OPTIMAL LOCATION OF AN IDEAL TRANSFORMER UPFC MODEL USING OPFFIRST-ORDER SENSITIVITIES

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ABSTRACT

This paper presents a screening technique for greatly reducing the computation involved in determining the optimal location of a unified power flow controller (UPFC) in a power system. The first-order sensitivities of the generation cost with respect to UPFC control parameters are derived. This technique requires running only one optimal power flow (OPF) to obtain UPFC sensitivities for all possible transmission lines. To implement asensitivity-based screening technique for guidance in optimally locating a single UPFC in a power system, we propose a new UPFC model, wrach consists of an ideal transformer with a complex turns ratio and a variable shunt admittance. In this model, the UPFC control variables do not depend explicitly on UPFC input and output currents and voltages. Accordingly, this model does not require adding extra buses for UPFC input and output terminals. IEEE five-, 14- and 30-bus systems were used to frustrate the technique.

Index Terms-Flexible ac transmission systems (FACTS), FACTS location, first-ordersensitivity, optimal power flow (OPF), screening technique, unified power flow controller (UPFC), UPFC ideal transformer model, UPFC placement, UPFC uncoupled model.

This study focuses on the development of an Ideal Transformer Unified Power Flow Controller (UPFC) model and its integration with Optimal Power Flow (OPF) first-order sensitivities analysis for determining optimal UPFC locations in power systems. The abstract outlines the significance of UPFCs in enhancing power system stability and efficiency by controlling voltage and power flow. It highlights the objectives of the research, including the development of the UPFC model, analysis of OPF first-order sensitivities, and their combined application for screening optimal UPFC locations. The study aims to contribute to the improvement of power system operation and control through strategic UPFC placement.

The abstract provides a concise overview of the study, summarizing the key aspects ofthe research. It outlines the development of an ideal transformer Unified Power Flow Controller (UPFC) model, the analysis of Optimal Power Flow (OPF) first-order sensitivities, and their application in determining optimal locations for UPFC installation in power systems

CHAPTER-1 INTRODUCTION

1.1 INTRODUCTION TO POWER QUALITY

The quality of electrical power may be described as a set of values of parameters, such as:

- Continuity of service (Whether the electrical power is subject to voltage drops or overagesbelow or above a threshold level thereby causing blackouts or brownouts)
- Variation in voltage magnitude
- Transient voltages and currents
- Harmonic content in the waveforms for AC power

It is often useful to think of power quality as a compatibility problem: It is the equipment connected to the grid compatible with the events on the grid, and is the power delivered by the grid, including the events, compatible with the equipment that is connected. Compatibility problems always have at least two solutions: in this case, either clean up the power, or make the equipment tougher. The tolerance of data-processing equipment to voltage variations is often characterized by the CBEMA curve, which give the duration and magnitude of voltage

1.1.1 Definitions of Power Quality

Power quality is a term that is different to different people. power quality is generally referring to quality of voltage supply. To a utility, it means supply of adequate and reliable power. To a customer it means adequate, uninterrupted power which does not affect the lifeof equipment. To the manufacture, it means the quality and tolerance of voltage and current parameters that is within the range of parameters for which he has manufactured and tested the products.

1.1.2 Importance of Power Quality

1. power quality is significant because:

2. Customers pays for good quality power, if power quality is poor, it breaches of trust.

3. Poor quality of power damages consumers equipment’s and affects equipment’s life. 4.Increases of system losses.
5.Bad power quality causes severe health hazards. variations that can be tolerated.

1.1.3 Effect of Poor Power Quality on Economy

1. If high harmonics are developed by the load, the rotating machine in generation side andconsumer get over heated.

2. Industries like rolling mills, paper mills, textile mills gets affected badly as the interruptionproduced is too high.

3. If there is frequent abnormalities, the cost incurred towards the equipment goes high 4.Poor quality increases, more losses.

1.2 ROLE OF FACTS DEVICES IN IMPROVEMENT OF POWER QUALITY

In electrical power systems, FACTS devices effectively control power flow and change bus voltages, leading to lower system losses and excellent system stability. The article discusses the research from the last decade that evaluated various methods for placing FACTS devices using the meta-heuristic approach to address the positioning of FACTS devices to maintain proper bus voltages and control line flow and improve the overall system efficiency

The combined cycle power station is a good example of a new development in power generation and flexible AC transmission systems, generally known as FACTS, are controllers that improve transmission systems. Worldwide transmission systems are undergoing continuous changes and restructuring. They are becoming more heavily loaded and are being operated in ways not originally envisioned.

In addition, the economical utilization of transmission system assets is of vital importance to enable utilities in industrialized countries to remain competitive and to survive. In developing countries, the optimized use of transmission systems investments is also important to support industry, create employment and utilize efficiently scarce economic resources.

FACTS controller is a technology that responds to these needs. It significantly alters the way transmission systems are developed and controlled together with improvements in asset utilization, system flexibility and system performance. Several models and techniques suggest that devices can be placed in a particular location with different parameter settings.

Finally, the optimization problem improved system performance by decreasing power loss, improving the voltage profile and power angle at each bus, raising the L-index, and minimizing generating costs. FACTS devices can increase the transmission line's capacity for transferring power by increasing the voltage at its terminals at both ends and reducing line reactance. The FACTS controller must be installed in the distribution and transmission lines to maximize the power flow. Various techniques are used for the best placement of FACTS controllers, including analytical methods, arithmetic programming approaches, meta-heuristic optimization approaches, and hybrid approaches this paper analyses numerous analytical and meta-heuristic optimization techniques to place FACTS controllers in the most advantageous locations.

1.3 OBJECTIVE OF THE PROJECT

To find the best location and setting of a UPFC device in a power system to optimize a certain objective function. The primary objective of this project is to develop a comprehensive understanding of the Ideal Transformer Unified Power Flow Controller (UPFC) model, integrate it with Optimal Power Flow (OPF) first-order sensitivities analysis, and apply these methodologies to screen for optimal UPFC locations in power systems. The specific objectives can be delineated as follows:

- **Simplified UPFC Modeling**: Develop an ideal transformer UPFC model that accurately represents the essential functionalities of a UPFC for sensitivity analysis. This model should be computationally efficient compared to more complex UPFC models.
- **First-Order Sensitivity Analysis**: Utilize first-order sensitivities to quantify the influence of UPFC placement on critical power system parameters. **These parameters could include**: Power flow in critical lines, Voltage magnitudes at key buses, System losses, Screening for Optimal UPFC **Locations**: Leverage the insights

from first-order sensitivities to develop a screening method. This method should efficiently identify a shortlist of promising locations for further, more detailed analysis using full-fledged OPF simulations.

- **Development of an Ideal Transformer UPFC Model**: The project aims to create a robust and accurate mathematical model of the Ideal Transformer UPFC. This model will

encapsulate the device's functionality, including its ability to regulate voltage and control power flow along transmission lines. Through rigorous theoretical analysis and simulation, the model will be validated against real-world data and benchmarks.

- **Integration with OPF First-Order Sensitivities Analysis**: Building upon the UPFC model, the project will integrate it with the OPF framework, incorporating first-order sensitivities analysis. This integration will enable the assessment of the impact of UPFC deployment on system-wide performance metrics such as power flow distribution, voltage stability, and line loading. By quantifying the sensitivity of these metrics to UPFC parameters, the project aims to identify critical factors influencing UPFC placement.
- **Application to Screening for Optimal UPFC Locations:** Leveraging the developed UPFC model and OPF sensitivities analysis, the project will conduct a systematic screening of potential locations for UPFC installation within power systems. This screening process will consider various factors such as network topology, load distribution, generation patterns, and existing control mechanisms. Through computational simulations and optimization algorithms, the project will identify candidate locations where UPFC deployment can yield the most significant improvements in systemperformance and stability.
- **Evaluation of Effectiveness and Robustness**: The project will evaluate the effectivenessand robustness of the proposed methodologies through extensive simulation studies and case analyses. By comparing different UPFC deployment scenarios and assessing their impact on key performance indicators, the project aims to demonstrate the efficacy of the proposed approach in enhancing power system operation and control. Sensitivity analyses will also be conducted to examine the robustness of the identified optimal UPFC locations under varying operating conditions and uncertainties.
- **Knowledge Dissemination and Practical Implications**: Finally, the project aims to disseminate its findings through academic publications, technical reports, and presentations. By sharing insights gained from the research, the project seeks to inform power system planners, operators, and policymakers about the potential benefits of UPFC deployment and the methodologies for identifying optimal installation locations. Ultimately, the project endeavors to contribute to the advancement of power system optimization practices and the enhancement of grid resilience and reliability.

1.4 PROPOSED SYSTEM

Here in this project, we use First order sensitivity Analysis method. Because this method is used to measure fractional contribution of a single parameter to the output variance. The proposed system for an ideal transformer UPFC model, along with first-order sensitivities and application for screening optimal UPFC locations, addresses a key challenge in power system management.

CHAPTER-2

UNIFIED POWER FLOW CONTROLLER (UPFC)

2.1 INTRODUCTION

A Unified power flow controller (UPFC) is an electrical device for providing fast- acting reactive power compensation on high-voltage electricity transmission networks. It usesa pair of three-phase controllable bridges to produce current that is injected into a transmis- sion line using a series transformer. The controller can control active and reactive power flows in a transmission line.

Unified Power Flow Controller (UPFC), as a representative of the third generationof FACTS devices, is by far the most comprehensive FACTS device, in power system steady- state it can implement power flow regulation, reasonably controlling line active power and reactive power, improving the transmission capacity of power system, and in power system transient state it can realize fast-acting reactive power compensation, dynamically supporting the voltage at the access point and improving system voltage stability, moreover, it can im- prove the damping of the system and power angle stability.

The UPFC uses solid state devices, which provide functional flexibility, generally not attainable by conventional thyristor controlled systems. The UPFC is a combination of a stat- ic synchronous compensator (STATCOM) and a static synchronous series compensator (SSSC) coupled via a common DC voltage link.

2.1.1 Principle of Operation

- The UPFC is the most versatile FACTS controller developed so far, with all- encompassing capabilities of voltage regulation, series compensation, and phase shift-ing.
- It can independently and very rapidly control both real- and reactive power flows in a transmission.
- It is configured as shown in Fig. and comprises two VSCs coupled through a common dc terminal.
- One VSC converter 1 is connected in shunt with the line through a coupling transform- er; the other VSC converter 2 is inserted in series with the transmission line throughan interface transformer.
- The dc voltage for both converters is provided by a common capacitor bank.

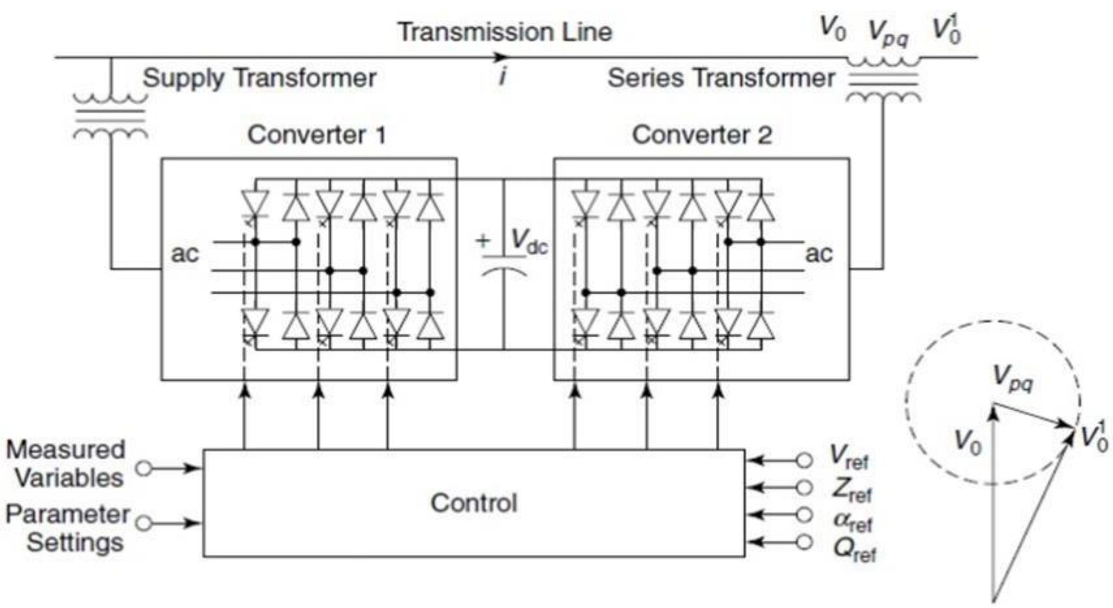

Fig 2.1: Unified power flow controller (UPFC)

- The series converter is controlled to inject a voltage phasor, *Vpq*, in series with the line,which can be

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Volume: 08 Issue: 05 | May - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

varied from 0 to *Vpq* max. Moreover, the phase angle of *Vpq* can be in- dependently varied from 0^0 to 360^0.

- In this process, the series converter exchanges both real and reactive power with the transmission line.
- Although the reactive power is internally generated/ absorbed by the series converter, the real-power generation/ absorption is made feasible by the dc-energy–storage de- vice that is, the capacitor.
- The shunt-connected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus.
- Thus, the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers.
- In addition, the shunt converter functions like a STATCOM and independently regu- lates the terminal voltage of the interconnected bus by generating/ absorbing a requi- site amount of reactive power.

2.1.2 Modes of Operation

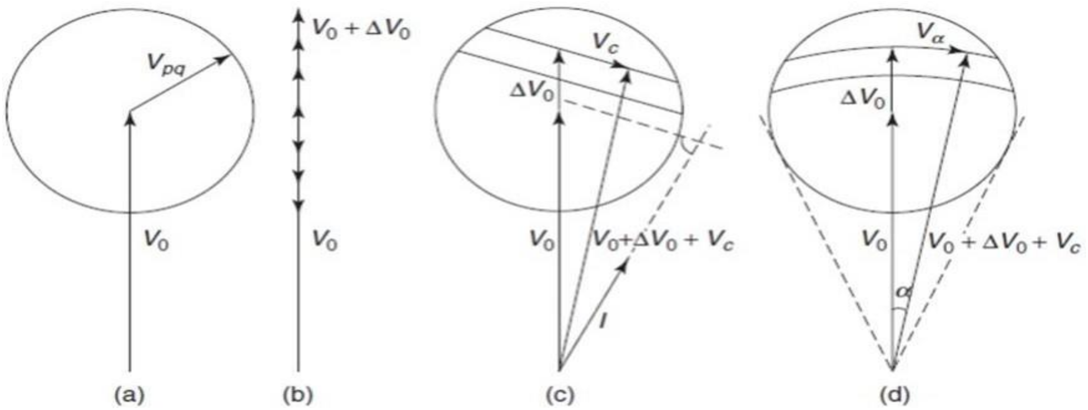

Fig 2.2 The phasor diagram illustrating the general concepts of series-voltage injection and attainable power flow control functions

The phasor diagram illustrating the general concept of series-voltage Injection and attainablepower flow control functions

a) Series-voltage injection; (b)terminal-voltage regulation;
(c) terminal-voltage and line-impedance regulation

(d) terminal-voltage and phase-angle regulation

1. The concepts of various power-flow control functions by use of the UPFC are illus- trated in Fig:2.2. Part (a) depicts the addition of the general voltage phasor *Vpq* to the existing bus voltage, *V*0, at an angle that varies from 0^0 to 360 ^{0}.
2. Voltage regulation is affected if *Vpq* =Δ*V*0 is generated in phase with *V*0. A combina- tion of voltage regulation and series compensation is implemented. Where *Vpq* is the sum of a voltage regulating component Δ*V*0 and a series compensation providing voltage component *Vc* that lags behind the line current by 90^0. In the phase-shifting process shown in part (d), the UPFC-generated voltage *Vpq* is a combination of volt- age-

regulating component Δ*V*0 and phase-shifting voltage component *V*a.

3. The function of *V*a is to change the phase angle of the regulated voltage phasor, *V*0 + Δ*V*, by an angle α. A simultaneous attainment of all three-foregoing power-flow con-trol functions is depicted.

4. The controller of the UPFC can select either one or a combination of the three func-tions as its control objective, depending on the system requirements.

The UPFC operates with constraints on the following variables:

- The series-injected voltage magnitude;
- The line current through series converter;
- The shunt-converter current;
- The minimum line-side voltage of the UPFC;
- The maximum line-side voltage of the UPFC; and
- The real-power transfer between the series converter and the shunt converter

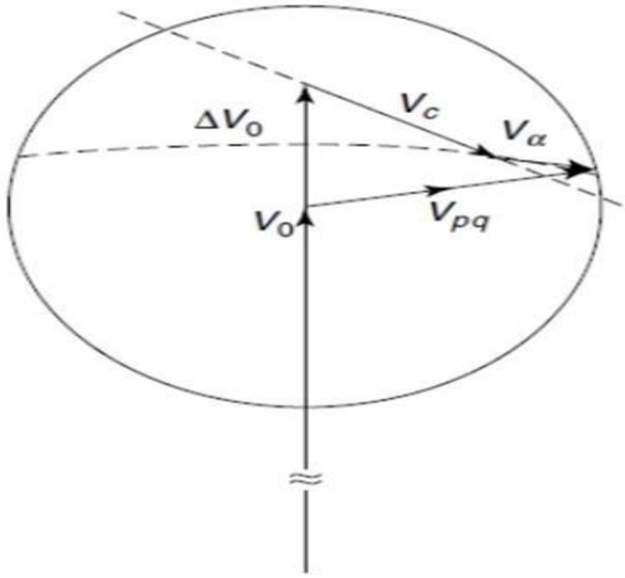

Fig: 2.1 A phasor diagram illustrating the simultaneous regulation of the terminal voltage, line impedance, and phase angle by appropriate series-voltage injection

A phasor diagram illustrating the simultaneous regulation of the terminal voltage, line imped-ance, and phase angle by appropriate series-voltage injection.

2.1.3 Applications of UPFC

- The power-transmission capability is determined by the transient-stability consid-erations of the 345-kV line.
- The UPFC is installed in the 138-kV network. A 3-phase-to-ground fault is ap- plied on the 345-kV line for four cycles, and the line is disconnected after the fault.
- The maximum stable power flow possible in the 138-kV line without the UPFC isshown in Fig. to be 176 MW.

- However, the power transfer with the UPFC can be increased 181 MW (103%) to 357 MW. Although this power can be raised further by enhancing the UPFC rat- ing, the power increase is correspondingly and significantly lower than the in- crease in the UPFC rating, thereby indicating that the practical limit on the UPFC size has been attained.
- The UPFC also provides very significant damping to power oscillations when it operates at power flows within the operating limits.
- The UPFC response to a 3-phase-line-to-ground fault cleared after four cycles, leaving the 345-kV line in service, is illustrated.

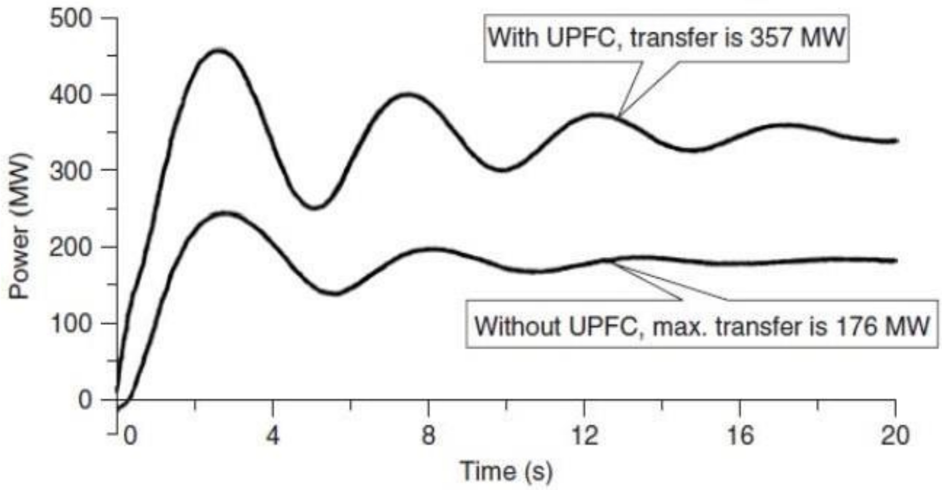

Fig: Power-transfer capability curve with the UPFC

2.1.4 Modelling of UPFC for Power Flow Studies

The steady state investigation of UPFC involves power flow studies which include the calcu- lation of busbar voltage, branch loadings, real and reactive transmission losses and the impactof UPFC.

- ✓ In this model two voltage sources are used to represent the fundamental componentsof the PWM controlled output voltage waveform of the two branches in the UPFC.
- ✓ The impedance of the two coupling transformers are included in the proposed modeland the losses of UPFC depicts the voltage source equivalent circuit of UPFC.

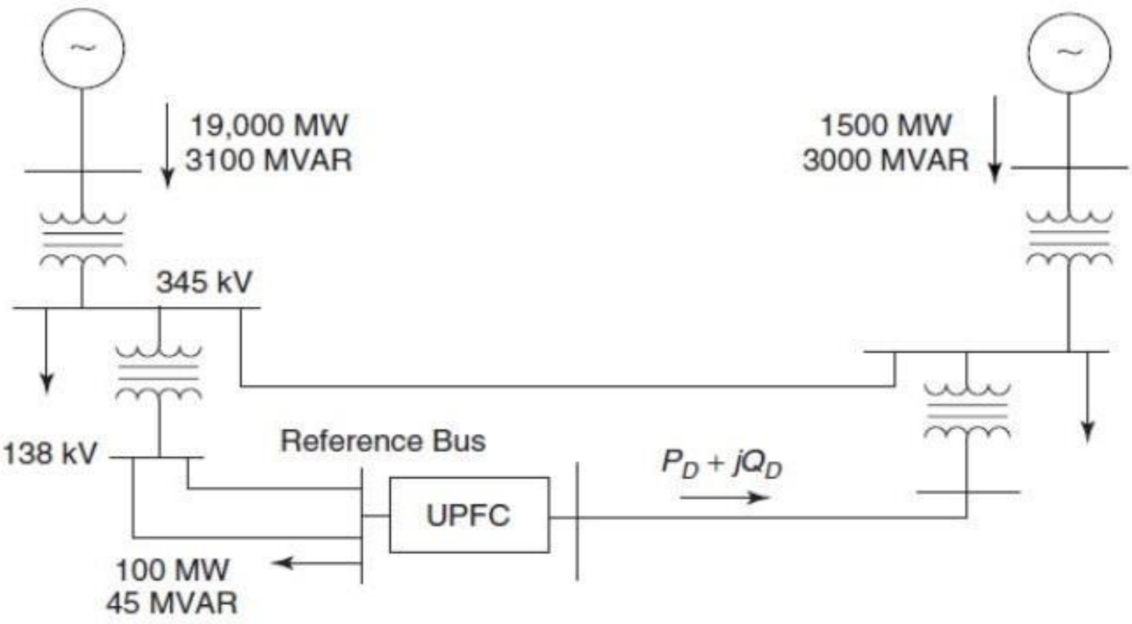

Fig 2.3: Principle of operation of UPFC

✓ The series injection branches a series injection voltage source and performs the main functions of controlling power flow whilst the shunt branch is used to provide real power demanded by the series branch and the losses in the UPFC.

✓ However, in the proposed model the function of reactive compensation of shunt branch is completely neglected

CHAPTER-3

STEADY STATE MODELS OF UPFC

3.1 INTRODUCTION

Steady-state models of Unified Power Flow Controller (UPFC) are essential for power system analysis and optimization. They typically involve mathematical representations of the UPFC's components, such as its converters, transformers, and control algorithms, to analyze its steady-state behavior, including voltage and power flow control. These models help in understanding the UPFC's impact on the power system and optimizing its operation for improved stability and efficiency.

The steady state models of UPFC can be classified into two categories

- Uncoupled model
- Ideal transformer model

3.1.1 Uncoupled model

To overcome these problems, we developed a new steady- state mathematical model for a UPFC, which consists of an ideal transformer with a complex turns ratio and a variable shunt admittance. In this model, UPFC control variables do not depend on UPFC input and output voltages and currents, and therefore addition of fictitious input and output buses is not necessary. This model is easily combined with transmission line models using ABCD two- port representations, which can then be con- verted to Y-parameter representations. Thus, furthermore, the system Ybus matrix is modified in only four locations if one UPFC is installed in a power system.

This paper proposes the first-order sensitivity (or dc) method to identify the most promising UPFC locations by running only one ac OPF using an ideal UPFC transformer model. Using this dc analysis, we can easily identify the potential UPFC locations and also filter out ineffective UPFC candidates.

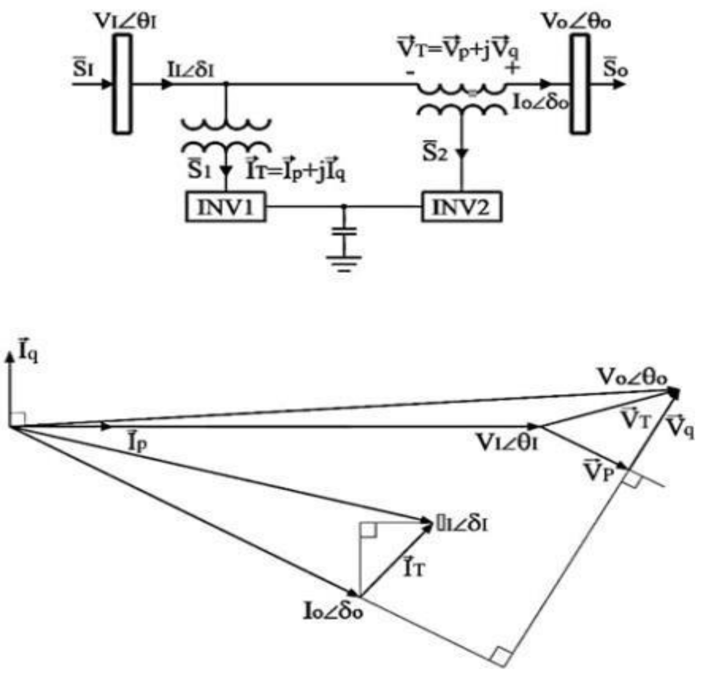

Fig 3.1: Phasor diagram of UPFC input-output Voltages and Currents

Fig. 3.1 shows a simplified UPFC circuit with two extra buses for UPFC input and output and phasor diagram illustrating UPFC input-output voltage and current relationships. The injectedseries voltage $\vec{v}_T$ can be resolved into in-phase component $\vec{v}_P$ and quadrature component $\vec{v}_q$with respect to the UPFC output current $\vec{I}_0$ and can be expressed as

$$\vec{v}_T = (v_p + jv_q)ej\delta_0 \quad (3.1)$$

Since $\vec{v}_T$ is dependent on the UPFC output current phase angle δ_0, it requires adding an extrabus for the UPFC output terminal. The current $\vec{I}_T$ injected by the shunt transformer contains a real component $\vec{I}_p$, which is in phase or in opposite phase with the input voltage. It also has a reactive component $\vec{I}_q$ which is in quadrature with the input voltage. Then, the injected current $\vec{I}_T$ can be written by

$$\vec{I}_T = (I_p + jI_q)e^{j\theta I} \quad (3.2)$$

where θ_I is the UPFC input voltage phase angle. Thus, a second extra bus is required for the UPFC input terminal.

The UPFC input-output voltage and current can be represented by

$$\vec{v}_0 = \vec{v}_I + \vec{v}_T = v_I e^{j\theta 1} + v_p e^{j} \delta_0 + j v_q e^{j\delta 0} \quad (3.3)$$

$$\vec{I}_0 = \vec{I}_I - \vec{I}_T = I_I e^{j\delta I} - I_p e^{j\mathrm{P} I} - j I_q e^{j\theta I} \quad (3.4)$$

where δ_I is the UPFC input current phase angle. Then, the com- plex power injected into the transmission line by the series trans- former can be resolved into the real and reactive power in simple form as

$$S_T = \vec{v}_T \cdot \vec{I}^* = v_p \cdot I_0 + j v_q \cdot I_0 \quad 0 \quad (3.5)$$

The in-phase voltage Vp is associated with a real power supply and the Quadrature voltage Vq with an inductive or capacitive reactance in series with the transmission line. Since the real power P_T (which may be negative) is provided by the current Ip in the shunt transformer, we can derive the following relationship for an ideal (lossless) UPFC:

$$v_I \cdot I_P = v_P \cdot I_0 \quad (3.6)$$

(Or) the real power input equals the real power output. Due to (6), the number of degrees of freedom for the UPFC is reduced to three.

Let us assume that the UPFC is located between buses i and k. Each part of the transmission line is represented as an equivalent II circuit. Now that two extra buses for the UPFC input and output terminals are added, and the UPFC voltage and current relationships (3), (4) and real power flow equation (6) are established, we can represent the UPFC uncoupled model as shown in Fig. 3. The currents injected into the UPFC input and output buses are

$$\vec{I}_I = \left(\frac{y_i}{2} + \frac{1}{z_i}\right)\vec{v}_I - \frac{1}{z_i}\vec{v}_i \quad (3.7)$$

$$\vec{I}_0 = \left(\frac{y_k}{2} + \frac{1}{z_k}\right)\vec{v}_0 - \frac{1}{z_k}\vec{v}_k \quad (3.8)$$

The magnitudes of the injected voltage v_T and current I_T are limited by the maximum voltage and current ratings of the inverters and their associated transformers, which need to be included as inequality constraints in the OPF problem formulation.

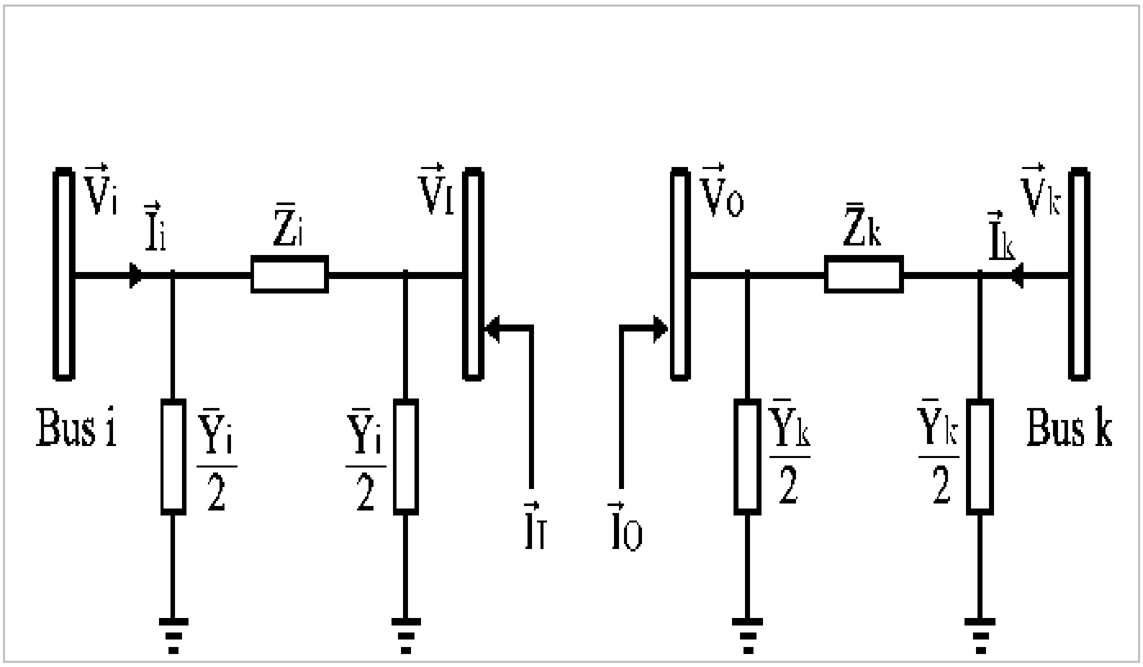

Fig 3.2Uncoupled UPFC Model in a transmission line.

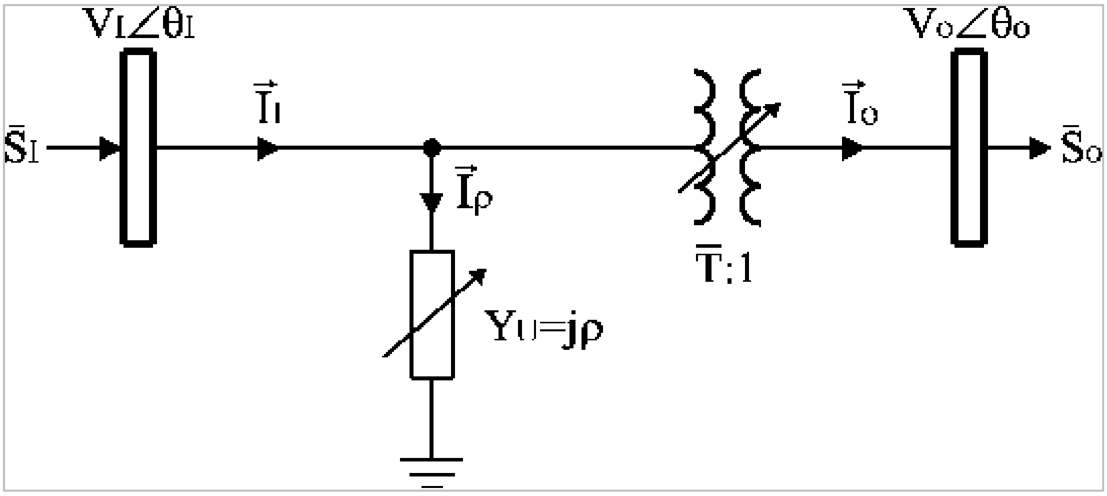

Fig 3.3: UPFC ideal transformer model

3.1.2 Ideal Transformer Model

Since the UPFC conserves real power and generates or consumes reactive power, it can be modeled using an ideal trans- former and a shunt branch, as shown in Fig. 4 [9]. The advantage of this model is that the ideal transformer turns ratio and the variable shunt susceptance are independent variables, which are not directly associated with the UPFC input-output voltages and currents. We define the UPFC variables as follows:

T transformer voltage magnitude turns ratio (real);

$\emptyset$ phase shifting angle;

ρ shunt susceptance;

and the ideal transformer turns ratio can be written by

$$\bar{T} = Te^{j\emptyset} \quad (3.9)$$

It is important to note that the ideal transformer does not generate real and reactive power,and the reactive power is generated (or consumed) by the shunt admittance only. Since the UPFC input-output voltage and current relationship can be expressed as

$$\vec{v}_I = \vec{v}_0 T < \emptyset \quad (3.10)$$

$$\vec{I}_I = j\bar{T}\rho\vec{v}_0 + \frac{1}{\bar{T}^*}\vec{I}_0 \quad (3.11)$$

the UPFC can be represented by an ABCD matrix as

$$\begin{bmatrix} \vec{v}_T \\ \vec{I}_I \end{bmatrix} = ABCDu \cdot \begin{bmatrix} \vec{v}_0 \\ \vec{I}_0 \end{bmatrix} \quad (3.12)$$

Where

$$ABCDu = \begin{bmatrix} \bar{T} & 0 \\ j\bar{T}\rho & \frac{1}{\bar{T}^*} \end{bmatrix} \quad (3.13)$$

Note that equation (11) does not represent a bilateral two-port network unless T = 1<0.

Now, we will show that this ideal transformer model represents the UPFC by comparing the complex power injections at the UPFC input and output. Using (11), the complex power injection at the UPFC input can be obtained by

$$\bar{s} = \vec{v}_I \vec{I}^*_I$$

$= \overline{\ } \quad \overline{\ } \qquad 1 \quad \rightarrow \; *$

$T\vec{v}_0\,(jT_\rho\vec{v}_0 + \frac{-}{T} * I_0)$

$= \vec{v}_0\vec{I}^* - j|\overline{T}|^2 \cdot |\vec{v}_0|^2\rho \qquad 0$

$= s_0 - j|\bar{T}|^2 \cdot |\vec{v}_0|^2 \rho$

and the real and reactive power injections can be obtained by

$P_I = Real(SI)$, QI=Imag(SI) (3.14)

P0=Real(S0), Q0=Imag(S0) (3.15)

Thus, we can derive the following relationships between the UPFC input and output:

$P_I = P_0$ (3.16)

$Q_0 = Q_I + |\bar{T}|^2 \cdot |\bar{v}_0|^2 \rho$ (3.17)

Equations (14) and (15) mean that the ideal transformer model conserves real power and generates or consumes (for ρ<0) reactive power. To determine how much real and reactive power is injected in the series and shunt transformers, we will map the complex turns ratio T in the ideal transformer and the shunt susceptance p to the injected voltage $\vec{v}_T$ and current $\vec{I}_T$ in the UPFC uncoupled model. Since the UPFC input voltage and current are expressed as

$\vec{v} = \vec{v} - \vec{v} = \vec{v}(1 - \vec{v}\vec{T}$ (3.18)

$\bar{I}$ 0 T $\vec{v}$ $) = \vec{v}_0 TL\phi$
0

$\vec{I}_I = \vec{I}_0 + \vec{I}_0 = \vec{I}_0(\bar{T}L\phi - 1)\vec{I}_0 + j\rho\vec{v}_I$ (3.19)

the injected voltage $\vec{v}_T$ and current $\vec{I}_T$ can be obtained by

$\vec{v}_T = (1 - TL^{\phi})\vec{v}_0$ (3.20)

$\vec{I}_I = \vec{I}_0 + \vec{I}_T = \vec{I}_0 + (\bar{T}L\phi - 1)\vec{I}_0 + j\rho\vec{v}_I$ (3.21)

Then, the power flows through each inverter, as shown in Fig. 1, can be obtained by

= _ ∅ 1

s_1 =

$\vec{v}_I I$

∅ $\vec{}^*$ T

$*$

$\vec{}$

$\vec{v}_0 T L$ $[(\frac{L}{T} - 1) I_0 + j\rho\vec{v}_0 T < \emptyset]$

$= (1 - TL^{\emptyset})s_0 - j\rho|\overline{T}|^2|\overline{v_0}|^2$

s_2 $= -\vec{v}_T \vec{I}^*_0$

$=(T < \emptyset - 1)\vec{v}_0\vec{I}^*_0$

$=(T < \emptyset - 1)\overline{s_0}$

Thus

$$s_1 + s_2 = -j\rho|\overline{T}|^2|\vec{v}_0|^2 \quad (3.22)$$

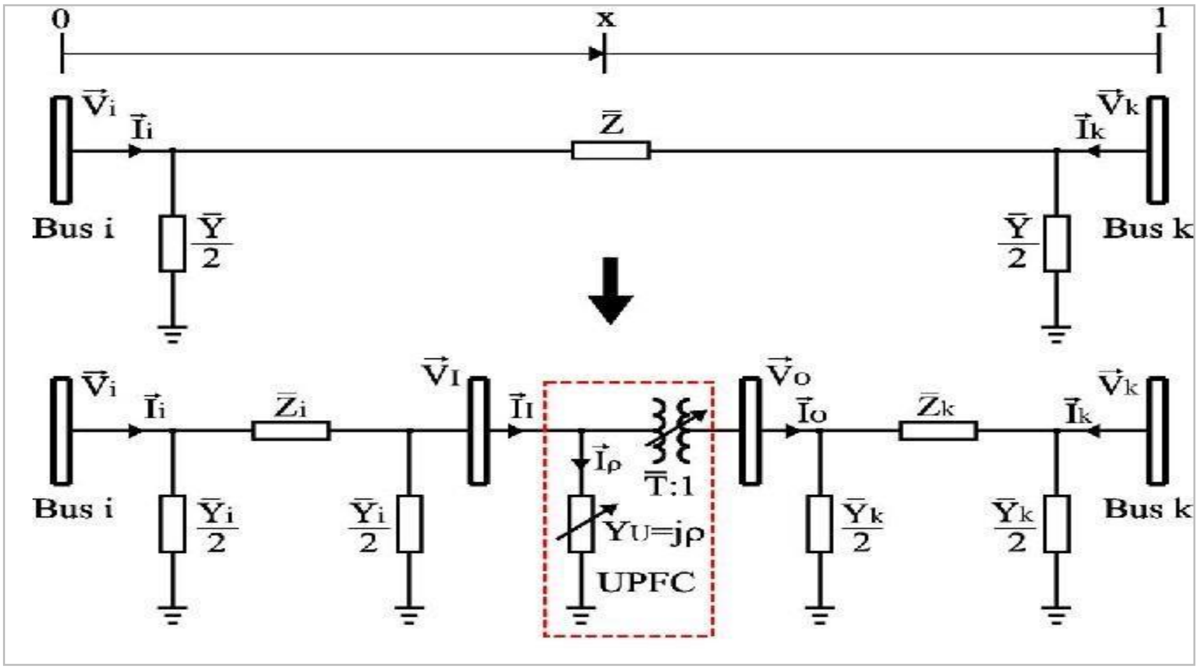

Fig: Cascaded transmission line with a UPFC.

Which verifies that the UPFC conserves real power and can generate (or consume) reactive power. Since the UPFC is modeled using passive circuit elements only, non-ideal UPFC characteristics, such as shunt and series transformer reactance's, can be easily incorporated into this framework.

3.2 UPFC in A Transmission Line

A two-port ABCD matrix is the most convenient method to represent cascaded networks [10]. Let us divide a transmission line between buses i and k with a UPFC into threecascaded net- works, a UPFC input transmission, a UPFC, and a UPFC output transmission, as shown in Fig. 5. The UPFC input transmission and the UPFC output transmission areeasily represented by two-port ABCD matrices since the transmission lines are modeled using

II Equivalent circuits. We call ABCDi and $ABCD_k$ as the ABCD matrices for each transmission line and defined by

$$ABCDi = \begin{bmatrix} A_i & B_i \\ C_1 & D_i \end{bmatrix} \text{ and } ABCDk = \begin{bmatrix} A_k & B_k \\ C_k & D_k \end{bmatrix}$$

where each element is defined b

$$A_i = D_i = 1 + \frac{Y_i z_i}{2}, B_i = z_i, c_i = y_i \left(1 + \frac{y_i z_i}{4}\right) \quad (3.23)$$

$$A_k = D_k = 1 + \frac{y_k z_k}{2}, B_k = z_k, C_k = Y_k \left(1 + \frac{Y_k z_k}{4}\right) \quad (3.24)$$

The ABCD parameters of each transmission line can be obtained after we identify the propagation constant γ and the characteristic impedance z_c. Since we are using IEEE test cases with no knowledge of γ or z_c, we compute these values using the expressions

$$\gamma = \frac{1}{L} cosh^{-1} \left(1 + \frac{Yz}{2}\right) \quad (3.25)$$

$$z_C = \frac{z}{sin(\gamma l)} \quad (3.26)$$

Where l is the distance between buses i and k measured in kilometers. Then, assuming the UPFC is installed in x(0<x<1) ,II equivalent circuit values for each section of the transmission line can be found by

$$z_i = asinh(\gamma l \cdot x) \quad (3.27)$$

$$Y_i = \frac{2}{z_i}(cosh(\gamma l X) - 1) \quad (3.28)$$

$$z_k = z_c\, sinh(\gamma l \cdot (1 - x)) \quad (3.29)$$

$$Y_k = \frac{2}{z_k}(cosh(\gamma l \cdot (1 - X)) - 1) \quad (3.30)$$

Now, the three cascaded networks are combined to obtain

$$\begin{bmatrix} v_i \\ I_i \end{bmatrix} = ABC_i \cdot ABCD_u \cdot ABCD_k \begin{bmatrix} v_k \\ -I_k \end{bmatrix} \quad (3.31)$$

$$= \begin{bmatrix} A_{ik} & B_{ik} \\ C_{ik} & D_{ik} \end{bmatrix} \begin{bmatrix} \vec{v}_k \\ -\vec{I}_k \end{bmatrix}$$

where ABCD is given , So

$$A_{ik} = A_k + j\bar{T}B A_k \; \rho + \frac{1}{\bar{T}*} B_i C_k$$

$$B_{ik} = \bar{T}A_i B_k + j\bar{T}B_i B_k \; \rho + \frac{1}{\bar{T}*} B_i D_k$$

$$C_{ik} = \bar{T}C_i A_k + j\bar{T}D_i A_k \rho + \frac{1}{\bar{T}*} D_i C_k$$

$$D_{ik} = \bar{T}C_i B_k + j\bar{T}D_i B_k \; p + \frac{1}{\bar{T}*} D_i D_k$$

By arranging (25) and solving for Ii and Ik, we have

$$\begin{bmatrix} \vec{I}_i \\ \vec{I}_k \end{bmatrix} = Y_{bus_{ik}} \begin{bmatrix} \bar{v}_i \\ v_k \end{bmatrix}$$

where

$$\bar{Y}_{bus_{ik}} = \begin{bmatrix} D_{ik} B_{ik}^{-1} & C_{ik} - A_{ik} D_{ik} B_{ik}^{-1} \\ -B_{ik}^{-1} & A_{ik} B_{ik}^{-1} \end{bmatrix} \quad 13$$

In general

$$\text{Det}\left(\begin{bmatrix} A_{ik} & B_{ik} \\ C_{ik} & D_{ik} \end{bmatrix}\right) = k2^{\phi}$$

If Ø=0 that is, complex T is real, this determinant is one at angle zero, and complex \ overline

{Y}{bus{ik} becomes symmetrical. Note that (25) represents a bilateral two-port network only if \ overline{T}= 120. As seen in (26), since the UPFC is embedded in the \ overline
{Y}{burs} matrix, the size of the \ overline{Y}{hns} matrix is not changed, so UPFC sensitivity analysis can be performed using this ideal transformer model.

3.3 Optimal Power Flow with UPFC

Suppose that a UPFC is installed in transmission line ik. The mathematical formulation of the OPF with the UPFC can be expressed as

$$\min_{y, x_{ik}} C(y, x_{ik})$$

subject to:

$h_i(y, x_{ik}) = 0$; i=1…., n

$g_j(y, x_{ik}) \leq 0$; j=1…, m

Where

C (y, x_{ik})	total generation cost, less consumer benefit;
y	vector of decision variables;
$x_{ik} = [T_{ik} \phi_{ik} \rho_{ik}]^T$	vector of the UPFC control variables in line ik;
$\{h_i: i = 1, \ldots . n\}$	set of equality constraint functions;
$\{g_j: j = 1, \ldots, m\}$	set of inequality constraint functions.

We use the UPFC ideal transformer model to construct the equations for OPF with a UPFC. It is important to note that the number of equality constraints is the same as that of the base case OPF with no UPFC. This is because the UPFC control variables do not depend on UPFC input and output voltages and cur- rents, and the

International Journal of Scientific Research in Engineering and Management (IJSREM)
Volume: 08 Issue: 05 | May - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

UPFC model is embedded in the
\overline{Y}_{bus} matrix, and because we ignore UPFC operational limits.Now, let us construct the Lagrange for the OPF problem as

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Volume: 08 Issue: 05 | May - 2024 SJIF Rating: 8.448 ISSN: 2582-3930

$$L0(y,\lambda,\ u,\ x_{ik}) = C(y,x_{ik}) + \sum_{i=1}^{n} \lambda_i h_i(y,\ x_{ik}) + \sum_{j=1}^{m} u_j\ g_j(y,\ x_{ik})$$

where λί and \mu_{j} are the Lagrange multipliers for the equality and inequalityconstraints, respectively. To solve the proposed OPF problem with inequality constraints, we

use the primal-dual interior-point method. At the optimum, the last term of (31) must satisfy the complementary slackness condition such that \mu_{j}g_{j}=0 for each j=1,..,m Therefore, if an inequality constraint is binding,

we could treat it as an equality constraint, and we could ignore it if it were not binding. Since we are using interior-point methods not active-set methods we do not have to distinguish between active and inactive constraints until the OPF problem is solved. This avoids "cycling" behavior in the active set associated with the methods such as Newton's. Then, to derive the first-order sensitivities, we rewrite Eq as

$$L0(y,\lambda,\ x_{lk}) = C\ (y,\ x_{ik}) + x_{ik}$$

CHAPTER-4

OPTIMAL LOCATION FINDING AND BASE VALUES OFUPFC CONTROL PARAMETERS

4.1 INTRODUCTION

UPFC is a flexible AC transmission system (FACTS) device used in power systems to control power flow, voltage, and impedance. Optimal location finding involves identifying the best locations to install UPFC devices within a power network to achieve specific objectives, such as minimizing transmission losses, maximizing power transfer capability, or enhancing voltage stability.

Determining the base values of UPFC control parameters involves setting the initial operating points for the UPFC devices, which can include parameters like line susceptance, series impedance, and shunt admittance. These values are crucial for the proper functioningof the UPFC in the power system.

4.2 FIRST ORDER SENSITIVE ANALYSIS

First-order sensitivity analysis, also known as sensitivity analysis or sensitivity study, is a technique used to analyze how the output of a model or system responds to variations or perturbations in its input parameters. In the context of power systems and UPFC control, first-order sensitivity analysis can be applied to understand the impact of changes in UPFC parameters on system performance.

Here's how first-order sensitivity analysis can be conducted for UPFC control parameters:

1. **Define the Objective**: Determine the objective of the sensitivity analysis. For example, you may want to assess the sensitivity of system performance metrics such as power flow, voltage stability, or transmission line losses to variations in UPFC parameters.

2. **Select Input Parameters**: Identify the UPFC control parameters that are relevant to the objective of the sensitivity analysis. These parameters may include the setting of the series and shunt controllers, line impedance parameters, or other relevant variables.

3. **Define the Range of Variation**: Specify the range over which each input parameter willbe varied. This range should be chosen based on engineering judgment and system requirements.

4. **Perform Simulations**: Use power system simulation software (e.g., PSCAD, MATLAB/Simulink) to simulate the behavior of the power system under different scenarios. For each scenario, vary the selected UPFC parameters within the defined range while keepingother system parameters constant.

5. **Collect Data**: Record the output variables of interest (e.g., power flow, voltage profiles, system losses) for each simulation scenario.

6. **Analyze Results:** Analyze the collected data to understand how changes in UPFC parameters affect system performance. This may involve statistical analysis, visualization techniques, or other methods to identify trends and relationships between input and output variables.

7. **Interpretation and Recommendations:** Interpret the results of the sensitivity analysis and draw conclusions regarding the sensitivity of system performance to changes in UPFC parameters. Based on these findings, recommendations can be made regarding the selection and tuning of UPFC control parameters to optimize system operation.

By conducting first-order sensitivity analysis, engineers can gain valuable insights into the influence of UPFC parameters on power system behavior, enabling informed decision-making in the design and operation of UPFC devices.

Consider the case where the UPFC is inserted in line i_k for clear mathematicalderivation, and the UPFC ideal transformer model is used for the analysis. The marginal values (MVs) of the UPFC, to be installed in line ik, are simply the amounts by which the total cost of system operation could be changed by allowing a small change of the UPFC control variables in line ik. We can obtain the MVs by assuming that there is a UPFC in line ik but that the UPFC is not operating. So, we add three extra constraints.

$$T_{ik} = \text{T},\ \phi_{ik} = 4,\ \rho_{ik} = \text{p} \tag{4.1}$$

to the original OPF problem, and for simplicity, we denote the constraints as can be written x_{ik}=x in vector form. Then, the new Lagrangian

$$L_{ik}(y, \lambda, x_{ik}, \lambda_x) = C(y, x_{ik}) + \sum_{j\in A} \lambda_j h_j(y, x_{ik}) + \lambda^T(\underset{x}{x} - x_{ik}) \tag{4.2}$$

Where

$$\lambda_x = [\lambda_T \lambda_\emptyset \lambda_\rho]^T \tag{4.3}$$

We define the function \lambda_{x}^{}(x) to be the optimal value of the Lagrange multiplieron the constraint x_{ik}=x. Here, we are most interested in \lambda_{x}^{}(x=x_{0}) whichis associated with the constraints

T_{ik}=1 \phi_{ik}=0 \rho_{ik}=0. (4.4)

This is because the OPF problem when solved with the UPFC control parameters x=x_{0} yields the same result for y and A as the base case where there is no UPFC in line ik. Using the first-order conditions for the solution of the OPF problem for x_{ik}=x_{0}

$$\frac{\partial L_{ik}}{\partial x_{ik}} = 0$$

we can solve for \lambda_{x}^{}(x_{0}) to obtain

$$\lambda_{x}^{x(x0)} = \left[\frac{\partial C(y^*,x_{ik})}{\partial x_{ik}} + \sum_{j \in A} \lambda_j^* \frac{\partial h_j (y^*,x_{ik})}{\partial x_{ik}}\right] \qquad (4.5)$$

Note that

$\frac{\partial C(y^*,x_{ik})}{\partial x_{ik}}$ and $\lambda_j^* \frac{\partial h_j (y^*,x_{ik})}{\partial x_{ik}}$ are easy to compute. Equation (35) indicates that the marginal value \lambda_{x}^{}(x_{0}) can be determined once we know y" and ", which are obtained from the base case OPF with no UPFC. Thus, if we know y^{} and \lambda^{\bullet} , we can obtain the first-order sensitivities of cost with respect to UPFC control variables x_{ik} for each possible transmission line by solving only the base case OPF. Since the UPFC modelis embedded in the \overline{Y}_{bus} matrix, as explained in (26), the first-order UPFC sensitivity analysis is only associated with complex power injections at buses i and k, and the thermal limit of transmission line ik if it is binding. If transmission flow is limited by steady- state stability, the following constraints can be included as well:

$$|P_{ik}| \leq P_{ikmax}$$

Or

$$|\theta_i - \theta_k| \leq \theta_{ikmax}$$

Where

P_{ik} real power flow bus i to bus k;

P_{ikmax} maximum real power flow bus i to bus k;

θi , θk voltage phase angles at buses i and k, respectively;

θi kmax maximum voltage phase angle difference between bus i and bus k.

4.3 BASE VALUES OF UPFC CONTROLLABLE PARAMETERS

We assume, for simplicity, that both inverters in a UPFC are equally sized, with SUPFC =a in per-unit on the system base. We also assume that the cost of the UPFC is proportional to its size SUPFC, regardless of voltage. In reality, many factors influence the cost of a UPFC, and in some cases, much of the value of a given UPFC location might result from reactive support, phase-shifting, or tap-changing alone, so that the final design decision may be to have shunt and series inverters of different sizes. However, since this paper presents a screening technique to evaluate total benefit of an ideal UPFC installation due to all three factors, we feel these simplifying assumptions are justified. Once the inferior UPFC locations have been screened out, a full study of the benefits of a real UPFC at eachpromising location would have to be conducted.

A UPFC of the same size will not produce equal benefits in different parts of the system, not only because of the location in the system but on also the size of the UPFC relative to the line in which it is located. A UPFC with a given MVA rating used to provide shunt VAr support only will likely have a greater impact on the voltage profil if located in an area of the system with small lines. Likewise, the series inverter can provide a larger phase ΔV in a line of lower voltage, but a given ΔV has less impact on total real or reactive power flows on lower-voltage lines.

So we choose SUPFC as our basis of comparison for the marginal values λ_T, λφ, and

λρ. In this way, each λ represents $/h savings per MVA of UPFC added (or, approximately, per dollar of UPFC capacity added) converted to per-unit.

The shunt inverter can produce up to reactive power (on system base). The series inverter caninject a ΔV of up to k, either in phase with the line current, or in quadrature. So our bases (device bases) for T, ϕ, and $\rho$are

ρ_{base} = kYbase (4.6)

$T_b ase$ = k, and (4.7)

$\phi_b ase$=tan-1(k) ≈ k radians (4.8)

where the last approximation assumes that is small (say, k < 0.30 ≈ 17°). The change from system base to device base causes the values of the multipliers λρ, λT ,λφ and to also change by κ. A larger means a larger UPFC, so the value of a small change in any.

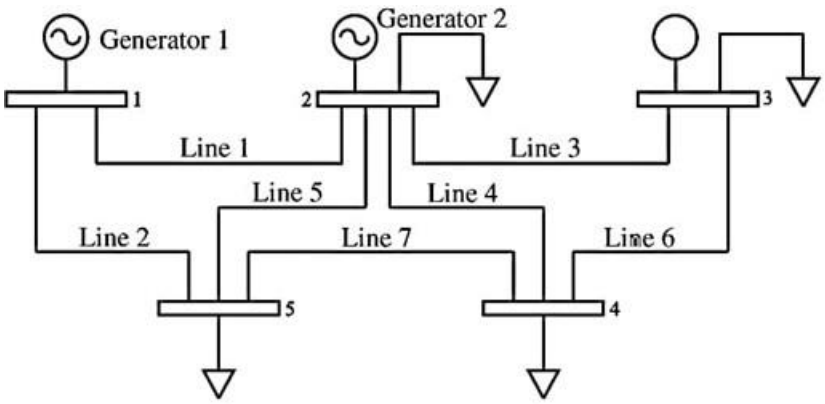

Fig 4.1: Diagram of five-bus subset of IEEE 14-bus system

TABLE I

LINE INPUT DATA FOR FIVE-BUS SYSTEM (S base =100 MV)

Line ♯	Bus-Bus	R per unit	X per unit	Y per unit	S_{max} MVA
1	1-2	0.01938	0.05917	0.0528	120
2	1-5	0.05403	0.22304	0.0492	90
3	2-3	0.04699	0.19797	0.0438	75
4	2-4	0.05811	0.17632	0.0374	75
5	2-5	0.05695	0.17388	0.0340	75
6	3-4	0.06701	0.17103	0.0346	75
7	4-5	0.01335	0.04211	0.0128	75

TABLE II: GENERATOR INPUT DATA FOR FIVE - BUS SYSTEM

Bus ♯	α	β	γ	P_{max}	P_{min}	Q_{max}	Q_{min}
	\$/h	\$/MWh	\$/MWh^2	MW		MVAR	
1	692.32	11	0.000820	250	45	150	-100
2	692.32	12	0.000776	150	15	50	-40
3	0	0	0	0	0	40	-40

one of the control variables, measured on device ratings, means a larger marginal value on a larger device. We will assume that k =0.1, although this is really irrelevant to marginal values (involving only small changes in control variables).

CHAPTER-5

RESULT AND CONCLUSION

5.1 RESULT ANALYSIS

The proposed sensitivity method was tested on a five-bus system derived from the IEEE 14-bus system, and IEEE 14- , and 30-bus systems to establish its effectiveness. These systems have seven, 15, and 33 lines, respectively. Fig. shows the five-bus system .The line input data for the five-bus system are given in Table I. The system consists of two generators at buses 1 and 2 and one synchronous condenser at bus 3. The generation cost function, measured in \$/h, is defined by

$$C\ (p_G)=\alpha+\beta P_G+\gamma P_G^2 \qquad (5.1)$$

Where PG is the unit's real power generation level measured in MW. The generator input data are summarized in Table II. It is shown that generator 2 has higher generation cost than generator 1. Loads are assigned such that the current flow constraint in line 1 is binding (we assume that thermal constraints limit line flow for this example). The load input data and bus voltage limits are given in Table III.

We assume that a UPFC is installed in the middle of the trans- mission line. Fig shows the marginal values ρ, $\lambda\phi$,λρ) for the five-bus system.

TABLE III : Input Load data and bus voltage limits for five-bus system

Bus ♯	P_{load}	Q_{load}	V_{max}	V_{min}
	MW	MVAR	per unit	per unit
1	0	0	1.08	0.95
2	21.72	4.41	1.08	0.95
3	94.06	19.10	1.08	0.95
4	91.61	18.60	1.05	0.95
5	51.48	10.45	1.05	0.95

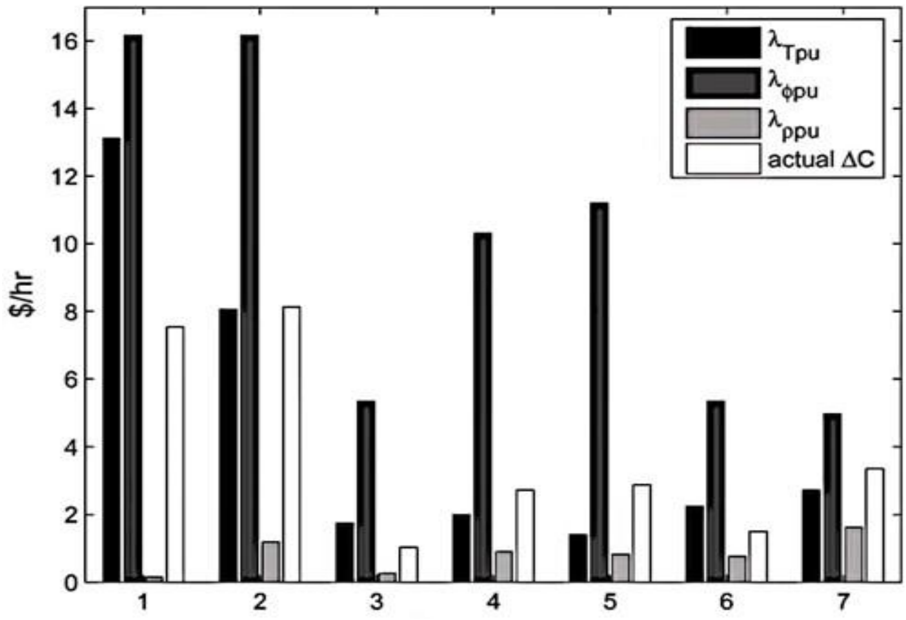

Fig 5.1 : Marginal values and total generation cost savings for five-bus system

Is irrelevant: A negative λ simply means that value is obtained by incrementally decreasing, rather than increasing, the relevant control variable. Thus, our graphs will show
$|\lambda|$ rather than λ it- self. The UPFC locations in transmission lines 1 and 2 produce high MVs for λT and $\lambda\phi$. Thus, the two lines appear to be the most promising places to install the UPFC. Then, a full OPF with a UPFC is implemented to obtain the total generation cost savings, that is ΔC = (optimal cost of operation with no UPFC) – (optimal cost of operation with a UPFC) for all possible cases. As shown in Fig. 7, we can see that the lines with higher MVs usually produce higher ΔC's, which provides confidence for the credibility of the first-order sensitivity analysis.

For the five-bus case, Table IV shows real power generation, transmission line losses, and the total generation cost to vali- date the effectiveness of the screening technique. Note that to compare MV screening results for much larger cases might be hard to understand in paper format, would take a large amount of time calculating ΔC's (which depend on full case studies for each possible location, which would still assume ideal UPFCs), and so are not shown here. Since the generation marginal cost, adjusted for marginal losses at bus 1, is lower than that at bus 2, it is profitable to obtain more real power from generator 1 as long as its adjusted marginal cost stays lower and no operational limits are reached. Therefore, for theoptimal location of the UPFC in this system, it is profitable to reduce the total generation costrather than the transmission line loss since two.

TABLE IV: REAL POWER GENERATION, LINE LOSS, AND TOTALGENERATION COST FOR FIVE-BUS SYSTEM

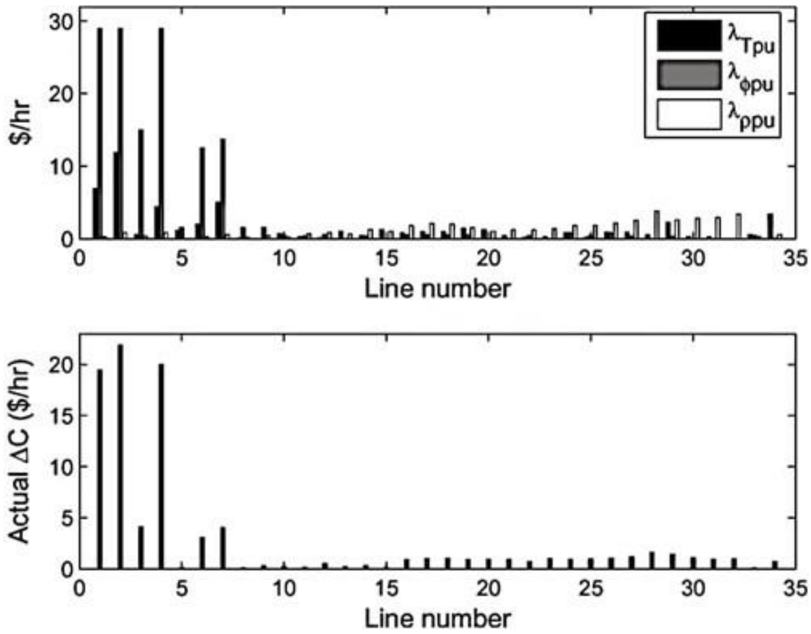

Fig 5.2: Marginal Values And Total Generation Cost Savings For IEEE 14-Bus Generators have different generation costs. An important thing at to note is that it is

more economical to locate the UPFC at the heavily loaded high voltage line 1 since it allows more power to be transmitted on the under-utilized line 2 while preventing line 1 from overloading. Eventually, no further savings due to UPFC operation can be achieved because of the voltage constraint at me bus 2. The test results of the IEEE 14-bus system are shown inFig.1.2.8. Similar load conditions as in the five-bus system were y used such that the constraint on current in line 1 is binding. As before, the lines with higher MVs produce higher actual ΔC"s. n, An important fact to note is that high voltage lines 1 through li- 7 are the most suitable locations to install the UPFC. This is to because higher voltage lines have lower p.u. impedances, and be therefore, most of the power will be transferred through those ant lines and some of the lines may reach their maximum transfer for capabilities.

The simulation result for the IEEE 30-bus system is shown in Fig.5.9. Again, lines with low marginal values tend to yield low actual incremental values, and the most valuable locations tend to be in the high voltage portions of the system. In addition, we see that locations with large incremental values are also those with large marginal values, thus

supporting the idea of using this type of sensitivity analysis to screen for promising locations for installation of a UPFC.

5.2 CONCLUSIONS

We have proposed the first-order sensitivity technique to screen for optimal UPFC locations in a large power system by ignoring the transmission lines with low MVs and running a full OPF only for the lines with higher MVs to obtain actual cost savings.

Thus, this technique can reduce the computational burden of determining the optimal locationof the UPFC in a large power system.

Not surprisingly, we also showed in the Seungwon An (M cases we studied that it is usually most economical to locate the UPFC on a heavily loaded high voltage transmission line.

The UPFC ideal transformer model has been developed for the UPFC sensitivity analysis.

This model does not require adding two extra buses, and the UPFC is embedded in the Ybus matrix.

Currently, we are developing methods to find the optimal location z for each line, and we are also developing methods based on second-order sensitivities, which should provide improved estimated incremental values as compared to the first-order methods.

In conclusion, the project "An Ideal Transformer UPFC Model, OPF First-Order Sensitivities, and Application to Screening for Optimal UPFC Locations" has provided valuable insights into the integration and optimization of Unified Power Flow Controllers (UPFCs) in power systems.

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FUTURE EXTENSION

For future extensions of the project "An Ideal Transformer UPFC Model, OPF First-Order Sensitivities, and Application to Screening for Optimal UPFC Locations," several avenues can be explored to further enhance the research and its practical applications. Here are some potential directions for future extension:

Non-ideal Transformer UPFC Modeling: Extend the UPFC model to account for non- idealities such as transformer losses, non-linearities in the control devices, and voltage source converter dynamics. Incorporating these factors would provide a more realistic representation of UPFC behavior and improve the accuracy of the simulations.

Dynamic Simulation and Control: Enhance the UPFC model to capture dynamic behavior and develop control strategies for dynamic operation. This could involve implementing dynamic models for the converters and integrating advanced control techniques such as model predictive control or adaptive control for real-time UPFC operation.

Multi-Objective Optimization: Extend the optimization framework to consider multiple conflicting objectives such as minimizing power losses, improving voltage stability, and reducing environmental impacts. Multi-objective optimization techniques like multi-objective evolutionary algorithms or Pareto optimization can be employed to find trade-off solutions between these objectives.

Integration of Renewable Energy Sources: Incorporate renewable energy sources such as wind and solar power into the power system model. Investigate the synergies between UPFC

deployment and renewable energy integration to improve grid stability, accommodate fluctuations in generation, and enhance overall system efficiency.

Uncertainty and Risk Analysis: Develop methodologies to assess the impact of uncertainty and risk factors on the effectiveness of UPFC deployment. This could involve probabilistic modeling of load and generation variations, as well as assessing the resilience of UPFC solutions to unexpected events such as equipment failures or extreme weather events.

Real-Time Monitoring and Control: Explore the integration of UPFCs into advanced grid monitoring and control systems. Develop algorithms for real-time UPFC parameter

adjustment and coordination with other grid devices such as FACTS devices, energy storage systems, and distributed generation resources to optimize grid operation dynamically.

Field Testing and Validation: Conduct field tests and validation studies to assess the performance of UPFC installations in real-world power systems. Collaborate with utilities and industry partners to deploy UPFCs in actual grid environments and evaluate their effectiveness in improving system stability and reliability.

Cost-Benefit Analysis and Economic Optimization: Extend the analysis to incorporate economic considerations such as UPFC deployment costs, maintenance expenses, and potential revenue streams from improved grid performance. Perform cost-benefit analysis and Economic Optimization to identify the most cost-effective UPFC deployment strategies for different grid scenarios.

By pursuing these future extensions, the project can continue to advance the state-of-the-art in UPFC modeling, optimization, and deployment strategies, ultimately contributing to the development of more resilient, efficient, and sustainable power systems.