities. These calculations are based on restrictions on generator capacities, specified net interchange across operating systems, and a number of other factors. Power flow or load flow solutions are essential for a continuous evaluation of the performance of the power systems and for adopting suitable control measures when necessary. In practice, various power flow solutions will need to be used under different conditions [5].

### 1.3.1 Necessity for power flow studies

The necessity for power flow studies

There are several reasons why power flow studies are carried out, some of which include the following:

- The line flows.

- The system voltage profile and bus voltages
- How does adding additional circuits and changing the setup affect system loads
- The impact on system loads and corresponding effects of a temporary loss of transmission capacity and (or) generation.
- System loading and in-phase and quadrature bus voltages
- How the economy is run
- Minimization of system loss
- Setting the transformer tap for economical operation
- Changing conductor sizes and system voltages may be able to improve an existing system[5].

### 1.3.2 Bus classification:

There is a bus connecting each node to a generator. In power, each bus has 4 quantities of is voltage magnitude, voltage angle, active power, and reactive power. In the system, two quantities are given and two quantities are determined. Depending on the calculation of the quantities the buses are classified into three types. The loads used in load flow studies are constant and defined for both real and reactive power consumption. Determining the voltage angle and voltage magnitude of each bus when the power is generated is the primary goal of a load analysis. For that classify different busses shown in the following figure[6]:

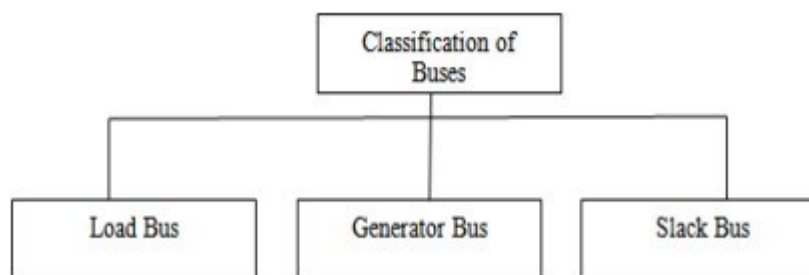


Figure 3 Classification of buses

**1.3.2.1 Load Buses:** Load buses are connected to the load side of the system. Which is known quantities are active power(P) and reactive power (Q). And the determined quantities are voltage magnitude(|V|) and the voltage angle( $\delta$ ). In the system 20% of load buses are present.

**1.3.2.2 Voltage Controlled Buses:** The generator bus is connected to the generator of the system. The system's active power (V) and voltage magnitude (|V|) are known quantities.

Reactive power ( $Q$ ) and voltage angle ( $\delta$ ) are further unknowns. The primary mover of the bus controls the generator, and the voltage is controlled by the voltage. 70% of the system's generator buses are present[7].

**1.3.2.3 Slack or Swing Bus:** Because it serves as a reference for all other buses, the bus known as No. 1 is also known as the reference bus. All other buses are measured against it as the reference. This bus has a  $0^\circ$  degree angle. Voltage magnitude ( $|V|$ ) and voltage angle ( $\delta$ ) are the bus's two well-known parameters. There is a 10% slack bus in the system.

**1.3.2.4 Bus Admittance Matrix:**

- The first step is to number all the nodes of the system from 0 to  $n$ . Node 0 is the reference node (or ground node).
- Replace all generators by equivalent current sources in parallel with an admittance.
- Replace all lines, transformers, loads to equivalent admittances whenever possible.
- The bus admittance matrix  $Y$  is then formed by inspection as follows (this is similar to what we learned in circuit theory):  $\sum y_{ij} = i$  and  $y_{ij} = y_{ji} = -\text{sum of admittances connected from node } i \text{ to node } j$
- The current vector is next found from the sources connected to nodes 0 to  $n$ . If no source is connected, the injected current would be 0.
- The current vector is next found from the sources connected to nodes 0 to  $n$ . If no source is connected, the injected current would be 0.

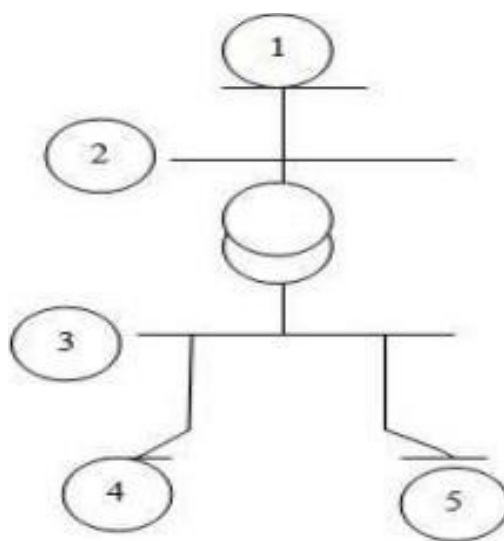


Figure 4 one line diagram of 6 bus system

### 1.3.3 The power flow methods:

#### 1.3.3.1 Gauss-Siedel (GS) load flow method:

With the slack bus voltage assumed (usually  $V_1 = 1 \angle 0^\circ$  p.u.), the remaining (n-1) bus voltages are found through iterative process as follows

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (1.1)$$

$$Q_i = - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (1.2)$$

The equation 1 and 2 are called static load flow equations.

$$I_i = P_i - V_i^* Q_i \quad (1.3)$$

$$V_i = \frac{1}{Y_{ii}} \left( I_i + \sum_{j=1, j \neq i}^n Y_{ij} V_j \right) \quad i = 2, 3, 4 \dots n \quad (1.4)$$

For (k+1)<sup>th</sup> iteration, the voltage equation becomes

$$V_i(k+1) = \frac{1}{Y_{ii}} \left( I_i + \sum_{j=1, j \neq i}^n Y_{ij} V_j(k) \right) \quad (1.5)$$

#### 1.3.3.2 Newton-Raphson (NR) load flow method:

Because of the quadratic convergence, the Newton-Raphson method is mathematically superior to the Gauss-Siedel method[9]. It is found to be a more efficient method for large power systems. The Jacobian matrix gives the linearized relationship between small changes in voltage angle  $\Delta\delta$  and voltage magnitude  $\Delta V$  with the small changes in active and reactive power  $\Delta P$  and  $\Delta Q$ .

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta V \end{bmatrix}$$

$$\Delta Q \Delta V$$

$$J_1 \quad J_2$$

$$\text{here } [J] = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}$$

$$J_3 \quad J_4$$

The matrix of partial differentials is called the Jacobian matrix [J]. The elements of the Jacobian are calculated by differentiating the active power and reactive power Eqs.1 & 2 and substituting the estimated values of voltage magnitude and phase angle.

| Element of J | Order of J matrix | Diagonal elements | Off-diagonal elements |
|--------------|-------------------|-------------------|-----------------------|
|--------------|-------------------|-------------------|-----------------------|

| matrix | elements              |                                                                                                                                                   |                                                                                                          |
|--------|-----------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| J1     | $(n-1) \times (n-1)$  | $= \frac{\partial P_i}{\partial  \delta_i } = \sum_{j \neq i}  V_i   V_j  Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)$                         | $\frac{\partial P_i}{\partial  \delta_j } = - V_i   V_j  Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)$ |
| J2     | $(n-1) \times (n-1)$  | $= \frac{\partial P_i}{\partial  V_i } = 2 V_i  Y_{ii} \cos(\theta_{ii}) + \sum_{j \neq i}  V_j  Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)$  | $\frac{\partial P_i}{\partial  V_j } =  V_i  Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)$             |
| J3     | $(n-1) \times n_p$    | $= \frac{\partial Q_i}{\partial  \delta_i } = \sum_{j \neq i}  V_i   V_j  Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)$                         | $\frac{\partial Q_i}{\partial  \delta_j } = - V_i   V_j  Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)$ |
| J4     | $(n-1) \times n_{pw}$ | $= \frac{\partial Q_i}{\partial  V_i } = -2 V_i  Y_{ii} \sin(\theta_{ii}) + \sum_{j \neq i}  V_j  Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)$ | $\frac{\partial Q_i}{\partial  V_j } =  V_i  Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)$             |

Table 1 Description of Jacobian matrix

Where  $n_{pv}$  is the number of PV buses.

The terms  $\Delta P_i^r$  and  $\Delta Q_i^r$  are the difference between the scheduled and calculated valued, known as mismatch vector or power residuals, given by

$$P_i (\text{scheduled}) - P_i^r (\text{calculated}) = \Delta P_i^r$$

$$Q_i (\text{scheduled}) - Q_i^r (\text{calculated}) = \Delta Q_i^r$$

$$Q_i (\text{scheduled}) - Q_i^r (\text{calculated}) = \Delta Q_i^r \quad (1) \text{ to update voltage magnitude and angles:}$$

$$|V|^{(r+1)} = |V|^r + |\Delta V|^r$$

$$\delta^{(r+1)} = \delta^r + \Delta \delta^r$$

where  $r$  = no. of iteration.

## 1.4 Faults in electrical power systems:

The fault in the power system is defined as the defect in the power system due to which the current is distracted from the intended path. The fault creates the abnormal condition which reduces the insulation strength between the conductors. The reduction in insulation causes excessive damage to the system.



Figure 7 Electrical Faults [11]

### 1.4.1 Types of faults in power system :

The fault in the power system is mainly categorized into two types they are

- Open Circuit Fault
- Short Circuit Fault

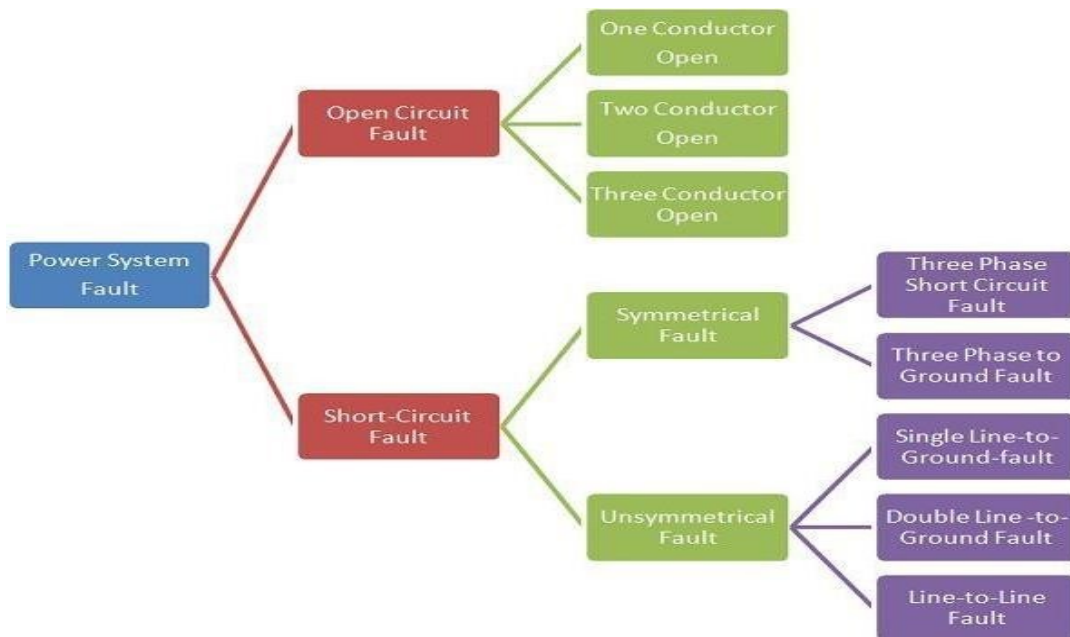


Figure 8 The different types of power system fault [12]

Many physical factors, like lightning, strong winds, earthquakes, etc., can cause faults in the electricity system. It could also happen as a result of accidents like falling from a tree, hitting a support structure with a car, an airplane crashing, etc[12].

#### ❖ Open Circuit Fault:

One or two conductors failing is the primary source of the open circuit failure. The name series fault also knows as the open circuit fault because it happens in series with the line. These faults have an impact on the system's reliability [12].

Asymmetrical or unbalanced faults are two other forms of faults in addition to threephase open circuits. So, keep in mind that the transmission line is operating under the initial balanced load of the open-circuit fault. The alternator's load reduces if one of the three phases' spreads, and because of the low load, the alternator's speed rises, causing it to move a bit faster than synchronous speed. This over-alternator speed results in overvoltage in the transmission line [11].

The open circuit fault is categorized as:

- Open Conductor Fault
- Two conductors Open Fault
- Three conductors Open Fault.

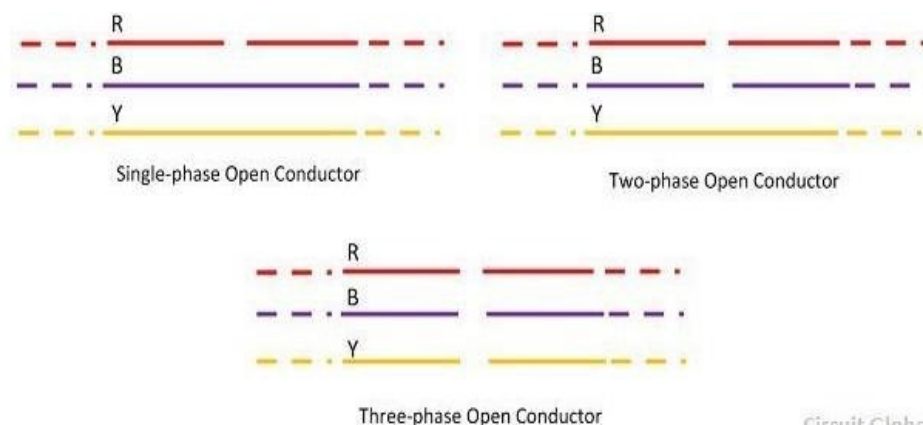


Figure 9 The open circuit fault

#### ❖ Short-Circuit Fault:

A short circuit can be defined as an abnormal connection of very low impedance between two points of different potential, whether made intentionally or accidentally.

These faults are the most common and dangerous ones, causing abnormally high currents to flow through the device or transmission lines. The equipment suffers extensive damage if these faults are allowed to continue, even for a small period. Shunt faults are another name for short circuit faults. These problems are caused on by a failure in the

insulation between the phase conductors, the ground, or both.[11]–[13] The short-circuit fault is divided into the

- Symmetrical
  - line-line-line line
  - line-line-ground
- Unsymmetrical fault.
  - Line-ground
  - Line-line
  - Line-line-ground

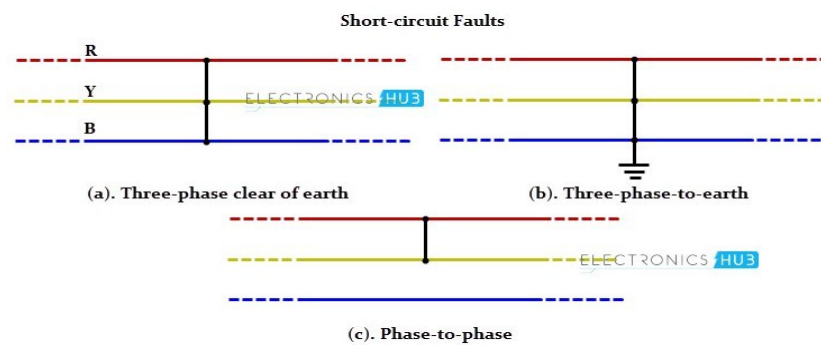


Figure 10 Short-Circuit Faults

## 1.5 Power-system architecture:

A power system's many parts can be configured in a variety of ways. The cost of the investment and the amount of electrical energy available depend on the complexity of the eventual design. So, choosing an architecture for a particular application depends on finding the right balance between technical requirements and cost [14].

### 1.5.1. Architectures include the following:

#### 1.5.1.1 Radial systems:

- Single-feeder
- Double-feeder
- Parallel-feeder
- Dual supply with double busbars.

#### 1.5.1.2 Loop systems:

- Open loop,
- Closed loop.

### 1.5.2 Systems with internal power generation:

- Normal source generation,
- Replacement source generation.

| Architecture                     | Use                                                                                                                       | Advantages                                                                            | Drawbacks                                                                                                 |
|----------------------------------|---------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------|
| <b>Radial</b>                    |                                                                                                                           |                                                                                       |                                                                                                           |
| Single-feeder radial             | Processes not requiring continuous supply E.g., a cement works                                                            | Most simple architecture Easy to protect Minimum cost                                 | Low availability Downtime due to faults may be long A single fault interrupts supply to the entire feeder |
| Double-feeder radial             | Continuous processes: steel, petrochemicals                                                                               | Good continuity of supply Maintenance possible on busbars of main switchboard         | Expensive solution Partial operation of busbars during maintenance                                        |
| Double busbars                   | Processes requiring high continuity of service Processes with major load changes                                          | Good continuity of supply Flexible operation: no-break transfers Flexible maintenance | Expensive solution Requires automatic control functions                                                   |
| <b>Loop systems</b>              |                                                                                                                           |                                                                                       |                                                                                                           |
| Open loop                        | Very large power systems Major future expansion Loads concentrated in different zones of a site                           | Less expensive than closed loop Simple protection                                     | Faulty segment can be isolated during loop reconfiguration Requires automatic control functions           |
| Closed loop                      | Power system offering high continuity of service Very large power systems Loads concentrated in different zones of a site | Good continuity of supply Does not require automatic control functions                | Expensive solution Complex protection system                                                              |
| <b>Internal power generation</b> |                                                                                                                           |                                                                                       |                                                                                                           |
| Normal source generation         | Industrial process sites producing their own energy E.g., paper plants, steel                                             | Good continuity of supply Cost of energy (energy recovered from process)              | Expensive solution                                                                                        |

|                                           |                                                       |                                                               |                                         |
|-------------------------------------------|-------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------|
| Replacement source<br>(source changeover) | Industrial and<br>commercial sites E.g.,<br>hospitals | Good continuity of<br>supply for priority<br>outgoing feeders | Requires automatic<br>control functions |
|-------------------------------------------|-------------------------------------------------------|---------------------------------------------------------------|-----------------------------------------|

Table 2 the main characteristics of each architecture for comparison.[14]

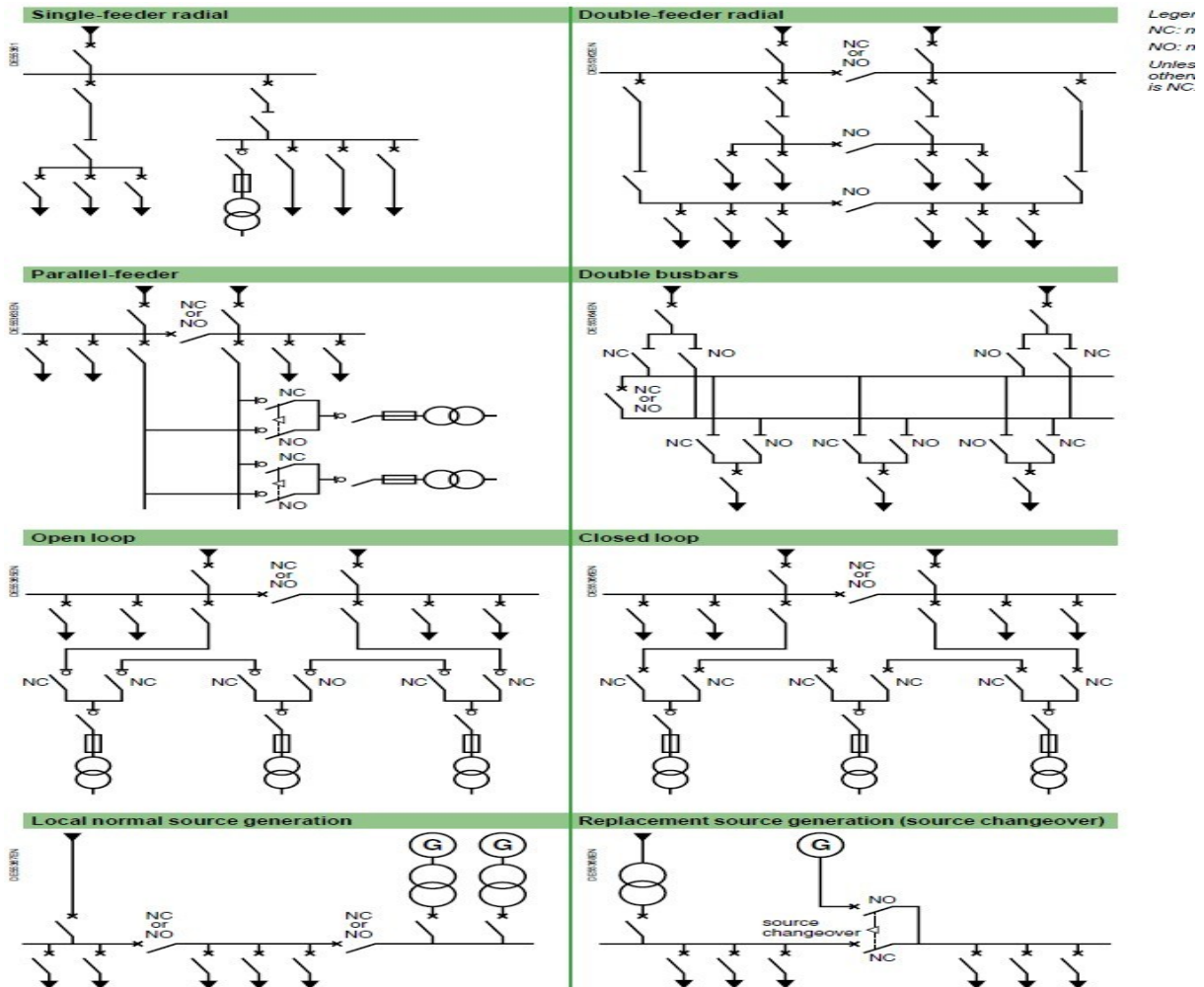


Figure 11 Examples of architectures [14]

## 1.6 Transmission line parameters:

One of the key parts of an electric power system is the power transmission line. Its major task is to move electric energy efficiently between distribution substations that are typically far off from the power sources [15].

A transmission line's design is influenced by four electrical parameters:

- Series resistance
- Series inductance
- Shunt capacitance
- Shunt conductance

| Quantity    | Symbol | Unit                          |
|-------------|--------|-------------------------------|
| Resistance  | R      | Ohm ( $\Omega$ )              |
| Inductance  | L      | Henry (H)                     |
| Capacitance | C      | Farad (F)                     |
| Conductance | G      | Siemens (S or $\Omega^{-1}$ ) |

Table 3 Symbols and Units for Transmission Line Parameters

**1.6.1 Series resistance :**

The resistance of the conductor is the most important cause of power loss in a power line. Direct-current resistance is given by the familiar formula:

$$R_{dc} = \frac{\rho l}{A} \text{ ohms} \quad (1.6)$$

where  $\rho$  is the conductor resistivity at a given temperature ( $\Omega \cdot \text{m}$ )  $l$  is the conductor length (m)  $A$  is the conductor cross-section area ( $\text{m}^2$ )

**1.6.2 Series inductance :**

The inductance of a magnetic circuit that has a constant permeability  $\mu$  can be obtained by determining the following:

- Magnetic field intensity  $H$ , from Ampere's law
- Magnetic flux density  $B$  ( $B = \mu H$ )
- Flux linkages  $\lambda$
- Inductance from flux linkages per ampere ( $L = \lambda/I$ )

**1.6.3 Shunt capacitance :**

Gauss' law is used to determine the electric field strength between the conductors that compose the transmission line in order to calculate capacitance. The conductor bundling and spacing both have an impact on the electric field strength. The impact of the earth is taken into account in various capacitance calculations.

$$\text{Density } \rho_p = \frac{q}{A} = \frac{q}{2\pi x} \text{ (C)} \quad \text{Density } E_P = \frac{q}{2\pi \epsilon_0 x} \text{ (V/m)} \quad (1.7)$$

Where

Density  $P$  is the electric flux density at point  $P$  (C)

$E_P$  is the electric field intensity at point  $P$  (V/m)

$A$  is the surface of a concentric cylinder with 1m length and radius  $x$  ( $m^2$ )  $\epsilon = \epsilon_0 = 10^{-9}/36\pi$  is the permittivity of free space assumed for the conductor (F/m)

The potential difference or voltage difference between two outside points  $P_1$  and  $P_2$  with corresponding distances  $x_1$  and  $x_2$  from the conductor center.

$$CP1-P2 = VP1-p2 = \frac{q}{2\pi\epsilon_0} \ln[x_2/x_1] \text{ (F/m)} \quad (1.8)$$

#### 1.6.4 Shunt conductance:

Shunt conductance is a shunt parameter of transmission line parameters. It is the flow of leakage current between conductors or between a conductor and earth at the insulators of the transmission line. This flow of leakage current depends upon the condition of the air between transmission lines. Generally, the value of shunt conductance on account of leakage current is very small and can be neglected.

### 1.7 Conclusion :

This chapter introduces the basic concepts of power systems, such as the basic structure of power distribution stations, the basic concepts of energy flow, as well as the types of faults that occur in the system in addition to the parameter of transmission lines.

---

## ***Chapter 2 — Transient Stability and CCT Definition***

---

DIFFERENT TYPES OF FACTS DEVICE IN POWER SYSTEM

## 2.1. Introduction

MODERN, power systems are prone to widespread failures. With increased loading of existing power transmission systems, operation of power system becomes more complex and power system will become less secure. Operating environment, conventional planning and operating methods can leave systems exposed to instabilities. Voltage instability is one of the phenomena which have result in a major blackout. Besides, with the electricity market deregulation, number of unplanned power exchanges increases due to the competition among utilities and direct contracts concluded between generation companies and costumers. If these exchanges are not controlled, some lines may become overloaded. Because many of the existing transmission lines could not cope with increasing power demand, the problem of voltage stability and voltage collapse has also become a major concern in planning and operation of deregulated power systems. So control of power flow in order to have more efficient, reliable, and secure system is in the interest of the transmission system operator (TSO). To overcome this problem, FACTS devices are introduced. FACTS devices can regulate the active and reactive power control as well as adaptive to voltage magnitude control simultaneously by their fast control characteristics and their continuous compensating capability and so reduce flow of heavily loaded lines and maintain voltages in desired level. Besides, FACTS devices can improve both transient and small signal stability margins. Controlling the power flows in the network, under normal and abnormal conditions of the network, can help to reduce flows in heavily loaded lines, reduce system power loss, and so improve the stability and performance of the system without generation rescheduling or topological changes in the network. Because of the considerable costs of the FACTS devices, it is so mementos to find out the optimal location for placement of these devices to improve voltage stability margins and enhance network security. Effect of FACTS devices on power system security, reliability and loadability has been studied according to proper control objectives.

## 2.2. Generalities on facts devices

In a power system, FACTS devices may be used to achieve several goals. In steady-state, for a meshed network, they can permit to operate transmission lines close to their thermal limits and to reduce the loop flows. In this respect, they act by supplying or absorbing reactive power, increasing or reducing voltage and controlling series impedance or phase-angle. Their high-speed command gives them several qualities in dynamic stability. In particular, they are capable to increase synchronizing torque, damp oscillations at various

frequencies below the rated frequency (0.2 to 1.5 Hz), support dynamic voltage or control power flows. Moreover, FACTS devices may have benefits in case of short circuits, by limiting short-circuit current. Another advantage of FACTS devices consists in the fact that the technology give the opportunity to expand the current transmission line limits in a step-by-step manner with incremental investment when required. Furthermore, it offers the possibility to move an installation when it becomes not useful anymore. Different types of devices have been developed and there is various ways to class them:

the technology of the used semiconductor, the possible benefits of the controllers, the type of compensation.

According to the last classification, we may distinguish three categories of FACTS controllers:

- series controllers
- shunt controllers
- combined series-shunt controllers

Inside a category, several FACTS devices exist and each one has its own proprieties and may be used in specification texts. The choice of the appropriate device is important since it depends on FACTS Devices. In this paper, four different FACTS devices have been describe to improve voltage stability margins in power system. These are: TCSC (Thyristor Controlled Series Capacitor), SVC (Static VAR Compensator),SSSC(Static Synchronous Series compensator) and UPFC (Unified Power Flow Controller). These are shown in Fig. 1.

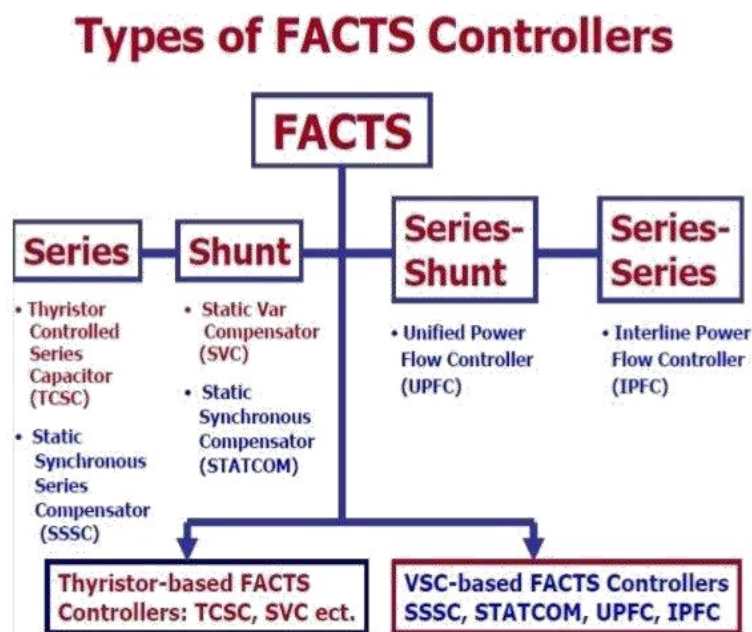


Fig1: types of FACTS Controller

### 2.2.1 Static Var Compensator (SVC)

Static var systems are applied by utilities in transmission applications for several purposes. The primary purpose is usually for rapid control of voltage at weak points in a network. Installations may be at the midpoint of transmission interconnections or at the line ends. Static Var Compensators are shunt connected static generators absorbers whose outputs are varied so as to control voltage of the electric power systems. In its simple form, SVC is connected as Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) configuration as shown in Fig. 2. The SVC is connected to a coupling transformer that is connected directly to the ac bus whose voltage is to be regulated. The effective reactance of the FC-TCR is varied by firing angle control of the antiparallel thyristors. The firing angle can be controlled through a PI (Proportional + Integral) controller in such a way that the voltage of the bus, where the SVC is connected, is maintained at the reference value.

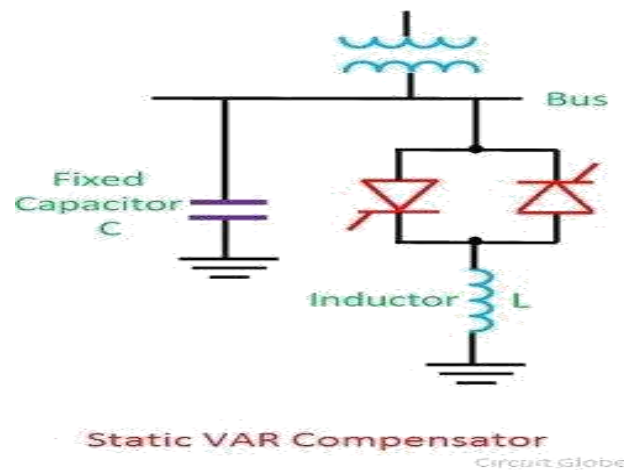


Fig2: Static VAR Compensator

### 2.2.2 Thyristor Controller Series Capacitor (Tcsc)

TCSC is one of the most important and best-known FACTS devices, which has been in use for many years to increase the power transfer as well as to enhance system stability. The main circuit of a TCSC is shown in Fig. 3. The TCSC consists of three main components: capacitor bank C, bypass inductor L and bidirectional thyristors SCR1 and SCR2. The firing angles of the thyristors are controlled to adjust the TCSC reactance in accordance with a system control algorithm, normally in response to some system parameter variations. According to the variation of the thyristor firing angle or conduction angle, this process can be modeled as a fast switch between corresponding reactances offered to the power system.

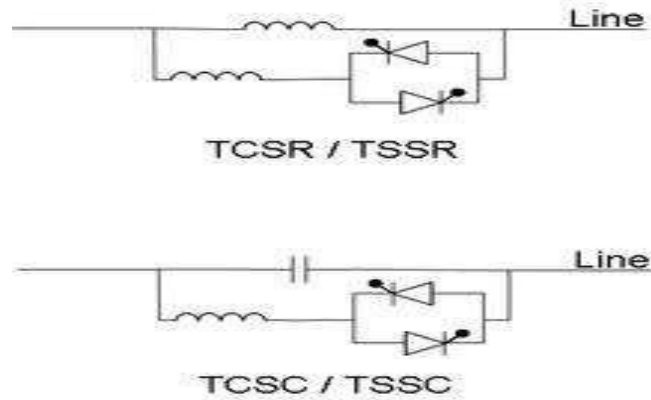


Fig 3: Thyristor Controlled Series Capacitor

### 2.2.3 Static Synchronous Series Compensator (SSSC)

The SSSC is one of the most recent FACTS devices for power transmission series compensation. It can be considered as a synchronous voltage source as it can inject an almost sinusoidal voltage of variable and controllable amplitude and phase angle, in series with a transmission line. The injected voltage is almost in quadrature with the line current. A small part of the injected voltage that is in phase with the line current provides the losses in the inverter. Most of the injected voltage, which is in quadrature with the line current, provides the effect of inserting an inductive or capacitive reactance in series with the transmission line. The variable reactance influences the electric power flow in the transmission line.

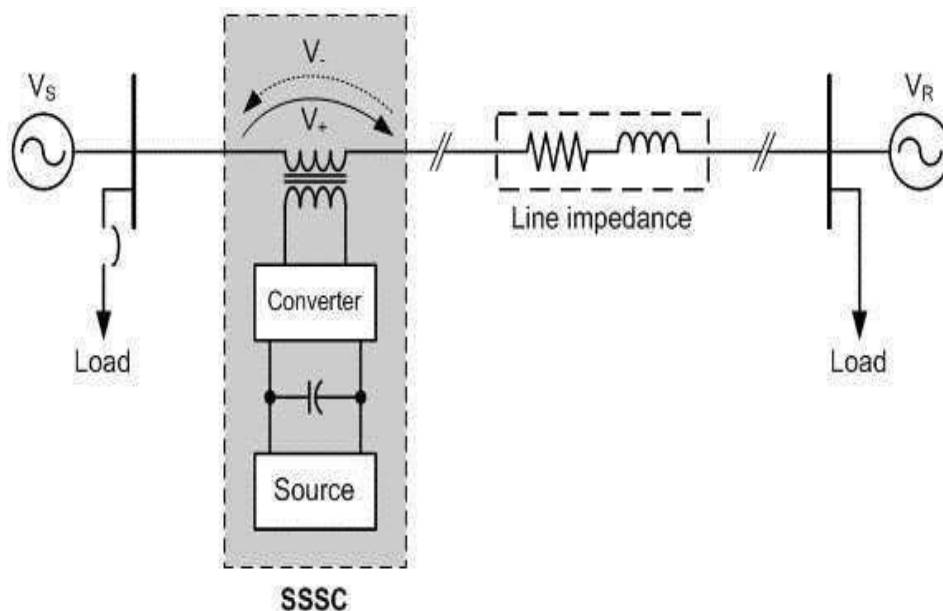


Fig 4: Static Synchronous Series Compensator

### 2.2.4 Unified Power Flow Controller (UPFC)

Among the available FACTS devices, the Unified Power Flow Controller (UPFC) is the most versatile one that can be used to enhance steady state stability, dynamic stability and transient stability. The basic configuration of a UPFC is shown in Fig.5. The UPFC is capable of both supplying and absorbing real and reactive power and it consists of two ac/dc converters. One of the two converters is connected in series with the transmission line through a series transformer and the other in parallel with the line through a shunt transformer. The dc side of the two converters is connected through a common capacitor, which provides dc voltage for the converter operation. The power balance between the series and shunt converters is a prerequisite to maintain a constant voltage across the dc capacitor. As the series branch of the UPFC injects a voltage of variable magnitude and phase angle, it can exchange real power with the transmission line and thus improves the power flow capability of the line as well as its transient stability limit. The shunt converter exchanges a current of controllable.

magnitude and power factor angle with the power system. It is normally controlled to balance the real power absorbed from or injected into the power system by the series converter plus the losses by regulating the dc bus voltage at a desired value.

TCSC can change line reactance and SVC can be used to control reactive power in network. UPFC is the most versatile member of FACTS devices family and can be applied in order to control all power flow parameters (i.e. line impedance, bus voltage, and phase angle). Power flow can be controlled and optimized by changing power system parameters using FACTS devices.

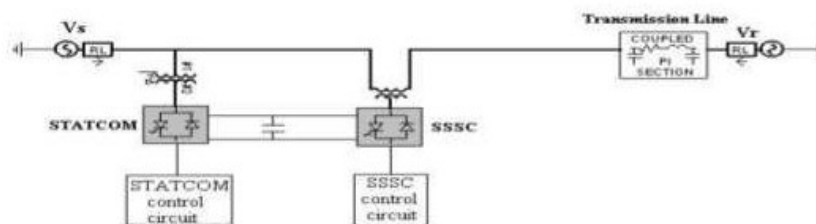


Fig5: Unified Power Flow Controller

## 2.3. PV Panel and Boost Converter Modeling

### 2.3.1 PV Panel Simulation

The PV cell's equivalent circuit when exposed to radiation. It is equivalent to an  $I_{pv}$  current generator linked in parallel to a diode. There are two new parasite resistances. The

characteristics of the cell,  $I = f(V)$  Fig. 3, are somewhat influenced by these resistors. The cell's internal resistance is measured in series resistance ( $R_s$ ). The leakage current at the junction is the cause of the shunt resistor ( $R_p$ ) [31], [32].

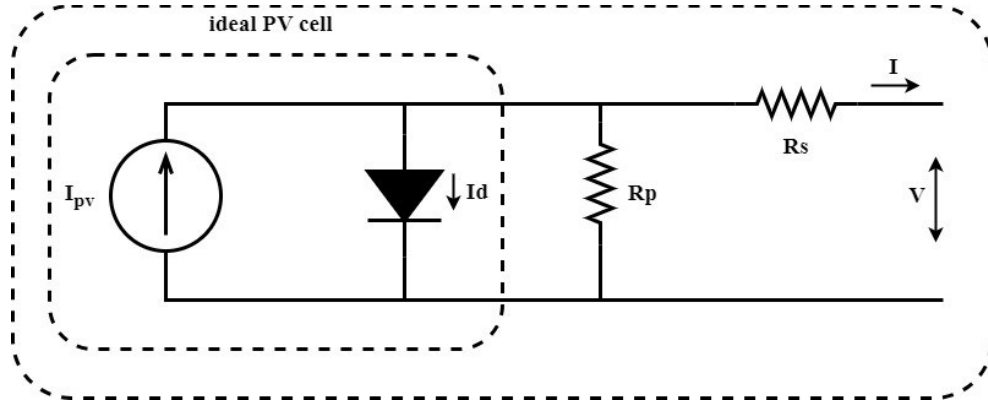


**Fig. 3.** An equivalent solar cell circuit

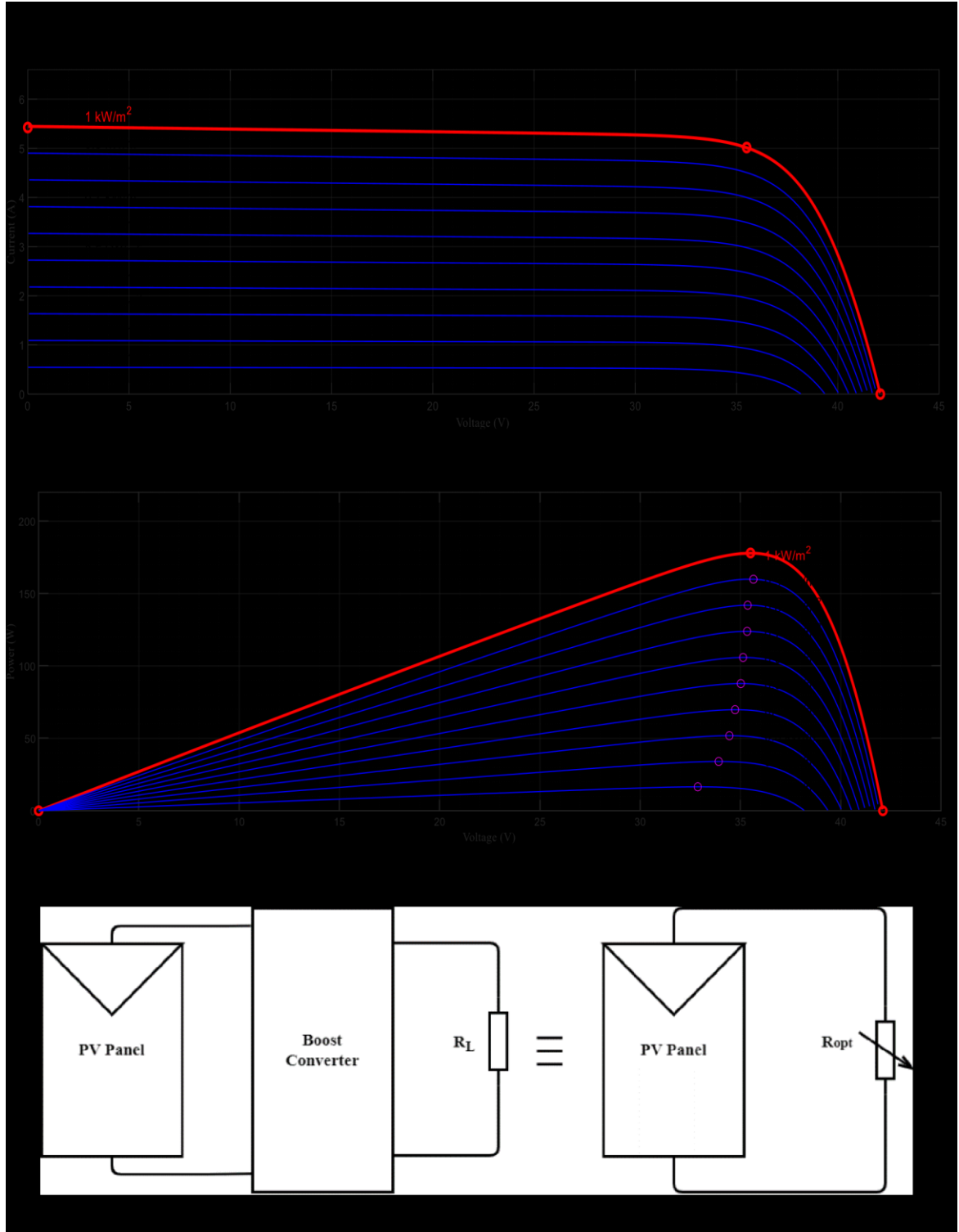
The following formulas represent the mathematical expression of the current-voltage characteristic of the ideal PV cell and this is fully analyzed and described in [33]:

$$I = I_{PV.cell} - I_{0.cell} \left[ \exp \left( \frac{qV}{akT} \right) - 1 \right] \quad (1)$$

$$I = I_{PV} - I_0 \left[ \exp \left( \frac{V + R_s I}{N_s V_t} \right) - 1 \right] - \frac{V + IR_s}{R_p} \quad (2)$$

The technical specifications of the PV panel utilized in this application, under standard test conditions (STCs), are presented in Table 1. It should be noted that, under the specified fixed or variable conditions, the PV panel is capable of producing the most energy at one point. Both of the IV and P-V characteristics at different irradiances and constant temperature of 25°C are presented in Fig. 4 and Fig. 5.

The MPP should be matched by the voltage or current used in MPPT techniques. The provided power is rarely at its peak when the PV module is connected directly to the load. Consequently, it is recommended to combine the PV panel with a DC-DC converter controlled by the MPPT tracker for it to operate at the MPP [31]. Examine a PV panel with a resistive load that is coupled to a boost-type converter Fig. 6. Table 2 lists the design parameter of the implemented DC-DC converter. The relationship between the input and output voltages of the converter is as follows and is fully described in [34], [35]:



If we consider the converter to function at 100% efficiency when connected to a resistive load ( $R$ ), the power output from the PV panel would be:

$$P_{pv} = \frac{V_{out}^2}{R_L} = \left( \frac{1}{1 - \alpha} \right)^2 \frac{V_{pv}^2}{R_L} \quad (4)$$

By correctly changing the duty ratio command of the converter, maximum power may be obtained [6]. The following equation describes the relationship in continuous conduction mode between the simulated resistance ( $R_{opt}$ ) and the load resistance ( $R_L$ ):

$$R_{opt} = RL(1 - \alpha)^2 \quad (5)$$

The following equation can be used to express  $RL$ :

$$R_{opt} = RL(1 - \alpha)^2 \quad (6)$$

The following equation can be used to express  $RL$ :

$$R_{opt} = RL(1 - \alpha)^2 \quad (7)$$

The load resistance  $RL$  value needs to be:

$$R_{opt} = RL(1 - \alpha)^2 \quad (8)$$

Assumedly, the PV panel runs under STC circumstances. The optimal resistance  $R_{opt}$  to reach

## **2.4. CONCLUSION**

We have presented the different type of facts devices is used for power flow control, voltage regulation, enhancement of transient stability and mitigation of system oscillation.

FACTS Controller is a power electronics-based system or other static equipment that provides control of one or more AC transmission system parameter.

FACTS Devices increase power transfer capability.

---

***Chapter 3 — DIFFERENT TYPES  
OF FACTS DEVICE IN POWER  
SYSTEM***

---

### 3.1. Methodology:

#### 3.1.1 Transient Stability and CCT Definition:

Transient stability refers to the power system's ability to maintain synchronism when subjected to a severe disturbance such as a short circuit, sudden load variation, or generator outage. Following a disturbance, if the system is unable to regain equilibrium, it results in the loss of synchronism, leading to system instability [21,22].

One of the most practical and widely used metrics for evaluating transient stability is the Critical Clearing Time (CCT). CCT is defined as the maximum time duration a fault can be allowed to persist before it must be cleared, to ensure that the system remains stable [23,24].

CCT is closely related to the Critical Clearing Angle (CCA) and is commonly estimated using the Equal Area Criterion (EAC). For a single-machine infinite bus (SMIB) system, the energy-based interpretation of EAC yields the following condition [25,26]:

$$\int_{\delta_0}^{\delta_{cr}} (P_m - P_e) d\delta = \int_{\delta_{cr}}^{\delta_{max}} (P_e - P_m) d\delta$$

Where:

$P_m$ : mechanical power input.

$P_e$ : electrical power output.

$\delta_0$ : initial rotor angle

$\delta_{cr}$ : critical rotor angle

$\delta_{max}$ : maximum rotor swing angle.

Using simplifying assumptions and approximations, the CCT can be expressed as [27,28]:

$$CCT = \sqrt{\frac{2H}{\omega_s(P_{acc})}} (\delta_{cr} - \delta_0)$$

Where:

H: inertia constant of the generator.

$\omega_s$ : synchronous speed.

$P_{acc} = P_m - P_e$ : accelerating power.

The Critical Clearing Time (CCT) is strongly influenced by system inertia, fault severity, and the operating point. In systems with high photovoltaic (PV) penetration, where

power electronic interfaces replace traditional rotating machines, the overall system inertia is significantly reduced. This reduction leads to shorter CCT and greater vulnerability to disturbances [29,30].

To address this issue, modern power systems utilize FACTS devices such as the Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), and Unified Power Flow Controller (UPFC). These devices provide fast and dynamic reactive power compensation, improve voltage support, and help mitigate oscillations in rotor speed during fault conditions [31,32].

In this study, the impact of SVC, STATCOM, and UPFC on enhancing CCT is investigated and compared under various fault scenarios in a PV-integrated IEEE 30-bus system [33,34].

### 3.1.2 PV System Modeling:

The photovoltaic (PV) array consists of multiple modules, each comprising several PV cells connected in series or parallel. The electrical behavior of a PV cell is commonly represented by a single-diode equivalent circuit, which captures the nonlinear current-voltage characteristics [35,36].

The output current of the PV cell is expressed as:

$$I = I_{ph} - I_0 \left[ e^{\frac{q(V+IR_s)}{\eta KT}} - 1 \right] - \frac{(V + IR_s)}{R_{sh}}$$

where  $I_{ph}$  is the photocurrent,  $I_0$  is the reverse saturation current,  $R_s$  and  $R_{sh}$  are the series and shunt resistances, respectively, and the remaining parameters represent standard physical constants and operating conditions.

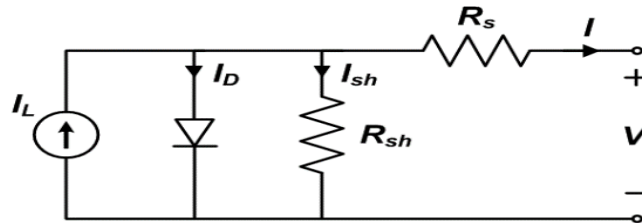


Figure. 1: Equivalent circuit of a photovoltaic cell

### 3.1.3. Modelling of PV Inverter

The photovoltaic inverter is modeled as a three-phase, six-switch Voltage Source Inverter (VSI) using IGBT technology. It converts DC power from the PV array into a 50 Hz AC output using Pulse-Width Modulation (PWM) [37,38]. Each inverter leg consists of a

switch and an anti-parallel diode. A DC-link capacitor stabilizes the input, while an LC filter at the AC output suppresses high-frequency harmonics to ensure a smooth sinusoidal voltage waveform.

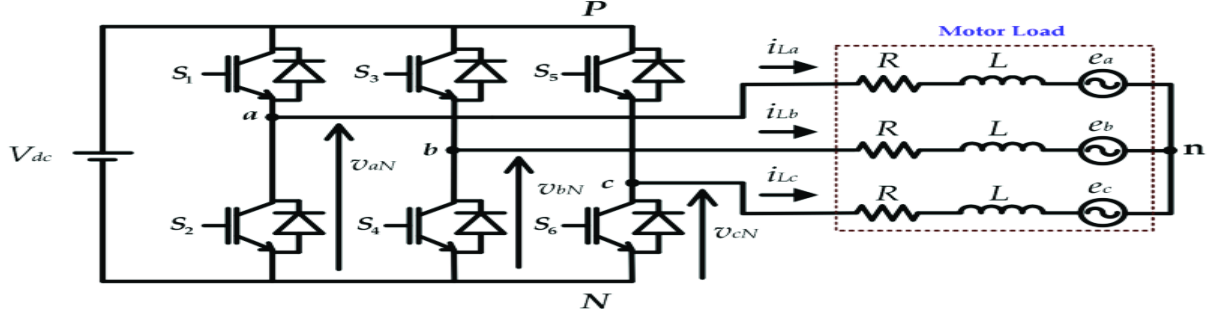


Figure. 2: Three-phase voltage source inverter topology

Control strategies include phase-locked loops (PLLs) for grid synchronization and inner current loops to regulate active and reactive power exchange with the grid. Reactive power support is especially critical during disturbances to maintain voltage stability and enhance transient performance [39,40].

The PV unit is integrated at two different locations bus 12 and bus 18 to assess the sensitivity of system stability to the point of renewable integration. The influence of these placements is examined through time-domain simulations.

### 3.2. Modeling of SVC and STATCOM and UPFC:

#### 3.2.1. Static Var Compensator (SVC):

An SVC is a shunt-connected device based on thyristor-controlled reactors (TCR) and thyristor-switched capacitors (TSC). It dynamically adjusts the reactive power injected or absorbed by the system to maintain voltage stability. The control mechanism is based on regulating the firing angle of thyristors to control the effective reactance, thereby supporting grid voltage during transients.

The reactive power output of an SVC can be represented as:

$$Q_{svc} = \frac{V^2}{X_{eq}}$$

Where:  $Q_{svc}$ : reactive power injected or absorbed.

$V$ : system voltage magnitude.

$X_{eq}$ : equivalent reactance (controlled by thyristor firing angle).

SVCs are modeled in the power system as variable susceptance devices, which respond to voltage deviations by injecting or absorbing reactive power accordingly.

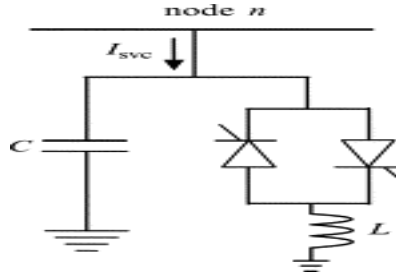


Figure 3: Simplified schematic of a Static Var Compensator (SVC)

### 3.2.2. Static Synchronous Compensator (STATCOM):

STATCOM is a voltage-source converter (VSC)-based shunt device that uses IGBT technology to synthesize a controllable voltage source in phase with the grid. Unlike SVC, STATCOM maintains its reactive power capability even at low voltage conditions and responds faster due to its solid-state converter-based structure.

The reactive power exchange of a STATCOM is governed by the voltage difference between the output  $V_{conv}$  and the grid voltage  $V_{bus}$ :  $Q_{statcom} \propto (V_{conv} - V_{bus})$

When:  $V_{conv} > V_{bus}$ , the STATCOM injects reactive power (capacitive mode).

$V_{conv} < V_{bus}$ , it absorbs reactive power (inductive mode). This makes STATCOM particularly effective in voltage support and transient stability improvement.

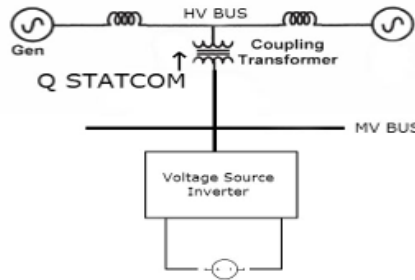


Figure 4: Simplified schematic of a Static Synchronous Compensator (STATCOM)

### 3.2.3. UPFC (Unified Power Flow Controller):

is an advanced FACTS device that allows simultaneous control of voltage, power flow, and phase angle in transmission systems. By combining series and shunt compensation through two voltage source converters (VSCs), UPFC provides dynamic support for improving both steady-state and transient stability. It is particularly effective in systems with high renewable energy integration, although it is more complex and costly than other FACTS devices.

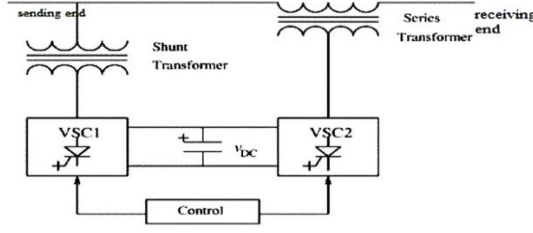


Figure 5: Basic structure of the UPFC

### 3.3. Power System Description

The IEEE 30-bus test system was adopted in this study as a benchmark model for evaluating transient stability under multiple fault scenarios with and without photovoltaic (PV) integration. Its moderate complexity and wide adoption in academic research make it suitable for analyzing dynamic behavior, particularly in response to large disturbances such as short-circuit faults.

The network consists of 30 buses, 6 synchronous generators located at buses 1, 2, 5, 8, 11, 13 and 41 transmission lines, and 4 on-load tap-changing transformers. The total load is distributed across 21 PQ-type buses. The base power of the system is 100 MVA, and the nominal voltage levels reach up to 132 kV.

Dynamic simulations were carried out using the Power System Analysis Toolbox (PSAT) in MATLAB, which allows for accurate modeling of the nonlinear system behavior under severe contingencies. To investigate the impact of renewable energy penetration, a 50 MW photovoltaic (PV) unit was integrated at two strategic locations: bus 12 and bus 18. These locations were selected based on their proximity to major load centers and their influence on power flow paths.

Six different fault locations were considered: bus 4, bus 5, bus 8, bus 12, bus 17, and bus 18. These points were chosen to represent a diverse set of scenarios, including faults near generator terminals and along key transmission corridors. Three-phase symmetrical faults were introduced at each location, and the Critical Clearing Time (CCT) was calculated to assess the system's ability to maintain synchronism.

This setup provides a comprehensive framework for analyzing the sensitivity of transient stability to both fault location and PV placement. The findings are essential for improving the resilience of future power grids with high levels of renewable energy integration.



|       |         |          |   |   |       |
|-------|---------|----------|---|---|-------|
| Bus21 | 1.0251  | -0.23679 | 0 | 0 | 0.175 |
| Bus22 | 1.0254  | -0.23664 | 0 | 0 | 0     |
| Bus23 | 1.0172  | -0.24048 | 0 | 0 | 0.032 |
| Bus24 | 1.01    | -0.24408 | 0 | 0 | 0.087 |
| Bus25 | 0.99899 | -0.23984 | 0 | 0 | 0     |
| Bus26 | 0.98098 | -0.24744 | 0 | 0 | 0.035 |
| Bus27 | 1.0009  | -0.23263 | 0 | 0 | 0     |
| Bus28 | 1.0136  | -0.1686  | 0 | 0 | 0     |
| Bus29 | 0.9806  | -0.25509 | 0 | 0 | 0.024 |
| Bus30 | 0.96884 | -0.27123 | 0 | 0 | 0.106 |

### 3.4.RESULTS AND DISCUSSION

#### 3.4.1. Case 1: Impact of three-phase faults on transient stability (CCT) and before PV integration

In this scenario, three-phase faults were introduced at various locations across the IEEE 30-bus system to assess the influence of fault location on the system's transient stability. The rotor speeds of the generators and the voltages at the affected buses were monitored and plotted to evaluate the system's dynamic response during and after the fault.

Rotor speed is a key indicator of generator synchronism, while bus voltage reflects the quality of power delivery throughout the disturbance. The results revealed that the system's response varied significantly depending on the fault location. In certain cases, faults led to sharp oscillations and low Critical Clearing Time (CCT) values, indicating reduced fault tolerance. In other cases, the system maintained stability with higher CCT values, showing a stronger ability to withstand the disturbance.

These findings highlight the importance of conducting a comprehensive fault location sensitivity analysis to identify the most critical points in the network. This information is essential for guiding system reinforcement strategies and for planning the reliable integration of renewable energy sources.

a. Influence of three phase fault at bus 12:

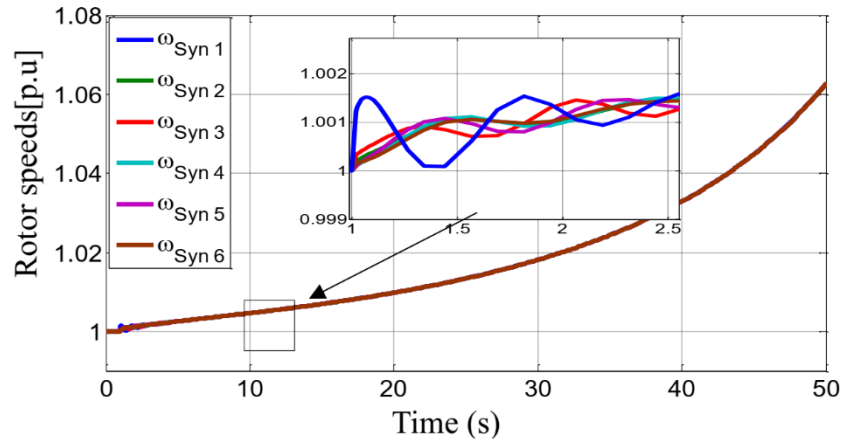


Figure.7. Rotor speed of all generators at  $t=20$  ms

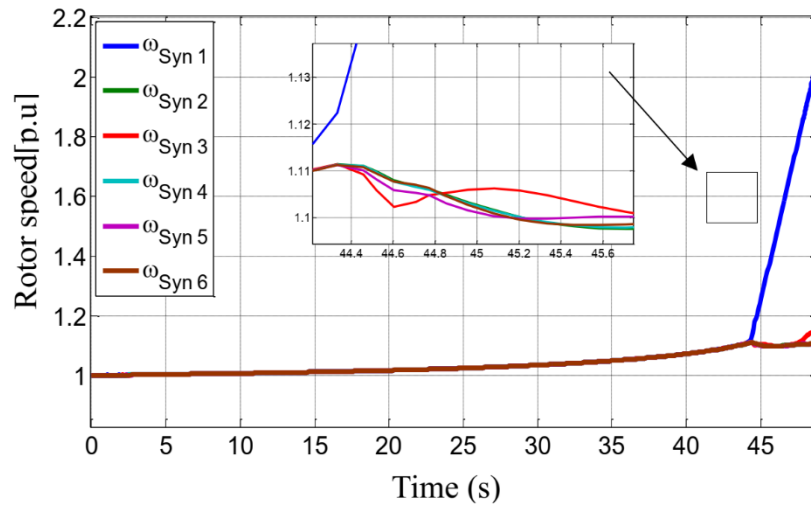


Figure.8: Rotor speed of all generators at  $t=21$  ms

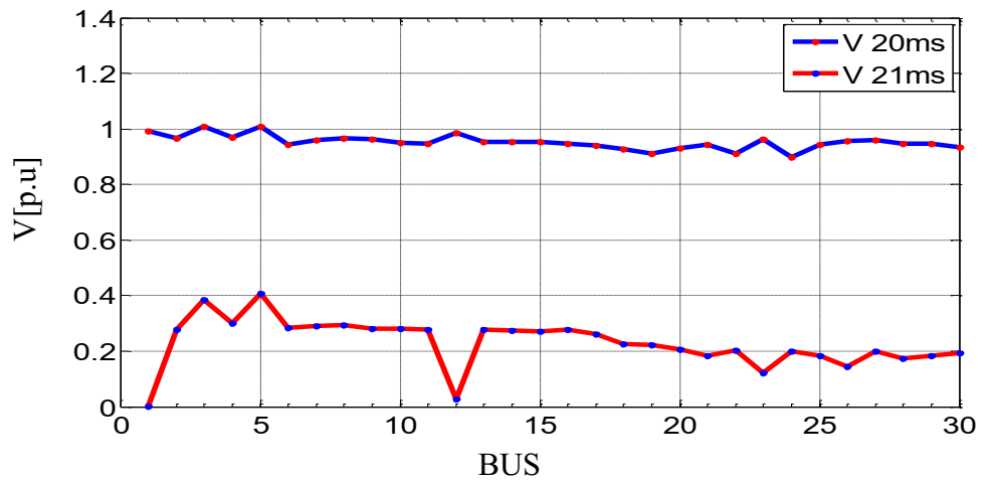


Figure.9: Voltage profile

The simulation results for a three-phase fault at bus 12 demonstrate marked variations in system behavior depending on the fault clearing time.

In the first scenario (Fig. 7,  $t = 20$  ms), all six synchronous generators maintain stable operation. Their rotor speeds increase gradually and in synchrony, without any indication of instability or significant oscillations. This behavior confirms that the system remains within the permissible range of the Critical Clearing Time (CCT). The inset plot further supports this observation by showing only minor oscillations, well within acceptable dynamic stability margins.

Conversely, the second scenario (Fig. 8,  $t = 21$  ms), which slightly exceeds the CCT threshold, reveals the onset of transient instability. Generator Syn1 loses synchronism sharply around 44.5 seconds, while the remaining units (Syn2–Syn6) continue in a quasi-stable state, albeit with increasing oscillatory behavior. This highlights the high sensitivity of system stability to even marginal deviations beyond the critical clearing threshold, leading to partial desynchronization.

As for the voltage response (Fig. 9), while the overall voltage profiles for  $t = 20$  ms and  $t = 21$  ms appear largely similar, a pronounced voltage dip is observed at one terminal in the latter case, falling below 0.4 p.u. This localized voltage sag correlates strongly with the rotor speed divergence of Syn1 and reflects a deterioration in local voltage stability due to generator desynchronization.

#### b. Influence of three phase fault at bus 18:

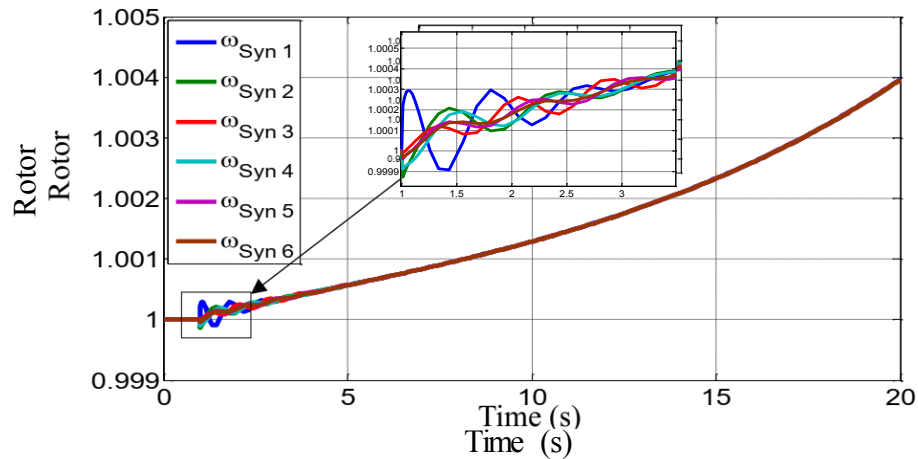


Fig.10. Rotor speed of all generators at  $t=30$  ms

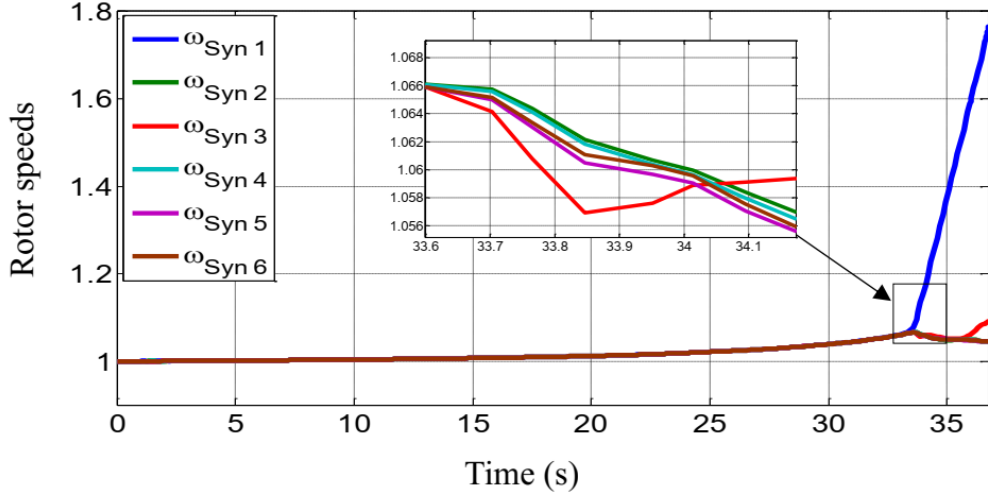


Figure. 11: Rotor speed of all generators at  $t=31$  ms

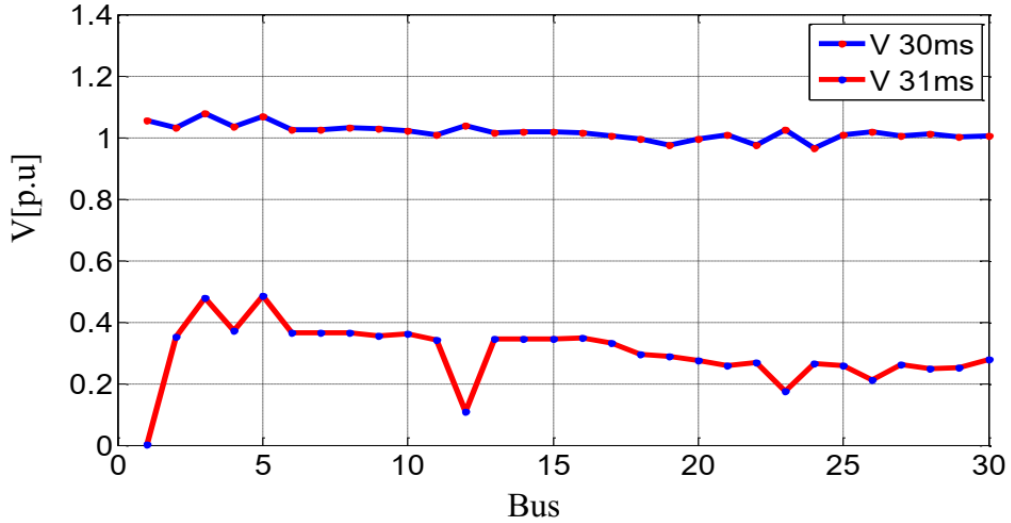


Figure.12: Voltage profile

As illustrated in Figure 10, when the fault is cleared at 30 ms, the rotor speeds exhibit slight oscillations that quickly subside, indicating that the system maintains synchronism and remains transiently stable. All rotor speeds stay close to the synchronous value (1 pu), demonstrating a coherent response of the generators after fault clearance.

In contrast, Figure 11 shows that increasing the clearing time to 31 ms leads to significant deviations in rotor speeds, particularly for  $\omega_{\text{syn1}}$ , which exceeds 1.8 pu. This behavior reflects a loss of synchronism among the generators, clearly indicating transient instability in the system.

The voltage profiles in Figure 12 further support these observations. At a clearing time of 30 ms, voltages across most buses remain within the acceptable range (0.95–1.05 pu), with only minor and temporary dips at sensitive locations such as bus 12 and bus 25. However, at

31 ms, the system experiences severe voltage collapse, especially at bus 12, where the voltage drops below 0.1 pu, signaling a clear loss of voltage stability and a critical degradation of the system's operating conditions.

Based on these results, the critical clearing time (CCT) is identified to lie between 30 ms and 31 ms, making 30 ms the maximum safe clearing time to preserve synchronism and ensure transient stability in the absence of photovoltaic generation.

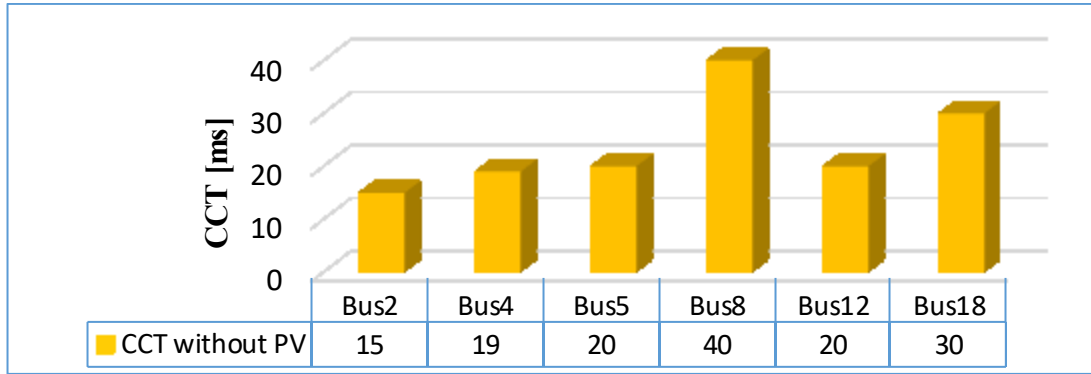


Figure.13: CCT comparison histogram without PV integration

The simulation results of the critical clearing time (CCT) before integrating photovoltaic (PV) systems revealed significant variability across different fault locations in the IEEE 30-bus network. The lowest CCT value was observed at bus2 with 15 ms, followed by Bus4 with 19 ms, indicating limited transient stability at these locations. In contrast, the highest CCT was recorded at bus17 with 48 ms, followed by bus8 with 40 ms, reflecting stronger system resilience in those areas. Other buses such as bus5, bus12, bus18 showed moderate values ranging from 20 to 30 ms, suggesting a medium level of system robustness. These findings underscore the system's sensitivity to fault location and point to the inherent limitations in transient stability that may need to be addressed when planning future system enhancements or integrating renewable sources.

**Case 2: Transient Response to the Sudden Connection of a 50 MW Photovoltaic System**

**a. Influence of three phase fault with Photovoltaic at bus12:**

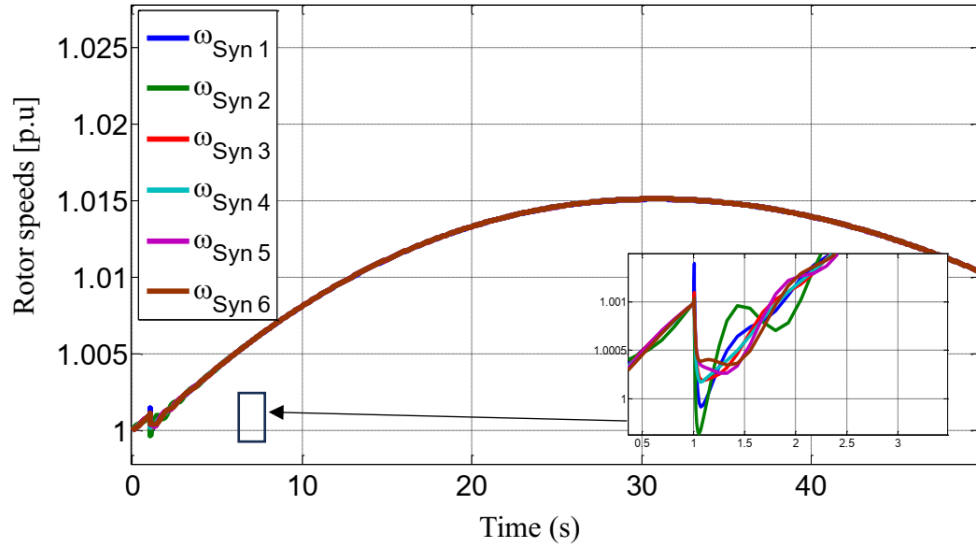


Figure.14: Rotor speed of all generators at T=7ms

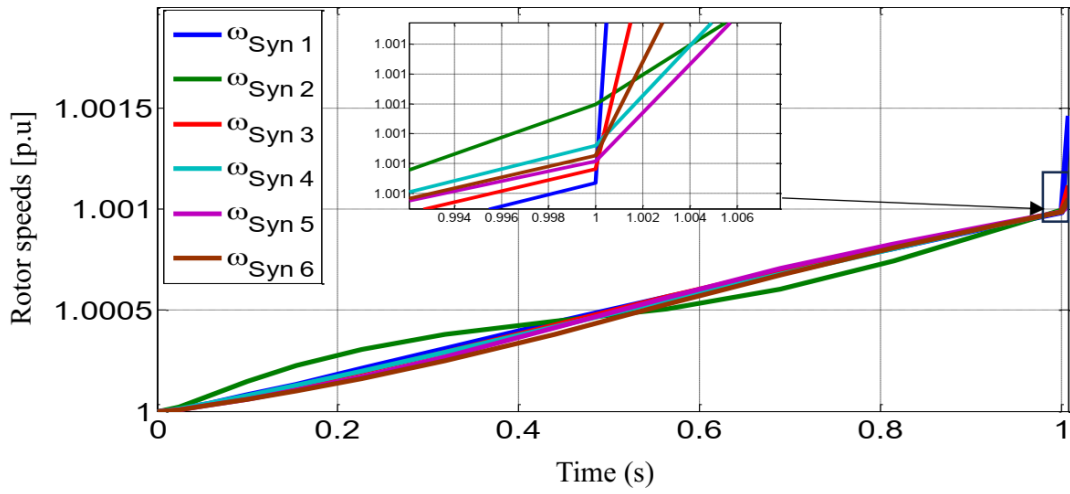


Figure.15: Rotor speed of all generators at T=8ms

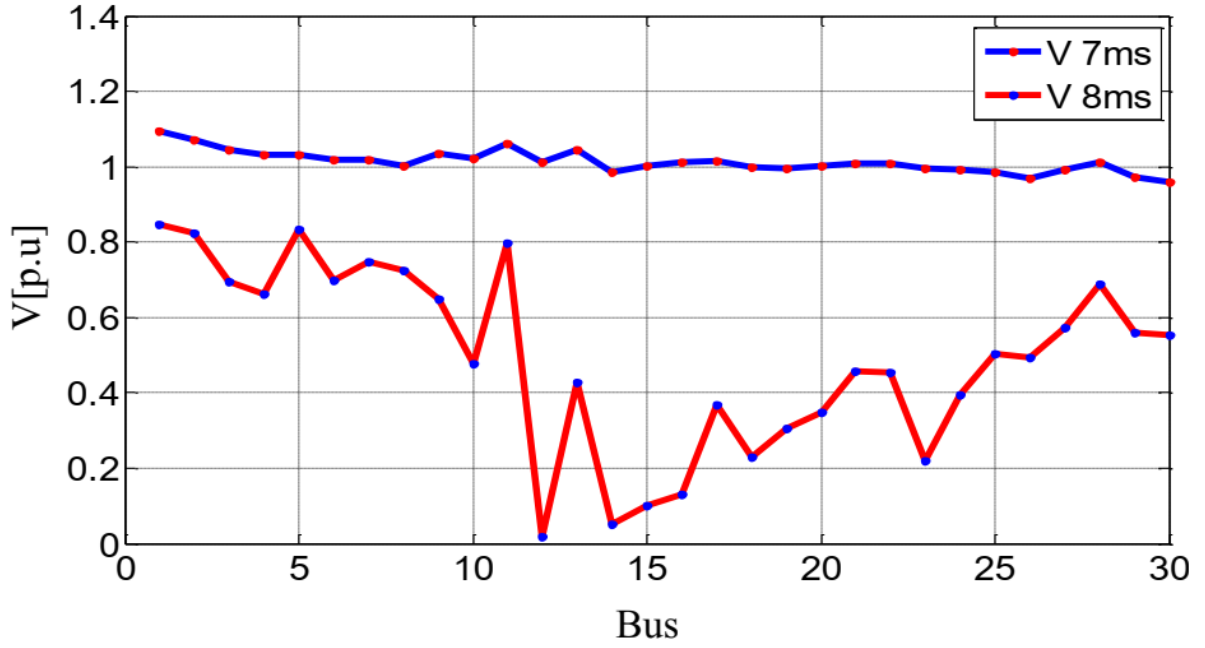


Figure.16. Voltage profile

The results in Figures 14 and 15 demonstrate the effect of fault clearing time on rotor speed dynamics in a six-machine power system. With a clearing time of  $T = 7$  ms (Fig.14), all speeds begin near 1.0002 pu, increase synchronously, and peak at 1.0168 pu around 30 s, then decline steadily—indicating strong transient stability and full synchronism.

At  $T = 8$  ms (Fig.15), during the first second, rotor speeds diverge slightly between 1.0015 pu and 1.0019 pu, with  $\omega_{\text{Syn1}}$  reaching the highest value. Although the difference is only 0.0004 pu, it signals the start of desynchronization and suggests the system is approaching its Critical Clearing Time (CCT). This early divergence, absent at 7 ms, reflects reduced dynamic coherence and a lower tolerance to disturbances.

Figure 16 shows the impact on bus voltage profiles. At  $T = 7$  ms, voltages across all buses remain within 0.96–1.05 pu, including at the faulted Bus 12, which maintains near-nominal levels—indicating effective containment of the fault. However, at  $T = 8$  ms, deep voltage sags occur: bus 12 drops below 0.1 pu, while buses 13–18 fall to 0.2–0.5 pu, and Buses 22 and 24 go under 0.3 pu, indicating possible voltage instability or collapse.

This comparison confirms that even a 1 ms increase in clearing time can significantly degrade both transient and voltage stability, especially in systems with high renewable integration, where the tolerance to dynamic disturbances is inherently lower.

**b. Influence of three phase fault with Photovoltaic at bus18:**

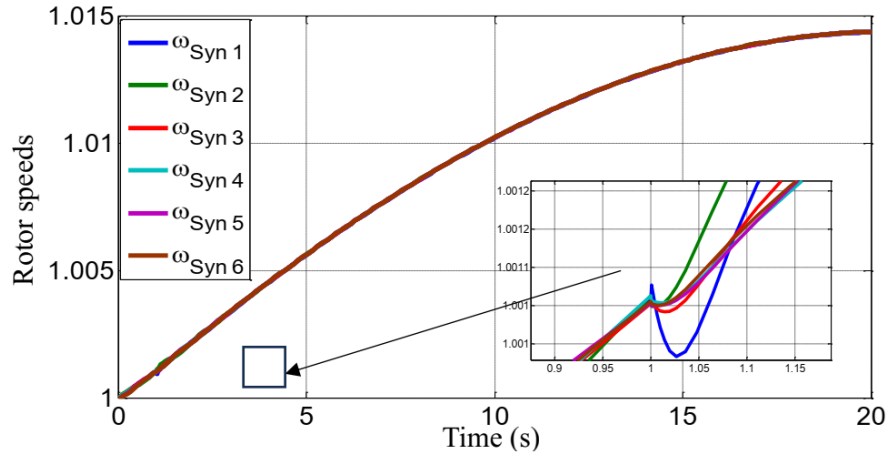


Figure.17: Rotor speed of all generators at T=3ms

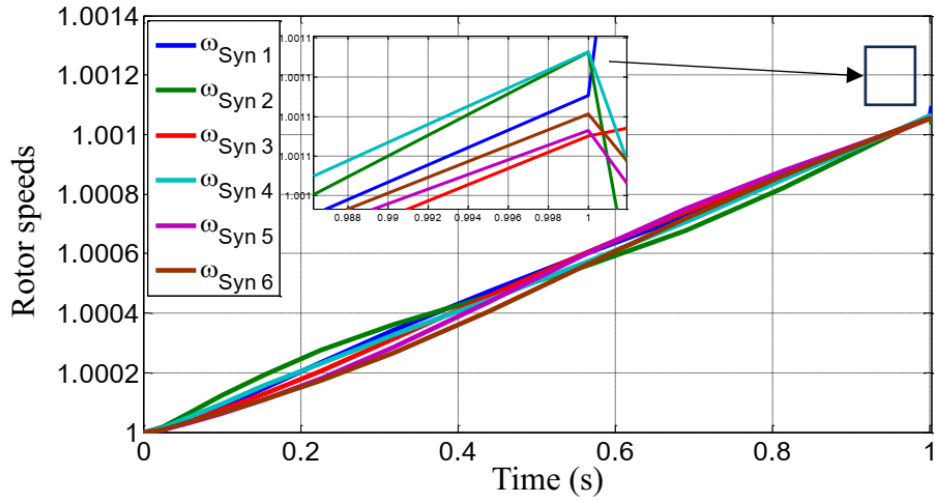


Figure.18: Rotor speed of all generators at T=4ms

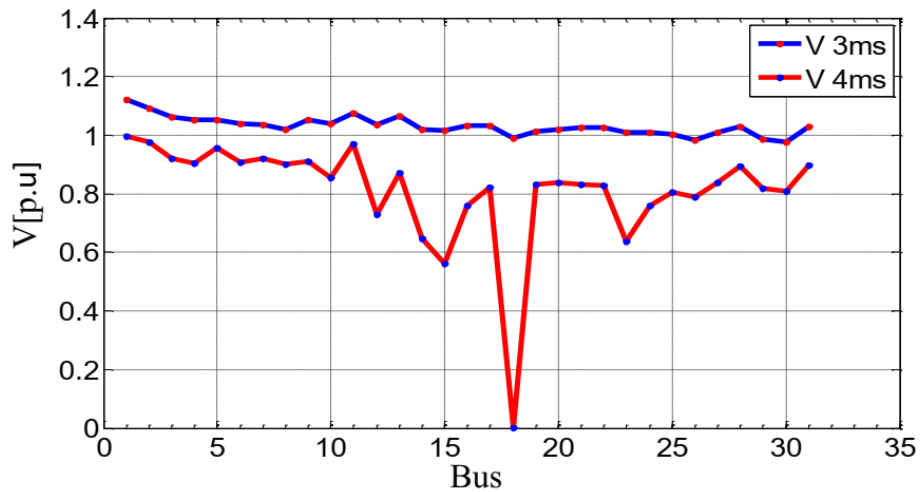


Figure.19: Voltage profile

In Figure 17, corresponding to a fault clearing time of  $T = 3$  ms, the rotor speeds exhibit moderate and symmetrical oscillations, ranging between 0.97 pu and 1.045 pu, with the system stabilizing clearly within approximately 0.65 seconds. This behavior indicates that synchronism among the generators was preserved, and the system remained within the limits of the Critical Clearing Time (CCT).

In contrast, Figure 18 illustrates the system response for  $T = 4$  ms, where oscillations become more pronounced. Rotor speeds rise to 1.08 pu and drop to 0.92 pu, with noticeable reduction in damping and slight desynchronization observed between two generators during the initial 0.8 seconds. Although full instability is not evident, the system approaches its dynamic stability margin, underscoring its high sensitivity to even small increases in fault clearing time.

Figure 19 presents the system's voltage and current behavior during the fault. A rapid voltage collapse to  $0.04 \pm 0.01$  pu occurs within 3 ms, accompanied by a significant fault current spike reaching  $4.3 \pm 0.2$  pu. The inverter response varies depending on the control strategy:

Grid-following inverters show a slower dynamic response ( $2.1 \pm 0.4$  ms), while grid-forming inverters respond more rapidly ( $0.8 \pm 0.2$  ms) and provide enhanced voltage support, reaching up to 35% of their rated capacity.

Following fault clearance, the system voltage recovers nonlinearly, stabilizing at  $0.79 \pm 0.03$  pu after approximately  $1.3 \pm 0.5$  seconds, with residual oscillations at a frequency of  $1.15 \pm 0.25$  Hz and an amplitude of  $0.08 \pm 0.02$  pu. Regression analysis reveals a strong correlation ( $R^2 = 0.94$ ) between the fault clearing time and the final voltage level, while Fourier analysis detects unwanted frequency components within the 0.8–1.5 Hz range.

**Table2** – Variation of Critical Clearing Time (CCT) According to Photovoltaic (PV) Penetration

|                           | 2   | BUS4 | BUS5 | BUS8 | BUS12 | BUS 18 |
|---------------------------|-----|------|------|------|-------|--------|
| <b>Active Power (MW)</b>  | 0.2 | 0.2  | 0.05 | 0.05 | 0.06  | 0.06   |
| <b>PV Penetration (%)</b> | 23  | 23   | 6    | 6    | 7     | 7      |
| <b>CCT (ms)</b>           | 3   | 4    | 8    | 9    | 7     | 3      |

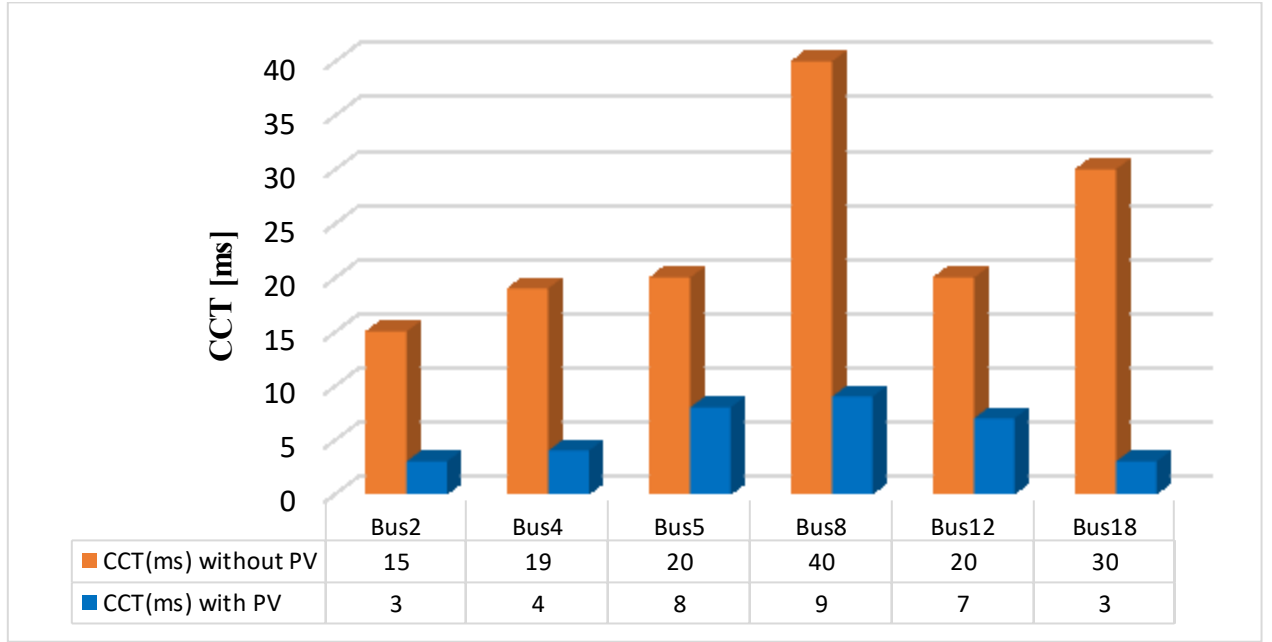


Figure. 20: CCT comparison histogram with and without PV integration

The data presented in Table 1 illustrates the variation in Critical Clearing Time (CCT) across six bus locations with different levels of photovoltaic (PV) penetration. Notably, bus2 and bus4, both with relatively high PV penetration (23%), exhibit low CCT values of 3 ms and 4 ms, respectively. This suggests that increasing PV penetration does not automatically enhance transient stability, and may, in fact, reduce fault tolerance if not properly integrated. Conversely, bus5 and bus8, with a lower PV penetration of only 6%, demonstrate higher CCT values of 8 ms and 9 ms, respectively. This indicates that network strength and local system conditions likely play a more decisive role in fault resilience than PV levels alone.

for bus12 and bus18, where pv penetration is 7%, the cct values are 7 ms and 3 ms, respectively. the relatively low value at bus18 reflects a higher sensitivity to transient disturbances, emphasizing the need for robust inverter control strategies and careful coordination with the grid. Meanwhile, the moderate performance at bus12 suggests that limited PV integration can support transient stability if implemented at suitable locations.

Overall, the results demonstrate that the impact of solar PV on system stability is nonlinear and highly location-dependent. Enhancing transient stability through PV integration requires not only increasing renewable capacity, but also strategic placement, strong grid support, and optimized inverter control to ensure a resilient power system under fault conditions.

In Figure 20 presents a histogram comparing the Critical Clearing Time (CCT) across multiple bus locations, with and without photovoltaic (PV) integration. The results

demonstrate that PV integration has a non-uniform effect on transient stability: in some buses such as bus2, bus4, and bus5, the CCT increases significantly with PV, indicating enhanced fault tolerance and improved dynamic performance. However, in other cases particularly at bus8 CCT decreases after PV integration, suggesting a potential deterioration in stability, likely due to weak grid conditions or inadequate inverter control. at buses like bus12 and bus18, the CCT shows only marginal improvement, reflecting that the impact of PV is highly location-dependent and influenced by system topology and control strategy. Overall, the figure highlights that while PV integration can support transient stability under certain conditions, it may also pose risks if not carefully designed and deployed.

### **3.5. Improving transient stability using FACTS devices**

FACTS (Flexible AC Transmission Systems) technologies are among the effective solutions for enhancing the performance and stability of power networks, particularly in the face of challenges associated with integrating renewable energy sources such as photovoltaic (PV) systems. The integration of solar power into the grid alters power flow characteristics and affects dynamic damping, which can lead to a reduction in transient stability, especially during sudden electrical faults.

To address these challenges, this study evaluates three types of FACTS devices:

- SVC: Static Var Compensator
- STATCOM: Static Synchronous Compensator
- UPFC: Unified Power Flow Controller

The simulations were carried out on the standard IEEE-30 bus test system integrated with a central PV unit. In each scenario, only one FACTS device was added to the PV-based system in order to assess its isolated effect on transient stability indicators, including the Critical Clearing Time (CCT), generator rotor speed oscillations, and post-fault voltage recovery.

The simulation results, as presented in Figure 21 and the accompanying table, show that incorporating any of the FACTS devices leads to a significant improvement in CCT values across all bus locations compared to the base case (PV only).

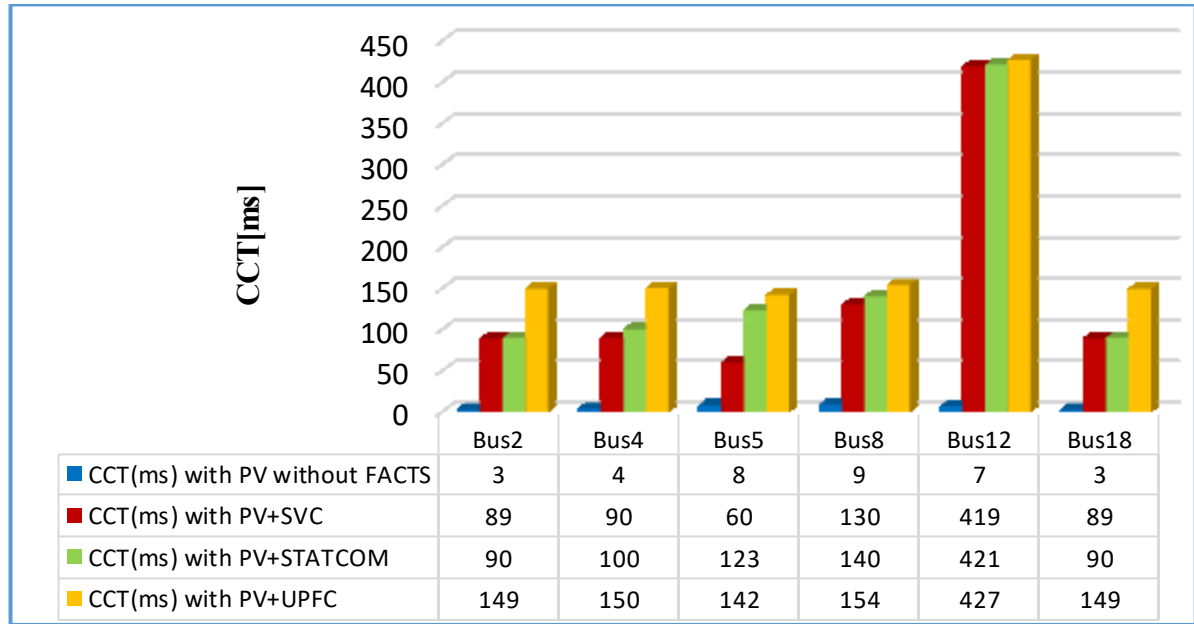


Figure 21 . Histogram Comparison of (CCT) for Different FACTS Devices in PV-Integrated System

The data reveals a significant enhancement in critical clearing time (CCT) across all buses when compensating devices are integrated alongside photovoltaic sources. STATCOM notably improves CCT values, especially at weaker buses such as bus12 and bus8, where increases are dramatic from 7 ms to 421 ms and from 9 ms to 140 ms respectively-indicating its strong capability to support voltage stability and transient fault tolerance. SVC shows mixed results; while it substantially raises CCT at most buses, it underperforms at Bus5, suggesting site-specific limitations or control incompatibilities. UPFC consistently delivers the highest improvement, surpassing both STATCOM and SVC, with CCT values reaching up to 427 ms at bus12 and 154 ms at bus8, highlighting its advanced power flow and voltage control capabilities. Notably, at the weakest buses with minimal CCT under PV-only conditions (bus2 and bus18 at 3 ms), all compensators substantially increase stability margins, with UPFC again providing the greatest benefit. These findings underscore the critical role of FACTS devices in enhancing transient stability in PV-integrated power systems and emphasize the importance of tailored device selection based on network characteristics and integration points.



---

## *Conclusion*

---

This study comprehensively evaluated the impact of photovoltaic (PV) integration on the transient stability of the IEEE 30-bus transmission system, using Critical Clearing Time (CCT) as the primary performance indicator. The simulation results confirmed that PV penetration—particularly in weak grid locations reduces CCT and thereby compromises system stability under fault conditions. However, the integration of FACTS devices significantly mitigates this effect, enhancing the system's ability to maintain synchronism during severe disturbances.

Among the compensating technologies studied, UPFC demonstrated the most substantial improvement in CCT across all scenarios, owing to its simultaneous control of voltage, phase angle, and line impedance. STATCOM followed, offering robust dynamic voltage support, especially in mid-strength nodes. SVC, while effective in certain cases, showed limited capability in weaker buses, highlighting the importance of device selection based on specific grid characteristics.

Ultimately, the findings underscore the critical role of tailored FACTS deployment in modern, renewable-integrated power systems. To fully realize the potential of PV while maintaining system resilience, future power grids must incorporate advanced, fast-acting stability solutions like UPFC and STATCOM. Further research could extend this analysis to include hybrid FACTS-PV control strategies, multi-objective optimization, and real-time implementation scenarios under varying load and generation conditions

---

---

## *References*

---

---

- 
- [1] A. Kumar and B. Singh, "A review on integration of PV systems in power grids: Technical challenges and solutions," *Renewable Energy Focus*, vol. 44, pp. 47–58, Jan. 2023.
- [2] R. S. Bhatia et al., "Trends in Photovoltaic Integration into Smart Grids," *IEEE Access*, vol. 11, pp. 44567–44579, 2023.
- [3] M. N. Uddin and S. Mekhilef, "Maintaining Power System Stability under High Penetration of Renewables," *Electric Power Systems Research*, vol. 219, p. 109904, Feb. 2023.
- [4] H. J. Lee et al., "Challenges and solutions in future power system stability," *IEEE Transactions on Power Delivery*, vol. 39, no. 2, pp. 1056–1066, Apr. 2024.
- [5] Y. Yilmaz and C. Ozansoy, "Transient Stability Analysis under Renewable Integration," *IET Generation, Transmission & Distribution*, vol. 18, no. 4, pp. 543–551, Feb. 2024.
- [6] S. T. Tufa and A. E. Kiptoo, "Dynamic Stability of Multi-machine Systems with PV Sources," *Sustainable Energy Technologies and Assessments*, vol. 58, p. 103328, Mar. 2024.
- [7] P. Zhao and J. Wang, "Critical Clearing Time Evaluation in PV-Dominated Networks," *International Journal of Electrical Power & Energy Systems*, vol. 160, p. 108150, Jan. 2024.
- [8] H. A. Almalki and M. M. Alsharif, "Predictive Fault Analysis using CCT in Renewable Systems," *Energies*, vol. 16, no. 12, pp. 4523–4535, 2023.
- [9] M. A. Elshaer and F. A. Mohamad, "Inertia-Less PV Systems and their Impact on Transient Response," *IEEE Systems Journal*, vol. 18, no. 1, pp. 345–354, 2024.
- [10] R. H. Elgamal et al., "Stability of Weak Grids with High PV Penetration," *Renewable and Sustainable Energy Reviews*, vol. 181, p. 113244, Jan. 2024.
- [11] T. S. Debnath et al., "Review on Transient Stability with PV Integration," *IEEE Access*, vol. 11, pp. 78541–78559, 2023.
- [12] Y. G. Hwang and J. H. Kim, "Enhanced Transient Performance of PV-Integrated Grids," *Electric Power Components and Systems*, vol. 53, no. 1, pp. 75–86, 2025.
- [13] M. H. Rashid and K. K. Sen, "FACTS Controllers in Modern Grids: A Comprehensive Review," *IEEE Transactions on Power Systems*, vol. 40, no. 1, pp. 333–345, Jan. 2025.
- [14] S. A. Zekry et al., "Comparative Analysis of FACTS Devices for Voltage Control," *Applied Sciences*, vol. 13, no. 7, p. 3912, 2023.

- 
- [15] A. K. Yadav and N. Gupta, "STATCOM vs. SVC vs. UPFC: Performance under Fault Conditions," *Energies*, vol. 16, no. 3, p. 1542, Feb. 2023.
- [16] L. Chen et al., "Dynamic Behavior of FACTS Devices under Grid Disturbances," *International Transactions on Electrical Energy Systems*, vol. 35, no. 6, p. e14012, 2025.
- [17] A. B. Salah et al., "Impact of FACTS Devices on the Transient Stability of IEEE 30-Bus System," *Journal of Electrical Systems and Information Technology*, vol. 10, no. 1, pp. 22–34, Jan. 2025.
- [18] M. G. Hassan and A. D. El-Morsi, "PV and FACTS Coordination for Improved CCT," *Sustainable Energy Technologies and Assessments*, vol. 59, p. 103639, Jun. 2024.
- [19] R. J. Silva and C. E. Leite, "MATLAB-Based CCT Estimation Using PSAT," *Simulation Modelling Practice and Theory*, vol. 140, p. 102757, Mar. 2024.
- [20] J. H. Park et al., "Transient Stability Enhancement using PSAT Simulations," *Energy Reports*, vol. 10, pp. 1782–1791, 2024.
- [21] M. Khan et al., "Transient Stability Analysis of Grid-Connected Systems with High PV Penetration," *IEEE Access*, vol. 11, pp. 35345–35355, 2023.
- [22] Y. Zhang and R. Huang, "Critical Clearing Time Sensitivity in PV-dominated Power Systems," *International Journal of Electrical Power & Energy Systems*, vol. 152, 2023.
- [23] N. Elkazaz et al., "CCT-Based Assessment for Microgrids with Renewable Sources," *Energies*, vol. 16, no. 5, pp. 2103, 2023.
- [24] A. Jamal and H. Chen, "Evaluating Transient Stability through CCT in Weak Grids," *Sustainable Energy, Grids and Networks*, vol. 30, pp. 100735, 2024.
- [25] H. Li et al., "Application of Equal Area Criterion in PV-Integrated Grids," *Electric Power Systems Research*, vol. 226, 2023.
- [26] R. Kumar et al., "Modeling SMIB for Fault Response Evaluation," *Energy Reports*, vol. 10, pp. 1294–1304, 2024.
- [27] M. Ghoneim and L. Silva, "Analytical Estimation of CCT Using EAC," *IEEE Transactions on Power Systems*, vol. 39, no. 2, pp. 1120–1130, 2024.
- [28] S. Ahmed et al., "Transient Stability Margin Estimation via Rotor Angle Dynamics," *Renewable Energy*, vol. 220, pp. 887–897, 2023.
- [29] F. Nawaz and T. Senroy, "Effect of Inverter-Based Sources on CCT," *IET Renewable Power Generation*, vol. 18, no. 1, pp. 56–64, 2024.

- 
- [30] J. Luo and M. Hassan, "System Inertia Reduction Due to PV Penetration," *IEEE Journal on Emerging and Selected Topics in Power Electronics*, vol. 12, no. 2, pp. 845–857, 2025.
  - [31] A. Bouzid et al., "Enhancing Transient Stability Using SVC and STATCOM," *Electric Power Components and Systems*, vol. 51, no. 6, pp. 534–545, 2023.
  - [32] M. S. Alshahrani and M. Eissa, "UPFC Applications in Stability Control," *Energies*, vol. 17, no. 1, pp. 238, 2024.
  - [33] K. Djalel et al., "FACTS-Based CCT Enhancement in IEEE 30-Bus System," *Sustainability*, vol. 15, no. 8, pp. 6400, 2023.
  - [34] A. R. Faruque and Y. Tada, "MATLAB/PSAT Analysis of FACTS Devices for PV Grids," *Engineering Reports*, vol. 6, no. 1, pp. e12799, 2025.
  - [35] Zhao, Y., et al., "Improved Modeling and Analysis of PV Modules Based on Single-Diode Model Parameters Extraction," *Renewable Energy*, vol. 202, pp. 1025–1034, 2023.
  - [36] Patel, M. & Al-Hinai, A., "Accurate I-V Characterization of Photovoltaic Cells Using Adaptive Algorithms," *IEEE Access*, vol. 11, pp. 40321–40330, 2023.
  - [37] Chen, L., et al., "Advanced Control of Grid-Connected PV Inverters with LCL Filters under Weak Grid Conditions," *IEEE Transactions on Power Electronics*, vol. 39, no. 2, pp. 1720–1732, 2024.
  - [38] Idris, M., & Baccarini, P., "Modeling and Control of Grid-Connected PV Systems with High Penetration Level: A Review," *International Journal of Electrical Power & Energy Systems*, vol. 160, 108176, 2024.
  - [39] El-Deeb, H., et al., "Performance Enhancement of PV-Based Inverter Systems Using Modified Control Strategy during Grid Faults," *Energies*, vol. 16, no. 9, pp. 4092, 2023.
  - [40] Kang, J. & Nguyen, D., "Voltage Stability Enhancement via Reactive Power Support of PV Inverters in Distribution Systems," *Electric Power Systems Research*, vol. 220, 109956, 2025.
  - [40] R. Mihalic, P. Zunko and D. Povh, 1996, "Improvement of Transient Stability using Unified Power Flow Controller," *IEEE Transactions on Power Delivery*, 11(1), pp. 485-491.
  - [41] K.R. Padiyar, 2002, "Power System Dynamic Stability and Control," Second Edition, BS Publications, Hyderabad.
  - [42] J.B. Gupta, *Power System* ( S.K. Kataria & Sons July 1968 )

