12-2019

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Recommended Citation

Nwosu, Nneka, "Optimal Reactive Power Dispatch using TLBO for Modelling and PowerWorld for Validation" (2019). *Culminating Projects in Electrical Engineering*. 4.
https://repository.stcloudstate.edu/ece_etds/4

Optimal Reactive Power Dispatch Using TLBO Algorithm for Modeling and PowerWorld for Validation

by

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A Starred Paper

Submitted to the Graduate Faculty of

St. Cloud State University

in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in Electrical Engineering

December, 2019

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Abstract

This research presents a Teaching Learning Based Optimization (TLBO) algorithm to solve Optimal Reactive Power Dispatch (ORPD) problem. The aim of the power system is to ensure safe and reliable power is delivered to consumers. Reactive power dispatch although contributes little or no cost in power systems, it is important in sustaining the voltages of the power system and ensuring efficiency of the transmission system and all electromagnetic equipment. Excess reactive power in the power system can contribute to losses in the transmission grid. Therefore, reactive power sources and sinks need to be provided to ensure balance. The primary objective of this paper is to minimize the active power transmission losses by the optimal settings of the control variables (generator set point voltages, tap changers on transformers and reactive power shunt compensators) within their limits and avoiding violations on the constraints. TLBO is a population- based algorithm and requires few algorithm specifications to compute making it a recommended option to solve various degrees of optimization problems. The TLBO algorithm was implemented using MATLAB programming and by incorporating MATPOWER, the algorithm was tested on the IEEE 30-bus test system to solve the ORPD problem. The optimal values obtained from the TLBO algorithm was validated on PowerWorld- a power system visualization tool. The visualized results from PowerWorld were analyzed and further improvements were made. The results obtained from the algorithm were compared with other algorithms in the literature and TLBO and PowerWorld proved to be efficient tools for solving the ORPD problem.

Acknowledgement

I would like to thank my Parents Dr & Mrs. Emmanuel Nwosu for their constant love, financial and moral support.

I would like to sincerely thank my advisor Dr Hossain, Md M, Department of Electrical and Computer Engineering for all suggestions and pushing me for successful execution of the research.

I would like to express my gratitude to members of my committee Dr Yao Aiping and Dr Hou Ling for their constructive criticism during the early phase of the research.

I would also like to thank Dr & Mrs. OluAde Ajayi for making St Cloud a home and for the guidance and prayers.

Lastly, it wouldn’t have been possible without the constant support of my ELEGang and siblings, who believed in me to finish strong.

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Acronyms

OPF	Optimal Power Flow
ORPD	Optimal Reactive Power Dispatch
TLBO	Teaching- Learning Based Optimization
IEEE	Institute of Electrical and Electronics Engineers
GA	Genetic Algorithm
PSO	Particle Swarm Optimization
SA	Simulated Annealing
GSA	Gravitational Search Algorithm
MFO	Moth Flame Optimization
LTC	Load Tap Changing

Nomenclature

P	active power
Q	reactive power
|V|	magnitude of the voltage bus
δ	phase angle of the voltage bus
S	apparent power
I_R	current flowing from resistive component
I_X	current flowing from reactive component
I^*	conjugate current
$f(x,u)$	objective function to be optimized
$g(x,u)$	equality constraints
$h(x,u)$	inequality constraint
x	vector of state variables
u	vector control variables
P_{loss}	active/real power loss
k	branch between buses i and j
NTl	total number of transmission lines
G_k	mutual conductance of branch k
B_k	mutual susceptance of the branch k
V_i, V_j	voltage magnitude at bus i,j
δ_{ij}	voltage angle difference between buses $i\ and\ j$

nG	number of generator buses
nL	number of load buses
nC	number of shunt compensators
nT	number of tap- changing transformers
P_{Gi}	active power generation at bus i
Q_{Gi}	reactive power generation at bus i
Q_{ci}	shunt capacitor at bus i
T_i	tap changing transformer
P_{Di}	active power load at bus i
Q_{Di}	reactive power load at bus i
$\lambda_V, \lambda_C, \lambda_T$	penalty factor of voltage, shunt compensator and transformer
V_i^{min}, V_i^{max}	minimum and maximum voltage at bus i
$Q_{Ci}^{min}, Q_{Ci}^{max}$	minimum and maximum shunt compensator
T_i^{min}, T_i^{max}	minimum and maximum tap changing transformers
V_{ref}	reference voltage
$u_{teacher}$	result of the best learner in a subject.
r_i	random number between 0 and 1.
u_{mean}	mean of the students in a subject.
T_F	teaching factor
u_i	result of student in a subject
$u_{new,i}$	updated result of student in a subject

Chapter I: Introduction

Research Background

The electric power system deals with the process of generating, transmission and utilization of electrical energy. The power system industry continuously encounters challenging problems of designing future power systems to supply increasing demand of electrical energy in an efficient, reliable and economical way. The rate of energy consumption has outpaced infrastructure development, placing pressure on the aging equipment [2]. It is important to get fast and reliable optimization methods that can address both security and economic issues simultaneously to power system operation and control [2].

Optimal power flow (OPF) problem, which was proposed by Carpentier in the early 1960s based on the economic dispatch problem is one of the major issues in operation and planning of power systems. This problem can be divided into 2 sub problems, optimal reactive power dispatch ORPD and real power dispatch. ORPD problem has received great attention as a result of the improvement on economy and security of power system operation [8]. The aim of the optimal reactive power dispatch in power system is to identify the optimal combination of control variables that minimize a given objective function while satisfying certain physical and operating constraints. Reactive power is automatically generated with very low cost to the power industry, it affects the total generating costs by ensuring the control of voltages within specified limits and keeping the power system in operation and balanced condition thereby reducing transmission losses as much as possible. ORPD is a complex non-linear highly constrained nonconvex optimization problem because of the presence of both continuous and integer/discrete control variables. These integer control variables may appear in the form of switching shunt capacitor banks and transformer tap settings. Several conventional optimization techniques have been applied to solve the optimal reactive power dispatch problem. These include the gradient method, interior point method, quadratic programming linear programming and non- linear programming. These traditional methods have severe limitation in handling non- linear and nonconvex nature of the ORPD problem. These techniques involving derivatives and gradients may not be able to determine the global optimum. Also, the discrete variables related to the tap changing transformer cannot be incorporated directly into the algorithm. These methods suffer from drawback such as the huge computations unlike execution time and inflexibility with practical system. Therefore, it is important to find more accurate and efficient algorithms capable off overcoming all the drawbacks of the conventional optimization techniques.

Recently, many studies are dedicated to using nature inspired optimization methods including genetic algorithm, particle swarm optimization, simulated annealing, Ant colony optimization, bacterial foraging technique, differential evolution etc for solving ORPD problems.

One of the recently developed optimization techniques is the teaching -learning-based optimization TLBO, which is a population-based optimization technique inspired by passing on knowledge within a classroom environment, where learners first acquire knowledge from teacher and then from classmates [6].

Research Motivation

Recent trends in power system is tasked with sustaining the load bus voltages within nominal range for consumer satisfaction especially in a deregulated power industry and if it is not handled properly can lead to huge active power transmission line losses. These power transmission losses lead to voltage collapse and blackouts. The minimization of these power transmission losses is important for reliable and economic operation of the power system. Reactive power dispatch is important to minimize these active power transmission losses and maintain the voltage profile of the total power system by modelling it as an ORPD problem with the active power transmission loss as the objective function.

Objective

The main objectives of this paper are listed as follows:

- To study the formulation of ORPD, their equality and inequality constraints and control and state variables.
- To Understand the TLBO technique.
- To implement the proposed algorithm on the IEEE 30-bus test case and compare the results with other population- based algorithm.
- to implement the optimal values obtained from the proposed TLBO algorithm to Power world.

Scope of Research

This paper is dedicated to using TLBO for solving ORPD and analysis using PowerWorld. It investigates the role of reactive power from various sources like generators and reactive compensators capacitor banks and transformers in maintaining voltages within the nominal value accepted range. It is also limited to investigating only active power transmission loss objective function and validation on the IEEE 30-bus test systems to solve for an ORPD on a MATLAB programming platform.

Chapter II: Review of Optimization Techniques and Definition of Terms

The first step in optimizing a problem is to model it. Creating an appropriate mathematical model for an optimization problem is as important as the optimization method itself. The objective of optimal reactive power dispatch is to give optimal settings off control variables (generator bus voltages, tap settings of the under- load tap changing, shunt compensators) to minimize the network power loss and improve voltage profiles subject to several constraints such as limits on bus voltages, reactive power of the generators etc.

This chapter presents a brief discussion of evolutionary techniques for solving ORPD. This chapter also covers definition of terms used in paper.

Optimization Techniques

It is important to recognise the characteristics of an optimization problem in order to identify the appropriate optimization algorithm to use. Optimization problems are classified according to the mathematical characteristics of the objective function, the constraints and the control variables. The most important characteristics is the nature of the objective function [9]. These classifications are summarised in table 1.

Table 1: Classification of Objective Functions

Characteristics	**Property**	**Classification**
Number of Variables	One	Univariate optimization
	Two or more	Multivariate optimization
Type of Independent variables	Continuous	Continuous optimization
	Integers or binary	Integer optimization
Problem function	Both continuous and integer	Mixed integer optimization
	Linear functions of independent variables	Linear optimization
	Quadratic functions of independent variables	Quadratic optimization
	Nonlinear functions of independent variables	Nonlinear optimization
Problem formulation	With constraints	Constrained optimization
	Without constraints	Unconstrained optimization

Optimization techniques are classified into 2 categories: analytical methods and metaheuristic optimization algorithms.

Analytical Methods

These methods are based on classical mathematical methods such as gradient method, linear search techniques, LaGrange multiplier method, Newton-Raphson optimization technique and Karush-Kahn-Tucker method. Most of the classical methods is based on gradient and derivation concept. These methods do not handle multi-objective non- linear functions well making it difficult to identify a global Optima and there is high risk on nonconvergence. They fail to deal with discrete variables, and they need complicated mathematical calculations which require long time for execution.

Metaheuristic Optimization Algorithm

These algorithms are based on the evolutionary techniques Such as Genetic Algorithm GA, Particle Swarm Optimization PSO, Simulated Annealing SA, Gravitational Search Algorithm GSA and Moth Flame Optimization MFO. In these methods, Candidate solution is selected either at random or by common sense and can be enhanced by successive iterations. The iterations are executed until reaching accurate global optima. Evolutionary algorithms have the following advantages: it doesn't get trapped at local optima, it handles large number of variables and constraints, it deals with highly non-linear nonconvex objective functions and they are simple algorithms to use with faster execution times.

i. Basic Concept of Genetic Algorithm

Genetic Algorithm (GA) is a generalized search and optimization technique inspired by the theory of genetic and evolution mechanisms observed in natural systems and living beings. GA maintains a population of candidate solutions to the problem. Everyone in the population is evaluated to give some measure of fitness to the problem using the objective function. The following components form the basis of Genetic Algorithm:

- genetic representation a potential solution.
- Creating initial population of potential solutions.
- Selection of individuals from the population according to their fitness.
- Crossover operators that combine substructures of two parent chromosomes to produce new children.
- Mutation operators that alter the composition of children.

A genetic search starts with a randomly generated initial population within which everyone is evaluated by means of a fitness function. Individuals are either duplicated or eliminated according to their fitness value on until there is a generation of high-performance individuals [9] [7].

ii. The Basic Concept of Particle Swarm Optimization

The concept of particles from optimization was different by Dr. Eberhart and Dr. Kennedy in 1995 based on the inspiration of birds flocking in nature. The PSO is also based upon the population consideration like the genetic algorithm but it doesn't use mutation/ crossover operators.

This algorithm searches a space of an objective function by adjusting the distance of individual agents, called particles, as the piecewise path formed by positional vectors in a quasi- stochastic manner. The particle movement has 2 major components: A stochastic component and a deterministic component. The particle is attracted towards the position of the current global best while at the same time it tends to move randomly. When a particle finds the location that is better than any previously found locations, then it updates it as the new current best for particle i. This is a current best for all n particles. The aim is to find global best among all the current best until the objective no longer improves or after a certain number of iterations [9] [4].

iii. The Basic Concept of Gravitational Search Algorithm

Gravitational such algorithm GSA is a meta heuristic and population-based search algorithm based on Newton's law of gravity and law of motion. It was first proposed by Rashedi et al. In 2009. According to GSA, agents are considered as objects and their performance is measured by their masses. Every object attracts every other object with gravitational force [8].

Definition of Terms Used in the ORPD Problem

Buses

The ORPD is formulated based on Kirchhoff’s laws in terms of voltage amplitude and voltage phase at each nodes and active and reactive power injections in the system. There are 3 different kinds of buses in power systems with associated known and unknown variables which form the Power flow equations.

Table 2: Power system buses classification

Type of Buses	Known variables	Unknown variables to be determined
Slack or reference bus	|V|, δ	P, Q
Generator or P-V Bus	P, |V|	Q, δ
Load or P-Q Bus	P, Q	|V|, δ

Where

P is the active power

Q is the reactive power

|V| is the magnitude of the voltage bus

δ is the phase angle of the voltage bus.

i. Slack or Reference Bus

The slack bus injects or absorbs active or reactive power in a power system. The magnitude and phase angle V and δ of the voltage are specified and set at 1 per unit and zero respectively. The active and reactive power P and Q of the bus is usually determined and subject to change.

ii. Generator Bus

The generator bus also known as the P-V bus has its voltage magnitude and active power specified. The reactive power generation and voltage phase angles need to be determined and are subject to change. The voltage magnitude is kept constant by the injection of reactive power.

iii. Load Bus

The load bus also known as the P-Q bus has the active and reactive power specified. The magnitude and phase angle of the voltage need to be determined.

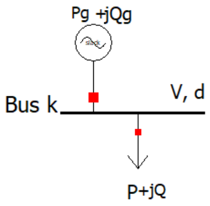

Figure 1: A Typical Bus in A Power System

Generators

Electric generator is any machine that converts mechanical energy from to electrical energy for the transmission or distribution over transmission lines to supply domestic or industrial needs. The mechanical energy can be obtained from several sources like the wind turbines, steam turbine, hydro turbines, gasoline or diesel generators. When the rotor is rotated, a voltage is induced in the stator coil and this voltage is proportional to the rate of change of the magnetic field with time. The flow of electric charges on the windings of generators produces alternating current and operates at a frequency of 50 or 60Hz.

The capacity of a generator is the product of the voltage per phase and the current per phase and the number of phases. It is normally rated in megavolt-amperes (MVA). The voltage (Volts) and current (Amperes) are the rms value which is equal to the peak value divided by$\sqrt{2}$.

Loads

Power systems deliver energy to loads. These loads range from household appliances to industrial machines. The instantaneous power absorbed by a load is the product of rms voltage across the load and the rms current into the load. Several types of loads exist:

i. Purely Resistive Load: the current is in phase with the load voltage. It consumes active power. Resistive loads include lamps, electric heaters.

$$P = VI_R \text{ in Watts} \qquad (2.2.1)$$

ii. Reactive loads: These are made up of inductive loads and capacitive loads. With inductive load, the current lags the voltage and it consume reactive power, and with capacitive Load, the current leads the voltage and generates reactive power.

$$Q = VI_X \text{ in VAR.} \qquad (2.2.2)$$

Apparent Power

The complex power S is the product of the voltage and the conjugate of the current

$S = VI^{*} = P + jQ$ and expressed as Volt-Amperes (2.2.3)

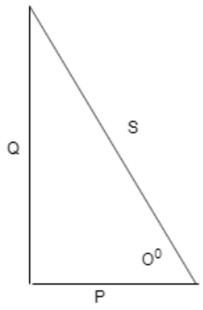

Figure 2: Power triangle

$Power\ factor = \frac{P}{S} = cos\emptyset$ (2.2.4)

Where

$\emptyset\ is\ the\ phase\ angle$

Reactive Power Compensation (Shunt Capacitors)

Inductors and capacitors are used on transmission lines to increase line loadability and maintain voltages near rated values. The shunt capacitors are further used to deliver reactive power and increase voltages regulations during heavy load conditions. These shunt capacitors can absorb reactive power during off peak periods (during light load conditions when voltage increases) and deliver reactive power during peak periods (during heavy loaded conditions when voltages fall). [4]. When the switched shunt is on automatic control, its reactive power is changed in integer steps or continuously to keep the voltage at the regulated bus within the per unit voltage range defined by the upper and lower limits.

Transmission Lines

It is not possible to store electrical energy, therefore, the net energy generated must be equal to the sum of the total system loads and power losses. Each load or generating point of the power system is called a bus and various buses are connected with transmission lines.

Transmission lines are used to connect electric power sources (generators) to electric power demand (loads) with minimal losses. Transmission lines are also used to interconnect neighbouring power systems. The design of a transmission line depends on four electrical parameters:

1. Series resistance
2. Series inductance
3. Shunt capacitance
4. Shunt conductance

The series resistance depends on the physical structure of the aluminium conductor at a given temperature. The series inductance and shunt capacitance are produced by the presence of magnetic and electric fields around the conductors and depends on their geometric arrangement. The shunt conductance is due to the leakage current flowing across insulators and air. Leakage current is considerably small compared to nominal current and it is therefore ignored during transmission line modelling.

Transmission lines have resistances and reactances which cause power losses. Transmission line impedances (resistance and reactance) are incorporated in the system design and are fixed parameters. Transmission line resistance results in active power loss and transmission line reactances result in reactive power loss. Line impedance is a fixed parameter chosen during system design.

Reducing losses involves reducing line current. It can also be stated as reducing the voltage difference between adjacent buses. Since loss is proportionate to the square of the line current, reducing the maximum current magnitude has a huge impact on total loss. Line losses are considered for optimization since losses can be controlled by adjusting voltages at different buses.

Transformers

Transformers are used to regulate real or reactive power flow through a transmission system. Most transformers are modelled with taps on the windings (makes up the transformer's active part with the core) to adjust either the voltage transformation or the reactive flow through the transformer. This allows the transformer to alter the phase angle (relationship between apparent power and active power). This change in the phase angle regulates the power factor.

Power factor is a measure between 0 and 1. Between 1 and 0 lagging mean a generator is producing reactive power and increasing overall voltage. Between 1 and 0 leading means a generator is absorbing reactive power and reducing overall voltage.

A transformer that adjusts the voltage is called a load-tap-changing (LTC) transformer and a transformer that adjusts the reactive flow of the power system is known as an on-load tap-changing (OLTC) transformer [5].

The off-nominal tap ratio indicates the voltage transformation. If the transformer is not on automatic control, the values can be changed manually. The off-nominal tap ratio determines the additional transformation relative to the nominal transformation. The off-nominal tap ratio ranges from 0.9 to 1.1.

There are several types of transformers:

i. No automatic control: these are transformers with fixed taps ratio and will remain fixed throughout the entire power flow process unless the value is manually changed.
ii. Automatic voltage regulator: the transformer taps automatically change to keep the voltage at the regulated bus within a voltage range between the minimum and maximum voltage values.
iii. Automatic reactive power control: the transformer taps automatically change to keep the reactive power flow through the transformer within a specified range.

The Per-Unit System

Power system quantities such as voltage, power, current, impedance and admittance are often expressed as percentage of specific base value. The Per unit system makes the calculation easier as all the values are taken in the same unit. The per unit value are dimensionless.

$$Per\ unit\ value = \frac{actual\ value}{base\ value} \qquad (2.2.4)$$

Role of Reactive Power (Var) on Voltage Management

Reactive power describes the background energy movement in an AC system resulting from the production of electric and magnetic fields. Reactive power plays a critical role in power system planning and operation.

Electricity consists of currents; the flow of electrons in the wire and voltage; the force pushing this current through the wire. The amount of work current and voltage do together is called $Power$ and is measured in $Watts$. This type of power is often called real power or active power. Electricity that turns on light bulbs, charges phones or heats water is the active power. However, getting the active power around the power system in an economic, efficient and safe manner requires something called *reactive power* which is used to pump active power around the power grid. Reactive power helps to keep electricity flowing and helps maintain voltage levels that are needed for system stability. Reactive power is measured in $Volt\ Amperes\ Reactive\ (VAR)$. Generators produce active power and reactive power, and both can be adjusted to change their outputs, but reactive power is fed into the power system in a slightly different manner, which leads to the limitation of how far it can travel. Reactive power can only be effective locally and cannot travel far. Power system generators are not the only source of reactive power. Capacitors and static VAR compensators which are installed in a power system are capable of injecting reactive power. Electronic devices like laptops and TVs produce and feed small amounts of reactive power into the power system, and in large quantities, there is need for the power system to absorb the excess reactive power. Although it is essential to have reactive power in the power system, it is important to have the right amount. Too much of reactive power and transmission lines become overloaded and causes damages on the power system, too little and the efficiency of the power system decreases.

This means generators must generate more reactive power when there is not enough or absorb it when there is an excess. This can happen when transmission lines are 'lightly loaded' such as overnight when electricity demand is lower. The lines start emitting reactive power causing voltage to rise and this creates a greater need for reactive power absorption and voltage control.

The ability to manage reactive power is important in controlling voltage as voltage must stay within 5% of its nominal rated value to avoid wear and tear of equipment or large-scale blackouts. Voltage control refers to regulating voltage by injecting or absorbing reactive power as needed.

The voltage at each bus in a power system is a sinusoidal waveform with frequency of 50Hz. This means that the voltage at each bus has a magnitude and a phase angle. The active and reactive powers and bus voltages and phases are all intricately linked, there is a stronger relationship between reactive power and voltage magnitude; between real power and voltage phase angle [10]. This phenomenon exists because of the decoupling of real and reactive powers that occurs if the transmission line resistance is much smaller than the reactance and voltage magnitude at all buses is maintained at around 1p.u [10]. Depending on the ratio of reactance and resistance of a transmission line, both active and reactive power may have equal effect on the voltage of the power system but by convention reactive power is chosen for control and compensation.

In VAR compensation injecting VAR into the power system increases the voltage while absorbing VAR reduces the voltage. Voltage control can be done by using capacitor bank compensators, transformers, load shedding etc. Various control techniques have dealt with optimizing the position of taps in the transformers, voltage on generator buses or controlling the outputs of the compensation devices while satisfying other system constraints.

The aim of reactive power (VAR) compensation/ planning is to dispatch reactive power of generation to minimize the real power transmission losses and voltage deviation while several equality and inequality constraints are satisfied. The main role of reactive power planning is related to individually or simultaneously determine optimal settings of control variables in a power system to minimize objective functions [12].

Chapter III: Optimal Reactive Power Dispatch Problem Formulation

Objective Function

Kirchhoff's current law and Ohm's law makes up the power flow equations. These equations define the relationship between the voltages at each bus and the generators and loads connected to them. With the voltage at each bus known, it is possible to know the current in all the lines, the power consumed or injected at each bus which can be described as follows [12]:

$$Minimize\ f(x,u) \tag{3.1}$$

subject to

$$g(x,u) = 0 \tag{3.2}$$

$$h(x,u) \leq 0 \tag{3.3}$$

If x goes out of bounds, u can be adjusted so that x can be within limits again. Line losses are considered for optimization since losses can be controlled by adjusting/ varying voltages at different nodes.

In this case, minimization of active power loss is considered the objective function and it can be defined mathematically as follows: [12].

The power lost as heat on a line between buses i and j is given as

$$P_{(loss)\ i,j} = I_{ij}^2 R_{ij} = \left(V_i - V_j\right)^2 / R_{ij} \tag{3.4}$$

$where$

$V = |V|\measuredangle\delta$ and

R_{ij} is the resistance of the line between buses $i\ and\ j$.

The total active power loss of the power system is calculated as a product of vectors and matrices as

$$P_{(loss)}^{total} = Real(VI^*) = \sum_{i,j} Real\{(V_i - V_j) {Z_{ij}^*}^{-1} (V_i - V_j)^*\} \qquad (3.5)$$

$$Z_{ij} = R_{ij} + jX_{ij} \qquad (3.6)$$

$$Z_{ij}^{-1} = \frac{1}{R_{ij}+jX_{ij}} = \frac{R_{ij}}{R_{ij}^2+X_{ij}^2} - j\frac{X_{ij}}{R_{ij}^2+X_{ij}^2} \qquad (3.7)$$

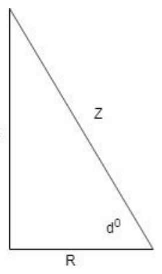

Figure 3. The impedance triangle

$$Z_{ij}^{-1} = Y_{ij} \qquad (3.8)$$

$$Y_{ij} = G_{ij} + jB_{ij} \qquad (3.9)$$

$$G_{ij} = \frac{R_{ij}}{R_{ij}^2+X_{ij}^2} \qquad (3.10)$$

$$B_{ij} = -\frac{X_{ij}}{R_{ij}^2+X_{ij}^2} \qquad (3.11)$$

$$F = Min(P_{loss}) = \sum_{k=1}^{NTl} G_k\left[V_i^2 + V_j^2 - 2V_iV_j\cos\delta_{ij}\right] \qquad (3.12)$$

Where

$f(x,u)$ is the objective function to be optimized

$g(x,u)$ is the equality constraint

$h(x, u)$ is the inequality constraint

x is a vector of state variables

u is a vector of control variables

P_{loss} is the active/real power loss

k is the branch between bus i and j

NTl is the total number of transmission lines

G_k is the mutual conductance of branch k

Y_{ij} is the admittance matrix

Z_{ij} is the impedance matrix

V_i, V_j: voltage magnitude at bus i, j

δ_{ij} is the voltage angle difference between buses i and j

Control Variables (u)

These are vectors of independence variables whose value can be adjusted directly to help minimize the objective function and satisfy the constraints. These include generator bus voltages, transformer tap ratio settings and shunt capacitors

u= $[V_{G1} \ldots V_{nG}, T_1 \ldots T_{nT}, Q_{c1}, \ldots, Q_{nC}]$ (3.12)

State Variables (x)

These are variables that are not controlled. They are free within limits to assume values to solve the problems. These include load bus voltages, active and reactive power generation of the slack bus.

x= $[P_{G1}, Q_{G1} \ldots Q_{nG}, V_{L1} \ldots V_{nL}]$ (3.13)

System Constraints

In the minimization process of objective functions, equality and inequality constraints must be met to ensure secure planning of the power system operation.

Power Flow Equality Constraints

These reflect the physics of the power system as well as desired voltage setpoint throughout the system. The physics are enforced through the power flow equations that require net injection of real and reactive power at each bus sum to zero [1].

$$P_i = (V_i \sum_{k=1}^{NB} V_j (G_k \cos(\delta_i - \delta_j) + B_k \sin(\delta_i - \delta_j)) \tag{3.7}$$

$$P_i = P_{Gi} - P_{Di} \tag{3.8}$$

$$P_{Gi} - P_{Di} - (V_i \sum_{k=1}^{NB} V_j (G_k \cos(\delta_i - \delta_j) + B_k \sin(\delta_i - \delta_j)) = 0 \tag{3.9}$$

$$Q_i = (V_i \sum_{k=1}^{NB} V_j (G_k \sin(\delta_i - \delta_j) - B_k \cos(\delta_i - \delta_j)) \tag{3.10}$$

$$Q_i = Q_{Gi} - Q_{Di} \tag{3.11}$$

$$Q_{Gi} - Q_{Di} - (V_i \sum_{k=1}^{NB} V_j (G_k \sin(\delta_i - \delta_j) - B_k \cos(\delta_i - \delta_j)) = 0 \tag{3.12}$$

Where

$P_i and\ Q_i$ are the real and reactive power injections at bus i

P_{Gi} is the active power generations at bus i

P_{Di} is the active power load demands at bus i

Q_{Gi} is the reactive power generations at bus i

Q_{Di} is the reactive power load demands at bus i

B_k is the mutual susceptance of the branch k

Inequality Constraints

In a power system components and devices have operating limits. These limits are created for security constraints. Thus, the objective function can be minimized by maintaining the network components within the security limits. These constraints include:

i. Generator inequality constraint: the generator voltages V_G and reactive power outputs Q_G are restricted by their limits:

$$V_{Gi}^{min} \leq V_{Gi} \leq V_{Gi}^{max},\ i \in nG \tag{3.13}$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max},\ i \in nG \tag{3.14}$$

ii. Transformer tap settings (T_i) inequality constraints: tap settings are restricted by the upper and lower bounds on the transformer tap ratios:

$$T_i^{min} \leq T_i \leq T_i^{max},\ i \in nT \tag{3.15}$$

iii. Reactive power compensation constraints:

$$Q_{ci}^{min} \leq Q_{ci} \leq Q_{ci}^{max},\ i \in nC \tag{3.16}$$

Where $nG, nT\ and\ nC$ are numbers of generators, tap changing transformers and shunt compensators respectively.

All constraints are satisfied in the simulation process as explained below [8].

Penalty Function

The use of penalty functions is the easiest and efficient method of handling constraints in the optimization problem with the goal of maintaining system security and dealing with unfeasible solutions. A quadratic penalty function method is used in which a penalty term is added to the objective function for any violation of constraint limit [2]. By adding penalty functions to the objective function, the augmented objective function F_{aug} becomes:

$$F_{aug} = F + \lambda_V(\sum_{i=1}^{NB}(V_i - V_i^{lim})^2 + \lambda_C(\sum_{i=1}^{nC}(Q_{ci} - Q_{ci}^{lim})^2 + \lambda_T(\sum_{i=1}^{nT}(T_i - T_i^{lim})^2 \tag{3.17}$$

Where

$$V_i^{lim} = \begin{cases} V_i^{min} \; if \; V_i \; < \; V_i^{min} \\ V_i^{max} \; if \; V_i \; > \; V_i^{max} \\ V_i \qquad\qquad\quad else \end{cases} \tag{3.18}$$

$$Q_{ci}^{lim} = \begin{cases} Q_{ci}^{min} \; if \; Q_{ci} \; < \; Q_{ci}^{min} \\ Q_{ci}^{max} \; if \; Q_{ci} \; > \; Q_{ci}^{max} \\ Q_{ci} \qquad\qquad\quad else \end{cases} \tag{3.19}$$

$$T_i^{lim} = \begin{cases} T_i^{min} \; if \; T_i \; < \; T_i^{min} \\ T_i^{max} \; if \; T_i \; > \; T_i^{max} \\ T_i \qquad\qquad\quad else \end{cases} \tag{3.20}$$

Chapter IV: Teaching- Learning -Based Optimization (TLBO) Algorithm

Overview of TLBO

The TLBO was first proposed by Rao et al. This algorithm is a powerful and dynamic search algorithm inspired by nature methods and mimics the philosophy of teaching and learning in a classroom. This optimization method is based on the impact of the effect of a teacher on the outcome of learners. TLBO does not require any algorithm -specific parameters and only requires such controlling parameters as population size and control variables for its operation. It is a population-based technique and employs a population of solutions to obtain the optimum solution. It is inspired by the process of knowledge, where learners first acquire knowledge from a teacher and then between themselves. A group of learners comprise the population in TLBO. In any optimization algorithms, there are numbers of different control variables. The different control variables in TLBO are analogous to the subjects offered to learners and the learners result is analogous to the fitness [13]. As the teacher is considered the most learned person in the class, the optimal solution so far is analogous to the teacher in TLBO [13].

In general, the teacher attempts to distribute knowledge among learners to increase their knowledge level and help enhance their grades [6].

Consequently, the teacher will increase the mean grade of the class according to his capability. However, despite the great effort made by the teacher, students will not only gain knowledge based on his teaching quality, but also on the quality of interactions of students sitting in the class. Quality of the students is assessed through the mean value of the population. Moreover, the teacher puts effort to increase the mean of students to a higher level, at which students will require another teacher of better quality to teach them [6].

TLBO Algorithm

The TLBO algorithm is given in algorithm 1. TLBO starts with an initialization phase where a randomly generated population of candidate solutions are placed in the search space of the problem consisting of n dimensions where each dimension is limited by an upper and lower bound. The TLBO is divided into two parts: Teacher Phase and Learner phase. The teacher is generally considered as a highly learned person who shares his or her knowledge with learners', so they can have better result. Learners also learn from themselves and improve their result in the process.

Teacher Phase

This is the first part of the algorithm where learners gain knowledge through the teacher. A good teacher is considered one who increases the knowledge of the learners. This is not possible in practice as increase in knowledge depends on other factors such as commitment and aptitude. However, a teacher can only move the mean result of the class up to some extent depending on the class capability. The difference between the existing mean result of each subject and the corresponding result of the teacher for each subject is given by [6].

$DifferenceMean = r_i(u_{teacher} - T_F u_{mean})$ (4.1)

Where

$u_{teacher}$ is the result of the best learner in a subject.

r_i is any random number between 0 and 1.

u_{mean} is the mean of the students in a subject.

T_F is the teaching factor that decides the value of the mean value to be changed. It can be either 1 or 2 and it is decided with equal probability. T_F is not a parameter of the TLBO algorithm.

Based on the $DifferenceMean$, the existing solution is updated in the teacher phase according to

$u_{new,i} = u_i + DifferenceMean$ (4.2)

Where

$u_{new,i}$ is the updated value of u_i. $u_{new,i}$ is accepted if it gives a better function value. Accepted values at the end of the teacher phase are maintained and becomes input to the learner phase.

Learner Phase

Learners increase their knowledge by interacting among themselves. A learner interacts randomly with other learners to enhance his or her knowledge. A learner gains new knowledge if the second learner has more knowledge [6].

Randomly select two learners i and j

$if\ j \neq i,$

$$u_{new,i} = u_i + r_i(u_i - u_j) \quad if\ f(u_i) < f(u_j) \tag{4.3}$$

Or

$$u_{new,i} = u_i + r_i(u_j - u_i) \quad if\ f(u_j) < f(u_i) \tag{4.4}$$

$u_{new,i}$ is accepted if it gives a better function value.

Algorithm 1 ($TLBO\ pseudocode$)

```
Set $maxiter$:    maximum number of iteration.
Set $iter$ =1
Objective function $f(u), u = [V_{G1} \dots V_{nG},\ T_1 \dots T_{nT}, Q_{c1}, \dots, Q_{nC}]$
Generate population size $u_i, i = 1,\ 2, \dots, m$        $m = population\ size$
$while\ iter < maxiter$
    $for\ i = 1{:}m$
        $T_F = round[1 + rand(0,1)\{2 - 1\}]$
        $u_{mean} = mean(u_i)$
        $u_{teacher} = best(u_i)$
        $DifferenceMean = r_i(u_{teacher} - T_F u_{mean})$
        $u_{new,i} = u_i + DifferenceMean$
        $if\ f(u_{new,i}) < f(u_i)$
            $u_i \leftarrow u_{new,i}$
        $end\ if$
        $j = randi(m)$
```

```
            $if\ j \neq i$
                $if\ f(u_i) < f(u_j)$
                    $u_{new,i} = u_i + r_i(u_i - u_j)$
                $else$
                    $u_{new,i} = u_i + r_i(u_j - u_i)$
                $end\ if$
            $end\ if$
            $if\ f(u_{new,i}) < f(u_i)$
                $u_i \leftarrow u_{new,i}$
            $end\ if$
        $end\ for$
        $iter = iter + 1$
    $end\ while$
```

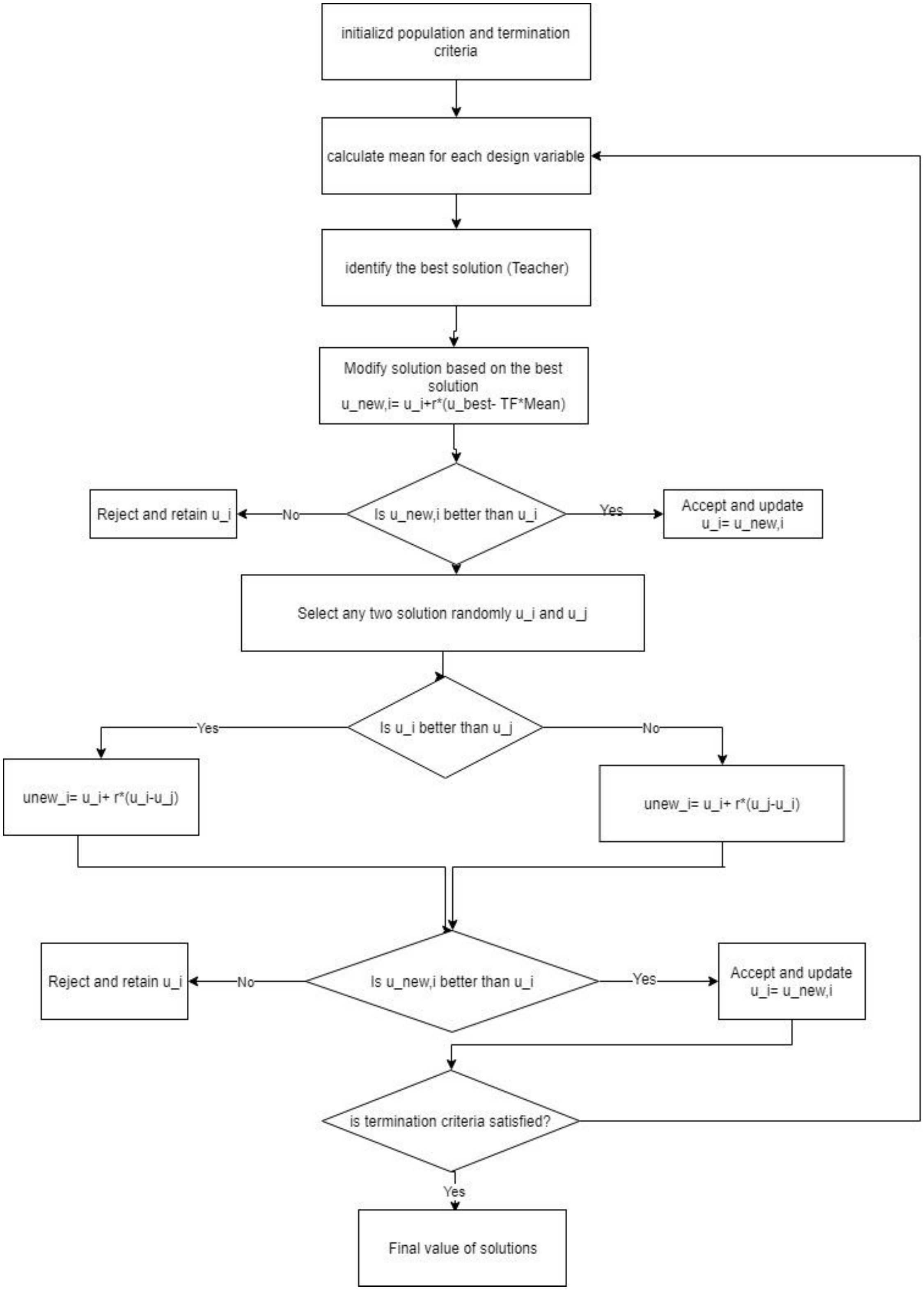

Figure 4. TLBO Flowchart

TLBO Combined with MATPOWER Toolbox

Optimization problems are more complicated with additional constraints. The TLBO algorithm is required to find the optimal settings of control variables. MATPOWER is applied with TLBO to solve the ORPD problem.

MATPOWER

MATPOWER is an important MATLAB programming extension package for solving power flow and optimal power floe. MATPOWER is easy to use and can easily modify the original code. MATPOWER can be summarized in the following steps [15]:

Step 1: load case (power system data-bus data, generator data, branch data, base MVA)

Step 2: calculate the power flow

Step 3: output all result

P*rocedure for TLBO Combined with MATPOWER*

The objective function of the ORPD problem is to minimize the total active power loss. The design variables for the solution consists of all control variables presented as generator bus voltages, transformer tap settings and shunt VAR compensation. The steps to implement the ORPD using TLBO combined with MATPOWER toolbox is given below.

Step 1: Initialization of TLBO parameters.

Step 2: Load test case information saved in MATPOWER case file.

Step 3: Initialize control variables.

Step 4: Call MATPOWER simulation function ‘$runpf$’ to run power flow

Step 5: Check if inequality constraints are violated and penalize the violations.

Step 6: Calculate the new objective function with penalized violations.

Step 7: Update new control variables using (4.1) and (4.2).

Step 8: Check whether inequality constraints are violated and penalize the violations.

Step 9: Repeat Step 4 for updated power flow calculation.

Step 10: Repeat Step 6 updated objective function.

Step 11: Compare results obtained in Step 10 with Step 6.

Step 12: If the new objective function value is better than the previous one, update the control variables with the better sets.

Step 13: Update new control variables using (4.3) and (4.4).

Step 14: Check whether inequality constraints are violated and penalize the violations.

Step 15: Repeat Step 4 for updated power flow calculation.

Step 16: Repeat Step 6 updated objective function.

Step 17: Compare results obtained in Step 16 with Step 10.

Step 18: If the new objective function value is better than the previous one, update the control variables with the better sets.

Step 19: Repeat above procedures from step 3 for maximum number of iterations.

Chapter V: Simulation Result and Analysis

Solving ORPD

This chapter presents the simulation results and analysis of the TLBO algorithm to solve the ORPD problem (active power loss minimization) using the IEEE 30 bus test system with 100MVA base for the entire test system. The TLBO algorithm was coded in MATLAB R2019b incorporating MATPOWER 7.0. The parameters of the TLBO algorithm is summarized in table III. The optimal control variables obtained at various phases of the TLBO algorithm are inputted to the PowerWorld and the simulation results are compared between TLBO and PowerWorld.

Table 3. Parameters for TLBO algorithm.

Parameter	**Symbol**	**Value**
Population size	N	50
Max. number of iterations	$miter$	100
Teaching factor	T_F	$round[1 + rand(0,1)\{2 - 1\}]$
Penalty factor	$\lambda_V, \lambda_c, \lambda_T$	10

IEEE 30-Bus Test System

The IEEE 30-bus test system was used to validate the proposed TLBO approach. The single line diagram of the IEEE 30-bus test case is shown in figure 3. The IEEE 30-bus test system consists of 6 generator buses at buses (1, 2, 5, 8, 11 and 13), 21 load buses, 41 transmission lines, 4 transformers with off-nominal tap ratio at branches (6-9, 6-10, 4-12, 27-28) and 2 shunt VAR compensators plugged in at buses (10 and 24). For this ORPD problem, a total of 12 optimized control variables are used.

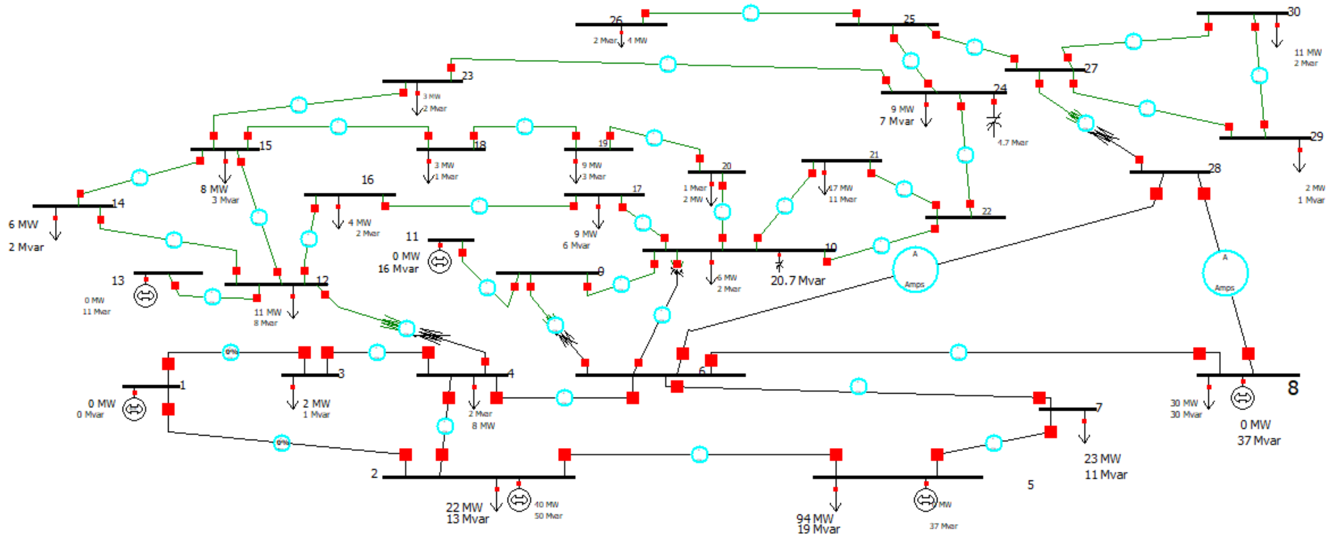

Figure 5. Single line diagram of IEEE 30-bus test system

The variable limits given in table IV were used as system constraints to solve the active power transmission loss objective function.

The total loads connected to the system, total generation and power losses for the IEEE-30-bus test system from the actual load flow study using Newton-Raphson method (base case) to observe the equality and inequality constraint limitation are presented below

$P_{LOAD} = 283.40$ $\quad$ $Q_{LOAD} = 126.20$

$P_{GEN} = 300.96$ $\quad$ $Q_{GEN} = 133.93$

$P_{LOSS} = 17.557$ $\quad$ $Q_{LOSS} = 67.69$

Table 4: IEEE 30-bus test system control variable limit

Control variables (p.u)	**Quantity**	**Minimum**	**Maximum**
Gen voltage V_{GEN}	6	0.95	1.10
Transformer tap ratio T	4	0.90	1.10
Shunt VAR compensator Q_c	2	0.00	0.20

The average convergence cure for the 30-bus test system TLBO algorithm power loss is shown in figure 4. The TLBO algorithm converged from 20-25 iterations.

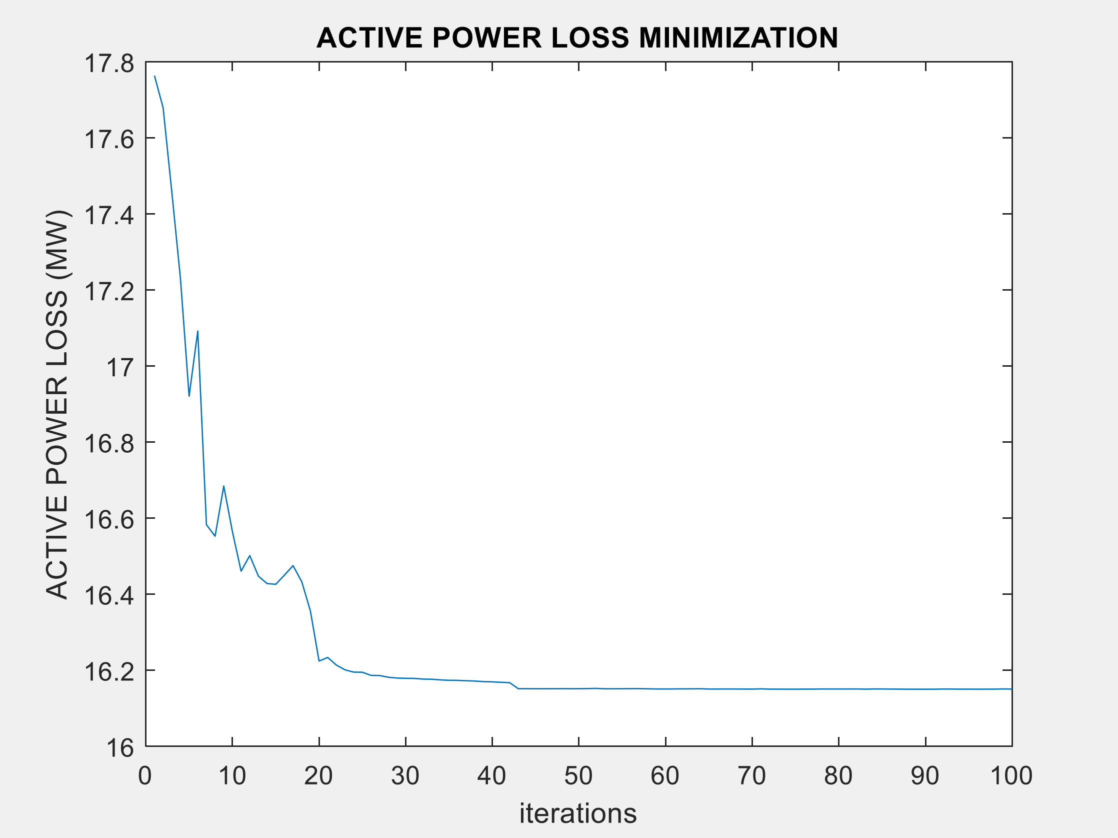

Figure 6: Convergence curve for 30-bus test system using TLBO

From the simulation results and convergence characteristics for solving ORPD on the IEEE 30-bus test system, the TLBO algorithm's real power loss outperformed the results obtained from selected methods in the literature.

Table 5: Minimum loss attained by selected methods of IEEE 30-bus system

Test system	**Best**	**Worst**	**Average**
DE [3]	16.4898	16.5194	16.4939
ABC [11]	16.2325	17.6930	16.5908
PSO [14]	16.1296	16.8190	16.5908
TLBO	**16.1503**	**17.6315**	**16.2752**

The optimal settings of control variables for IEEE 30-bus system is presented in table VI. It can be observed from the table that the control variables are restricted within their constraint limit.

Table 6: Control variables for various phases of optimization for IEEE 30-bus test system

Control variables	**Base case**	**TLBO (First phase)**	**TLBO (Final phase)**
V_{G1}	1.060	1.091	1.100
V_{G2}	1.045	1.074	1.0848
V_{G5}	1.010	1.010	1.0538
V_{G8}	1.010	1.035	1.059
V_{G11}	1.082	0.971	1.100
V_{G13}	1.071	1.099	1.100
T_{6-9}	0.980	0.9960	1.0699
T_{6-10}	0.970	1.0437	0.90
T_{4-12}	0.930	1.0460	1.0495
T_{27-28}	0.970	0.9435	0.9784
Q_{C10}	0.19	0.1816	0.0277
Q_{C24}	0.043	0.0200	0.20
P_loss	**17.557**	**17.207**	**16.1504**

Analysis in POWERWORLD

PowerWorld Simulator is a power system simulation package designed for solving power system analysis problems. It is interactive and graphical and can be used to explain power system operations for non-technical audiences

The optimal control variables are plugged into PowerWorld to visualize the losses and observe improvements in the system.

Base Case Analysis

With the base case values of the control variables, it can be observed that some of the transmission lines are working more than 75% of their rated value.

Table 7: Transmission lines above 75% of rated value for Base Case $\boldsymbol{P_{LOSS} = 18.13MW}$

Branch	**% of MVA**
1-2	175
1-3	88
3-4	83
2-5	82
4-6	73

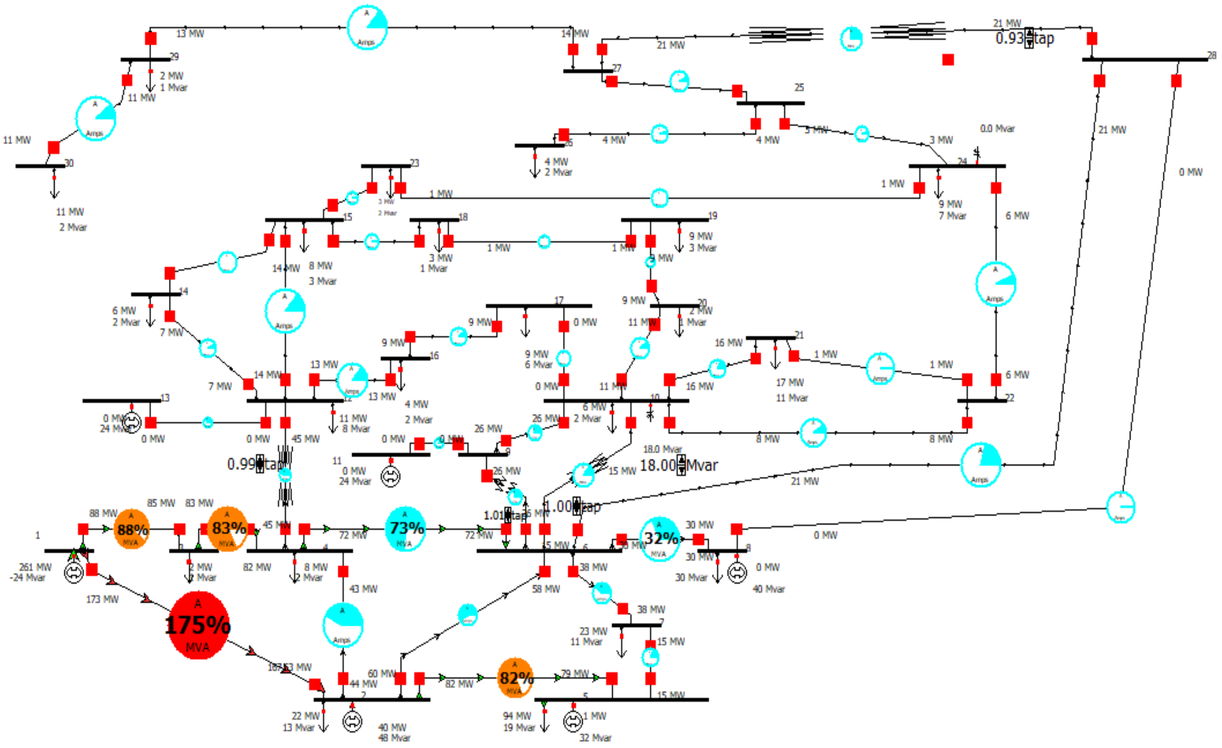

Figure 7: PowerWorld visualization of IEEE 30-bus test system Base case

First Phase Analysis

The optimal values obtained from the TLBO algorithm solved with MATLAB is plugged into PowerWorld to observe the practical representation of the algorithm. Some observations were made and are presented below:

i. The real power loss observed in PowerWorld is 17.36MW against the 17.207MW obtained from the TLBO algorithm

ii. There is a slight reduction in the overloaded transmission lines from what was observed in the base case in branch 1-2.

Table 8: Transmission lines above 75% of rated value for First Phase

Branch	**% of MVA**
1-2	173
1-3	88
3-4	83
2-5	83
4-6	75

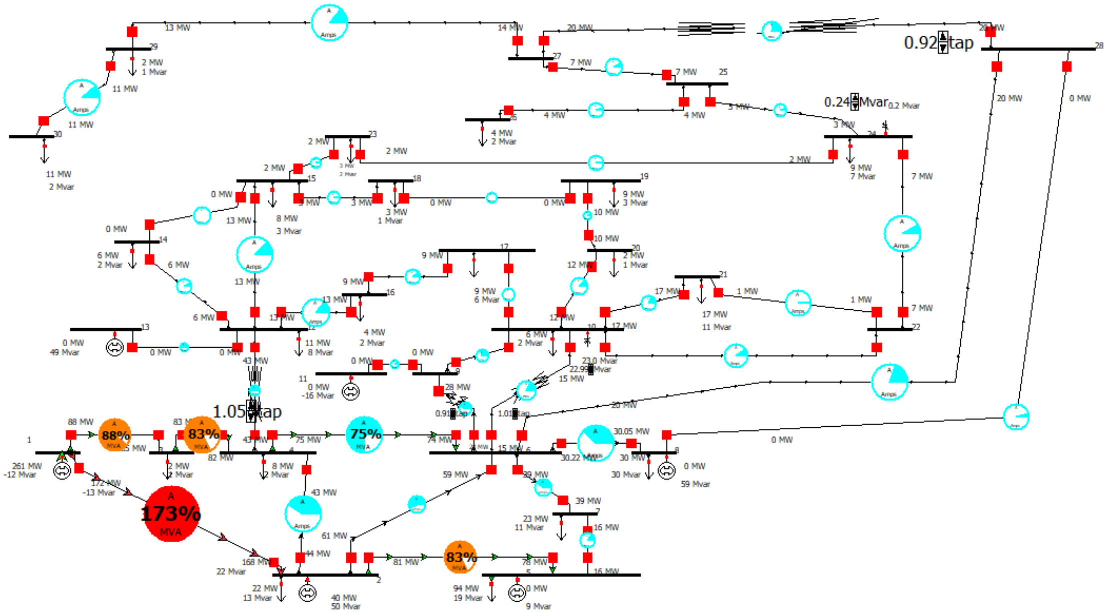

Figure 8: PowerWorld visualization of IEEE 30-bus test system First Phase

Final Phase Analysis

The final optimal values obtained from the TLBO algorithm solved with MATLAB is plugged into PowerWorld to observe the practical representation of the algorithm. Some observations were made and are presented below:

i. The real power loss observed in PowerWorld is 16.27MW against the 16.1504MW obtained from the TLBO algorithm.

ii. With the final control variables plugged in, there is better performance and slight reduction in the overloaded transmission line on branch 1-2 from 175% of rated MVA rating to 172%.

Table 9: Transmission lines above 75% of rated value for Final Phase

Branch	**% of MVA**
1-2	172
1-3	87
3-4	82
2-5	82
4-6	75

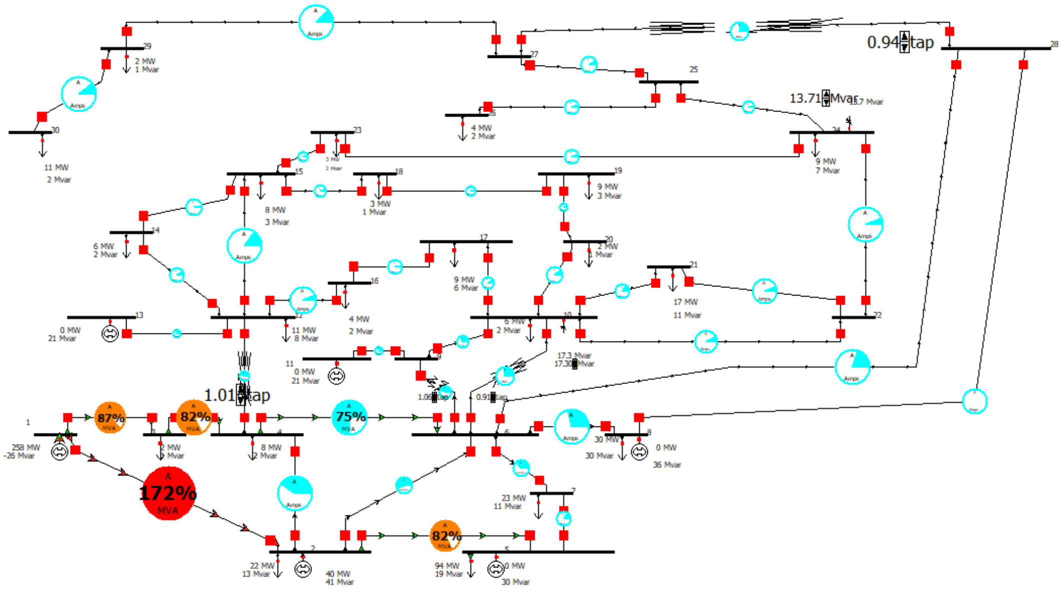

Figure 9: PowerWorld visualization of IEEE 30-bus test system Final Phase

Summary

Comparing the result of the TLBO algorithm and the PowerWorld simulator, there are slight difference in the results obtained as seen in table 10

Table 10: Power Loss comparison for the same optimal control variables

	TLBO **(Power Loss (MW))**	**PowerWorld** **(Power Loss (MW))**
Base Case	17.56	18.13
First Phase	17.207	17.36
Final Phase	16.15	16.27

The PowerWorld simulator shows a more realistic solution for practical application using the values predicted from the TLBO algorithm.

From the PowerWorld simulator, the result can be interpreted effectively.

i. It can be observed that some major transmission lines are overloaded as shown in figures 7, 8 and 9 and there is a slight improvement on the overloaded lines as we implement the final phase. These overloaded lines could be as a result of various factors;

    a. Large reactive power flow in the lines due to steady control of bus voltages within specified limits done by generators operating in AVR mode complemented by shunt capacitors and load tap changers in transformers.
    b. The power system is in peak load demand.

    If the overloading continues, the frequency of the power system starts failing endangering the power system stability and leading to voltage collapse. Several actions can be carried out to correct line overloads and reduce transmission losses;

    a. Generator output rescheduling: Decreasing a generation station relieves some transmission line overload but to maintain the power equilibrium other generation station output must be increased considering no additional transmission lines are being overloaded.
    b. Load shedding: It is a controlled process in which part of the load is dropped in order to balance the demand and the generated capacity. It involves disconnecting some circuits to prevent overload condition. This would allow line currents to be reduced and prevent voltage collapse

which may occur when the system tries to serve much more load than the voltage can support.

ii. To control the voltage within the upper and lower limits, it can be observed that the reactive power sources are modelled as automatic voltage regulators (AVRs) to keep the power system safe and efficient. Although it is essential to have reactive power, it is important to have the right amount. Too much and the power lines become overloaded and creates volatility on the network. Too little and efficiency decreases.

    a. When the reactive power at the generator is a negative value, the generator is absorbing reactive power to lower bus voltages. When the reactive power is a positive value, the generator is producing reactive power thereby increasing the voltage on a system.

iii. It can be observed from the PowerWorld solution that although generators 5, 8, 11 and 13 doesn’t provide any real power contribution to the power system, they are available for reactive power generation/ absorption and voltage control. The removal of any one of them could lead to voltage instability and increase in real power loss of the system.

Optimized Result

By correcting the overloaded lines, the real power losses on the transmission lines have been reduced to 7.37MW and the reactive power loss was 0 MVAR. This was achieved by rescheduling the output of the generators, adjusting the shunt capacitors and tap changer values.

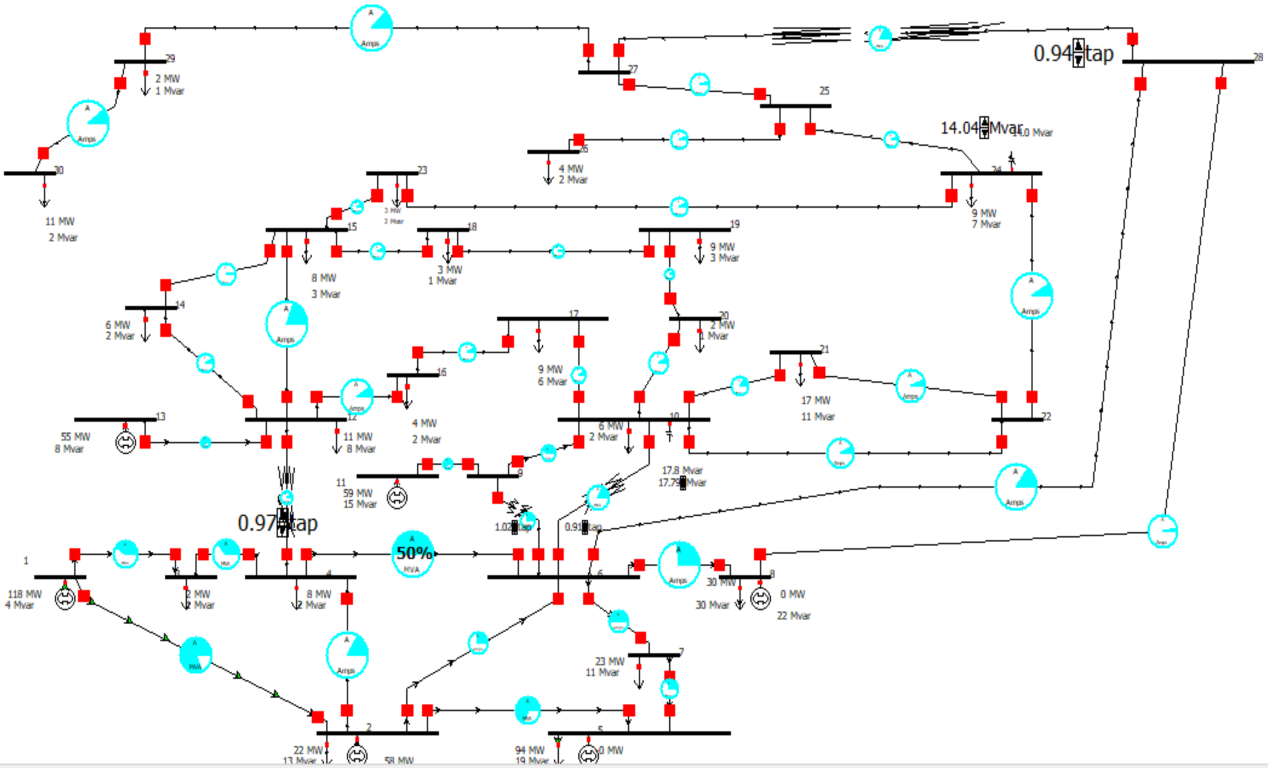

Figure 10: Optimized result

Chapter VI: Conclusion

The TLBO algorithm was evaluated and tested on the IEEE 30-bus test systems to solve the ORPD. Simulation results confirm the robustness and efficiency of the algorithm when compared with other metaheuristic algorithms and validated using PowerWorld. The simulation results show that TLBO method reduced the active power transmission line losses from 17.557MW to 16.1504MW (about 8.01% loss reduction). The simulation results show that the application of TLBO to ORPD is a good prediction model to obtain optimal values but the PowerWorld solution provides a realistic solution to solving the ORPD problem by showing areas where improvements need to be made and transmission lines that need to be corrected for overloading while keeping the control variables within their constraint limits. The simulation results from the PowerWorld shows a reduced active power transmission loss from 18.13MW to 16.27MW (about 10.26% loss reduction) for the same values used in the TLBO algorithm. By implementing corrections to the ORPD problem, an optimized result was obtained to be 7.30MW real power loss.

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Appendix A: Matlab Codes for Tlbo Algorithm (IEEE 30-BUS Test System)

```
%% TLBO Algorithm for solving Optimal Reactive Power Dispatch
%% NNEKA PRECIOUS NWOSU
%% DEPARTMENT OF ELECTRICAL ENGINEERING
%% ST CLOUD STATE UNIVERSITY

clear all;
clc;
tic
[baseMVA, bus, gen, branch]= loadcase(case_ieee30);
N=50;
miter=4;
nbr=size(branch,1);
nbus=size(bus,1);
  branch(:,9)=ones(nbr,1);

Control=[unifrnd(0.95, 1.1, N,6),unifrnd(0.90, 1.1, N,4), unifrnd(0.0, 0.2, N,2)]; % generate initial population

 for iter=1:miter
%

for i=1:N
    v1=Control(i,1);
    bus(1,8)=v1;  % bus voltage magnitude
    gen(1,6)=v1;  % generator voltage
    v2= Control(i,2);
    bus(2,8)=v2;
    gen(2,6)=v2;
    v5= Control(i,3);
    bus(5,8)=v5;
    gen(3,6)=v5;
    v8= Control(i,4);
    bus(8,8)=v8;
    gen(4,6)=v8;
    v11= Control(i,5);
    bus(11,8)=v11;
    gen(5,6)=v11;
    v13= Control(i,6);
    bus(13,8)=v13;
    gen(6,6)=v13;

    t1= Control(i,7); % tap 6-9
    branch(11,9)=t1;
    t2=Control(i,8); % tap 6-10
    branch(12,9)=t2;
    t3=Control(i,9); % tap 4-12
    branch(15,9)=t3;
    t4=Control(i,10); % tap 27-28
```

```
    branch(36,9)=t4;
    qc10=Control(i,11); % shunt capacitor 10
    bus(10,6)=qc10;
    qc24=Control(i,12);
    bus(24,6)=qc24;

 eval(['savecase(''case_ieee30_test', num2str(i), '.mat'', baseMVA, bus, gen, branch)']);
eval(['initial_results_',num2str(i),'=runpf(''case_ieee30_test',num2str(i),'.mat'')']);
eval(['initial_losses_',num2str(i),'=sum(real(get_losses(initial_results_',num2str(i),')))']);
%
% Penalty for bus voltage violation
bus_inf= bus(:,8);
for bus_num=1: nbus
    if bus_inf(bus_num)>1.10
        penalty_V1(bus_num)=10*(bus_inf(bus_num)-1.10)^2;
        bus_inf(bus_num)=1.10;
    elseif bus_inf(bus_num) <0.95
        penalty_V1(bus_num)=10*(bus_inf(bus_num)-0.95)^2;
        bus_inf(bus_num)=0.95;
    else
        penalty_V1(bus_num)=0;
    end
 end
 penalty_V1_violation= sum(penalty_V1);
%
% Penalty for tap position  violation
brch_inf= [branch(11,9); branch(12,9); branch(15,9); branch(36,9)];
for brch_num=1:4
    if brch_inf(brch_num)>1.10
        penalty_Tk(brch_num)=10*(brch_inf(brch_num)-1.10)^2;
        brch_inf(brch_num)=1.10;
    elseif brch_inf(brch_num) <0.90
        penalty_Tk(brch_num)=10*(brch_inf(brch_num)-0.90)^2;
        brch_inf(brch_num)=0.90;
    else
        penalty_Tk(brch_num)=0;
    end
end
penalty_Tk_violation= sum(penalty_Tk);

% Penalty for shunt violation
buus_inf= [bus(10,6); bus(24,6)];
for bus_num=1: size(buus_inf)
    if buus_inf(bus_num)>0.20
        penalty_Qc(bus_num)=10*(buus_inf(bus_num)-0.20)^2;
        buus_inf(bus_num)=0.20;
    elseif buus_inf(bus_num) <0.00
        penalty_Qc(bus_num)=10*(buus_inf(bus_num)-0.00)^2;
        buus_inf(bus_num)=0.02;
    else
```

```
        penalty_Qc(bus_num)=0;
    end
end
penalty_Qc_violation= sum(penalty_Qc);
% %%%%Objective function=sum ofactive power losses of the transmission lines
 losses(i)= eval(['initial_losses_', num2str(i)]); % sum of real power losses of all branches
% % augmented objective function
 obj_fun_initial(i)= losses(i)+ penalty_V1_violation + penalty_Tk_violation+ penalty_Qc_violation;
 end
% %
% %
%  %%%%%% Teacher's phase of TLBO
% %
 [n_row, n_col]=size(Control);
 r=rand(n_col,1);
 [min_objfunc, pos]= min(obj_fun_initial);
% %
%   %%%TLBO LOOP
%  figure('NumberTitle', 'off', 'Name', 'TLBO Algorithm for Optimal Reactive Power Dispatch')
%   title('ACTIVE POWER LOSS MINIMIZATION')
%  ylabel('ACTIVE POWER LOSS (MW)')
%  xlabel('iteration number')
%   grid on;
%  hold on;
 Ave_subjects= mean(Control);
% % % % for iter=1:100
   for m=1:n_col
  diff_mean(m)=r(m)*(Control(pos,m)-Ave_subjects(m));
  end
  new_Control= Control+diff_mean;
%
% % % Control= new_Control;

 for k=1:N
     % % % % Penalty for bus voltage violation
 bus_inf= new_Control(k,1:6);
 for bus_num=1: 6
    if bus_inf(bus_num)>1.10
        penalty_V1(bus_num)=10*(bus_inf(bus_num)-1.10)^2;
        bus_inf(bus_num)=1.10;
         new_Control(k,bus_num)=1.10;
    elseif bus_inf(bus_num) <0.95
        penalty_V1(bus_num)=10*(bus_inf(bus_num)-0.95)^2;
        bus_inf(bus_num)=0.95;
         new_Control(k,bus_num)=0.95;
     else
         penalty_V1(bus_num)=0;
     end
 end
 penalty_V1_violation= sum(penalty_V1);
%
```

```
% % Penalty for tap position  violation
 brch_inf= new_Control(k,7:10) ;
 for brch_num=1:4
     if brch_inf(brch_num)>1.10
         penalty_Tk(brch_num)=10*(brch_inf(brch_num)-1.10)^2;
         brch_inf(brch_num)=1.10;
         new_Control(k,6+bus_num)=1.10;
     elseif brch_inf(brch_num) <0.90
         penalty_Tk(brch_num)=10*(brch_inf(brch_num)-0.90)^2;
         brch_inf(brch_num)=0.90;
         new_Control(k,6+bus_num)=0.90;
     else
         penalty_Tk(brch_num)=0;
     end
 end
 penalty_Tk_violation= sum(penalty_Tk);
%
% Penalty for shunt violation
buus_inf= new_Control(k,11:12) ;
for bus_num=1: size(buus_inf)
    if buus_inf(bus_num)>0.20
        penalty_Qc(bus_num)=10*(buus_inf(bus_num)-0.20)^2;
        buus_inf(bus_num)=0.20;
        new_Control(k,10+bus_num)=0.20;
    elseif buus_inf(bus_num) <0.00
        penalty_Qc(bus_num)=10*(buus_inf(bus_num)-0.00)^2;
        buus_inf(bus_num)=0.02;
        new_Control(k,10+bus_num)=0.02;
    else
        penalty_Qc(bus_num)=0;
    end
end
penalty_Qc_violation= sum(penalty_Qc);

     v1n=new_Control(k,1);
     bus(1,8)=v1n;  % bus voltage magnitude
     gen(1,6)=v1n;  % generator voltage
     v2n= new_Control(k,2);
     bus(2,8)=v2n;
     gen(2,6)=v2n;
     v5n= new_Control(k,3);
     bus(5,8)=v5n;
     gen(3,6)=v5n;
     v8n= new_Control(k,4);
    bus(8,8)=v8n;
    gen(4,6)=v8n;
    v11n= new_Control(k,5);
    bus(11,8)=v11n;
    gen(5,6)=v11n;
    v13n= new_Control(k,6);
    bus(13,8)=v13n;
```

```
    gen(6,6)=v13n;
    t1n= new_Control(k,7); % tap 6-9
    branch(11,9)=t1n;
    t2n=new_Control(k,8); % tap 6-10
    branch(12,9)=t2n;
    t3n=new_Control(k,9); % tap 4-12
    branch(15,9)=t3n;
    t4n=new_Control(k,10); % tap 27-28
    branch(36,9)=t4n;

     qc10n=new_Control(k,11); % shunt capacitor 10
    bus(10,6)=qc10n;
    qc24n=new_Control(k,12);
    bus(24,6)=qc24n;
eval(['savecase(''case_ieee30_test', num2str(k), '.mat'', baseMVA, bus, gen, branch)']);
eval(['fin_results_',num2str(k),'=runpf(''case_ieee30_test',num2str(k),'.mat'')']);
eval(['fin_losses_',num2str(k),'=sum(real(get_losses(fin_results_',num2str(k),')))']);
%
 losses_temp(k)= eval(['fin_losses_', num2str(k)]);
obj_fun_temp(k)= losses_temp(k)+ penalty_V1_violation + penalty_Tk_violation+ penalty_Qc_violation;
 end
% %% update values of control variables and objective function based on fitness comparison
newer_Control= zeros(n_row,n_col);
obj_fun_final=zeros(1,n_row);
 for i=1:N
    if obj_fun_initial(i)<obj_fun_temp(i)
        newer_Control(i,:)= Control(i,:);
        obj_fun_final(i)= obj_fun_initial(i);
     else
         newer_Control(i,:)= new_Control(i,:);
        obj_fun_final(i)= obj_fun_temp(i);
     end
 end
% %% learners phase
 ra=rand(1,n_col);
%  j=randperm(N);
  for i=1:N
     j=randi(N);
     if j~=i

         if obj_fun_final(i)< obj_fun_final(j)
             newest_Control(i,:)= newer_Control(i,:)+ra.*(newer_Control(i,:)-newer_Control(j,:));
         else
             newest_Control(i,:)= newer_Control(i,:)+ra.*(newer_Control(j,:)-newer_Control(i,:));
         end
     end
  end

 for l=1:N
     % % % % Penalty for bus voltage violation
```

```
bus_inf= newest_Control(l,1:6);
for bus_num=1: 6
    if bus_inf(bus_num)>1.10
        penalty_V1(bus_num)=10*(bus_inf(bus_num)-1.10)^2;
        bus_inf(bus_num)=1.10;
        newest_Control(l,bus_num)=1.10;
    elseif bus_inf(bus_num) <0.95
        penalty_V1(bus_num)=10*(bus_inf(bus_num)-0.95)^2;
        bus_inf(bus_num) =0.95;
        newest_Control(l,bus_num)=0.95;
    else
        penalty_V1(bus_num)=0;
    end
end
penalty_V1_violation= sum(penalty_V1);

% Penalty for tap position  violation
brch_inf=newest_Control(l,7:10) ;
for brch_num=1:4
    if brch_inf(brch_num)>1.10
        penalty_Tk(brch_num)=10*(brch_inf(brch_num)-1.10)^2;
        brch_inf(brch_num)=1.10;
        newest_Control(l,6+brch_num)=1.10;
    elseif brch_inf(brch_num) <0.90
        penalty_Tk(brch_num)=10*(brch_inf(brch_num)-0.90)^2;
        brch_inf(brch_num)=0.90;
        newest_Control(l,6+brch_num)=0.90;
    else
        penalty_Tk(brch_num)=0;
    end
end
penalty_Tk_violation= sum(penalty_Tk);
% Penalty for shunt violation
buus_inf= newest_Control(l,11:12) ;
for bus_num=1:2
    if buus_inf(bus_num)>0.20
        penalty_Qc(bus_num)=10*(buus_inf(bus_num)-0.20)^2;
        buus_inf(bus_num)=0.20;
        newest_Control(l,10+bus_num)=0.20;
    elseif buus_inf(bus_num) <0.00
        penalty_Qc(bus_num)=10*(buus_inf(bus_num)-0.00)^2;
        buus_inf(bus_num)=0.02;
        newest_Control(l,10+bus_num)=0.02;
    else
        penalty_Qc(bus_num)=0;
    end
end
penalty_Qc_violation= sum(penalty_Qc);

    v1nn=newest_Control(l,1);
```

```
     bus(1,8)=v1nn;  % bus voltage magnitude
     gen(1,6)=v1nn;  % generator voltage
     v2nn= newest_Control(l,2);
     bus(2,8)=v2nn;
     gen(2,6)=v2nn;
     v5nn= newest_Control(l,3);
     bus(5,8)=v5nn;
     gen(3,6)=v5nn;
    v8nn= newest_Control(l,4);
    bus(8,8)=v8nn;
    gen(4,6)=v8nn;
    v11nn= newest_Control(l,5);
    bus(11,8)=v11nn;
    gen(5,6)=v11nn;
    v13nn= newest_Control(l,6);
    bus(13,8)=v13nn;
    gen(6,6)=v13nn;

    t1nn= newest_Control(l,7); % tap 6-9
    branch(11,9)=t1nn;
    t2nn=newest_Control(l,8); % tap 6-10
    branch(12,9)=t2nn;
    t3nn=newest_Control(l,9); % tap 4-12
    branch(15,9)=t3nn;
    t4nn=newest_Control(l,10); % tap 27-28
    branch(36,9)=t4nn;

    qc10nn=newest_Control(l,11); % shunt capacitor 10
    bus(10,6)=qc10nn;
    qc24nn=newest_Control(l,12);
    bus(24,6)=qc24nn;

eval(['savecase(''case_ieee30_test', num2str(l), '.mat'', baseMVA, bus, gen, branch)']);
eval(['final_results_',num2str(l),'=runpf(''case_ieee30_test',num2str(l),'.mat'')']);
eval(['final_losses_',num2str(l),'=sum(real(get_losses(final_results_',num2str(l),')))']);


losses_final(l)= eval(['final_losses_', num2str(l)]); % sum of real power losses of all branches;
%
 obj_fun_final(l)= losses_final(l)+ penalty_V1_violation + penalty_Tk_violation+ penalty_Qc_violation;
 end
for i=1:N
    if obj_fun_temp(i)<=obj_fun_final(i)
        most_new_Control(i,:)= newer_Control(i,:);
        objec_fun_final(i)= obj_fun_temp(i);
    else
        most_new_Control(i,:)= newest_Control(i,:);
        objec_fun_final(i)= obj_fun_final(i);
    end
end
```

```
 miniobj(iter)=min(objec_fun_final);
%
Control= most_new_Control;

 end

plot(miniobj)
ylabel('ACTIVE POWER LOSS (MW)');
xlabel('iterations')
title('ACTIVE POWER LOSS MINIMIZATION')
```

Appendix B: Results for Simulation using TLBO algorithm

Result of Base Case Simulation for IEEE 30 Bus Test Data

$P_{LOSS} = 17.56MW$

```
|     Bus Data                                                    |
===========================================================
==============================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.060    0.000*   260.96    -20.42       -         -
    2  1.045   -5.378     40.00     56.07     21.70     12.70
    3  1.021   -7.529       -         -        2.40      1.20
    4  1.012   -9.279       -         -        7.60      1.60
    5  1.010  -14.149      0.00     35.66     94.20     19.00
    6  1.011  -11.055       -         -         -         -
    7  1.003  -12.852       -         -       22.80     10.90
    8  1.010  -11.797      0.00     36.11     30.00     30.00
    9  1.051  -14.098       -         -         -         -
   10  1.045  -15.688       -         -        5.80      2.00
   11  1.082  -14.098      0.00     16.06       -         -
   12  1.057  -14.933       -         -       11.20      7.50
   13  1.071  -14.933      0.00     10.45       -         -
   14  1.043  -15.825       -         -        6.20      1.60
   15  1.038  -15.916       -         -        8.20      2.50
   16  1.045  -15.515       -         -        3.50      1.80
```

```
  17  1.040  -15.850       -         -        9.00       5.80
  18  1.028  -16.530       -         -        3.20       0.90
  19  1.026  -16.704       -         -        9.50       3.40
  20  1.030  -16.507       -         -        2.20       0.70
  21  1.033  -16.131       -         -       17.50      11.20
  22  1.034  -16.116       -         -         -          -
  23  1.027  -16.307       -         -        3.20       1.60
  24  1.022  -16.483       -         -        8.70       6.70
  25  1.018  -16.055       -         -         -          -
  26  1.000  -16.474       -         -        3.50       2.30
  27  1.024  -15.530       -         -         -          -
  28  1.007  -11.677       -         -         -          -
  29  1.004  -16.759       -         -        2.40       0.90
  30  0.992  -17.642       -         -       10.60       1.90
                        --------  --------  --------  --------
               Total:    300.96    133.93    283.40    126.20

================================================================
================================
|     Branch Data                                              |
================================================================
================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2    173.31    -24.70   -168.09     34.47     5.213     15.61
   2      1      3     87.65      4.28    -84.54      2.65     3.108     11.36
```

3	2	4	43.65	4.75	-42.63	-5.54	1.018	3.10
4	3	4	82.14	-3.85	-81.29	5.44	0.856	2.46
5	2	5	82.36	2.78	-79.42	5.17	2.943	12.36
6	2	6	60.38	1.37	-58.43	0.58	1.946	5.90
7	4	6	72.13	-15.91	-71.50	17.19	0.632	2.20
8	5	7	-14.78	11.49	14.95	-13.13	0.169	0.43
9	6	7	38.13	-2.78	-37.75	2.23	0.381	1.17
10	6	8	29.56	-7.20	-29.46	6.66	0.108	0.38
11	6	9	27.72	-8.09	-27.72	9.72	0.000	1.62
12	6	10	15.84	0.19	-15.84	1.10	0.000	1.28
13	9	11	-0.00	-15.60	0.00	16.06	-0.000	0.46
14	9	10	27.72	5.88	-27.72	-5.08	0.000	0.80
15	4	12	44.19	14.41	-44.19	-9.72	0.000	4.69
16	12	13	0.00	-10.32	-0.00	10.45	0.000	0.13
17	12	14	7.86	2.40	-7.78	-2.25	0.074	0.15
18	12	15	17.89	6.79	-17.67	-6.36	0.217	0.43
19	12	16	7.24	3.35	-7.19	-3.24	0.054	0.11
20	14	15	1.58	0.65	-1.58	-0.64	0.006	0.01
21	16	17	3.69	1.44	-3.68	-1.41	0.008	0.03
22	15	18	6.02	1.60	-5.98	-1.52	0.039	0.08
23	18	19	2.78	0.62	-2.77	-0.61	0.005	0.01
24	19	20	-6.73	-2.79	6.74	2.83	0.017	0.03
25	10	20	9.03	3.71	-8.94	-3.53	0.082	0.18
26	10	17	5.33	4.43	-5.32	-4.39	0.014	0.04
27	10	21	15.79	10.01	-15.67	-9.77	0.111	0.24
28	10	22	7.62	4.60	-7.57	-4.49	0.053	0.11

```
29   21   22   -1.83   -1.43    1.83    1.43   0.001    0.00
30   15   23    5.04    2.91   -5.00   -2.84   0.031    0.06
31   22   24    5.74    3.06   -5.69   -2.99   0.046    0.07
32   23   24    1.80    1.24   -1.80   -1.23   0.006    0.01
33   24   25   -1.21    2.01    1.22   -2.00   0.010    0.02
34   25   26    3.54    2.37   -3.50   -2.30   0.045    0.07
35   25   27   -4.76   -0.37    4.79    0.42   0.024    0.05
36   28   27   18.07    5.04  -18.07   -3.75   0.000    1.29
37   27   29    6.19    1.67   -6.10   -1.51   0.086    0.16
38   27   30    7.09    1.66   -6.93   -1.36   0.162    0.31
39   29   30    3.70    0.61   -3.67   -0.54   0.034    0.06
40    8   28   -0.54   -0.54    0.55   -3.80   0.002    0.01
41    6   28   18.67    0.11  -18.62   -1.23   0.058    0.20
                                           --------  --------
                                  Total:    17.557     67.69
```

Result of First Case Simulation for IEEE 30 Bus Test Data With $\boldsymbol{P_{LOSS} = 17.207MW}$

```
Bus Data                                             |
==================================================
=========================
 Bus    Voltage        Generation          Load
  #   Mag(pu) Ang(deg)  P (MW)  Q (MVAr)  P (MW)  Q (MVAr)
----- ------- --------  --------  --------  --------  --------
   1  1.091   0.000*   260.61   -16.10       -        -
   2  1.074  -5.039     40.00    74.87    21.70    12.70
```

3	1.050	-7.092	-	-	2.40	1.20
4	1.041	-8.739	-	-	7.60	1.60
5	1.010	-13.066	0.00	10.91	94.20	19.00
6	1.029	-10.291	-	-	-	-
7	1.013	-11.951	-	-	22.80	10.90
8	1.035	-11.134	0.00	58.81	30.00	30.00
9	1.006	-13.315	-	-	-	-
10	0.998	-15.007	-	-	5.80	2.00
11	0.971	-13.315	0.00	-16.20	-	-
12	1.038	-14.909	-	-	11.20	7.50
13	1.099	-14.909	0.00	48.61	-	-
14	1.019	-15.784	-	-	6.20	1.60
15	1.011	-15.749	-	-	8.20	2.50
16	1.013	-15.172	-	-	3.50	1.80
17	0.997	-15.313	-	-	9.00	5.80
18	0.994	-16.232	-	-	3.20	0.90
19	0.987	-16.316	-	-	9.50	3.40
20	0.989	-16.048	-	-	2.20	0.70
21	0.987	-15.489	-	-	17.50	11.20
22	0.988	-15.473	-	-	-	-
23	0.995	-15.976	-	-	3.20	1.60
24	0.982	-15.910	-	-	8.70	6.70
25	0.997	-15.626	-	-	-	-
26	0.978	-16.063	-	-	3.50	2.30
27	1.014	-15.163	-	-	-	-
28	1.024	-10.927	-	-	-	-

```
  29  0.994  -16.416       -         -        2.40      0.90
  30  0.982  -17.316       -         -       10.60      1.90
                        --------  --------  --------  --------
               Total:    300.61    160.89    283.40    126.20

================================================================
================================
|     Branch Data                                            |
================================================================
================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2    172.79    -21.69   -167.92     30.10     4.874     14.60
   2      1      3     87.82      5.60    -84.86      0.52     2.954     10.80
   3      2      4     44.04      5.48    -43.06     -6.59     0.987      3.01
   4      3      4     82.46     -1.72    -81.65      3.14     0.814      2.34
   5      2      5     81.35     18.28    -78.47    -10.72     2.882     12.11
   6      2      6     60.82      8.30    -58.90     -6.62     1.917      5.82
   7      4      6     73.09     10.23    -72.49     -9.11     0.600      2.09
   8      5      7    -15.73      2.62     15.84     -4.42     0.118      0.30
   9      6      7     39.04      5.93    -38.64     -6.48     0.396      1.22
  10      6      8     30.10    -25.65    -29.93     25.30     0.175      0.61
  11      6      9     26.95     26.70    -26.95    -24.02     0.000      2.68
  12      6     10     15.29      7.65    -15.29     -6.13     0.000      1.51
  13      9     11      0.00     16.78     -0.00    -16.20    -0.000      0.58
  14      9     10     26.95      7.24    -26.95     -6.39     0.000      0.85
```

15	4	12	44.01	-8.38	-44.01	13.41	0.000	5.03
16	12	13	0.00	-45.87	-0.00	48.61	0.000	2.74
17	12	14	8.08	3.68	-7.99	-3.49	0.090	0.19
18	12	15	17.81	11.82	-17.53	-11.27	0.281	0.55
19	12	16	6.93	9.45	-6.81	-9.20	0.121	0.25
20	14	15	1.79	1.89	-1.77	-1.88	0.014	0.01
21	16	17	3.31	7.40	-3.27	-7.28	0.034	0.12
22	15	18	6.30	4.93	-6.23	-4.79	0.067	0.14
23	18	19	3.03	3.89	-3.02	-3.86	0.016	0.03
24	19	20	-6.48	0.46	6.50	-0.43	0.015	0.03
25	10	20	8.77	0.43	-8.70	-0.27	0.072	0.16
26	10	17	5.74	-1.45	-5.73	1.48	0.011	0.03
27	10	21	14.90	8.27	-14.80	-8.05	0.101	0.22
28	10	22	7.03	3.47	-6.98	-3.38	0.045	0.09
29	21	22	-2.70	-3.15	2.71	3.15	0.002	0.00
30	15	23	4.80	5.72	-4.74	-5.61	0.054	0.11
31	22	24	4.28	0.22	-4.26	-0.19	0.022	0.03
32	23	24	1.54	4.01	-1.52	-3.96	0.025	0.05
33	24	25	-2.92	-2.53	2.95	2.58	0.029	0.05
34	25	26	3.55	2.37	-3.50	-2.30	0.047	0.07
35	25	27	-6.50	-4.95	6.57	5.09	0.074	0.14
36	28	27	19.86	10.23	-19.86	-8.44	0.000	1.79
37	27	29	6.19	1.67	-6.10	-1.51	0.088	0.17
38	27	30	7.10	1.67	-6.93	-1.36	0.165	0.31
39	29	30	3.70	0.61	-3.67	-0.54	0.034	0.06
40	8	28	-0.07	3.51	0.09	-7.98	0.020	0.06

```
 41    6    28    20.02     1.11    -19.95    -2.25    0.065     0.23
                                            --------  --------
                                    Total:    17.207     71.18
```

Result of Final Phase Simulation for IEEE 30 Bus Test Data With $P_{LOSS} = 16.1504MW$

```
 Bus Data                                             |
=================================================================
======================
 Bus     Voltage         Generation           Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)  P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.100    0.000*   259.55    -26.49      -        -
    2  1.085   -4.941     40.00     41.02    21.70    12.70
    3  1.072   -7.062       -         -        2.40     1.20
    4  1.066   -8.689       -         -        7.60     1.60
    5  1.051  -13.016      0.00     32.01    94.20    19.00
    6  1.057  -10.264       -         -        -        -
    7  1.048  -11.880       -         -      22.80    10.90
    8  1.058  -10.973      0.00     41.33    30.00    30.00
    9  1.042  -13.386       -         -        -        -
   10  1.041  -14.953       -         -       5.80     2.00
   11  1.100  -13.386      0.00     30.59      -        -
   12  1.049  -14.437       -         -      11.20     7.50
   13  1.100  -14.437      0.00     40.28      -        -
   14  1.034  -15.297       -         -       6.20     1.60
   15  1.030  -15.355       -         -       8.20     2.50
```

```
  16  1.038  -14.929       -         -        3.50       1.80
  17  1.035  -15.160       -         -        9.00       5.80
  18  1.022  -15.916       -         -        3.20       0.90
  19  1.020  -16.055       -         -        9.50       3.40
  20  1.025  -15.838       -         -        2.20       0.70
  21  1.028  -15.385       -         -       17.50      11.20
  22  1.029  -15.366       -         -         -         -
  23  1.021  -15.641       -         -        3.20       1.60
  24  1.017  -15.670       -         -        8.70       6.70
  25  1.025  -15.317       -         -         -         -
  26  1.007  -15.731       -         -        3.50       2.30
  27  1.039  -14.833       -         -         -         -
  28  1.053  -10.850       -         -         -         -
  29  1.019  -16.026       -         -        2.40       0.90
  30  1.008  -16.882       -         -       10.60       1.90
                      --------  --------  --------  --------
              Total:    299.55    158.74    283.40    126.20

================================================================
======================
|     Branch Data                                               |
================================================================
======================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2    171.82    -23.85   -167.07     31.78     4.753     14.23
   2      1      3     87.73     -2.64    -84.86      8.33     2.875     10.51
```

3	2	4	43.22	-3.05	-42.32	1.55	0.905	2.76
4	3	4	82.46	-9.53	-81.67	10.84	0.790	2.27
5	2	5	81.86	2.01	-79.17	4.55	2.696	11.33
6	2	6	60.29	-2.42	-58.49	3.57	1.794	5.45
7	4	6	75.08	0.45	-74.49	0.60	0.591	2.05
8	5	7	-15.03	8.46	15.17	-10.37	0.132	0.33
9	6	7	38.32	-0.28	-37.97	-0.53	0.351	1.08
10	6	8	29.87	-11.34	-29.77	10.71	0.108	0.38
11	6	9	26.97	-24.80	-26.97	27.66	0.000	2.86
12	6	10	18.07	30.42	-18.07	-25.42	0.000	4.99
13	9	11	0.00	-28.98	-0.00	30.59	0.000	1.61
14	9	10	26.97	1.32	-26.97	-0.58	0.000	0.74
15	4	12	41.30	-14.44	-41.30	19.27	-0.000	4.84
16	12	13	0.00	-38.40	-0.00	40.28	0.000	1.88
17	12	14	7.51	2.37	-7.44	-2.23	0.069	0.14
18	12	15	16.55	6.45	-16.36	-6.08	0.190	0.37
19	12	16	6.04	2.80	-6.00	-2.72	0.038	0.08
20	14	15	1.24	0.63	-1.23	-0.63	0.004	0.00
21	16	17	2.50	0.92	-2.50	-0.91	0.003	0.01
22	15	18	5.39	1.36	-5.36	-1.29	0.031	0.06
23	18	19	2.16	0.39	-2.15	-0.39	0.003	0.01
24	19	20	-7.35	-3.01	7.37	3.05	0.021	0.04
25	10	20	9.66	3.96	-9.57	-3.75	0.094	0.21
26	10	17	6.52	4.94	-6.50	-4.89	0.020	0.05
27	10	21	15.58	10.32	-15.47	-10.08	0.112	0.24
28	10	22	7.49	4.80	-7.43	-4.69	0.053	0.11
29	21	22	-2.03	-1.12	2.03	1.12	0.001	0.00
30	15	23	4.01	2.85	-3.99	-2.80	0.023	0.05

31	22	24	5.40	3.57	-5.35	-3.50	0.046	0.07
32	23	24	0.79	1.20	-0.78	-1.20	0.003	0.01
33	24	25	-2.56	-1.07	2.58	1.10	0.014	0.02
34	25	26	3.54	2.37	-3.50	-2.30	0.044	0.07
35	25	27	-6.12	-3.46	6.17	3.56	0.051	0.10
36	28	27	19.45	8.44	-19.45	-6.88	-0.000	1.56
37	27	29	6.19	1.66	-6.10	-1.50	0.084	0.16
38	27	30	7.09	1.65	-6.93	-1.36	0.157	0.30
39	29	30	3.70	0.60	-3.67	-0.54	0.033	0.06
40	8	28	-0.23	0.61	0.24	-5.37	0.005	0.02
41	6	28	19.75	1.83	-19.69	-3.07	0.060	0.21

-------- --------

Total: 16.1504 71.25

Appendix C: Y-Bus Matrix Formulation

The figure below shows the schematic representation for a 3- bus system between bus i and j.

The series impedance is given by

$$z_{ij} = r_{ij} + x_{ij} \tag{C.1.1}$$

Y is admittance matrix which indicates the transmission line parameters. The Admittance Y_{ij} is a measure of how easily a circuit or device will allow a current to flow. The Y matrix is a data requirement needed to formulate a power flow study.

$$Y_{ij} = {}^{1}/_{Z_{ij}} \tag{C.1.2}$$

The Admittance between the bus in consideration and another bus can be described by

$$y_{ij} = g_{ij} + jb_{ij} \tag{C.1.3}$$

It is important to note that y_{ij} is non-zero only when there is a physical connection between 2 or more buses.

Each y_{ij} defines one element of N X N matrix

$$Y = \begin{bmatrix} Y_{11} & \cdots & Y_{1N} \\ \vdots & \ddots & \vdots \\ Y_{N1} & \cdots & Y_{NN} \end{bmatrix} \tag{C.1.4}$$

To illustrate the admittance matrix of the 3 -bus network

$$Y = \begin{matrix} y_1 + y_{12} + y_{13} & -y_{12} & -y_{13} \\ -y_{12} & y_2 + y_{12} + y_{23} & -y_{23} \\ -y_{13} & -y_{23} & y_3 + y_{13} + y_{23} \end{matrix} \tag{C.1.5}$$

$$Y_{ij} = \begin{cases} y_i + \sum_{i \neq j} y_{ij} & if\ i = j \\ -y_{ij} & if\ i \neq j \end{cases} \tag{C.1.6}$$

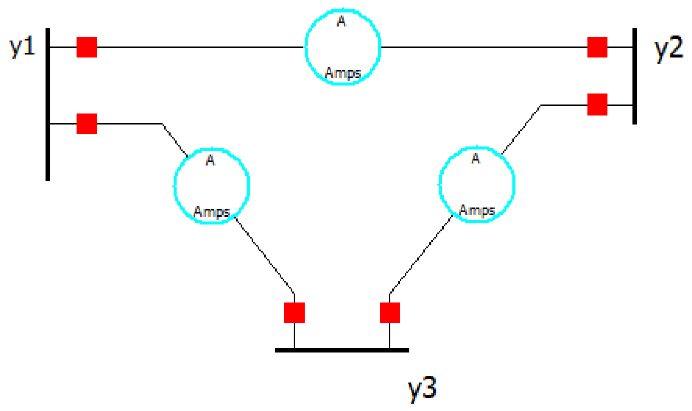

Figure 11: 3-bus network to illustrate Y-matrix formulation

The Y-matrix diagonal elements Y_{11}, Y_{22}, Y_{NN} are called self-admittance at the nodes and each equals the sum of all the admittances terminating on the node identified by the repeated subscripts.

The other admittances are mutual admittances of the nodes and equals the negative of the sum of all the admittances connected directly between the nodes identified by the double subscript. The admittance matrix is typical symmetric $y_{ij} = y_{ji}$

Appendix D: Net Power Injected into A Bus (P_i)

$$P_{Gi} - P_{Di} - P_i = 0 \tag{C.2.1}$$

$$Q_{Gi} - \; Q_{Di} - Q_i = 0 \tag{C.2.2}$$

For a 'N' bus system, the current injection into any bus i can be expressed as

$$I_i = \sum_{j=1}^{N} Y_{ij} V_j \tag{C.2.3}$$

Where Y_{ij} are admittance matrix elements

$$\begin{matrix} I_1 \\ \vdots \\ I_N \end{matrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1N} \\ \vdots & \ddots & \vdots \\ Y_{N1} & \cdots & Y_{NN} \end{bmatrix} \begin{matrix} V_1 \\ \vdots \\ V_N \end{matrix} \tag{C.2.4}$$

Complex power injected at bus 'i' is given by

$$S_i = V_i I_i^* \tag{C.2.5}$$

$$S_i = V_i \left(\sum_{j=1}^{N} Y_{ij} V_j \right)^* \tag{C.2.6}$$

$where * is\ the\ conjugate$

$V_i\ and\ V_j$ are phasors having magnitude and phase angles such that

$$V_i = |V_i| \angle \delta_i \tag{C.2.7}$$

$$V_j = |V_j| \angle \delta_j \tag{C.2.8}$$

Y_{ij} is complex and $G_{ij} and\ B_{ij}$ are the real and imaginary parts of the admittance matrix element Y_{ij} such that

$$Y_{ij} = = G_{ij} + jB_{ij} \tag{C.2.9}$$

We may rewrite equation (C.2.6) as

$$S_i = V_i \left(\sum_{j=1}^{N} Y_{ij} V_j \right)^* = |V_i| \angle \delta_i \sum_{j=1}^{N} (G_{ij} + jB_{ij})^* \;\; |V_j| \angle {\delta_j}^*$$

$$= |V_i| \angle \delta_i \sum_{j=1}^{N} (\, G_{ij} - jB_{ij})(|V_j| \angle -\delta_j)$$

$=\sum_{j=1}^{N}(|V_i||V_j|\angle(\delta_i-\delta_j)(G_{ij}-jB_{ij})$ (C.2.10)

From Euler relation, a phasor can be expressed as complex function of sinusoids, i.e.

$$V=|V|\angle\delta=|V|(cos\delta+jsin\delta)$$

We may rewrite equation (C.2.10) as

$S_i=\sum_{j=1}^{N}(|V_i||V_j|(\cos(\delta_i-\delta_j)+jsin((\delta_i-\delta_j))(G_{ij}-jB_{ij})$ (C.2.11)

If we perform the algebraic multiplication of the two terms inside the parentheses of equation (C.2.11) and collect real and imaginary parts and recall that $S_i=P_i+jQ_i$, we can express equation (C.2.11) as two equations, one for the real part P_i and one for the imaginary part Q_i according to

$P_i=\sum_{j=1}^{N}|V_i||V_j|(G_{ij}cos(\delta_i-\delta_j)+B_{ij}sin(\delta_i-\delta_j)$

$Q_i=\sum_{j=1}^{N}|V_i||V_j|(G_{ij}cos(\delta_i-\delta_j)-B_{ij}sin(\delta_i-\delta_j)$ (C.2.12)