KASDI MERBAH UNIVERSITY OUARGLA
Faculty of Applied Sciences
Department of Electrical Engineering

Academic Master Memory
Field: Science and Technology
Branch: Electrotechnics
Specialty: Electrical networks

Presented by :

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Theme:

Application of Meta-Heuristic Algorithm for Finding the Best Solution for the Optimal Power Flow Problem

Publicly defended on: 06/06/2024

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Academic year 2023/2024

ملخص

تعرض هذه الأطروحة دراسة التدفق الطاقة الكهربائية الأمثل متعدد الأهداف. لبلوغ الأهداف اقتراحنا طريقة التحسين القائم على التعلم والتعليم. تم تطبيق هذه الطريقة على نظام اختبار 30 عقدة ودراسة عدة أهداف مثل تقنين تكلفة الوقود، التقليل من انبعاث الغازات السامة، انحراف الجهد، استقرار الجهد والتقليل من الضياع في الاستطاعات في الشبكة الكهربائية. تمت دراسة حالات التوزيع الأمثل للطاقة أحادية الهدف والمحصلة المرجحة، تم تحليل نتائج المحاكاة ومقارنتها بأحدث الدراسات حول المشكلة.

الكلمات المفتاحية : التوزيع الأمثل للطاقة، التوزيع الاقتصادي، خوارزميات التحسين، تقنين تكلفة الوقود، التقليل من الضياع في الاستطاعات.

Abstract

This thesis, a teaching learning based optimization TLBO approach is applied to solve the problem of optimal power flow (OPF) incorporating distributed generation DG with five different objective functions that reflect fuel cost, emissions, voltage deviation improvement, voltage stability and power losses minimization. The formulation of the OPF problem incorporating DG with five different objective functions is introduced in this thesis. Then, the suggested TLBO technique is employed to solve this problems by converting the multi-objective function into a single objective function using price and weighting factors. In addition, the scalability of the proposed TLBO is tested. To prove the effectiveness of the proposed TLBO technique, it is applied to standard IEEE 30-bus test system. The obtained results of different scenarios using the proposed TLBO method are compared with those obtained using other published methods in the literature. The comparisons with other published methods show the superiority of the proposed TLBO algorithm over other methods with different complexities.

Keywords: Optimal power flow, economic dispatch, optimization methods, fuel cost minimization, power losses minimization, TLBO.

Résumé

Cette thèse présente l'application de la méthode d'optimisation basée sur l'enseignement-apprentissage, la méthode suggérée est appliquée pour résoudre le problème de la répartition optimale de puissances (OPF) intégrant des sources d'énergie renouvelables (RES) avec cinq fonctions objectives différentes qui reflètent le coût du production, les émissions, l'amélioration de l'écart de tension, maximisation de la stabilité de la tension et la minimisation des pertes de puissance. La formulation du problème OPF intégrant les RES avec cinq fonctions objectives différentes est introduite dans cette thèse. Ensuite, le TLBO proposé est utilisé pour résoudre ce problème en le convertissant en une seule fonction objective en utilisant les coéfficients de prix et de pondération (poids). De plus, l'évolutivité du TLBO proposé est testée. Pour prouver l'efficacité de la technique TLBO, cette dernière est appliquée au système standard IEEE 30-JB. Les résultats obtenus de différents scénarios utilisant la méthode TLBO sont comparés à ceux obtenus en utilisant d'autres méthodes publiées dans la littérature. Les comparaisons avec d'autres méthodes publiées montrent la supériorité de l'algorithme TLBO sur d'autres méthodes de complexité différente.

Mots clés : Répartition optimale de puissance, dispatching économique, méthodes d'optimisation, minimisation de coût du combustible, TLBO.

Dedication

We would like to dedicate this humble work to our dear parents, for all their sacrifices, their love, their tenderness, their support and their prayers throughout our studies, To all those who have contributed from close to far to make this project possible, we say thank you.

ACKNOWLEDGMENT

In the name of ***Allah****, the most gracious, the most merciful all praise is to Almighty Allah for having guided me all over my life. Acknowledgement is due to Kasdi Merbah Ouargla University for the great support to this work.*

My deep appreciation is reserved for thesis advisor Prof. ***BOUDJELLA Houari*** *for his guidance, valuable time and attention he devoted throughout the course of this work. Thanks are also due to jury commission members, Mr.* ***AYAD Ahmed Nour El Islam*** *and* ***LAROUCI Benyekhlef*** *to assess our master thesis and their interest, attention and suggestions.*

I wish also to thank all other parties who has contributed to support me in this work My great appreciations are also due to all members of my family and to friends who give me the self-confidence to face the challenge.

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Nomenclature

Acronyms :

OPF	Optimal Power Flow
PSP	Particle Swarm Optimization
ML	Machine Learning
RG	Reduced Gradient
CG	Conjugate Gradient
GRG	Generalized Reduced Gradient
GA	Genetic Algorithm
ACO	Ant Colony Optimization
M2 OBA	Must-have Multi-objective Bee method
DQLF	the Decoupled Quadratic Load Flow
EGA	the Enhanced Genetic Algorithm
FACTS	Flexible Alternating Current Transmission Systems
FBICLPSO	Fuzzy-Based Improvised Comprehensive Learning Particle Swarm Optimization
MBICLPSO	Multi-Objective Particle Swarm Optimization

Sets :

P_i	Active power generated by unit i
P_D	Power demand
P_L	Power losses
F_i	Fuel cost function
F_t	Total cost function
E_t	Quantitative function of emission
a_i, b_i, c_i, d_i	Coefficients cost of generator i

e_i, f_i	Coefficients cost of generator i corresponding of valve point effect
αi,βi ,γi ,ωi ,μi	Coefficients of the second generator emission function
$Pmini$,$Pmaxi$	Minimum and maximum active power of second generator
$Qmini$,$Qmaxi$	Minimum and maximum reactive power of second generator
$Vmini$,$Vmaxi$	Second generator minimum and maximum voltage
$VminLp$,$VmaxLp$	Minimal and maximum voltage of load bus
B_{ij}	Matrix of B Kron’s coefficient
N	Total number of bars sets in the network.
N_g	Number of power generators
NL	Number of load bus
nl	Number of transmission lines
N_C	Number of Compensator shunt
N_T	Number of Transformers
Std. Dev	Standard Deviation
δ	Voltage angle
$s.\ c$	Under constraints
$c.\ s$	Additional constraints
x	Status vector
u	Control variable vector
$g(x,u)$	Equality constraints
$h(x,u)$	Inequality constraints
T_j	Report of the controller supporting the transformer
Q_{Ck}	Reactive power injected by hunts
$QminCk$,$QmaxCk$	Minimum and maximum reactive powers of shunts compensators

Nomenclature

$faug$	Augmented Lens Function
fppenalty	Penalty Function
VD	Voltage Deviation
Y_{LL}, Y_{LG}, Y_{GL} et Y_{GG}	Y_{bus} admittance matrix partial matrices
$Gq(ij)$	Conductivity of the branch q connecting the bar sets I and j
$Bq(ij)$	Suspension of the branch q connecting the bar sets I and j.
$x^{min}{}_i$, $xmax_i$	Minimum and maximum limits on dependent variable x
$f_1(x,u)$	Fuel cost function
$f_2(x,u)$	NOx toxic gas emission function
$f_3(x,u)$	Voltage deviation function
$f_4(x,u)$	Voltage stability function
$f_5(x,u)$	Active Power Loss Function
$f_6(x,u)$	Reactive Power Loss Function

General Introduction

In last decade, the optimal power flow (OPF) problem has a significant role in the operation and planning of the modern power system [1]. OPF is employed to adjust the parameters of different control variables to attain the required objective function, normally are minimizing the total operating cost of generating units and/or emission of it, to meet the required demand load, while satisfying the certain of equality and inequality constraints [2].

The OPF is formulated as single or multi-objective problem of minimizing fuel cost, emission, transmission loss, voltage deviation etc. Nowadays, renewable energy sources (RES) (i.e. Solar systems, wind energy and hydro power generators) contribute in reducing the transmission power losses, improving the reliability and quality of power system.

Various optimization techniques are employed in literature to solve the OPF or OPF with emission problems with or without renewable sources. The conventional methods such as Gradient's method, quadratic programming, non-linear programming and interior point methods have been employed in literature to solve OPF problem. These methods suffer from some downsides such as trapping in the local minima, curse of dimensionality, some theoretical assumptions which do not guarantee to get the global optimum solution [3].

In general, the OPF problem is non-smooth, non-convex and non-differentiable objective functions. Therefore, it is very important to develop new methods to get the global optimum solution of OPF problem especially when the emission objective function is considered. Consequently, various heuristic algorithms are used to solve the OPF problem.

In this thesis, a teaching learning based optimization (TLBO) algorithm is proposed to get a better solution of the OPF problem with RES and different objective functions in comparison with other methods.

The major contributions of the thesis can be summarized as below:

In Chapter 1, a short comprehensive review and problems formulations of OPF is involved

In Chapter 2, we propose the TLBO approach to solve OPF problems without and with RES.

In Chapter 3, the proposed TLBO is tested and evaluated using IEEE 30-bus system. The results of TLBO are then compared with recently published methods.

I

OPF: Short review and problems formulations

I.1 INTRODUCTION

The Optimal Power Flow (OPF) Is an Important technique for ensuring that power systems operate economically and securely. The goal of addressing the OPF Issue Is to maximize a specific objective function by altering the power system's control variables while meeting a set of operational restrictions [1]. In Its most basic form, the OPF is a nonlinear, non-convex, large-scale, static optimization problem with both continuous and discrete control variables [2]. In recent years, several population-based metaheuristic optimization strategies have been proposed to solve the OPF Issue. Their key benefit over conventional (deterministic) optimization methods is that they are not constrained by constraints such as differentiability, non-convexity, and continuity of the objective function, as well as control variable types. Furthermore, these approaches may be applied to actual power systems while accounting for a variety of objective functions and restrictions. Metaheuristic approaches rely on Iterative correction of solutions, which Involves producing new populations by applying stochastic search operators to Individuals from the present population. Metaheuristic' key advantages capacity to explore huge solution spaces quickly, locate global solutions, and avoid local optima [3].

I.2 Related works:

A power system optimization challenge is optimal power flow (OPF) [4-5]. Carpentier [6] first raised this issue in 1962. The objective of OPF is to identify a steady-state operating point that meets operating constraints and demands while minimizing the cost of power generation.

Authors in [7], offered the first solution to the OPF issue in 1968, and several others have subsequently been put forth. The authors of [8, 9] provide an excellent summary of the literature on traditional optimization techniques applied to OPF during the past 30 years.

A modified coyote optimization algorithm (MCOA) is proposed for finding highly effective solutions for the optimal power flow (OPF) problem [10]. Optimal power flow solution with nature inspired Antlion meta-heuristic algorithm is applied in [11]. A new multi-objective approach is suggested [12], known as multi-objective backtracking search algorithm (MOBSA) in order to formulate and solve the optimal power flow (OPF) problem in power systems. The OPF problem is solved under deregulated environment considering different load levels using improved Mayfly Algorithm (IMA) [13]. Grey Wolf Optimizer (GWO) and Harris Hawks Optimization (HHO), are applied in Ref [14] to handle multi-objective optimal power flow (MOOPF) issues, validate and evaluate on two standard IEEE bus systems 30-bus and 57-bus power systems. An adaptive multiple teams perturbation-guiding Jaya (AMTPG-Jaya) technique is implemented in [15] to tackle with diverse single goal optimum power flow (OPF) forms. Scholars in [16], have been used Symbiotic organisms search (SOS) algorithm to address multi-objective optimal power flow (OPF) problems in power systems considering several operational constraints. Researchers in [17] proposes and scrutinizes a novel fuzzy adaptive hybrid configuration oriented to a joint self-adaptive particle swarm optimization (SPSO) and differential evolution algorithms, namely FAHSPSO-DE, to address the multi-objective OPF (MOOPF) problem. In paper [18], an effective whale optimization algorithm for solving optimal power flow problems (EWOA-OPF) is proposed and a standard IEEE 6-bus, IEEE 14-bus, IEEE 30-bus, and IEEE 118-bus test systems are used to evaluate the proposed EWOA-OPF. In Ref [19], the particle swarm optimization (PSO) method and the teaching-learning based optimization (TLBO) method have been proposed and applied to find optimal solutions with different objectives of OPF. A novel Variable Neighborhood Descent (VND) meta-heuristic approach is presents in [20] to solve the OPF problem for large-scale systems. In the paper [21], the authors have been proposed a combination of phasor particle swarm optimization (PPSO) and a gravitational search algorithm, namely a hybrid PPSOGSA algorithm, for optimal power flow (OPF) in power systems with an integrated wind turbine (WT) and solar photovoltaic (PV) generators. A fuzzy-based improved comprehensive-learning particle swarm optimization (FBICLPSO) algorithm is introduced in [22], the FBICLPSO approach is scrutinized on IEEE 30-bus test system, which is a commonly used test system for solving the non-smooth and non-convex versions of the OPF problem considering FACTS devices. Scholars in [23], are proposed a novel design of Slim Mould (SM) algorithm for the solution of optimal power flow problems incorporating renewable energy sources (RES) and different objective functions. The proposed SMA is examined on the IEEE 30-bus test system, and a real-sized Algerian electricity grid 114-bus power system. In [24], a hybridization of particle swarm optimization (PSO) with grey wolf optimization (GWO), namely a hybrid PSO-GWO algorithm is suggested for the solution of OPF problems integrated with stochastic solar photovoltaics (SPV) and wind turbines (WT) to enhance global search capabilities towards an optimal solution. Article [25], employs the Newton- based OPF-TCSC solver of MATLAB Simulator, thus it is essential to understand the development of OPF and the suitability of Newton-based algorithms for solving OPF-TCSC problem.

I.3 Mathematical formula of the OPF

Optimal power flow is a nonlinear-non convex optimization problem that minimizes some objective function in the power system and satisfies several constraints. Mathematically, the OPF problem can be represented by [19]:

$$Min \;\; f(x,u) \tag{I.1}$$

Subject to: $$\begin{aligned} g(x,u) &= 0 \\ h(x,u) &\leq 0 \end{aligned}$$

With u is the vector of control variables presented by the independent quantities of the control variables, x is the vector of state variables presented by the dependent quantities of the control variables. $f(x,u)$ is the objective function of the OPF, $g(x,u)$ and $h(x,u)$ represent the equality and inequality constraints respectively.

I.3.1 Variables

I.3.1.1 Control variables

The set of control variables, also called decision variables that can control the power flow in the power system is represented by the following vector:

$$u = \left[P_i \ \ldots P_{Ng}, V_1 \ldots V_{Ng}, Q_{C_1} \ldots Q_{C_{N_C}}, T_1 \ldots T_{N_T}\right] \tag{I.2}$$

where

$(P_2 \ldots P_{Ng})$: present the active power generated by Ng generators (except the reference one).

$(V_1 \ldots V_{Ng})$: denote the voltage modules of all generator bus.

I.3.1.2 State variables

The changes in the state of the power system are defined by the state variables which can be expressed by the vector x [19]:

$$x = \left[P_{slack}, V_{L_1} \ldots V_{L_{NL}}, Q_1 \ldots Q_{Ng}, S_{l_1} \ldots S_{l_{nl}}\right] \tag{I.3}$$

These variables are not directly controlled in the optimization process. These are unknown variables and usually are obtained by solving the power flow equation [25].

I.3.1.3 Handling constraints

The most effective and simple way to handle constraints in optimization problems is to use penalty functions [19]. The direction of the search process and thus the quality of the optimal solution are strongly Impacted by these functions. An appropriate penalty function must be chosen to solve a particular problem. The main purpose of a penalty function is to maintain system security.

These penalty functions are associated with many user defined coefficients that must be rigorously tuned to fit the given problem.

This research used a quadratic penalty function method in which a penalty term is added to the objective function for any constraint violation. The inequality constraints which include generator constraints, reactive compensation sources and transformer constraints are combined in the objective function as a penalty term, while the equality constraints and generator reactive power limits are satisfied by the Newton-Raphson method (NR power flow). By adding the Inequality constraints to the objective function $f(x,u)$ in Eq. (I.1), the augmented objective function f_{aug} to be minimized becomes:

$$f_{aug}(x,u) = f(x,u) + f_{pénalité} \tag{I.4}$$

$f_{aug}(x,u)$ is the proposed augmented objective function, f(x,u) is the objective function, $f_{pénalité}$ is the penalty function given in Eq. (I.5).

$$f_{pénalité} = \delta_P \left(P_1 - P_1^{\lim}\right)^2 + \delta_V \sum_{p=1}^{NL} \left(V_{L_P} - V_{Lp}^{\lim}\right)^2 + \delta_Q \sum_{i=1}^{Ng} \left(Q_i - Q_i^{\lim}\right)^2 + \delta_S \left(S_{lq} - S_{lq}^{\lim}\right)^2 \tag{I.5}$$

$$P_i^{\lim} = \begin{cases} P_i^{\min} & si \quad P_i \langle\ P_i^{\min} \\ P_i^{\max} & si \quad P_i \rangle\ P_i^{\max} \\ P_i & si \quad P_i^{\min} \langle\ P_i \langle\ P_i^{\max} \end{cases} \tag{I.6}$$

$$V_{Lp}^{\lim} = \begin{cases} V_{Lp}^{\min} & si \quad V_{Lp} \langle\ V_{Lp}^{\min} \\ V_{Lp}^{\max} & si \quad V_{Lp} \rangle\ V_{Lp}^{\max} \\ V_{Lp} & si \quad V_{Lp}^{\min} \langle\ V_{Lp} \langle\ V_{Lp}^{\max} \end{cases} \tag{I.7}$$

$$Q_i^{\lim} = \begin{cases} Q_i^{\min} & si \quad Q_i \langle\ Q_i^{\min} \\ Q_i^{\max} & si \quad Q_i \rangle\ Q_i^{\max} \\ Q_i & si \quad Q_i^{\min} \langle\ Q_i \langle\ Q_i^{\max} \end{cases} \tag{I.8}$$

$$S_{lq}^{\lim} = \begin{cases} S_{lq}^{\min} & si \quad S_{lq} \langle\ S_{lq}^{\min} \\ S_{lq}^{\max} & si \quad S_{lq} \rangle\ S_{lq}^{\max} \\ S_{lq} & si \quad S_{lq}^{\min} \langle\ S_{lq} \langle\ S_{lq}^{\max} \end{cases} \tag{I.9}$$

I.4 Objective functions

The objective function takes various forms such as fuel cost, transmission losses and reactive power source allocation. Usually, the objective function of Interest is the minimization of the total cost of the generated powers of all the scheduled production units. This is the most widely used because it reflects current practice of economic dispatch and, more importantly, the cost aspect is always ranked among the operational requirements of power systems.

I.4.1 Minimization of generation fuel cost

Fuel cost minimization is the most fundamental objective function of OPF studied in almost all literatures. The association between the fuel cost ($/h) and the quadratic relation approximately gives the generated power (MW) and thus the objective function to be minimized is described as [26-30]:

$$f_1(x,u)=\sum_{i=1}^{Ng} a_i + b_i.P_i + c_i.P_i^2 \tag{I.10}$$

I.4.2 Minimization of emission

The production of electrical energy from conventional energy sources emits harmful gases into the environment, such as carbon dioxide (CO_2), nitrogen oxide (NOx), sulfur dioxide (SO_2) and mercury (Hg). The number of emissions of these pollutants in tons per hour (t/h) increases with the increase of the power produced in (MW) according to the relation given in equation (I.11). Minimizing emissions is the goal of the OPF.

Mathematically, the emission rate of gases can be represented as an objective function of the generated power given by [31]:

$$f_2(x,u)=\sum_{i=1}^{Ng} \alpha_i + \beta_i.P_i + \gamma_i.P_i^2 + \omega_i e^{(\mu_i P_i)} \tag{I.11}$$

Where, $\alpha_i, \beta_i, \gamma_i, \omega_i$ and μ_i are the coefficients of the emission function of each generator *i*,

I.4.3 Voltage profile improvement

The voltage deviation VD is a measure of the voltage quality in the network. The VD deviation index is also important from a safety point of view. VD is formulated as a cumulative deviation of the voltages of all load bus of a power system from the nominal voltage (1.0 p.u). Mathematically, it is expressed as follows [32, 33]:

$$f_3(x,u)=VD=\sum_{p=1}^{NL}\left|V_{L_p}-V^{ref}\right|=\sum_{p=1}^{NL}\left|V_{L_p}-1.0\right| \qquad \text{(I.12)}$$

I.4.4 Voltage stability enhancement

Voltage stability problems are receiving increasing attention in power systems, as system collapses have been experienced in the past due to voltage Instability. Under normal conditions and after being subjected to disturbances, the stability of a power system Is characterized by Its ability to maintain all bus voltages within acceptable limits. On the other hand, a network enters a state of voltage Instability when a disturbance, an Increase In load, a change in the state of the system or damage to equipment (lines, cables, transformers, metering reducers, circuit breakers, etc.) causes a progressive and uncontrollable decrease in voltage [34]. Systems with long transmission lines and large loads are more prone to voltage I instability problems. In a power system, improving the voltage stability of a system is an important aspect. As a result, much research work has been directed towards the development and control of voltage stability processes. In [34], authors have developed analyses and proposed a voltage stability index called the L-Index.

The L_{index} of each node serves as a good indicator of the stability of the power system [35]. The value of the Index varies from 0 to 1, 0 being the case with no load while 1 means voltage collapse.

The index l_j is determined from the basic power flow equation, and which is formulated as follows [19, 36]:

$$I_{bus}=Y_{bus}\,.\,V_{bus} \qquad \text{(I.13)}$$

By separating the load buses (PQ bus) from the generation bus (PV bus), equation (I.22) can be rewritten as follows:

$$\begin{bmatrix} I_L \\ I_G \end{bmatrix}=\left[Y_{bus}\right].\begin{bmatrix} V_L \\ V_G \end{bmatrix}=\begin{bmatrix} Y_{LL} & Y_{LG} \\ Y_{GL} & Y_{GG} \end{bmatrix}.\begin{bmatrix} V_L \\ V_G \end{bmatrix} \qquad \text{(I.14)}$$

where Y_{LL}, Y_{LG}, Y_{GL}, and Y_{GG} are the partial matrices of the admittance matrix Bus. V_L, I_L, are the voltages and currents of the load nodes respectively. V_G, I_G are the voltages and currents of the generating nodes respectively. Eq. (I.14) can be rewritten with another formula like [19, 37],

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = [H] \cdot \begin{bmatrix} I_L \\ V_G \end{bmatrix} = \begin{bmatrix} H_{LL} & H_{LG} \\ H_{GL} & H_{GG} \end{bmatrix} \cdot \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{I.15}$$

Where, H is determined by the partial inversion of the admittance matrix Y_bus; H_{LL}, H_{LG}, H_{GL}, and H_{GG} are sub-matrices of H.

Finally, the index L of load bus j denoted by L_j is formulated as follows [19]:

$$L_j = \left| 1 - \sum_{i=1}^{Ng} F_{ji} * \frac{V_i}{V_j} \right|, \quad j = 1,2,\dots, NL \tag{I.16}$$

and $F_{ji} = -[Y_{LL}]^{-1}[Y_{LG}]$

To ensure voltage stability the condition $L_j \leq 1$ must not be violated for all bus in the network. The voltage stability index L-index (L_{max}) can be given by equation (I.17)

$$L - index = L_{\max} = \max(L_j), \quad j = 1,2,\dots, NL \tag{I.17}$$

According to Eq. (I.26), the Improvement In voltage stability can be achieved by minimizing the voltage stability index (L-Index) at each bus in the system [30]. Therefore, to consider the voltage stability in the OPF problem, the objective function is given by the expression (I.18) [19].

$$f_4(x,u) = L_{\max} = \max(L_j) \tag{I.18}$$

I.4.5 Minimization of active power losses

The total active losses in the transmission lines of an electrical network Is unavoidable because the lines have an Inherent resistance. The active power loss in (MW) to be minimized is expressed by [37]:

$$f_5(x,u) = P_{loss} = \sum_{q=1}^{nl} G_{q(i\,j)} \cdot \left[V_i^2 + V_j^2 - 2 V_i V_j \cos(\delta_{ij}) \right] \tag{I.19}$$

Where, $\delta_{ij} = (\varphi_i - \varphi_j)$, is the difference in voltage angles between bus *i* and bus *j* and $G_{q(i,j)}$ the conductance of the branch *q* connecting between the bus *i* and *j*.

I.4.6 Minimization of reactive power losses

The objective function represents total reactive losses of transmission lines; it is given by the expression [37, 38]:

$$f_6(x,u)=Q_{loss}=\sum_{q=1}^{nl} B_{q(i\,j)}.\left[-V_i^2-V_j^2+2V_iV_j\cos(\delta_{ij})\right] \quad (I.20)$$

Where, $B_{q(i,j)}$ is the susceptance of the branch *q* connecting between the bus *i* and *j*.

I.5 Constraints

As mentioned earlier, the OPF problem has both equality and inequality constraints that must be satisfied. The constraints are separated and provided here.

VL.1 Equality constraints

In the OPF, the power balance equations are the equality constraints present in the non-linear power flow equations in all branches, where the sum of the active and reactive powers Injected In each bus is zero. These are represented by [19, 37]

$$P_i - P_{D_P} - V_i\sum_{j=1}^{N} V_j\left[G_{ij}\cos\left(\delta_{ij}\right)+\ B_{ij}\sin\left(\delta_{ij}\right)\right]=0\ \forall i\in N,\ p\in NL \quad (I.21)$$

$$Q_i - Q_{D_P} - V_i\sum_{j=1}^{N} V_j\left[G_{ij}\sin\left(\delta_{ij}\right)-B_{ij}\cos\left(\delta_{ij}\right)\right]=0\ \forall i\in N,\ p\in NL \quad (I.22)$$

Where, , P_i, Q_i are the generated active and reactive power, P_D,Q_D are the active and reactive power demand, G_{ij} *i*s the conductance and B_{ij} is the susceptance of the line connecting bus *i* and bus *j* respectively, *N i*s the total number of buses in power system.

I. Inequality constraints

The inequality constraints in the OPF reflect the physical and technical limits of operation of the equipment present in the power system but also the limits imposed on the load lines and bus to guarantee the security of the system.

a. Generator constraints:

The voltage, active power and reactive power of all generating unit in power system are limited by their lower and upper limits.

$$V_i^{\min} \le V_i \le V_i^{\max} \quad \forall i\in Ng \quad (I.23)$$

$$P_i^{\min} \le P_i \le P_i^{\max} \quad (I.24)$$

$$Q_i^{\min} \le Q_i \le Q_i^{\max} \quad (I.25)$$

b. Transformer constraints:

The ratio of the transformer load adjuster is limited by a minimum and a maximum.

$$T_j^{\min} \le T_j \le T_j^{\max} \quad \forall\, j \in N_T \tag{I.26}$$

c. Shunt compensator constraints:

The reactive powers Injected by the shunt compensation sources must be within the limits.

$$Q_{C_k}^{\min} \le Q_{C_k} \le Q_{C_k}^{\max} \quad \forall\, k \in N_C \tag{I.27}$$

d. Security constraints:

The system is said to be in a secure state if it meets the following security constraints:

The voltages of (PQ) bus must not exceed their permissible limits.

Power lines must meet transit power limits.

$$V_{L_p}^{\min} \le V_{L_p} \le V_{L_p}^{\max} \quad \forall\, p \in NL \tag{I.28}$$

$$S_{l_q} \le S_{l_q}^{\max} \quad \forall\, q \in nL$$

(I.29)

$V_{L_p}^{\max}$: Maximum power allowed in the *q-the* branch, corresponding to the maximum value of the current flowing in the same branch.

II. Conclusion

In this chapter, we have presented basic notions and formulations of the OPF problems. Different objective functions were presented such as the economic dispatch function, environmental dispatch, voltage deviation improvement, voltage stability enhanced, active and reactive power loss minimization. Given the complexity of OPF problems and the limitations of deterministic methods, as they do not converge to local optima, we propose the optimization of OPF problems by metaheuristic methods and this will be the subject of the next chapter.

II

Teaching-Learning-Based Optimization (TLBO) algorithm

II.1 Introduction

The teaching-learning-based optimization (TLBO) method [38], which simulates the teaching-learning process in a classroom, is one of the population-based heuristic stochastic swarm intelligence algorithms. TLBO uses comparable repetitive evolution processes as a regular evolutionary algorithm. Unlike classic evolutionary algorithms and swarm intelligence algorithms, the iterative computation process of teaching-learning-based optimization is separated into two stages, each of which performs an iterative learning operation. In this study, we provide a detailed assessment of recent improvements in TLBO. A survey of the present literature identifies fascinating difficulties and prospective future research avenues.

II.2 Principle of the TLBO algorithm

TLBO, like other population-based algorithms, starts with an initialization phase in which randomly generated populations of potential solutions are placed in a problem search space with n dimensions. Every dimension has an upper and lower limit. The TLBO operating technique is then divided into two parts: the "Teacher Phase" and the "Student (Learner) Phase," which refers to learning through interaction among students. The TLBO's operational idea is explained below [38, 39].

II.2.1 Teaching phase

During the first phase, the students learn through the teacher, the latter (best solution) is designated to provide his knowledge to all the students to improve the average of his class. At each iteration, the best individual (student) from the population is selected to become the teacher whose objective value is defined by. Learners are then averaged for each design variable to form the vector. The teacher seeks to increase the result of each student by the difference between his value and the group average in the following way [38]:

$$Difference_{mean} = r_i \times \left(\mu_{Teacher} - T_F \times \mu_{mean}\right) \tag{II.1}$$

Where, is a random number between 0 and 1 and is a learning factor that decides the value of the average value to modify. It can be 1 or 2 and it is decided with equal probability. is not a parameter of the TLBO algorithm. Eq. (II.6) is used to generate $r_i T_F T_F T_F$

$$T_F = round\left[1 + rand(0,1)\{2-1\}\right] \tag{II.2}$$

Based on, the existing solution is updated in the teacher phase according to the following expression:$Diff\acute{e}rence_{moyenne}$

$$X^{'}_{i,j} = X_{i,j} + Difference_{mean} \tag{II.3}$$

Where is a new solution obtained from the first phase to iteration. If is a solution worse than , then replace in the next phase.$X'_{i,j}ijX'_{i,j}X_{i,j}X_{i,j}X'_{i,j}$

II.2.3 Learning phase

In the second phase, students randomly increase their knowledge through interaction with each other, using an approach similar to discussion groups. The solutions will be compared together randomly. Each solution is compared with another random solution from the population (), as follows [38]:

$$X^{"}_{i,j} = \begin{cases} X^{'}_{i,j} + r \times \left(X^{'}_{i,j} - X^{'}_{p,j}\right), & si \quad f\left(X^{'}_{i,j}\right) \langle \ f\left(X^{'}_{p,j}\right) \\ \\ X^{'}_{i,j} + r \times \left(X^{'}_{p,j} - X^{'}_{i,j}\right), & si \quad f\left(X^{'}_{p,j}\right) \langle \ f\left(X^{'}_{i,j}\right) \end{cases} \tag{II.4}$$

Where is the new solution obtained. If the solution gives us a value of the fitness function less better than that given by , then, in this case, the solution is rejected and will be the final solution retained in the new population. These two phases are repeated until the stopping criterion is reached. Eq. (II.8) is used for minimization optimization problems. In the case of maximization problems, Eq. (II.9) is used [38-40]. The flowchart of the TLBO method is shown in Fig.II.1.

$$X^{"}_{i,j} = \begin{cases} X^{'}_{i,j} + r \times \left(X^{'}_{p,j} - X^{'}_{i,j}\right), & si \quad f\left(X^{'}_{p,j}\right) \langle \ f\left(X^{'}_{i,j}\right) \\ \\ X^{'}_{i,j} + r \times \left(X^{'}_{i,j} - X^{'}_{p,j}\right), & si \quad f\left(X^{'}_{i,j}\right) \langle \ f\left(X^{'}_{p,j}\right) \end{cases} \tag{II.5}$$

II.5 Conclusion

This chapter describe in detail the covers global (metaheuristic) optimization strategy based on teaching learning-based optimization TLBO.

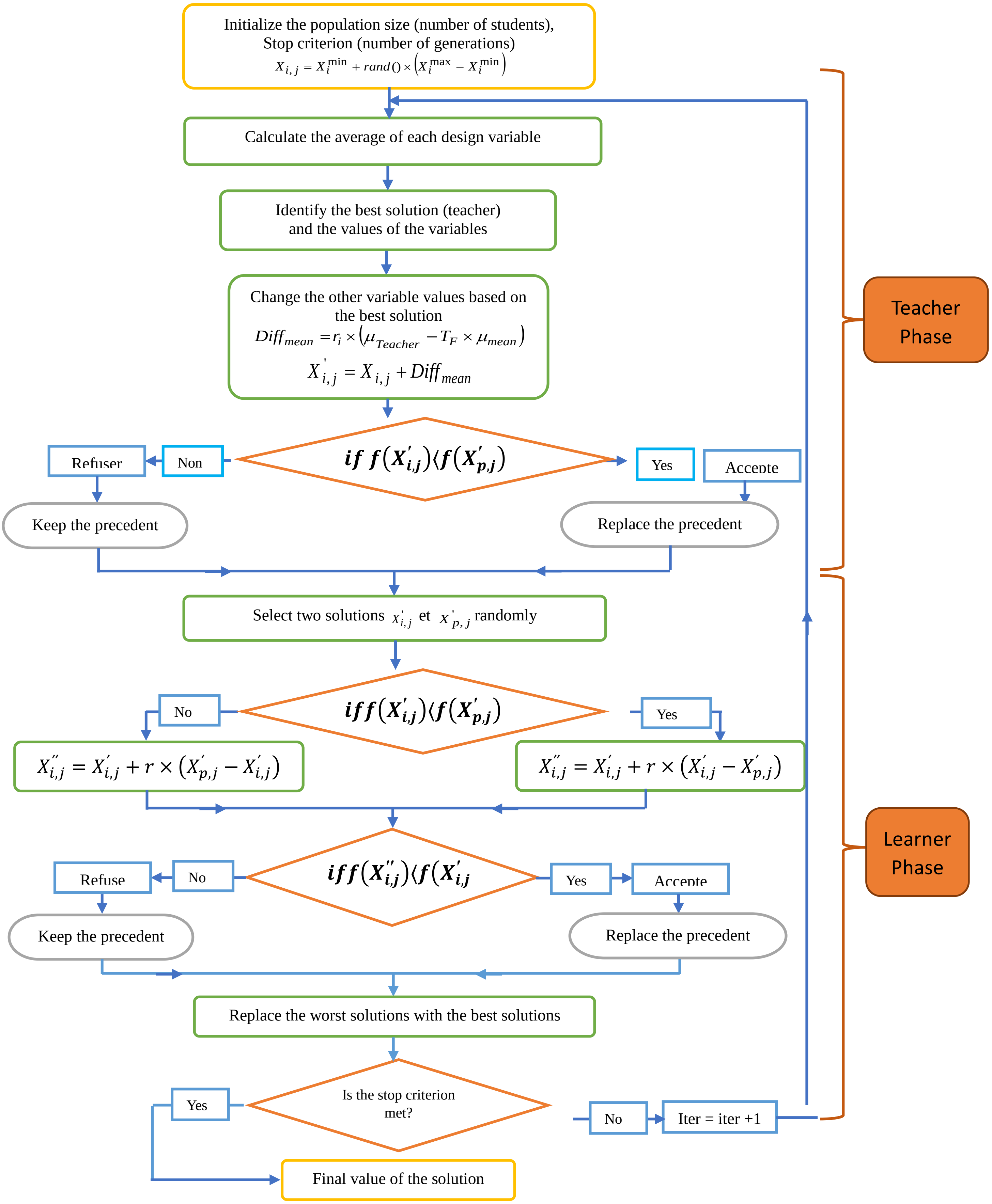

Figure II.1: Flowchart of TLBO algorithm [19].

III

Simulation results and discussion

III. 1 Introduction

To evaluate the efficacy of the TLBO algorithm, a number of case studies with single and multi-objective have been performed for standard IEEE 30 bus test system with varying aims. Table III.1 provides an overview of the key components (viz. generators. Transformers, shunt compensators etc.), installed in the test system and other relevant useful parameters. In the IEEE 30 bus test system, bus 1 is the slack bus often termed as $V\delta$ bus. Figure (III.1) depicts the single-line scheme for the IEEE 30 bus test system.

Table III. 1: Summary of IEEE 30 bus system.

Items	Quantity	Details
Bus	30	[Appendix A.1]
Branches	40	[Appendix A.2]
Generators	6	Buses : 1 (Slack bus). 2. 5. 8. 11 and 13
Shunt VAR compensation	9	Bus : 10. 12. 15. 17. 20. 21. 23. 24 and 29
Transformer with tap changer	4	Branches: 11. 12. 15 and 36
Control variables	24	-
Connected load	-	283.4 MW. 126.2 MVar
Load bus voltage range allowed	24	[0.95 – 1.05] p.u.
Transformer ratio limite	-	[0.90 – 1.10] p.u.
The power range of QC compensator shunt	-	[0 – 5] MVar.

III.2. TLBO algorithm to OPF problems

The main steps in solving the OPF problem by TLBO are:

Step 1: Enter all power system data such as generator limits, transformer limits and safety constraints. Population size and number of generations are also introduced.

Step 2: Initialize the control variables.

Step 3: Apply the power flow by the fast-decoupled Newton-Raphson method. Check if the inequality constraints has violated and sanction the violations.

Step 4: Calculate the new objective function with the penalized violations.

Step 5: Update the new control variables using Eq. (II. 1) and (II. 3)

Step 6: Obtain a new solution of the power flow using the new control variables.

Step 7: Repeat step 4 to update the lens function.

Step 8: Compare the results obtained in step 7 with step 4.

Step 9: if the new value of the objective function, is better than the previous one. Update the control variables with the better parameters.

Step 10: Update the new control variables using Eq. (II. 4)

Step 11: Repeat step 3 for the power flow calculation update.

Step 12: Repeat step 4 to update the target function.

Step 13: Compare the results obtained in step 12 with step 7.

Step 14: if the new value of the objective function, is better than the previous one. Update the control variables with the better parameters.

Step 15: Repeat the above procedures from step 2 for the maximum number of iterations.

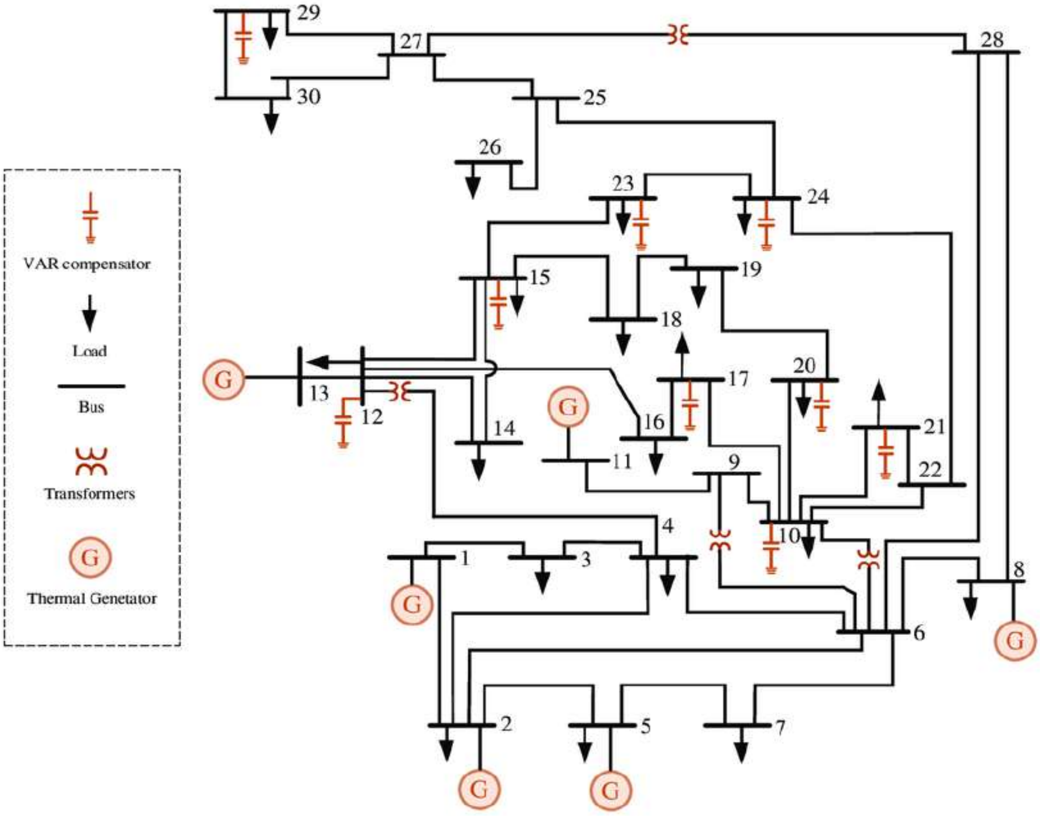

Figure III.1: One line diagram of IEEE 30-bus network.

III.2 Results and discussion

To examine the accuracy of the TLBO algorithm for all cases OPF problems considering distributed generator (DG). The algorithm is performed in the computational environment of MATLAB R2017b [41] and implemented on a PC with a 2.7 GHz Intel® Core™ i5 CPU and 16 GB RAM. The case considered for the IEEE 30-bus network is carried out with a population size (m = 40) and a maximum of (200/500) iterations.

A total of four study cases are performed for the system. First two case studies minimize single objective function of OPF. The remaining cases are for multi-objective optimizations which are converted to single objectives with weight factors as in many previous studies and reproduced herein. The IEEE 30-bus system is modified by inserting DG. Allocation of this DG to a proper location is selected according to the sensitivity of active power loss and generation cost to each active and reactive power as mentioned in Ref. [42]. According to study in [42]. Bus number 30 is the nominee location for DG and the value selected of all DG is 10 MW.

The cases study in this work provided as follow:

- Case I: Minimization of generation fuel cost.
- Case II: Minimization of active power transmission losses.
- Case III: Minimization of generation fuel cost with considering emission.
- Case IV: Minimization of generation fuel cost, emission, voltage deviation and power

Losses.

III.2.1 Case I: Fuel Cost Minimization

In this section, fuel cost minimization is considered the goal function during the implementation of TLBO algorithm with and without incorporating of DG. Figure III.2 illustrates the convergence graph of fuel cost minimization using the TLBO approach with and without the influence of distributed generation unit at nodes 30 and 3. Without considering DG's effect. The method requires 64 iterations to obtain the global optima, which reveals the excellent convergence rate of the TLBO method. The best adjustments of the design variables and optimal values of cost minimization are tabulated in Table III.2.

The results present a significant reduction in fuel cost from 902.0207 \$/h to 799.0679 \$/h. when the TLBO algorithm is executed without considering DG. These results point out the robustness of the TLBO algorithm in terms of solution optimality and fast convergence. Implementing TLBO method for fuel cost reduction when accommodating the DG at bus 30 produces an even more significant reduction in fuel cost reaching 763.0752 $/h. an attractive L_{max} value (0.0898), and a great expansion of shunt compensators reactive power saving of up to 22.5175 MVAR. Most importantly, a considerable reduction in active power losses (8.1328 MW) is achieved.

Table III. 2: Simulation results of best solutions for IEEE 30-bus system (case I).

Parameters	limits		Initial Status	Case I	
	Min	Max		Without DG	With DG at bus 30
P_2(MW)	20	80	80	48.6967	47.2227
P_5(MW)	15	50	50	21.3053	21.7652
P_8(MW)	10	35	20	21.0801	17.9252
P_{11}(MW)	10	30	20	11.8840	10.4819
P_{13}(MW)	12	40	20	12.0000	12.0067
V_1 (p.u)	0.95	1.1	1.05	1.0999	1.09856
V_2 (p.u)	0.95	1.1	1.04	1.0878	1.0796
V_5 (p.u)	0.95	1.1	1.01	1.0618	1.0457
V_8(p.u)	0.95	1.1	1.01	1.0694	1.04812
V_{11}(p.u)	0.95	1.1	1.05	1.0999	1.0555
V_{13} (p.u)	0.95	1.1	1.05	1.0999	1.0790
T_{6-9}(p.u)	0.90	1.1	1.078	1.0449	0.9422
T_{6-10} (p.u)	0.90	1.1	1.069	0.9000	0.9462
T_{4-12}(p.u)	0.90	1.1	1.032	0.9864	0.9863
T_{28-27}(p.u)	0.90	1.1	1.068	0.9658	0.9743
Q_{C10}(Mvar)	0.00	5.00	0	4.9999	4.9646
Q_{C12}(Mvar)	0.00	5.00	0	4.9999	2.7164
Q_{C15}(Mvar)	0.00	5.00	0	4.9991	0.1347
Q_{C17}(Mvar)	0.00	5.00	0	4.9999	3.5301
Q_{C20}(Mvar)	0.00	5.00	0	4.9999	4.9976
Q_{C21}(Mvar)	0.00	5.00	0	4.9999	2.0340
Q_{C23}(Mvar)	0.00	5.00	0	3.8387	1.7594
Q_{C24}(Mvar)	0.00	5.00	0	4.9999	2.3799
Q_{C29}(Mvar)	0.00	5.00	0	2.7589	2.1325
Cost ($/hr)	-	-	902.0207	799.0679	763.0752
Emission (kg/hr)	-	-	-	0.3686	0.3569
P_L (MW)	-	-	5.8482	8.6246	8.1328
Q_L (MVar)	-	-	-	4.1695	-3.9017
VD (p.u)	-	-	-	0.8568	0.84978
L_{max}	-	-	0.1732	0.1164	0.08978
P_1(MW)	50	200		177.0576	172.3192

Graphical comparisons of convergences of TLBO technique for case I of fuel cost related objective function is illustrated in Fig III.2.

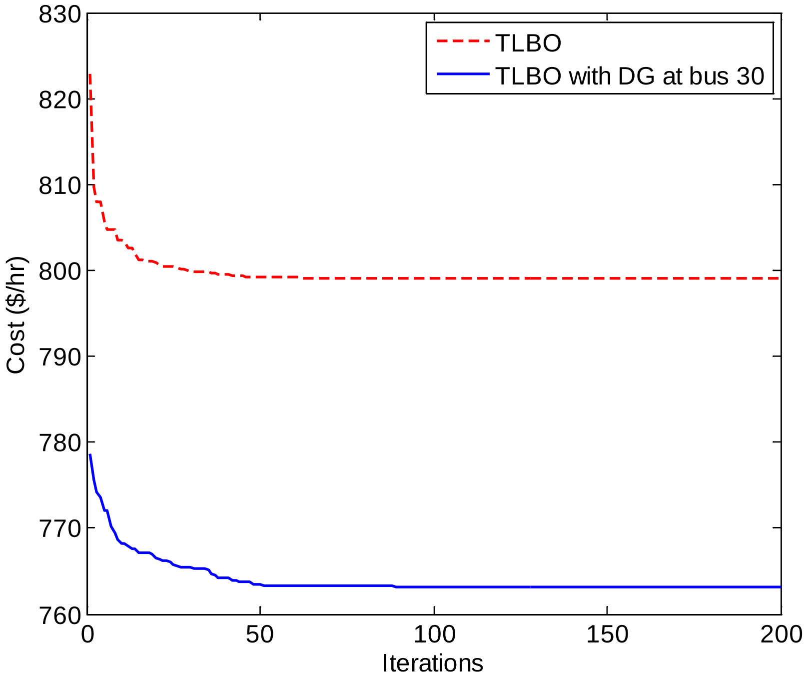

Figure III.2: Comparative convergence of case I for IEEE 30-bus system.

III.2.2 Case II: Minimization of active power transmission losses

The goal considered in this case was active power losses minimization. The TLBO algorithm was utilized to attain the optimum solution. The results of which are given in Table III.3. The TLBO approach is clearly efficient for determining the optimum settings of the control variable, which minimizes system losses. Consequently. real power losses is decreased significantly from 5.8482 MW to 2.8861 MW when TLBO algorithm is performed without considering DG and is decreased to 2.4377 MW with DG penetration. Figure III.3 shows the steep convergence of real power losses using the TLBO algorithm while considering DG placement at bus 30.

The algorithm fully reaches to the optimum solution with 400 iterations. demonstrating the fast convergence of the TLBO algorithm.

Table III. 3: Simulation results of best solutions for IEEE 30-bus system (case II).

Parameters	limits		Case II	
	Min	Max	Without DG	With DG at bus 30
P_2(MW)	20	80	80	70.7759
P_5(MW)	15	50	50	50
P_8(MW)	10	35	34.9999	34.9999
P_{11}(MW)	10	30	29.9999	29.9999
P_{13}(MW)	12	40	40	39.9999
V_1 (p.u)	0.95	1.1	1.0999	1.09999
V_2 (p.u)	0.95	1.1	1.0976	1.09717
V_5 (p.u)	0.95	1.1	1.0798	1.08008
V_8(p.u)	0.95	1.1	1.0868	1.08844
V_{11}(p.u)	0.95	1.1	1.0999	1.09607
V_{13} (p.u)	0.95	1.1	1.1000	1.09999
T_{6-9}(p.u)	0.90	1.1	1.0544	1.06012
T_{6-10} (p.u)	0.90	1.1	0.9000	0.90002
T_{4-12}(p.u)	0.90	1.1	0.9841	0.98749
T_{28-27}(p.u)	0.90	1.1	0.9726	1.01374
Q_{C10}(Mvar)	0.00	5.00	5	4.99404
Q_{C12}(Mvar)	0.00	5.00	4.9999	4.99875
Q_{C15}(Mvar)	0.00	5.00	5	5
Q_{C17}(Mvar)	0.00	5.00	5	4.9999
Q_{C20}(Mvar)	0.00	5.00	4.8190	4.1852
Q_{C21}(Mvar)	0.00	5.00	4.9999	4.9999
Q_{C23}(Mvar)	0.00	5.00	3.6387	3.1195
Q_{C24}(Mvar)	0.00	5.00	4.9999	4.9999
Q_{C29}(Mvar)	0.00	5.00	2.5235	5.3531
Cost ($/hr)	-	-	967.1484	961.9014
Emission (kg/hr)			0.2216	0.2214
P_L (MW)	-	-	2.8506	2.3749
Q_L (MVar)	-	-	-18.5736	-21.749
VD (p.u)	-	-	0.9114	0.9104
L_{max}	-	-	0.1150	0.0832
P_1(MW)	50	200	51.2490	49.9978

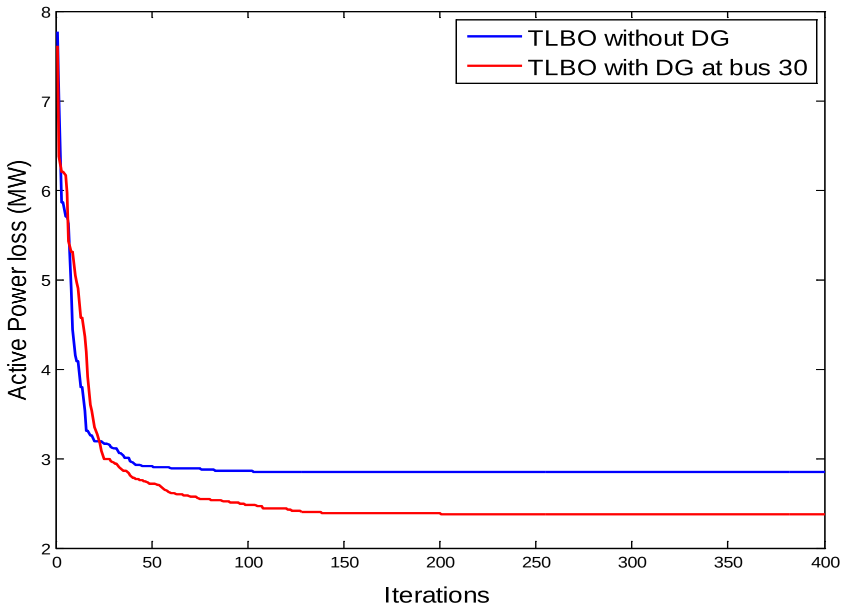

Figure III.3: Comparative convergence of case II for IEEE 30-bus system.

5.1.3. Case 3: Minimization of generation fuel cost with considering emission.

Table III.4 displays the variations in fuel cost and voltage deviation during iteration 400 determined by the proposed approach. The suggested TLBO approach achieves satisfactory convergence. Statistics for cost, voltage deviation, and objective function. In this scenario. The cost and VD acquired from TLBO are 817.181 $/h and 1.9868 p.u. respectively. The emission rate is 0.27059 tons per hour.

Table III.4: Simulation results of best solutions for IEEE 30-bus system (case III).

Paramètres	Limites		Case 3	
	Min	Max	Without DG	With DG at bus 30
P_2(MW)	20	80	56.9877	54.9777
P_5(MW)	15	50	25.6604	24.9544
P_8(MW)	10	35	35	35
P_{11}(MW)	10	30	22.7323	20.9110
P_{13}(MW)	12	40	19.6094	18.2083
V_1 (p.u)	0.95	1.1	1.05078	1.05056
V_2 (p.u)	0.95	1.1	1.03466	1.03512
V_5 (p.u)	0.95	1.1	1.00361	1.00416
V_8(p.u)	0.95	1.1	1.01029	1.01289
V_{11}(p.u)	0.95	1.1	1.01831	1.00617
V_{13} (p.u)	0.95	1.1	1.06191	1.05848
T_{6-9}(p.u)	0.90	1.1	1.01413	1.00257
T_{6-10} (p.u)	0.90	1.1	0.90000	0.90000
T_{4-12}(p.u)	0.90	1.1	0.99069	0.99077
T_{28-27}(p.u)	0.90	1.1	0.95390	0.98449
Q_{C10}(Mvar)	0.00	5.00	4.99223	4.93558
Q_{C12}(Mvar)	0.00	5.00	0.55671	0.00133
Q_{C15}(Mvar)	0.00	5.00	4.99662	4.96956
Q_{C17}(Mvar)	0.00	5.00	4.99931	4.99585
Q_{C20}(Mvar)	0.00	5.00	5	4.64598
Q_{C21}(Mvar)	0.00	5.00	5	4.99865
Q_{C23}(Mvar)	0.00	5.00	3.86280	3.21886
Q_{C24}(Mvar)	0.00	5.00	4.98909	4.99994
Q_{C29}(Mvar)	0.00	5.00	2.55112	0
Cost ($/hr)	-	-	817.181	780.379
Emission (kg/hr)			0.27059	0.26519
P_L (MW)	-	-	5.84167	5.33483
Q_L (MVar)	-	-	-6.40497	-10.2638
VD (p.u)	-	-	1.986862	1.938393
L_{max}	-	-	0.115226	0.079274
P_1(MW)	50	200	1.297874	1.297874

Graphical comparisons of convergences of TLBO technique for case III of the simultaneous minimization of fuel cost and emission is illustrated in Figure (III.4). (a-without DG / b- with DG at bus 30).

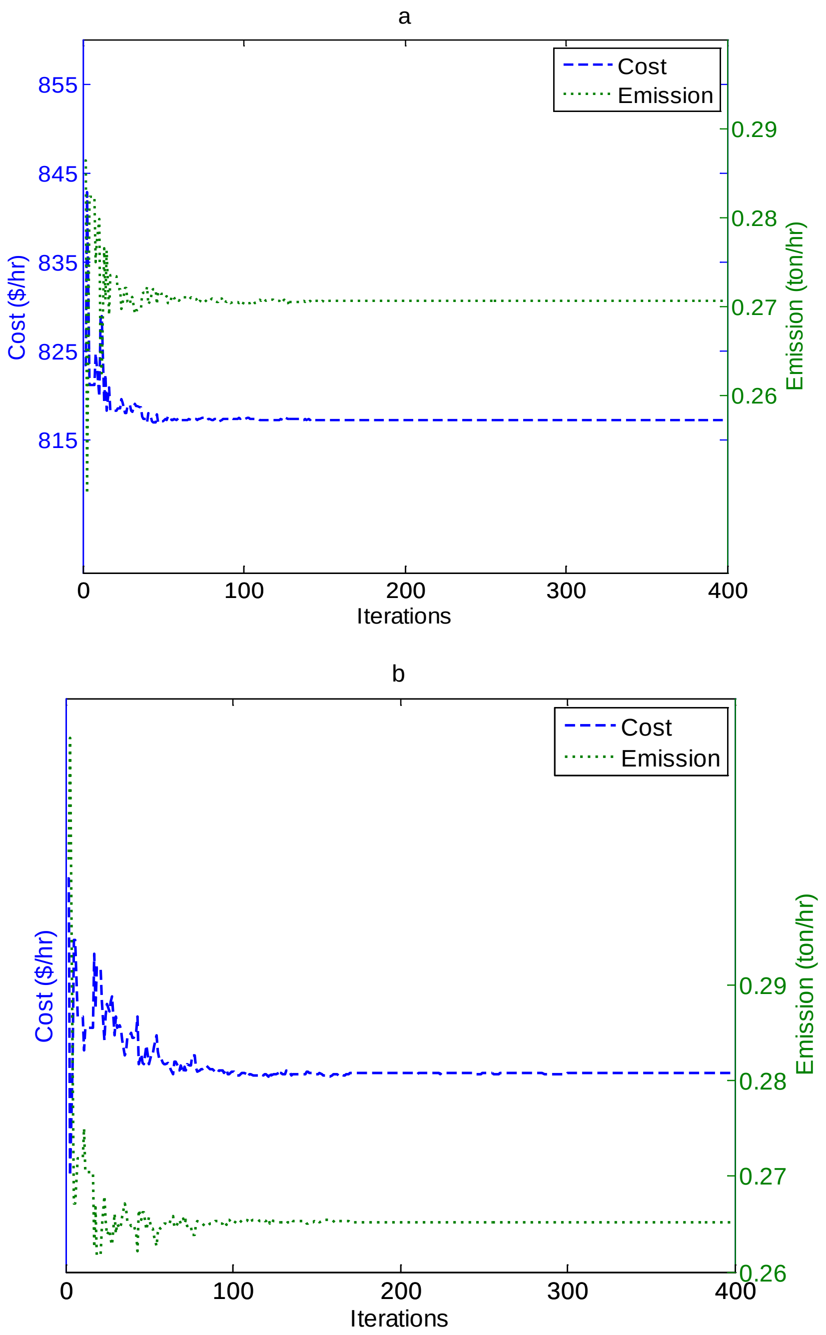

Figure III.4: Comparative convergence of case III for IEEE 30-bus system.

a-without DG / b- with DG at bus 30.

Case 4: Minimization of generation fuel cost, emission, voltage deviation, and power Losses

In this section, generating fuel cost, emission, voltage variation, and active power losses are chosen as a single-objective function to improved based on the proposed TLBO without and with DG penetration at bus 30 as shown in figures III.5 and III.6 respectively. figures III.5 and III.6 illustrates the sketched graphs of the objective function over repetitions.

Table III. 5: Simulation results of best solutions for IEEE 30-bus system (case IV).

Parameters	Limits		Case IV	
	Min	Max	Without DG	With DG at bus 30
P_2(MW)	20	80	52,5099	51.5235
P_5(MW)	15	50	30,9506	30.5171
P_8(MW)	10	35	35,0000	34.9998
P_{11}(MW)	10	30	26,2761	27.1314
P_{13}(MW)	12	40	20,5345	20.0638
V_1 (p.u)	0.95	1.1	1,1000	1.0997
V_2 (p.u)	0.95	1.1	1,0883	1.0893
V_5 (p.u)	0.95	1.1	1,0629	1.0642
V_8(p.u)	0.95	1.1	1,0721	1.0766
V_{11}(p.u)	0.95	1.1	1,0129	1.0271
V_{13} (p.u)	0.95	1.1	1,0290	1.0348
T_{6-9}(p.u)	0.90	1.1	1,1000	1.0731
T_{6-10} (p.u)	0.90	1.1	0,9902	0.9809
T_{4-12}(p.u)	0.90	1.1	1,0721	1.0845
T_{28-27}(p.u)	0.90	1.1	1,0349	1.0377
Q_{C10}(Mvar)	0.00	5.00	4,9935	2.7824
Q_{C12}(Mvar)	0.00	5.00	0,0252	1.8776
Q_{C15}(Mvar)	0.00	5.00	4,0884	2.4268
Q_{C17}(Mvar)	0.00	5.00	5,0000	1.3214
Q_{C20}(Mvar)	0.00	5.00	4,9995	3.3244
Q_{C21}(Mvar)	0.00	5.00	4,9987	3.3267
Q_{C23}(Mvar)	0.00	5.00	4,1657	1.9234
Q_{C24}(Mvar)	0.00	5.00	5,0000	4.1067
Q_{C29}(Mvar)	0.00	5.00	2,5432	3.1894
Cost ($/hr)	-	-	827,5099	825.9343
Emission (kg/hr)			0,2591	0.2612
P_L (MW)	-	-	5,4236	5.5300
Q_L (MVar)	-	-	-13,9828	-12.3525
VD (p.u)	-	-	0,4559	0.4890
L_{max}	-	-	0,1337	0.1333
P_1(MW)	50	200	124.6529	123,5530

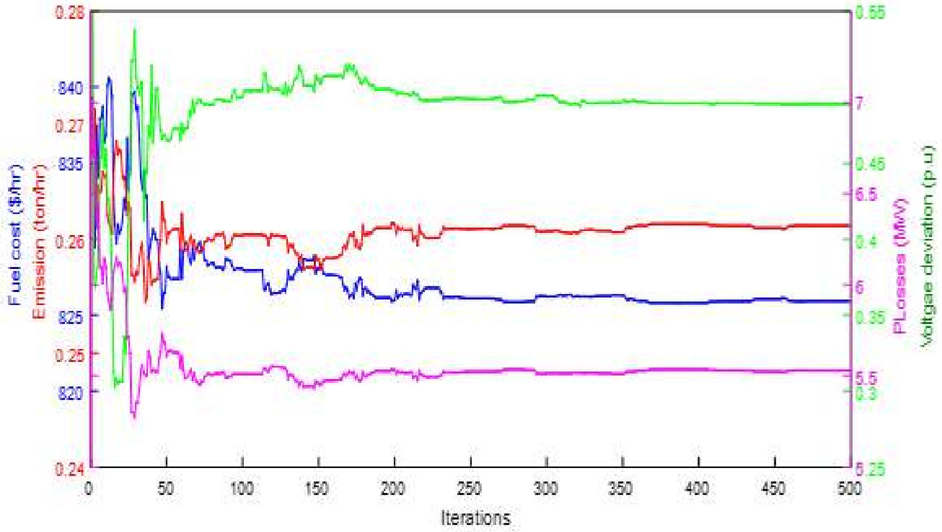

Figure III.5: Comparative convergence of case IV for IEEE 30-bus system without DG.

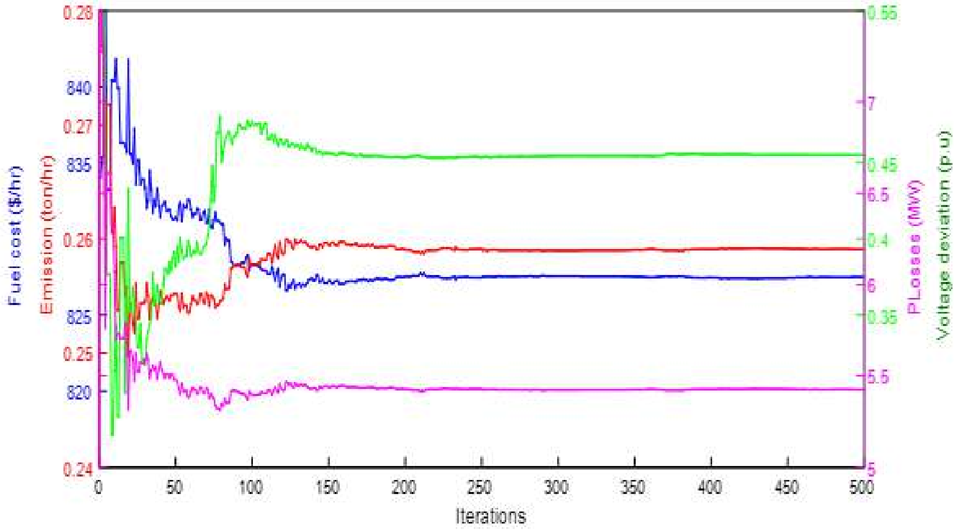

Figure III.6: Comparative convergence of case IV for IEEE 30-bus system with DG.

Table III.6 Comparison of the solutions obtained for cost reduction (modified IEEE 30-bus).

Algorithm	Fuel Cost ($/h)	Real Power Losses (MW)	L-Index
Enhanced Genetic Algorithm (EGA) [43]	802.06	NA	NA
Enhanced Genetic Algorithm with Decoupled Quadratic Load Flow (EGA-DQLF) [44]	799.56 a	8.697	0.111
Hybrid Particle Swarm Optimization and Gravitational Search Algorithm (PSOGSA) [45]	800.49859	9.0339	0.12674

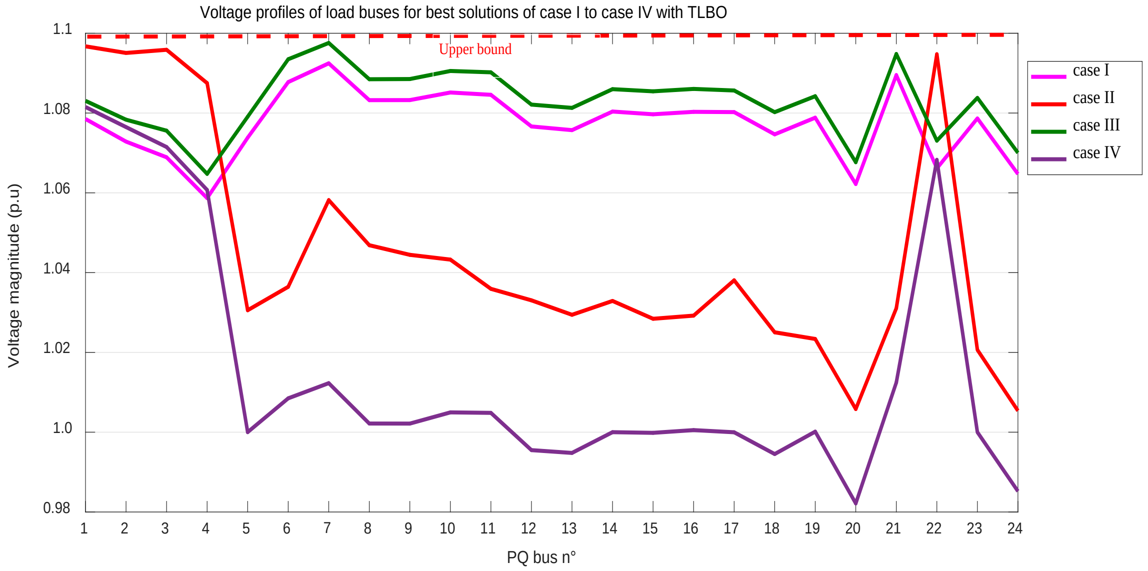

Figure III.7: Voltage profile of PQ bus obtained by TLBO without DG.

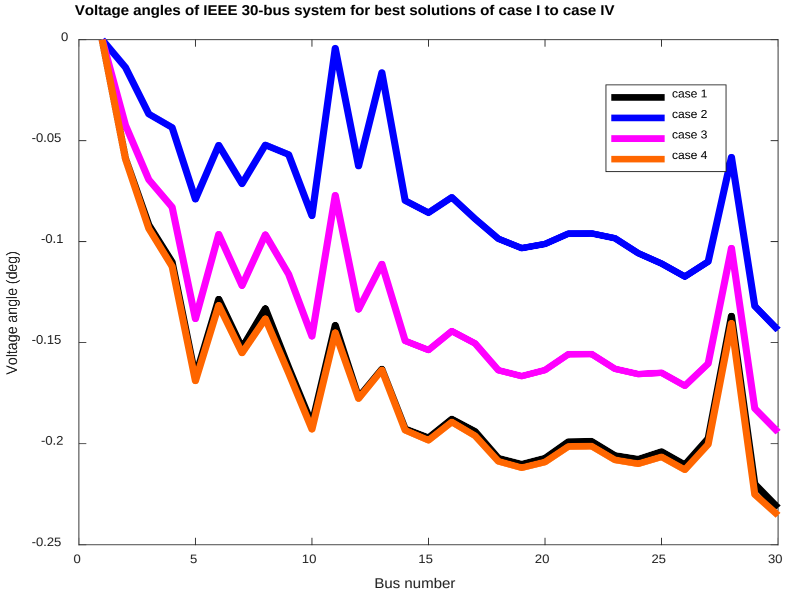

Figure III.8: Voltage angles of PQ bus obtained by TLBO without DG.

III. Conclusion

This chapter aims to optimize power flow with the TLBO teaching-learning-based optimization approach. Four cases were analyzed to maximize basic objective functions such as fuel cost. active and reactive power losses. and poisonous gas emission rate. In other circumstances. optimization involves optimizing many objectives concurrently. including fuel cost. emission rate. voltage deviation. and voltage stability index at the bus bar level.

Conclusion General

This thesis discusses in detail the application and usefulness of TLBO technique for optimal power flow (OPF) problem incorporating renewable energy sources considering the cost, emission, power loss and voltage profile improvement has been proposed.

A short literature review is and detailed mathematic problem of OPF are described in Chapter 1. Weighting factors is introduced to convert multi-objective functions to single objective functions.

The TLBO method is discussed in chapter 2.

In Chapter 3, the application of the TLBO technique to optimal power flow problem with various (single) objectives including distributed generation (DG) is presented. Comparative analyses with other algorithms are also performed.

The scalability of the TLBO algorithm is tested using the IEEE 30-bus system. It is clear from the results that the TLBO approach gave better reduction of the objective function for all cases over other methods used in the comparison.

The research works presented in the thesis cover only some of the optimization problems in power system. The scope of optimization in power system is diverse and vast. We intend to perform many more tasks related to the optimization in power electronics and power systems in the future.

Reference

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APPENDIX

Appendix **A** : IEEE 30 bus test system data

Table A.1: Bus data used for 30-bus system.

N° JB	Type de JB	V_i (p.u)	V_{angle} (deg)	P_{Dp} (p.u)	Q_{Dp} (p.u)	Q_i^{min} (p.u)	Q_i^{max} (p.u)
1	1	1	0	0	0	2.0000	-0.2000
2	2	1.0430	0	0.2170	0.1270	1.0000	-0.2000
3	3	1	0	0.0240	0.0120	0	0
4	3	1	0	0.0760	0.0160	0	0
5	2	1.0100	0	0.9420	0.1900	0.8000	-0.1500
6	3	1	0	0	0	0	0
7	3	1	0	0.2280	0.1090	0	0
8	2	1.0100	0	0.3000	0.3000	0.6000	-0.1500
9	3	1	0	0	0	0	0
10	3	1	0	0.0580	0.0200	0	0
11	2	1.0820	0	0	0	0.5000	-0.1000
12	3	1	0	0.1120	0.0750	0	0
13	2	1.0710	0	0	0	0.6000	-0.1500
14	3	1	0	0.0620	0.0160	0	0
15	3	1	0	0.0820	0.0250	0	0
16	3	1	0	0.0350	0.0180	0	0
17	3	1	0	0.0900	0.0580	0	0
18	3	1	0	0.0320	0.00900	0	0
19	3	1	0	0.0950	0.0340	0	0
20	3	1	0	0.0220	0.0070	0	0
21	3	1	0	0.1750	0.1120	0	0
22	3	1	0	0	0	0	0
23	3	1	0	0.0320	0.0160	0	0
24	3	1	0	0.0870	0.0670	0	0
25	3	1	0	0	0	0	0
26	3	1	0	0.0350	0.0230	0	0
27	3	1	0	0	0	0	0
28	3	1	0	0	0	0	0
29	3	1	0	0.0240	0.0090	0	0
30	3	1	0	0.106	0.0190	0	0

Note: Bus type: Slack bus =1. P-V bus = 2. P-Q bus = 3.

Table A.2: Branch data used for 30-bus system.

Branch no.	From	to	R (p.u)	X (p.u)	B (p.u)	Tap (p.u)	Rating (MVA)
1	1	2	0.01920	0.0575	0.0264	1	130
2	1	3	0.04520	0.1852	0.0204	1	130
3	2	4	0.05700	0.1737	0.0184	1	65
4	3	4	0.01320	0.0379	0.0042	1	130
5	2	5	0.04720	0.1983	0.0209	1	130
6	2	6	0.05810	0.1763	0.0187	1	65
7	4	6	0.01190	0.0414	0.0045	1	90
8	5	7	0.04600	0.1160	0.0102	1	70
9	6	7	0.02670	0.0820	0.0085	1	130
10	6	8	0.01200	0.0420	0.0045	1	32
11	6	9	0	0.2080	0	1. 078	65
12	6	10	0	0.5560	0	1. 069	32
13	9	11	0	0.2080	0	1	65
14	9	10	0	0.1100	0	1	65
15	4	12	0	0.2560	0	1.032	65
16	12	13	0	0.1400	0	1	65
17	12	14	0.1231	0.2559	0	1	32
18	12	15	0.0662	0.1304	0	1	32
19	12	16	0.0945	0.1987	0	1	32
20	14	15	0.2210	0.1997	0	1	16
21	16	17	0.0824	0.1923	0	1	16
22	15	18	0.1073	0.2185	0	1	16
23	18	19	0.0639	0.1292	0	1	16
24	19	20	0.0340	0.0680	0	1	32
25	10	20	0.0936	0.2090	0	1	32
26	10	17	0.0324	0.0845	0	1	32
27	10	21	0.0348	0.0749	0	1	32
28	10	22	0.0727	0.1499	0	1	32
29	21	22	0.0116	0.0236	0	1	32
30	15	23	0.1000	0.2020	0	1	16
31	22	24	0.1150	0.1790	0	1	16
32	23	24	0.1320	0.2700	0	1	16
33	24	25	0.1885	0.3292	0	1	16
34	25	26	0.2544	0.3800	0	1	16
35	25	27	0.1093	0.2087	0	1	16
36	28	27	0	0.3960	0	1.068	65
37	27	29	0.2198	0.4153	0	1	16
38	27	30	0.3202	0.6027	0	1	16
39	29	30	0.2399	0.4533	0	1	16
40	8	28	0.0636	0.2000	0.0214	1	32
41	6	28	0.0169	0.0599	0.0650	1	32

Table A.3: Cost coefficients of generators for IEEE 30-bus system.

N° bus	P_i^{min}	P_i^{max}	Q_i^{min}	Q_i^{max}	a_i	b_i	c_i	e_i	f_i
1	50	200	-20	200	0	2	0.00375	50	0.063
2	20	80	-20	100	0	1.75	0.0175	40	0.098
5	15	50	-15	80	0	1	0.0625	0.0	0.0
8	10	35	-15	60	0	3.25	0.00834	0.0	0.0
11	10	30	-10	50	0	3	0.025	0.0	0.0
13	12	40	-15	60	0	3	0.025	0.0	0.0

Table A.4: Emission coefficients of generators for IEEE 30-bus system.

N° bus	α_i	$\beta_i \times 10^{-4}$	$\gamma_i \times 10^{-6}$	$\omega_i \times 10^{-4}$	μ_i	h_i
1	0.0409	-5.5540	6.4900	2.0000	0.0286	436.80
2	0.0254	-6.0470	5.6380	5.0000	0.0333	2068.965
5	0.0426	-5.0940	4.5860	0.0100	0.0800	1016.1713
8	0.0533	-3.5500	3.3800	20.0000	0.0200	680.2857
11	0.0426	-5.0940	4.5860	0.0100	0.0800	1031.7460
13	0.0614	-5.5550	5.1510	10.0000	0.0667	640.7746