# Optimization Techniques to Enhance Voltage Stability in Power System: A Review Towards Improving Bhutanese Power Network

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**Abstract** –*With the rising trend of restructuring in the electric power industry like the inclusion of renewable energy (RE) and stretching of long lines, several transmission lines are forced to operate at almost full capacity. As a result, more incidents of voltage instability are being recorded, culminating in major system failures. Bhutanese people are used to experiencing numerous voltage dips and swells since decades but no hue and cry was heard. However, with more sensitive equipments and devices imported into the country, the need of stable and reliable power are realized. The voltage stability studies seek to maintain consistently acceptable voltages in all power system buses under normal and post-disturbance situations. It is critical to focus on voltage integrity, which might otherwise result in massive losses. One of the primary causes of voltage failure, among others, is an insufficient supply of reactive power in the system. The reactive power handling capabilities of a system can be enhanced by using a flexible AC transmission systems (FACTS) device. Nonetheless, given the cost implications, Bhutan may not opt for FACTS devices. This paper, therefore, presents and examines different optimization algorithms used to improve the voltage profile of the network through various methods. The paper makes a comparative analysis of modern and widely used optimization techniques to achieve enhancement in voltage stability. The hybrid optimization techniques are preffered over one but focusing on having effective control system in the generation, optimal tap setting for every transformer, and encouraging DG integration at weak buses are recommended.*

***Keywords***: *enhancement of voltage stability,optimization techniques, reactive power planning, real power loss minimization*

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## I. Introduction

Bhutanese people are blessed with tremendous potential to harness renewable energy. Bhutan has so far harnessed only 2,326 MW of the estimated potential of 36,900 MW of hydropower [1] and just 9 MW of combined wind and solar of the estimated potential of 12 gigawatts (GW) of solar and 760 megawatts (MW) of wind energy, respectively [2]. Bhutan's power sector provides a significant contribution to its national economy by selling almost 70 % of its power generated to India. The country generates surplus power during the monsoon season from its run-of-river hydropower infrastructure but in lean seasons (November–March) owing to reduced flow in the rivers, the country relies on energy imports. With the inclusion of wind and solar energy generation in recent years, the issue of insufficient domestic demand in lean seasons is expected to be met.

With the rising trend of restructuring in the electric power industry like the inclusion of renewable energy (RE) and stretching of long lines, several transmission lines throughout the world have been forced to operate at almost full capacity. As a result, more incidents of voltage instability and collapse are being recorded, culminating in major system failures. Bhutan also have been facing similar issues since the country started generating electricity. But interestingly, people did not seem to bother much. With more sensitive equipments and devices come into the country, now people are realizing the need of stable and reliable power.

To avoid these adverse situations, a rapid and exact estimation of voltage stability margin is required. In a power system, reliability is the key factor, but varying terminal voltages and frequency oscillations tend to impair the system's reliability [3]. Voltage instability occurs primarily because reactive power, unlike active power, cannot be transferred over long distances. As a result, a power system with a lot of reactive power resources is less likely to have voltage stability issues.

The line losses cannot be removed, but they can be reduced to a certain extent by employing modern optimization algorithms [4]. Power System Optimization (PSO) presents traditional and meta-heuristic optimization approaches and algorithms for power system research. The classic aspects of optimization in power systems covered optimal power flow, economic dispatch, unit commitment, and power quality optimization. Moreover, issues relating to distributed generation sizing, allocation problems, scheduling of renewable resources, energy storage, power reserve-based problems, efficient use of smart grid capabilities, and protection studies in modern power systems are also included. The optimization methods are widely used in reactive power planning (RPP) and enhancement of voltage stability.

Voltage deviation and stability constrained RPP, is a critical and hard topic in power systems due to its complex goal functions, restrictions, and solution techniques [5], [6]. However, voltage stability is a key concern for engineers in power system construction, operation, and planning [7]. To supply customers with efficient, consistent, clean, and stable electrical power, the power system must operate closer to its stability limitations [8], [9]. For example; Automatic Voltage Regulator (AVR) and Load Frequency Controller (LFC) are used to maintain terminal voltages and reduce frequency oscillations, respectively [3]. The power system stabilizer (PSS) can compensate for the negative damping of AVR. PSS includes counter-stabilizing signals to reduce oscillations caused by AVR and LFC. The generator must be outfitted with gear that allows it to cope with fluctuating load circumstances and simultaneous flickering. PSS's efficacy is determined by the controller it includes. In this circumstance, the stability of the power system becomes the center of attention and remains one of the most difficult challenges confronting the power community and particularly in the Bhutanese power system [10].

Typically, a reactive power dispatch is performed to get the optimal values of control variables in order to decrease transmission loss and enhance the system's voltage profile while satisfying the device and system constraints. This type of circumstance gives rise to a non-linear optimization mixed-integer problem [11]. Several techniques have been used to tackle the problem, however, there have been difficulties in dealing with the restrictions [12].

Multi-objective optimization is expected to be used in most real-life problems. Therefore, all the optimization techniques work to optimize (whether to maximize or minimize) the objective functions based on the different constraints.

The problem is constructed based on the following assumptions:

- The system under consideration is balanced.
- Active and reactive power is calculated at the fundamental frequency, and extra power at harmonic frequency is considered insignificant.
- The size of the reactive source is regarded as a continuous variable, even though it is discrete.
- The reactive capability of a generator is portrayed by the conventional P-Q diagram, but for the planning study, it is usually sufficient to assume a fixed upper limit relevant to the generator MW output.

This paper provides an extensive review of the optimization methods used in the world recently and some feasible suggestions are made in connection to the Bhutanese situation. The paper is sequenced with the formulation of problem. The different optimization methods are then discussed with comparative analysis of each and then the results are discussed. The probable recommendations are made and finally conclusion is proposed.

## II. Materials and Method

### *A. Voltage stability evaluations*

The voltage profile for a typical IEEE-30 bus for line outage is presented in Fig. 1.

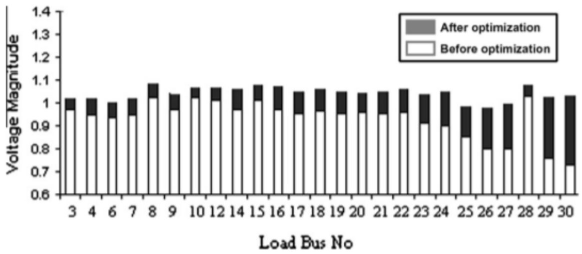


Fig. 1. The voltage profile with line-outage 28-27 [13]

It is evident from Fig. 1 that the voltage is never the same for all the buses. Rather the bus voltage keeps decreasing (the voltage profile before optimization) as the distance from the generation increases. The voltages at buses 26, 27, 29, and 30 are very low even defying the voltage regulation of the system. However, the voltage level could be somehow brought to the stability range by using optimization techniques.

The major causes of voltage instability are: unsuitable positions of FACTS controllers, high load reactive power usage, frequency of contingencies, ON-Load Tap-Changer (OLTC) reverse action, voltage sources too far from load centers, poor communication between multiple FACTS controllers, continuous power load presence, transmission gap [14]. Therefore, there is a need to find out the mitigation measures to this. Voltage instability may be avoided using a variety of approaches:

- the installation of Series or Shunt Capacitors
- Installation of Synchronous condensers
- Shedding of Low-Voltage Load
- Tap-Changer in Reverse Operation
- Rescheduling of generations
- distributed generations (DGs)
- Multi-FACTS Controller Coordination
- the placement of FACTS devices

There can be series of methods to improve the voltage stability but to achive the place and value of of devices and methods mentioned above requires good optimization methods/algorithms. For example, optimization methods can be used to get the optimal location of shunt capacitors or FACTS devices.

### *A.1 Model Analysis for voltage stability Evaluation*

Modal analysis is one of the most effective approaches for improving voltage stability in power systems. The power flow equations for a steady-state system are provided by:

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{bmatrix}J_{P\delta} & J_{PV}\\ J_{Q\delta} & J_{QV}\end{bmatrix}\begin{bmatrix}\Delta \delta\\ \Delta V\end{bmatrix} \quad (1)$$

where,
$\Delta P$- incremental change in bus real power
$\Delta Q$- incremental change in bus reactive power injection
$\Delta\delta$- incremental change in voltage angle
$\Delta V$- incremental change in bus voltage magnitude
$J_{P\delta}$, $J_{PV}$, $J_{Q\delta}$, $J_{QV}$ are Jacobian matrices and the sub-matrices of the system voltage stability affected by $P$ and $Q$.

If $\Delta P = 0$, then

$$\Delta Q = \left[J_{QV} - J_{Q\delta}J_{P\delta}^{-1}J_{PV}\right]\Delta V = J_R\Delta V \quad (2)$$

$$\Delta V = J_R^{-1} - \Delta Q \quad (3)$$

Where,

$$J_R = \left(J_{QV} - J_{Q\delta}J_{PQ}^{-1}J_{PV}\right) \quad (4)$$

$J_R$ is called the reduced Jacobian matrix of the system.

### *A.2 Modes of voltage instability*

The system's voltage stability characteristics were determined by calculating the Eigenvalues and Eigenvectors.

Let,

$$J_R = \xi\varphi\eta \quad (5)$$

Where, $\xi$- right eigenvector matrix of $J_R$
$\eta$- left eigenvector matrix of $J_R$
$\varphi$- diagonal eigenvalue matrix of $J_R$, and

$$J_R^{-1} = \xi\varphi^{-1}\eta \quad (6)$$

From Eq. (3) and (6),

$$\Delta V = \xi\varphi^{-1}\eta\Delta Q \quad (7)$$

Or,

$$\Delta V = \sum \frac{\xi_i\eta_i}{\lambda_\mathrm{i}}\Delta Q \quad (8)$$

where, 'suffix' '$i$' represents the $i^{th}$ column/row for eigenvector.
$\lambda_i$- the $i^{th}$ eigenvalue of $J_R$
The corresponding $i^{th}$ modal voltage variation is given by:

$$\Delta \mathrm{Q}_{\mathrm{mi}} = K_i\xi_i \quad (9)$$

where,

$$\mathrm{K_i} = \sum_j \xi_{ij}^2 - 1 \quad (10)$$

$\xi_{ij}$ is the $j^{th}$ element of $\xi_i$
The corresponding $i^{th}$ modal voltage variation is given by:

$$\Delta \mathrm{V}_{\mathrm{mi}} = \left[\frac{1}{\lambda_i}\right]\Delta Q_{mi} \quad (11)$$

If $|\lambda_i| = 0$, then the $i^{th}$ modal voltage will collapse.

In Eq. (11), let $\Delta Q_{mi}$ has all its elements zero except for $k^{th}$ as 1. Then Eq. (8) can be restated as,

$$\Delta V = \sum_k \frac{\eta_{1k}\xi_1}{\lambda_1} \quad (12)$$

Where, $\eta_{1k}$ represents $k^{th}$ element of $\eta_1$

Then, the $V-Q$ sensitivity at bus $k$ would be:

$$\frac{\partial V_k}{\partial Q_k} = \sum \frac{\xi_1\eta_{1k}}{\lambda_1}\Delta Q = \sum_i \frac{P_{ki}}{\lambda_1} \quad (13)$$

### B. Optimization Problem Formulation

#### B.1 Minimizing Real Power Loss

The major worry with increasing load is an increase in transmission loss as well as a difficulty with voltage stability. As a result, when the system loading is gradually raised, reactive power assistance is required to maintain the voltage stability. As a result, the primary goal of any RPP study is to reduce the real power loss, as represented by Eq. (14), and to minimize voltage variation at weak buses under various loading circumstances. The cost of the system rises as a result of the system's significant losses. To lower this cost, the device's power loss is minimized [38]. As a result, the economic goal is largely to reduce active power loss in the transmission system [16]–[18]. It may be expressed numerically as:

$$P_L = \sum_{k=(i,j)}^{n} g_k\left(V_i^2 + V_j^2 + 2V_iV_j\cos\delta_{ij}\right) \qquad (14)$$

Where, $n$ is the number of transmission lines, $g_k$ is the conductance of the branch $k$, $V_i$ and $V_j$ are voltage magnitudes at bus $i$ and bus $j$, $\delta_{ij}$ is the voltage angle difference between two buses.

According to Eq. (14), active power loss is a function of bus voltages, phase angles, and line conductance. The Var sources in the power network, such as generators, OLTCs, static capacitors, and FACTS devices can help to enhance voltage profile. FACTS devices particularly affect line reactance and thus have a great impact on power flow control.

#### B.2 Minimizing voltage deviation

Fitness function for voltage deviation (VD) provides information about the minimization of voltage deviation magnitudes at load buses. However, keeping a steady voltage profile in the power system for secure operation is a challenging objective. Mathematically, the reduction of (VD) can be characterized as [18], [19]:

$$V_D = \sum_{i=1}^{N_{BUS}} |V_i - 1.0| \qquad (15)$$

where, $N_{BUS}$ is the number of buses.

#### B.3 System Constraints

a. Load flow equality constraint: -

Nodal active and reactive power balance [16]

$$P_{Gi} - P_{Di} - P(V,\delta) = 0 \qquad (16)$$

$$Q_{Gi} - Q_{Di} - Q(V,\delta) = 0 \qquad (17)$$

Where, $i = 1,2 \ldots n$, $n$ is the number of buses. $P_G$ and $Q_G$ are real and reactive power of the generator, $P_D$ and $Q_D$ are the real and reactive power load of the generator.

b. Inequality constraints: -

1. Bus voltage limits:

$$V_i^{min} \le V_i \le V_i^{max} \qquad (18)$$

2. Transformer tap-setting limit:

$$T_k^{min} \le T_k \le T_k^{max} \qquad (19)$$

3. Reactive power generation limit:

$$Q_{Gi}^{min} \le Q_{Gi} \le Q_{Gi} \qquad (20)$$

4. Reactive power source installation limit:

$$Q_{Ci}^{min} \le Q_{ci} \le Q_{Ci}^{max} \qquad (21)$$

5. Transmission line apparent power flow limit:

$$S_l \le S_l^{max} \qquad (22)$$

These limitations represent the system's operational restrictions. The control variables include generator terminal bus voltages, transformer tap setting, and reactive power generated by the capacitor bank. Slack bus voltage, load bus voltages, reactive power production, and line flow limit where active power is created are state variables. The state variables are satisfied by applying a penalty to the objective function. Depending on the kind of issue, different optimization techniques employ all or some of the equations given above.

## III. Optimization Algorithms used in Power System

There is now a big push in the field of soft computing research to find novel optimization strategies based on nature. Fig. 2 depicts several approaches to optimization strategies. However, many other techniques are being proposed by combining one or more of the techniques presented.

A number of traditional mathematical programming-based approaches have been offered to tackle the reactive power dispatch problem. The Newton technique [17], Monte Carlo Simulations [20], Linear Programming (LP) [21], [22] are examples of these methods. Certain disadvantages are, however, mentioned. Such approaches using derivatives and gradients, for example, may be incapable of determining the global optimum. It is also not viable to incorporate the discrete variables associated with the tap-changing transformer directly into the algorithm. These approaches also have downsides, such as a long calculation time and a lack of flexibility for a real system. As a result, it is critical to develop more accurate and effective algorithms capable of overcoming all of the drawbacks of traditional optimization approaches. [23], [24]. As a result, classical algorithms are not explored in depth in this work, instead focusing on several popular and frequently utilized nature-inspired metaheuristics approaches.

When an optimization issue involves more than one objective function, the process of assessing one or more optimum solutions is known as multi-objective optimization [25]. One of these techniques is multi-objective differential equation [26]–[28], Eagle Strategy Particle Swarm Optimization (EPSO) [29], [30], Genetic algorithm (GA) [11], [31]–[35], micro-genetic algorithm [10], Enhanced Genetic Algorithm [36], whale optimization algorithm (WOA) [37], Artificial Neural Network (ANN) [38], Red Wolf Optimization (ERWO) [12], Crow Search Algorithm [39], firefly algorithm [40], Ant Algorithm [41] and gravitational search algorithm (GSA) [42].

A few of the most popular and trendy optimization approaches are described here.

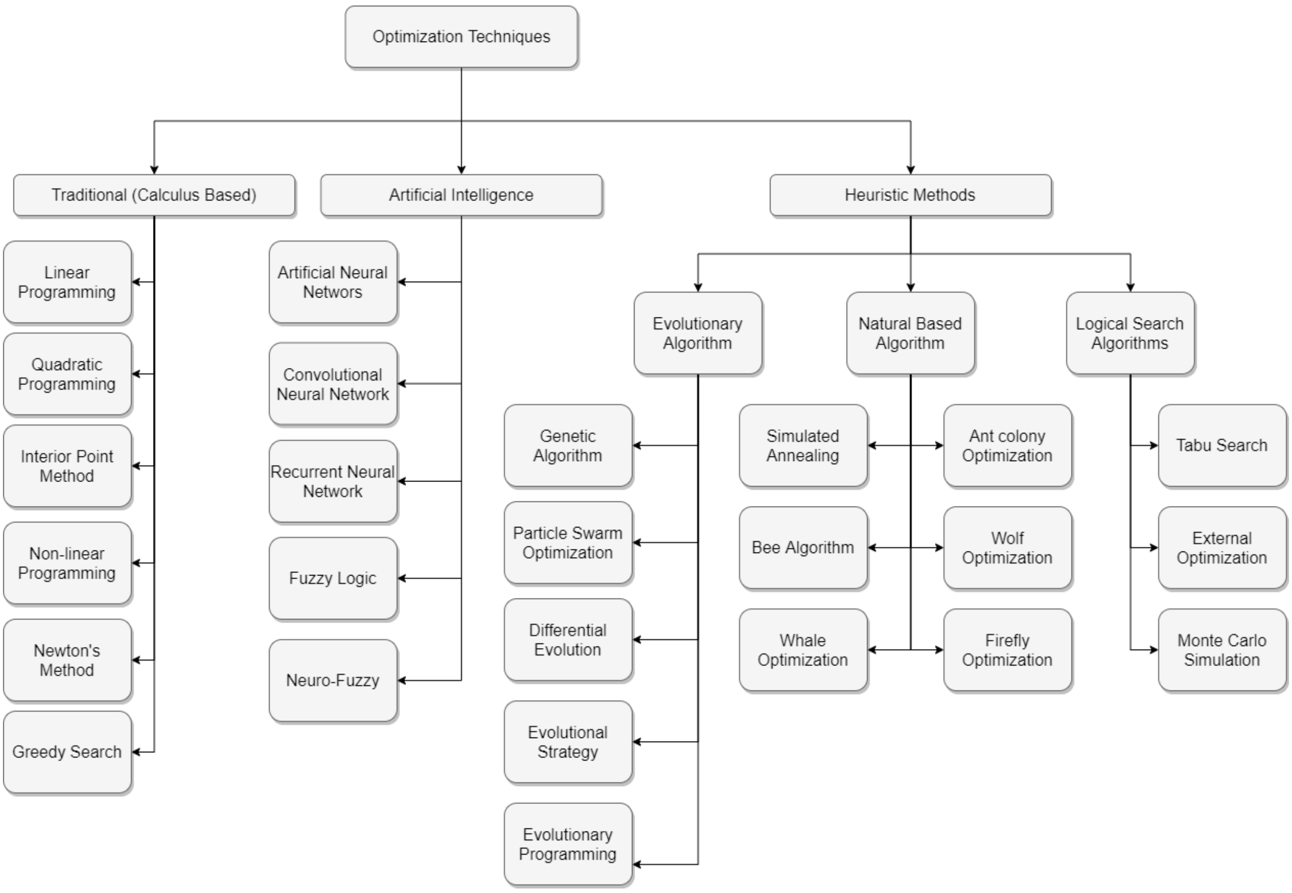


Fig. 2. The optimization techniques used in the power system

## 1. *Particle swarm optimization*

Particle swarm optimization (PSO) is a stochastic optimization that is inspired by the behavior of an intelligent group of species like birds and fish. The flow chart of general PSO is presented in Fig. 3. In PSO, the possible solutions, or particles, travel through the problem area by following the optimal already existing particles. In terms of both speed and memory requirements, PSO is more effective compared to many other traditional techniques. Much research is conducted to enhance the voltage stability while reducing the active power losses. In reference [46], PSO is used along with voltage stability constraints- optimal power flow (VSC-OPF) to obtain enhancement of voltage stability. Similarly, PSO can also be used to tune PSS for dynamic stability improvement [47]. PSO can also be used to find the optimal location and optimal reactive power reserve management with FACTS devices [48], [49]. The hybridization of PSO with other methods is also used in voltage stability enhancement to derive the best characteristics of the combined methods. Lenin [50] has used Eagle Strategy (ES) with Particle Swarm Optimization (PSO). Similarly, reference [51] has proposed hybrid PSO and ANN to predict the voltage stability in the power system network.

*2. Genetic Algorithm*

Genetic Algorithms (GA) ideas are directly drawn from natural evolution [52]. It is based on Darwin's theory of evaluation's'survival of the fittest' premise. Furthermore, to reach the global optimum, they integrate function evaluation with the random exchange of information among solutions [53]. The evident limits of PSO, as previously mentioned, are less straightforward and dependable than GA. This approach is a mixed-integer nonlinear optimization problem [11]. GA adheres to the flow chart depicted in Fig. 4.

Chandrasekhar et al, [33] have investigated the use of GA in voltage stability improvement. It is based on the monitoring of the 'L-index' of load buses. Similar research was conducted by Wahab et al, [54] where they tried to search the optimal transformer tap setting to minimize the line losses. Devaraj et al [32] has provided an improved Genetic algorithm (GA) approach as a means to enhance voltage stability. The suggested approach is based on minimizing the maximum of load bus L-indices. This problem's optimization variables include generator voltages, switchable VAR sources, and transformer tap changers.

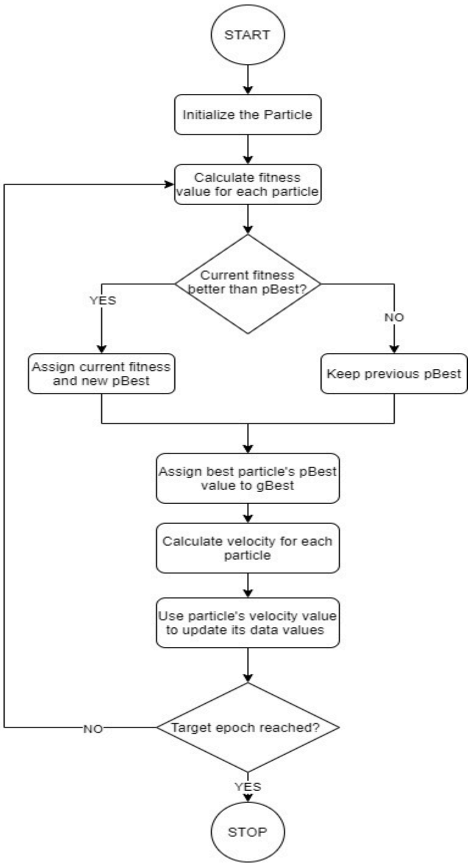


Fig. 3. Flow chart for PSO algorithm

Singh and Srivastara [55] proposed a genetic algorithm-based back propagation neural network (GABPNN). It has been suggested for estimating voltage stability margins, which indicate how close the power system is to voltage collapse. The suggested method employs a hybrid algorithm that combines a genetic algorithm and a backpropagation neural network. Nassar et al. [56] conducted a case study in which they used genetic algorithms to improve voltage profiles in power networks. The condenser bank is allocated using the genetic algorithm (GA) approach.

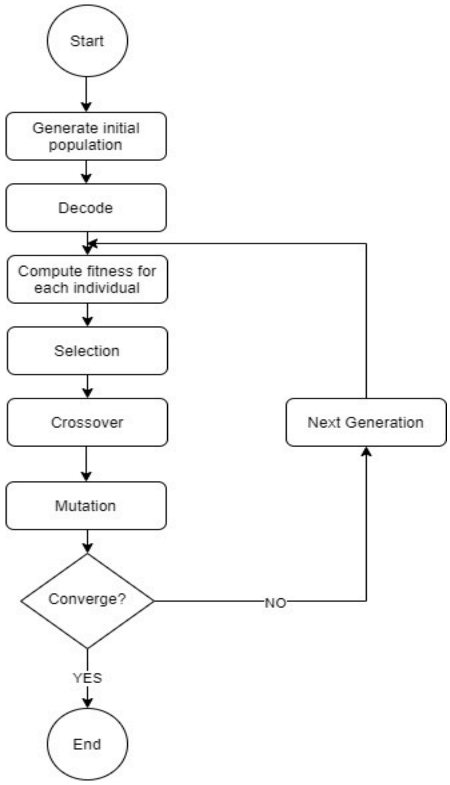


Fig. 4. Flow chart for GA [54]

The most recent GA optimization scenario [57] yields the greatest results. In [58], they discovered that GA may be used to optimize complicated system calculations. To extract the benefits of both GA and ant algorithm methods, overcome their shortcomings, and balance their benefits and drawbacks, [41] has proposed a combined algorithm. To obtain the initial pheromone distribution, the main concept is to apply the genetic algorithm in earlier procedures, taking full use of its rapid, random, global convergence. In the latter phase, an ant algorithm is employed, taking advantage of parallelism, positive feedback, high solution efficiency, and so on. The FACTS device's optimal locations are also calculated using GA in [59]-[61]. Generally, the GA is found to be the best algorithm for obtaining voltage stability [8], [62].

*3. Nature-based Algorithms*

### *3.1 Wolf optimization*

Many swarm intelligence systems resemble some animals' hunting and searching habits. However, because grey and red wolf optimization mimic the internal leadership hierarchy of wolves, the position of the best answer may be thoroughly examined by three solutions during the search process. Other swarm intelligence systems, on the other hand, seek the optimal answer led by a single solution. As a result, WOs can substantially reduce the likelihood of being premature and falling into the local optimum [63].

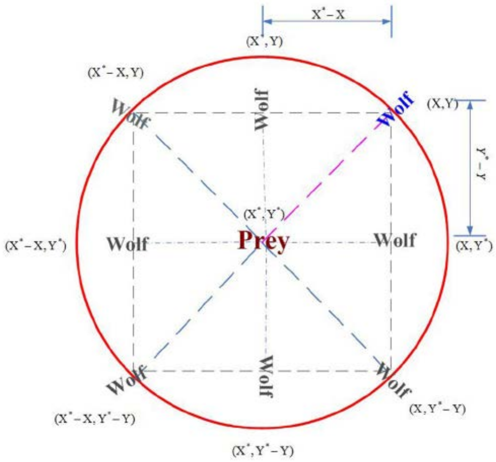


Fig. 5. The 2D location vector and next possible positions

In the optimization process, the locations of wolves (or whales in whale optimization) are pictorially represented in Fig. 5 and the location updating can occur based on Eq. (23) and (24).

$$\vec{D} = \left|\vec{C}.\overrightarrow{X_p}(t) - \vec{X}(t)\right| \tag{23}$$

$$\vec{X}(t+1) = \overrightarrow{X_p}(t) - \vec{A}.\vec{D} \tag{24}$$

where, $t$ represents the $t^{th}$ iteration, $A$, and $C$ are coefficient vectors, $X_p$ is the position vector of prey, $X$ represents the wolf position. The vector $A$ and $C$ can be expressed by:

$$\vec{A} = 2a.\vec{r}_1 - \vec{a} \tag{25}$$

$$\vec{C} = 2.\overrightarrow{r_2} \tag{26}$$

where, the coefficient $\vec{a}$ linearly decreases from 2 to 0 with the increasing of iteration number, $\overrightarrow{r_1}$and $\overrightarrow{r_2}$ are random vectors located in the scope [0, 1].

The works of literature [64], [65] have proposed a grey wolf optimization algorithm for voltage stability enhancement. Weak bus determination, orientation, and real power loss minimization by Var planning using GWOA were also proposed in [66], [67]. Similarly, the GWOA along with PSO is proposed for post-fault transient stability status prediction in [68].

Lenin [12], [69] in his two distinct papers has made the extensive task to provide an improved form of Red Wolf Optimization (RWF). In his earlier paper, the optimal reactive power dispatch problem (ORPD), has been solved by the Enriched Red Wolf Optimization (ERWO) algorithm. It is proposed as a hybridization of the wolf optimization (WO) algorithm with the particle swarm optimization (PSO) algorithm. Each red wolf in the approach has a flag vector whose length is equal to the entire number of integers in the wolf optimization data. In the standard IEEE 30 bus test system, the efficiency of ERWO was tested. According to a simulation research, the enhanced red wolf optimization (ERWO) approach reduces actual power losses and improves voltage stability. In the latter case, he tried another algorithm called an opposition-based red wolf optimization (ORWO) algorithm for the same problem. The red wolf optimization method has been combined with opposition-based learning in this suggested algorithm. The suggested algorithm's convergence speed is expected to be enhanced by this amalgamate method. To find an enhanced candidate solution, estimate the concurrent evaluation of a probability and its corresponding opposite that is closer to the global optimum than an arbitrary candidate solution. The proposed algorithm has been tested in standard IEEE 14-bus and 300-bus test systems. The simulation results demonstrate that the suggested method significantly decreased the real power loss.

### *3.2 Whale optimization Algorithm*

Whale optimization is a newly developed algorithm. It is also a swarm-based algorithm that is used to solve complex optimization problems. It is an algorithm that mimics humpback whale hunting behavior. Because of its distinct advantages, it has found a place in mature population-based methods in a wide range of scientific and engineering fields. A novel technique was designed to tackle the multi-objective actual power loss and bus voltage deviation (VD) minimizations for the grid. Power loss reduction utilizing WOA was proposed in reference [70] when DGs and shunt capacitors were considered.Ang et al, [71] have proposed a multi-objective real power loss and voltage deviation minimization technique using WOA. Similarly, [72] has determined the maximum loadability limit for PS network. The multi-objective WOA is proposed in [73], [74] for optimal allocation and sizing of DGs into the distribution system. Furthermore, [63] has proposed an improved GWO to achieve the proper compromise between exploration and exploitation. It is based on the differential evolution and elimination mechanism. Furthermore, [75] has proposed WOA for the optimal allocation of STATCOM for voltage stability and system loadability. Reference [72] has proposed WOA to determine the maximum loadability limit for power networks. The comparison of WOA result with differential evolution algorithm (DE), multi-agent hybrid PSO (MAHPSO) and hybridized DE and PSO (DEPSO) for IEEE 30- bus and 118-bus are performed.

### 4. Artificial Intelligence-based Algorithms

Recently, machine learning regression approaches have piqued the curiosity of many people who want to analyze voltage stability margins in power systems for online use. The performance of Gaussian Process Regression (GPR), artificial neural network (ANN), support vector machine (SVM), and decision tree (DT), which are frequently used regression models in machine learning, are analyzed and compared in [76]. If the training data is limited, ANN suffers from prediction accuracy. The training data may not be sufficient in the actual world since it is very dependent on the communication method used in the electric grid. This difficulty can be exacerbated if the model is subjected to unforeseen circumstances and topological changes.

In today's world, a power system must be operated in various operating points using a dependable and secure technique. One of the key aspects in achieving this goal is a constant evaluation of voltage stability margin (VSM) [77].

The primary goal of voltage stability analysis is to evaluate if the power system's present operating point is stable. If the total active power provided to the load at the current operating point is $P_{current}$ and $P_{max}$ is the maximum power at that bus as shown in Fig. 6, then the Voltage Stability Margin (VSM) for each load bus may be computed as [76]:

$$VSM_i = P_{max,i} - P_{current,i}; \quad i = 1,2 \ldots l \qquad (27)$$

Where $l$ is the total number of load buses in the power system.

Similarly, the voltage stability margin index (VSMI) for the network is calculated by:

$$VSMI = \min\left(\frac{VSM_i}{P_{max,i}}\right) \qquad (28)$$

VSMI is a voltage collapse indicator in the power system. The VSMI ranges from 1 (no load) to 0 (highest load) (maximum loadability).

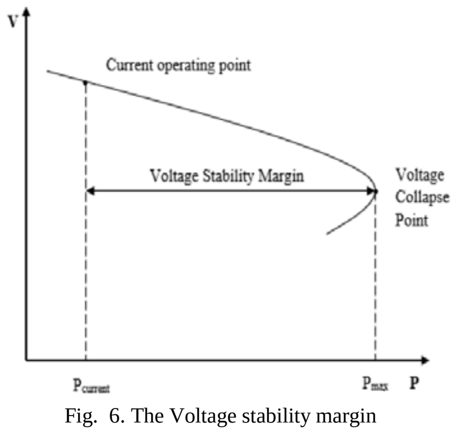


Fig. 6. The Voltage stability margin

### 4.1 Artificial Neural Network

Artificial neural networks (ANNs) have recently been proposed for voltage stability monitoring and evaluation [78]–[83] because they can correctly identify a highly nonlinear relationship and, once trained, can classify fresh data much quicker than solving the model analytically. However, most of the published work in the field of voltage stability used either multilayer perceptron networks or backpropagation algorithms to train them. The general flow chart for any neural network is presented in Fig. 7.

The reason for using ANN in the assessment of voltage stability is as summarized below [78]:

- ANNs can model dynamic, nonlinear, and noisy data. Voltage stability evaluation and live monitoring are simple tasks for ANNs.
- To create a successful system design, ANNs do not require sophisticated programming, perplexing algorithms, or logical inference systems. In other words, ANN-based systems are simple to put in place.
- ANN covers arbitrarily defined forms of dependent and independent variables and requires only a few facts on the process's physical backdrop.

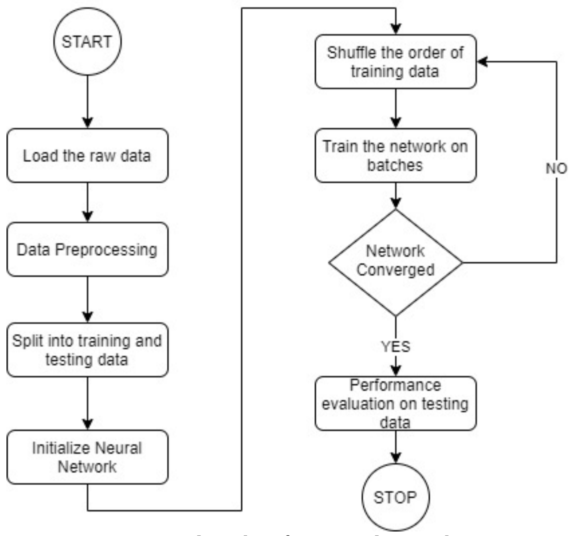


Fig. 7. Flow chart for a neural network

The ANN is proposed, respectively in [84] and [85] for the application for voltage control and power flow control of using Unified power flow controller (UPFC) and studying voltage and power stability margins of the electrical power system. Online voltage stability monitoring and assessment are performed using ANN respectively in [82] and [86].

### *4.2 Convolutional Neural Network*

CNN [87], [88] is also proposed as a fast assessment of short-term and transient voltage stability. The radial basis function neural network outperforms the feedforward neural network in estimating voltage stability margin [89].

### *4.3 Fuzzy Logic System*

When the fuzzy set idea is employed in power system analysis, only a small amount of work has been done in the application of fuzzy theory to voltage stability enhancement. Reference [90] used fuzzy approaches to locate optimal placement and sizing of multiple DGs. Reference [91] performed voltage stability analysis based on adaptive FL considering load fluctuation. Similarly, the PSS was designed for a multi-machine system having dynamic loads using the adaptive-neuro fuzzy system in [92]. Reference [93] proposed a damping controller to minimize the uncertainties to have improved PS stability using wide-area fuzzy-2 logic. Moreover, reference [94], the voltage stability is predicted using an L-index, and the accompanying uncertainties are efficiently represented. However, more of the fuzzy logic algorithm is adapted in DGs and micro-grids [95]–[99].

The fuzzy logic system can also be used along with the FACTS devices. For instance, [100] used Fuzzy-PID-based STATCOM to analyze power system stability. Similarly, [101] used fuzzy logic for examining the performance of UPFC.

Some combinations of fuzzy logic and neural networks (ANFIS) are combined to obtain the hybrid behavior in the optimization. Reference [102], [103] have proposed ANFIS to enhance voltage stability on wind farms using the optimally controlled SVC. Reference [102] proposed ANFIS and PSO algorithm to determine the optimal location of STATCOM for voltage stability enhancement. Reference [105], [106] proposed ANFIS as the hybrid algorithm to further improve the results.

## IV. Result and Discussion

The best algorithm for solving an optimization issue is largely determined by the problem type. A linear solver, such as the Simplex technique, can be used to efficiently solve a linear programming issue. A convex programming procedure, such as the interior-point technique, can be used to solve a nonlinear convex programming issue. Similarly, a nonconvex nonlinear programming issue can be effectively addressed using a nonconvex method. However, when an issue is extremely complicated and it is impossible to determine the nature of the problem, it can be solved utilizing metaheuristic algorithms such as the genetic algorithm, particle swarm optimization, differential evolution, and so on. In brief, the best optimization algorithm is problem-specific.

It is determined by a variety of factors, including:

1. Computational complexity
2. The number of iterations
3. Mutation factors/particle speed/initial weights

For instance, if computing complexity is not of concern, Differential Evolution provides a more accurate solution to issues. Remember that all these options are for offline tuning since online tuning may not be a viable answer in terms of implementation.

The comparative analysis is performed on few widely used algorithms. It is found out that WOA followed by PSO gives the minimum loss as shown in Table I.

TABLE I
COMPARISON OF ACTIVE POWER LOSSES BY DIFFERENT METHODS

| Optimization Method | Losses before Optimization (MW) | Losses after Optimization (MW) |
|---|---|---|
| *Genetic Algorithm* | 14.72 | 13.91 |
| *Red Wolf Optimization* | 14.72 | 13.87 |
| *Particle Swarm Optimization* | 14.72 | 13.85 |
| *Wale Optimization Algorithm* | 14.72 | 13.70 |

Nevertheless, the Genetic Algorithm was found to be yielding the best performance when the voltage deviation is taken into consideration as presented in Table II. The results are further improved when two or more optimization techniques are used parallelly. However, it happens at the cost of complexity, cost, and simulation time.

TABLE II
COMPARISON OF ACTIVE POWER LOSSES CONSIDERING VOLTAGE DEVIATION BY DIFFERENT METHODS

| Optimization Method | Losses before Optimization (MW) | Losses after Optimization (MW) |
|---|---|---|
| *Genetic Algorithm* | 0.44 | 0.295 |
| *Red Wolf Optimization* | 0.44 | 0.298 |
| *Particle Swam Optimization* | 0.44 | 0.297 |
| *Wale Optimization Algorithm* | 0.44 | 0.296 |

As it was evident from Fig. 1, the voltage stability marin is well maintained within the regulation by improving the voltage at the weaker buses by the use of optimization techniques.

## V. Recommendation

It is not so viable for Bhutanese power operators to go for the FACTS devices provided with the fact that Bhutan has control of just about 30 % of whole power generation although 99 % of households in Bhutan are connected to electricity with less than 700,000 people. The payback period and the impact made to the power system would not be prominent even if these devices are installed. The 70 % power is exported to India via five different export points. The optimum dispatch needs to be evaluated because it enhances system security, voltage proficiency, power transfer capability, and overall network efficiency.

The Bhutanese power system's situation is dependent on how the Indian grid performs. Therefore, it is recommended that the controller system in the generation is improved, encourage interconnection of DGs at the weaker buses, use optimal tap settings in the transformer and explore economic dispatch ways to export the power. This can be achieved by the use of the appropriate optimization technique discussed in this paper.

Bhutan might potentially benefit from a hybrid artificial neural network-based technique for monitoring the online voltage security of electric power systems. Voltage stability can be assessed completely, using a proper security index, and locally, by establishing adequate voltage margins for recognizing the buses of the system where the instability phenomena occur [80]. Based on the online monitoring system, Indian counterparts can always be cautioned on the issue and ask them to commit their loads to meet the requirement.

## VI. Conclusion

In this paper, it is investigated that transmission loss, voltage index, and voltage deviation can be minimized with the use of various optimization methods. It becomes difficult with more complex problems to be solved but hybrid optimization techniques are the ultimate solution. However, the best algorithm for solving an optimization issue is largely determined by the problem type. For example, a linear solver, such as the Simplex technique, can be used to efficiently solve a linear programming issue. However, when an issue is extremely complicated and it is impossible to determine the nature of the problem, it can be solved utilizing metaheuristic algorithms such as the genetic algorithm, particle swarm optimization, and differential evolution. Artificial intelligent techniques are in their infant state in solving the optimization problem, but it is expected that it will be dominating soon as lots of research are done on it. Bhutan however can still think of focusing on the cheap, fast, and easy optimization techniques which can help to maintain generation, transmission, and distribution systems at optimal running conditions. For instance, having a good control system in the generation, optimal tap setting for every transformer, and encouraging DG integration at weak buses.

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