CHAPTER 2

OPTIMAL RECONFIGURATION OF RADIAL DISTRIBUTION SYSTEM USING HYBRID FUZZY - TEACHING LEARNING ALGORITHM

2.1 INTRODUCTION

Distribution system reconfiguration is one of the most important techniques followed for the control of power loss. Due to the more usage of non-linear loads by the utility customers, more harmonics are being injected into distribution systems, which may lead to high distortion levels. In order to reduce the distortion level, power quality constraints are included as one among the other operating constraints with the main objective. The primary objective is to minimize the power loss cost of the distribution system while satisfying the power flow, operational and power quality constraints. This chapter proposes Teaching-Learning Algorithm (TLA) to solve the problem. The backward-forward sweep Harmonic Load Flow (HLF) is used to evaluate the harmonics present in the distribution system, which has been integrated with TLA.

Sequentially, to consider the constraints along with the objective, heuristic fuzzy has been integrated with TLA. The constraints are modified as objectives and effectively handled through fuzzy. The proposed hybrid FTLA method has been validated with benchmark systems such as IEEE-33 bus distribution system and 83-bus Taiwan power company distribution system.
2.2 MULTI-OBJECTIVE CRITERIA

The operational and power quality constraints of the reconfiguration problem are modified as objectives. In total, four objectives have been formulated, which includes power loss minimization, bus voltages deviation minimization, branch currents deviation minimization and %THD minimization. The objective functions are given through the equations from (2.1) to (2.4).

The objective function for power loss is given by,

Minimize \( P = P_{\text{Loss}} \) 

(2.1)

The objective function for bus voltages deviation is given by,

Minimize \( V = V_{\text{dev,j}} \); for \( j \in 1 \) to \( nb \) 

(2.2)

The objective function for branch currents deviation is given by,

Minimize \( I = B_{\text{dev,k}} \); for \( k \in 1 \) to \( nl \) 

(2.3)

The objective function for %THD is given by,

Minimize \( F = F_{\text{THD,j}} \); for \( j \in 1 \) to \( nb \) 

(2.4)

The above mentioned single objective functions (equations from (2.1) to (2.4)) are combined into multi objective with the support of fuzzy logic. The detailed description about the combined process using fuzzy logic is explained in section 2.5 and the final expression is arrived at in equation 2.70.
2.3 HARMONIC LOAD FLOW

Once all system components are accurately modeled and the harmonic current sources in RDS are determined, the harmonic power flow calculations can be carried out. The harmonic power flow algorithm (HPF) to be implemented is the one developed by Teng (2002). Interestingly enough, both power flow algorithms and the HPF algorithm, are based on backward-forward sweep technique. In the HPF algorithm, the backward sweep is used to form the relationship matrix between the branch currents and bus current injections for the h\textsuperscript{th} harmonic order, while the forward sweep is utilized to build the relationship matrix between the harmonic bus voltages and harmonic bus current injections.

2.3.1 Harmonic Power Flow Development

To describe the different stages of the harmonic power flow algorithm development, a distorted n-bus RDS whose one line diagram is shown in Figure 2.1.

![A single line diagram of a distorted w-bus radial distribution system](image)
In Figure 2.1, bus 1 represents the main substation (the supply source) and is modeled as a slack bus. The (2-w) load buses are composed of linear and nonlinear loads. The \( h^{th} \) harmonic currents contributed by nonlinear and linear loads can be written in a vector form as follows,

\[
[Ih]^{(h)} = [Ih_2^{(h)} \ldots Ih_{i-1}^{(h)} Ih_i^{(h)} Ih_{i+1}^{(h)} \ldots Ih_n^{(h)}]^T
\]  

(2.5)

Where, \((\cdot)^T\) : the transpose of a vector or a matrix.

In addition to the linear and nonlinear loads, a shunt capacitor is installed at bus \( i \) as shown in Figure 2.1.

The harmonic current absorbed by the shunt capacitor at bus \( i \) is expressed by,

\[
[Is]^{(h)} = [Is^{(h)}]
\]  

(2.6)

Note that the harmonic current vector of shunt capacitors involves only one element and that is the harmonic current absorbed by the shunt capacitor at bus \( i \). The harmonic current vector of shunt capacitors would be of \((\text{No. of capacitors} \times 1)\) dimension in the case of \( nc \) shunt capacitors being installed in RDS. The \( h^{th} \) harmonic currents flowing through the branches are given by,

\[
[I^{(h)}] = \begin{bmatrix}
Ih^{(h)} \\
\ldots \\
Is^{(h)}
\end{bmatrix}
\]  

(2.7)

The backward current sweep is employed to calculate the harmonic currents flowing through the branches as given below,

\[
B^{(h)}_{n-1,n} = Ih_n^{(h)}
\]  

(2.8)
Equations (2.8-2.12) may be written in a matrix form as given in 2.13,

\[
\begin{bmatrix}
B_{i_{2}}^{(h)} \\
\vdots \\
B_{i_{2},i-1}^{(h)} \\
B_{i_{1},i}^{(h)} \\
\vdots \\
B_{n_{-1},n}^{(h)}
\end{bmatrix} =
\begin{bmatrix}
1 & \cdots & 1 & 1 & \cdots & 1 & 1 \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & 1 & 1 & \cdots & 1 \\
0 & \cdots & 0 & 0 & 1 & \cdots & 1 \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & \cdots & 0 & 0 & 0 & \cdots & 1
\end{bmatrix}
\begin{bmatrix}
I_{i_{2}}^{(h)} \\
\vdots \\
I_{i_{1}}^{(h)} \\
I_{i+1}^{(h)} \\
\vdots \\
I_{n}^{(h)} \\
I_{i}^{(h)}
\end{bmatrix}
\]  

(2.13)

Equation (2.13) can be expressed in a compact form given by,

\[
[B^{(h)}] = [A^{(h)}][I^{(h)}]
\]

(2.14)

Where, \([A^{(h)}]\) is the coefficient matrix due to the harmonic current flows through the branches.

The \(h\)th harmonic branch current of any branch can be obtained by:

\[
[B^{(h)}] = [A_{ij}^{(h)}]^T[I^{(h)}]
\]

(2.15)

Where, \([A_{ij}^{(h)}]\) is the coefficient vector of branch (i-j)
The coefficient vector of branch (i-j) is defined by,

\[
[A_{ij}^{(k)}] = \begin{bmatrix}
A_{h_{ij}}^{(h)} \\
\vdots \\
A_{s_{ij}}^{(h)}
\end{bmatrix}
\]  \hspace{1cm} (2.16)

Where, \([A_{h_{ij}}^{(h)}]\) is the coefficient vector of branch (i-j) due to the harmonic current flows of the nonlinear and linear loads through branch (i-j).

\([A_{s_{ij}}^{(h)}]\) is the coefficient vector of branch (i-j) due to the harmonic currents absorbed by the shunt capacitors.

The coefficient vector due to the system harmonic current flows through the branch (1-2) is given by,

\[
[A_{12}^{(h)}] = [A_{s_{12}^{(h)}} : A_{s_{12}^{(h)}}] = [1 \ 1 \ 1 \ 1 \ 1 \ 1]^{T} \hspace{1cm} (2.17)
\]

Note that all the harmonic currents flow through the branch (1-2) towards the supply source (bus 1). Thus, the corresponding elements in the coefficient vector of branch (1-2) take the value of 1.

Similarly, the coefficient vectors of the other branches can be obtained as follows,

\[
[A_{i,j+1}^{(h)}] = [A_{h_{i,j+1}}^{(h)} : A_{s_{i,j+1}}^{(h)}]^{T} = [1 \ \cdots \ 1 \ 1 \ 1 \ 1 : 1]^{T} \hspace{1cm} (2.18)
\]

\[
[A_{i-1,l}^{(h)}] = [A_{h_{i-1,l}}^{(h)} : A_{s_{i-1,l}}^{(h)}]^{T} = [0 \ \cdots \ 0 \ 1 \ 1 \ 0 : 1]^{T} \hspace{1cm} (2.19)
\]

\[
[A_{n-1,n}^{(h)}] = [A_{h_{n-1,n}}^{(h)} : A_{s_{n-1,n}}^{(h)}]^{T} = [0 \ \cdots \ 0 \ 0 \ 0 \ 1 : 0]^{T} \hspace{1cm} (2.20)
\]
From equation (2.20), the only harmonic current flow in branch (n-1, n) is the harmonic current contributed by the load at bus n. Thus, the corresponding element in the coefficient vector is equal to 1, while the remaining elements in the coefficient vector take the value of zero since the harmonic currents associated with these elements in the coefficient vector do not flow through the branch n-1, n. The harmonic voltage drop along the branch (1-2) can be calculated in terms of the harmonic branch impedance and the harmonic branch current as follows,

\[ \Delta V^{(h)}_{12} = Z^{(h)}_{12} B^{(h)}_{12} \]  \hspace{1cm} (2.21)

Equation (2.21) can be expressed in terms of the system harmonic currents as follows:

\[ \Delta V^{(h)}_{12} = Z^{(h)}_{12} [A^{(h)}_{12}]^T [I^{(h)}] \]

\[ = Z^{(h)}_{12} (Ih_2^{(h)} + \ldots + Ih_i^{(h)} + Ih_{i+1}^{(h)} + \ldots + Ih_n^{(h)} + Is_i^{(h)}) \]  \hspace{1cm} (2.22)

In a similar manner, the voltage drops of other branches for the \( h \)th harmonic order are obtained as follows:

\[ \Delta V^{(h)}_{i-1,i} = Z^{(h)}_{i-1,i} [A^{(h)}_{i-1,i}]^T [I^{(h)}] = Z^{(h)}_{i-1,i} (Ih_i^{(h)} + Ih_{i+1}^{(h)} + \ldots + Ih_n^{(h)} + Is_i^{(h)}) \]  \hspace{1cm} (2.23)

\[ \Delta V^{(h)}_{i,i+1} = Z^{(h)}_{i,i+1} [A^{(h)}_{i,i+1}]^T [I^{(h)}] = Z^{(h)}_{i,i+1} (Ih_{i+1}^{(h)} + \ldots + Ih_n^{(h)}) \]  \hspace{1cm} (2.24)

\[ \Delta V^{(h)}_{n-1,n} = Z^{(h)}_{n-1,n} [A^{(h)}_{n-1,n}]^T [I^{(h)}] = Z^{(h)}_{n-1,n} (Ih_n^{(h)}) \]  \hspace{1cm} (2.25)

The forward voltage sweep is utilized to obtain the harmonic bus voltages with respect to harmonic bus current injections as follows:
\[ V_2^{(h)} = V_1^{(h)} - \Delta V_{12}^{(h)} \] (2.26)

Where, \( V_1^{(h)} \) is the slack bus voltage for the \( h^{th} \) harmonic order.

The slack bus voltage for the \( h^{th} \) harmonic order takes the value of zero as the supply source is assumed to supply a pure sinusoidal voltage waveform. In other words, the nonlinear loads are considered the only harmonic sources in RDS. Thus,

\[ V_2^{(h)} = Z_{12}^{(h)} I_{h_2}^{(h)} + \cdots + Z_{12}^{(h)} I_{h_{i-1}}^{(h)} + Z_{12}^{(h)} I_{h_i}^{(h)} + Z_{12}^{(h)} I_{h_{i+1}}^{(h)} + \cdots + Z_{12}^{(h)} I_{h_n}^{(h)} + Z_{12}^{(h)} I_s^{(h)} \] (2.27)

\[ V_{i-1}^{(h)} = Z_{12}^{(h)} I_{h_2}^{(h)} + \cdots + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)}) \] (2.28)

\[ I_{h_i}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_i}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_{i+1}}^{(h)} + \cdots + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_n}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_s^{(h)} \] (2.29)

\[ V_i^{(h)} = Z_{12}^{(h)} I_{h_2}^{(h)} + \cdots + Z_{12}^{(h)} I_{h_{i-1}}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_i}^{(h)} + \cdots + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_{i+1}}^{(h)} + \cdots + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_n}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_s^{(h)} \] (2.30)

\[ V_{i+1}^{(h)} = Z_{12}^{(h)} I_{h_2}^{(h)} + \cdots + Z_{12}^{(h)} I_{h_{i-1}}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_i}^{(h)} + \cdots + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_{i+1}}^{(h)} + \cdots + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_{h_n}^{(h)} + (Z_{12}^{(h)} + \cdots + Z_{i-2,i-1}^{(h)})I_s^{(h)} \] (2.31)
Equation (2.27 – 2.31) may be expressed in a compact form as given by,

\[
[V^{(h)}] = [HA^{(h)}][I^{(h)}] \quad (2.32)
\]

Where, \([V^{(h)}]\) is the harmonic bus voltages vector.

\[
[V^{(h)}] = \begin{bmatrix} V_2^{(h)} & \ldots & V_{i-1}^{(h)} & V_i^{(h)} & V_{i+1}^{(h)} & \ldots & V_n^{(h)} \end{bmatrix}^T \quad (2.33)
\]

\([HA^{(h)}]\) is the relationship matrix between the harmonic bus voltages and system harmonic currents.

The harmonic bus voltages of the shunt capacitors are determined by,

\[
[V_s^{(h)}] = [HA_s^{(h)}][I^{(h)}] \quad (2.34)
\]

Where, \([HA_s^{(h)}]\) is the row vectors of the matrix \([HA^{(h)}]\) associated with the buses at which shunt capacitors are installed.

Note that the dimension of the matrix \([HA_s^{(h)}]\) is 1 \times n for RDS with a single phase shunt capacitor. However, if an n-bus radial distribution system (n-Bus-RDS) is compensated through nc shunt capacitors, then the matrix \([HA_s^{(h)}]\) will be of \(nc \times ((n - 1) + nc)\) dimension. The harmonic voltage of the shunt capacitor at bus i can be expressed in terms of the harmonic impedance of the shunt capacitor as follows,

\[
V_{s_i}^{(h)} = -IS_i^{(h)} \times Z_{s_i}^{(h)} \quad (2.35)
\]

Where, \(IS_i^{(h)}\) is the harmonic current of the shunt capacitor at bus i.
\(Zs_i^{(h)}\) is the harmonic impedance of the shunt capacitor at bus i.
Substituting equation (2.35) into (2.34), equation (2.36) can be obtained.

\[-I_{S_i}^{(h)} \times Z_{S_i}^{(h)} = [H_{A_S}^{(h)}] \begin{bmatrix} I_{h_2}^{(h)} \\ \vdots \\ I_{h_n}^{(h)} \end{bmatrix} \]  
(2.34)

Where, \( I_{h_i}^{(h)} \) is the harmonic current vector of the nonlinear and linear loads.

\( I_{S_i}^{(h)} \) is the harmonic current vector of the shunt capacitors.

The RDS at hand is composed of \((n-1)\) nonlinear and linear loads as well as a single phase shunt capacitor at bus \(i\). Consequently,

\[-I_{S_i}^{(h)} \times Z_{S_i}^{(h)} = \begin{bmatrix} H_{A_S}^{(h)} I_{h_2}^{(h)} \cdots I_{h_{i-1}}^{(h)} I_{h_i}^{(h)} I_{h_{i+1}}^{(h)} \cdots I_{h_n}^{(h)} \end{bmatrix}^{T} \]  
(2.35)

The elements of \((n-1)\) columns in the vector \([H_{A_S}^{(h)}]\) are associated with the harmonic currents of the nonlinear and linear loads, while the last element in \([H_{A_S}^{(h)}]\) is related to the harmonic current of the shunt capacitor at bus \(i\). Therefore, \([H_{A_S}^{(h)}]\) can be written in the form as given in equation (2.38),

\[ [H_{A_S}^{(h)}] = [H_{A_{sh}}^{(h)} : H_{A_{ss}}^{(h)}] \]  
(2.38)

Substituting (2.38) into (2.37) yields,

\[-I_{S_i}^{(h)} \times Z_{S_i}^{(h)} = \begin{bmatrix} H_{A_{sh}}^{(h)} : H_{A_{ss}}^{(h)} \end{bmatrix} \begin{bmatrix} I_{h_2}^{(h)} \cdots I_{h_{i-1}}^{(h)} I_{h_i}^{(h)} I_{h_{i+1}}^{(h)} \cdots I_{h_n}^{(h)} \end{bmatrix}^{T} \]
\[-I_S^{(h)} \times Zs_i^{(h)} = \begin{bmatrix} H_{A_{sh}}^{(h)} \\ I_{h_i}^{(h)} \\ \vdots \\ I_{h_{l-1}}^{(h)} \\ I_{h_{l+1}}^{(h)} \\ \vdots \\ I_{h_n}^{(h)} \end{bmatrix} + [HA_{ss}^{(h)}] \times I_s^{(h)} \] 

(2.39)

\[
([HA_{ss}^{(h)}] \times Zs_i^{(h)}) \times I_s^{(h)} = \begin{bmatrix} H_{A_{sh}}^{(h)} \\ I_{h_i}^{(h)} \\ \vdots \\ I_{h_{l-1}}^{(h)} \\ I_{h_{l+1}}^{(h)} \\ \vdots \\ I_{h_n}^{(h)} \end{bmatrix} + [HA_{ss}^{(h)}] \] 

(2.40)

Note that solving equation (2.40) in terms of the shunt capacitor current for $I_S^{(h)}$ the $h^{th}$ harmonic order requires finding the inverse of $([HA_{ss}^{(h)}] \times Zs_i^{(h)})$. That is;

\[
I_S^{(h)} = [HLF^{(h)}]^{-1} \times [HA_{sh}^{(h)}] 
\] 

(2.41)

Where, 
\[
[HLF^{(h)}] = \left([HA_{sh}^{(h)}] + Zs_i^{(h)}\right) 
\] 

(2.42)

If $nc$ shunt capacitors are installed in RDS, $[HLF^{(h)}]$ will be a square matrix of $(nc \times nc)$ dimension.
Where,

\[ (2.43) \]

It can be observed from equation (2.43) that for an \( n \)-Bus-RDS with \( nc \) shunt capacitors, the calculation of the harmonic currents vector of the shunt capacitors requires building the matrix \( [H_{LF}^{(h)}] \) of \( (nc \times nc) \) dimension and finding the inverse of it. The RDS with three single phase capacitors, for example, would have a matrix \( [H_{LF}^{(h)}] \) of \( (3 \times 3) \) dimension. Once the harmonic currents absorbed by the shunt capacitors are obtained, the harmonic branch currents and bus voltages can be calculated using (2.14) and (2.32) respectively. The harmonic bus voltages are iteratively computed until a pre-specified tolerance is reached.

\[ (2.45) \]

Where,

\( V_{i}^{(h),k+1} \) is the harmonic voltage of bus \( i \) for the iteration \( k + 1 \).

\( V_{i}^{(h),k} \) is the harmonic voltage of bus \( i \) for the iteration \( k \).

\( k \) is the iteration index.

\( \epsilon \) is the pre-specified tolerance.
The total real power loss formula for the $h^{th}$ harmonic order is defined by,

$$P_{loss}^{(h)} = \sum_{i=1}^{nb} P_{loss_i}^{(h)} = \sum_{i=1}^{nb} \sum_{h=h_0}^{h_{max}} |B_i^{(h)}|^2 R_i^{(h)} \quad (2.46)$$

Where, \( h \) is the harmonic order.

\( h_0 \) is the smallest harmonic order of interest.

\( h_{max} \) is the highest harmonic order of interest.

\( |B_i^{(h)}| \) is the magnitude of the \( r^{th} \) branch current for the \( h^{th} \) harmonic order.

\( R_i^{(h)} \) is the \( r^{th} \) branch resistance for the \( h^{th} \) harmonic order.

The total harmonic real power loss can be described in terms of the system harmonic current vector as follows,

$$P_{loss}^{(h)} = [A^{(h)}]^T \cdot [A^{(h)}] \cdot [I^{(h)}]^2 \quad (2.47)$$

Once the harmonic bus voltages are calculated for all harmonic frequencies, the root mean square (rms) values of the bus voltages can be computed by:

$$V_{rms_i} = \sqrt{\left|V_i^{(l)}\right|^2 + \sum_{h=h_0}^{h_{max}} \left|V_i^{(h)}\right|^2}, \; i = 1,2,\ldots,n \quad (2.48)$$

Where, \( \left|V_i^{(l)}\right| \) is the magnitude of bus voltage at the fundamental frequency.

\( h_0, h_{max} \) is the minimum and the maximum harmonic orders of interest.

The total harmonic distortion level of bus \( i \) is defined by,
2.3.2 Harmonic Power Flow Algorithm Implementation

The harmonic power flow algorithm (HPF) is described in Teng (2002) by the following steps:

Step 1. Set the harmonic order to the smallest value of interest \( h = h_0 \).

Step 2. Build the coefficient vector of each branch.

Step 3. Form the relationship matrix \([HA^{(h)}]\) between the harmonic bus voltages and system harmonic currents.

Step 4. For \( nc \) shunt capacitors, build the \([HLF^{(h)}]\) matrix for all harmonic frequencies of interest.

Step 5. Calculate the harmonic currents of the shunt capacitors.

Step 6. Compute the harmonic bus voltage vector for the \( k\)th iteration.

Step 7. Repeat steps (4-5) until a stopping criterion is met.

Step 8. Repeat steps (1-7) until the maximum harmonic order of interest \((h_{max})\) is considered.

Step 9. Calculate the rms values of the harmonic bus voltages.

Step 10. Measure the total harmonic distortion (\% THD) of each bus.

The flow chart of the HPF algorithm is depicted in Figure 2.2.

\[
\text{\% THD}_i = \sqrt{\sum_{h=h_0}^{h_{max}} \left| v_i^{(h)} \right|^2} / \left| v_i^{(0)} \right|^2
\] (2.49)
Figure 2.2 A flow chart of the harmonic power flow algorithm

Set harmonic order $h = h_0$

Build $[HA^{(h)}] & [A_i^{(h)}]$

Form matrix $[HA^{(h)}]$

Calculate system harmonic currents

Compute harmonic bus voltage

Converged?

Yes

$h = h_0 + \Delta h$

$h_{max}$ considered?

No

Yes

Calculate $THD_i(\%)$ for each bus
2.4 TEACHING-LEARNING ALGORITHM

The Teaching Learning Algorithm (TLA) method is based on the effect of the influence of a teacher on the output of learners in a class which is described in Rao et al (2011). It is a population based method and like other population based methods it uses a population of solutions to proceed to the global solution. A group of learners constitute the population in TLA.

In any optimization algorithms there are numbers of different design variables. The different design variables in TLA are analogous to different subjects offered to learners and the learners’ result is analogous to the ‘fitness,’ as in other population-based optimization techniques. As the teacher is considered the most learned person in the society, the best solution so far is analogous to Teacher in TLA. The process of TLA is divided into two parts. The first part consists of the “Teacher phase” and the second part consists of the “Learner phase”. The “Teacher phase” means learning from the teacher and the “Learner phase” means learning through the interaction between learners.

2.4.1 Initialization

Following are the notations used for describing the TLA, N: number of learners in class i.e. “class size”, D: number of courses offered to the learners, MAXIT: maximum number of allowable iterations.

The population X is randomly initialized by a search space bounded by matrix of N rows and D columns. The $j^{th}$ parameter of the $i^{th}$ learner is assigned values randomly using the equation,

$$x_{(i,j)}^0 = x_{j}^{\text{min}} + \text{rand} \times (x_{j}^{\text{max}} - x_{j}^{\text{min}})$$

(2.50)

Where, \( \text{rand} \) represents a uniformly distributed random variable within the range (0, 1).
\( x_j^{min} \) and \( x_j^{max} \) represents the minimum and maximum value for \( j^{th} \) parameter.

### 2.4.2 Teacher Phase

The parameters of \( i^{th} \) learner for the generation \( g \) are given by,

\[
x_{(i)}^g = [x_{(i,1)}^g, x_{(i,2)}^g, x_{(i,3)}^g, \ldots, x_{(i,j)}^g, \ldots, x_{(i,D)}^g]
\]  

(2.51)

The mean parameter \( M^g \) of each subject of the learners in the class at generation \( g \) is given as,

\[
M^g = [m_1^g, m_2^g, \ldots, m_j^g, \ldots, m_D^g]
\]  

(2.52)

The learner with the minimum objective function value is considered as the teacher \( X_{Teacher}^g \) for respective iteration. The Teacher phase makes the algorithm proceed by shifting the mean of the learners towards its teacher. To obtain a new set of improved learners a random weighted differential vector is formed from the current mean and the desired mean parameters and added to the existing population of learners.

\[
X_{new}^g_{(i)} = X_{(i)}^g + rand \times (X_{Teacher}^g - T_F M^g)
\]  

(2.53)

\( T_F \) is the teaching factor which decides the value of mean to be changed. Value of \( T_F \) can be either 1 or 2. The value of \( T_F \) is decided randomly with equal probability as,

\[
T_F = round[1 + rand(0.1)(2 - 1)]
\]  

(2.54)

Where, \( T_F \) is not a parameter of the Teaching Learning Algorithm (TLA).
The value of $T_F$ is not given as an input to the algorithm and its value is randomly decided by the algorithm using the above equation. After conducting a number of experiments on many benchmark functions it is concluded that the algorithm performs better if the value of $T_F$ is between 1 and 2. However, the algorithm is found to perform much better if the value of $T_F$ is either 1 or 2 and hence to simplify the algorithm, the teaching factor is suggested to take either 1 or 2 depending on the rounding up criteria given by the above equation.

If $X_{new}^{g}(i)$ is found to be a superior learner than $X_{(i)}^{g}$, in generation $g$, then it replaces inferior learner $X_{(i)}^{g}$ in the matrix.

### 2.4.3 Learner Phase

In this phase the interaction of learners with one another takes place. The process of mutual interaction tends to increase the knowledge of the learner. The random interaction among learners improves his or her knowledge. For a given learner $X_{(i)}^{g}$, another learner $X_{(r)}^{g}$ is randomly selected ($i \neq r$). The $i^{th}$ parameter of the matrix $X_{new}$ in the learner phase is given as,

$$X_{new}^{g}(i) = \begin{cases} X_{(i)}^{g} + rand \times (X_{(i)}^{g} - X_{(r)}^{g}) & \text{if } f\left(X_{(i)}^{g}\right) < f\left(X_{(r)}^{g}\right) \\ X_{(i)}^{g} + rand \times (X_{(r)}^{g} - X_{(i)}^{g}) & \text{otherwise} \end{cases}$$

(2.55)
2.4.4 Pseudo Code of TLA Implementation

The Pseudo code of the proposed algorithm has been described below,

Set Maximal iteration number (MAXIT), Number of Courses Offered (V), Number of learners (P), generation=0
// Initial Population
G(P,V)=random()
// Find the mean for all the courses offered by the learners of generation
Mean (V) = f(V,P)
// Calculate the fitness value for all population
Obj(G(P))
//Execute the following steps for fixed number of iterations (MAXIT) till (generation<MAXIT)
{
    //Find the best individual of the generation and becomes the teacher
    V_{best,generation}=Minimum(Obj(G(P)))
    //Find the best individual population
    G_{best}=f(V_{best,generation})
    //Evaluate the teaching factor
    tf=(1+Math.random()*(2-1))
    //Produce the improved learners and produce the teachers
    G_{teacher}(P,V)=G(P,V)+(Math.random()*(G(G_{best}, V)-tf*Mean(V)))
    //find the best population and prepare the set of learners
    if(Obj(G(P))>Obj(G_{teacher}(P)))
        G_{learners}(P,V) =G_{teacher}(P,V)
    Else
        G_{learners}(P,V) =G(P,V)
    //Interaction phase of the learners, i and j refers integers (< V) and i≠j
    if(Obj(G_{learner}(P,i))>Obj(G_{learner}(P,j)))
        G(P,V)=G_{learner}(P,i)+ Math.random()*(G_{learner}(P,i)- G_{learner}(P,j))
    Else
        G(P,V)=G_{learner}(P,i)+ Math.random()*(G_{learner}(P,j)- G_{learner}(P,i))
    //increment the generation count
    generation =generation+1;
}
2.5 SEARCH STRATEGIES WITH FUZZY LOGIC

Fuzzy Logic (FL) is a subset of Artificial Intelligent (AI). The goal of introduction of AI in equipment or software is to produce a machine or a system that simulates or emulates a human being’s intelligence. AI consists of few sub-fields. Apart from those related to pattern recognition and natural language processing, it covers the fields of expert system, neural networks, fuzzy logic and genetic algorithms. The last four techniques have found an increasing number of applications in industry in general, and in power engineering in particular. FL is a calculus for dealing with vagueness and imprecision. It can be implemented in hardware, software, and a combination of both.

FL provides a simple way to arrive at a definite conclusion based upon vague, ambiguous, imprecise, noisy, or missing input. It has proved itself to be an excellent choice for many control system applications since it mimics human control logic. The FL incorporates a simple, rule-based approach for solving control problem rather than attempting to model a system mathematically. The FL model is empirically-based, relying on an operator's experience rather than their technical understanding of the system alone. The distinction between Boolean logic and FL is that, Boolean logic assigns a conventional zero or one in its evaluations, whereas FL serves as a multi-valued logic by defining intermediate values between the conventional true or false scenarios. The degree of belongingness depends on the closeness of the assigned value to either zero or one. In FL the truth of any statement is a matter of degree.

FL can be applied in complex decision making processes, but the human experience or knowledge on the problem to be solved must be available. The following are the justifications for using fuzzy logic in problem solving:
- It can handle multiple constraints simultaneously
- It resolves conflicting objectives by designing weights appropriate to a selected objective
- It is based on natural language
- It can control nonlinear systems that would be difficult to model mathematically
- It is inherently robust since it does not require precise or noise-free inputs

The point of fuzzy logic is to map an input space to an output space, and the primary mechanism for doing this is a list of “if-then” statements called rules.

All rules are evaluated in parallel. The order of the rules is not important. The rules themselves are useful because they refer to variables and the adjectives that describe those variables.

### 2.5.1 Fuzzy Sets

A fuzzy set is an obvious extension of the idea of a crisp set, in which the Membership Function (MF) is allowed to take on values between 0 and 1. It is represented by a graph of membership value vs. input domain value. A fuzzy set contains elements with only a partial degree of membership. For example, a fuzzy set with a degree of truth or false may consists of almost true, very true, more or less true, very false, quite false, more or less false, almost false, etc.
2.5.2 Membership Function

A MF is a curve that defines how each point in the universe of discourse (input space) is mapped to a membership value (or degree of membership) between 0 and 1. The only condition a MF must really satisfy is that it must vary between 0 and 1. The function itself can be an arbitrary curve whose shape can be defined. It associates a weighting with each of the inputs that are processed, define functional overlap between inputs, and ultimately determines an output response. There are 11 various types of MFs that are already built into the FL, such as Triangular MF, Trapezoidal MF, Gaussian MF, etc.

2.5.3 Logical Operations

Logical operations such as union (OR) and intersection (AND) can be established between fuzzy sets which include the normal meanings as a special case. Suppose there exist two fuzzy sets namely ‘A’ and ‘B’.

i) Union (OR)

A OR B is the largest set which includes both sets. In terms of the MFs \( \mu_A \) and \( \mu_B \),

\[
\mu_{(A \ OR \ B)} = \text{max}(\mu_A, \mu_B)
\]  

(2.56)

ii) Intersection (AND)

A AND B is the smallest set included in both sets. In terms of the MFs \( \mu_A \) and \( \mu_B \),

\[
\mu_{(A \ AND \ B)} = \text{min}(\mu_A, \mu_B)
\]  

(2.57)
2.5.4 “If-Then” Rules

“If-then” rules use the input membership values as weighting factors to determine their influence on the fuzzy output sets of the final output conclusion. The sample Linguistic (verbal) rules are given below to yield a numeric output,

If <condition A> and <condition B> then <action C>
If <condition D> or <condition E> then <action F>

2.5.5 Fuzzy Operations for Reconfiguration Problem

There are four fuzzy-set models developed for optimization as described in Thiruvenkadam et al (2008). They are responsible for restricting any configuration from bus voltage deviation, branch current deviation, increase in %THD and increase in real power loss.

2.5.5.1 Fuzzy-set model of the bus voltage deviation

The voltage at the buses must be maintained within the permissible limits for each new configuration and is given as,

\[ V_{\text{min}} < V_{\text{new},i} < V_{\text{max}} \text{ for } i=1,2,3,\ldots\ldots n \]  \hspace{1cm} (2.58)

Where, \( n \) is the total number of buses present in the RDS

\( V_{\text{new},i} \) is \( i^{th} \) bus new configuration voltage

\( V_{\text{min}}=0.9\text{pu} \) and \( V_{\text{max}}=1\text{pu} \) have been considered

The new configuration bus voltages are compared with the voltage limits. The voltages at the buses have been obtained from radial load flow for each new configuration. Moreover, the amount of the \( V_{\text{new},i} \) resulting from any
branch exchange can be estimated as ‘very close’, ‘close’ or ‘not close’ to the $V_{\text{min}}$. Therefore, the linguistic terms can be formulated as a membership function by the fuzzy notation. The membership function can be expressed as follows,

$$
\mu v, n = \begin{cases} 
1 & \text{for } \Delta V_n = 0 \\
1 - \frac{\Delta V_n}{v_{\text{min}}} & \text{for } \Delta V_n > 0 \& \& V_{\text{new}, n} < V_{\text{max}} \\
0 & \text{for otherwise}
\end{cases}
$$

(2.59)

Where, $\Delta V_n = V_{\text{new}, n} - V_{\text{min}}$

(2.60)

$V_{\text{new}, n}$ is the system voltage at the $n^{th}$ bus after reconfiguration.

The minimum amongst the membership values of voltage of all the bus in the system is obtained after reconfiguration is expressed as,

$$
\mu_v = \min \{\mu_{v,1}, \mu_{v,2}, \ldots, \mu_{v,n}\}
$$

(2.61)

### 2.5.5.2 Fuzzy-set model of the branch current loading

The main purpose of this membership function is to determine the branch current loading during each new configuration. Initially, all the branch current capacities are defined as $I_{\text{set}, i}$; where, $i=1, 2, 3, \ldots, n$; $n$ is the total number of branches in the RDS.

During each new configuration the new values of branch currents are received through radial load flow and defined as $I_i$; where $i=1, 2, 3, \ldots, n$; $n$ is the total number of branches. The small difference between $I_{\text{set}, i}$ and $I_i$ are estimated and deviation of $I_{\text{set}, i}$ with $I_i$ set as ‘very close’, ‘close’ or ‘not close’. 
The membership function of the $n^{th}$ branch $\mu_{B,n}$ can be defined as,

$$
\mu_{B,n} = \begin{cases} 
1 & \text{for } \Delta I_n = 0 \\
1 + \frac{\Delta I_n}{I_{set,n}} & \text{for } \Delta I_n < 0 \\
0 & \text{for otherwise}
\end{cases}
$$

Where, $\Delta I_n = I_n - I_{set,n}$

The membership function of all the branches can be similarly expressed as equation (2.62). A large current variation $\Delta I_n$ produces a small value of the membership function $\mu_{B,n}$ and vice versa.

The branch loading level of the selected switch operation can further be defined when all the branches membership values are determined. It can be expressed as,

$$
\mu_B = \min\{\mu_{B,1}, \mu_{B,2}, \ldots, \mu_{B,n}\}
$$

Where, $\mu_B$ is the membership value after switching.

2.5.5.3 Fuzzy-set model of the THD

This fuzzy membership function is developed to determine how much the present configurations %THD ($T_j$) deviates from the $T_{set}$ (0.03), where, $j=1, 2, 3, \ldots, n$; $n$ is the total number of buses present in the RDS. The small difference between $T_j$ and $T_{set}$ are estimated and $T_{set}$ with $T_j$ is set as ‘very close’, ‘close’ or ‘not close’.

The membership function of the $n^{th}$ bus $\mu_{T,n}$ can be defined as,
The membership function of all the buses can be similarly expressed as given in equation (2.65). A large current variation $\Delta T_n$, produce a small value of the membership function $\mu_{T,n}$ and vice versa.

The branch loading level of the selected switch operation can further be defined when all the branch membership values are determined. It can be expressed as,

$$\mu_T = \min \{\mu_{T,1}, \mu_{T,2}, \ldots, \mu_{T,n}\}$$

Where $\mu_T$ is the membership value after switching

2.5.5.4 Fuzzy-set model of the real power loss

The deviation of new configuration’s power loss ($P_{n\text{loss}}$) from the previous configuration loss ($P_{t\text{loss}}$) is to be identified for the objective of minimizing the system power loss. The power loss of the system has been obtained from RLF for each new configuration. Moreover, the amount of the $P_{n\text{loss}}$ resulting from any branch exchange can be estimated as ‘very close’, ‘close’ or ‘not close’ to the $P_{t\text{loss}}$. Therefore, the linguistic terms can be formulated as a membership function by the fuzzy notation. The proposed membership function $\mu_{p,n}$ has been depicted using equation (2.65). A small difference between $P_{n\text{loss}}$ and $P_{t\text{loss}}$ possesses a larger membership value.

$$\mu_{T,n} = \begin{cases} 
1 & \text{for } \Delta T_n = 0 \\
1 + \frac{\Delta r_n}{T_{set}} & \text{for } \Delta T_n < 0 \\
0 & \text{for otherwise}
\end{cases}$$

Where $\Delta T_n = T_n - T_{set}$ (2.66)
The membership function can be expressed as follows,

\[ \mu_{p,n} = \begin{cases} 
1 & \text{for } \Delta P = 0 \\
1 + \frac{\Delta P}{P_{tloss}} & \text{for } \Delta P < 0 \\
0 & \text{for otherwise}
\end{cases} \]  

(2.68)

Where \( \Delta P = P_{nloss} - P_{tloss} \)  

(2.69)

\( P_{tloss} \) is the system power loss before switching.

The purpose of the feeder reconfiguration can be achieved by the decision fuzzy set \( D \), which is derived from the intersection of the four membership functions \( \mu_V, \mu_B, \mu_T \) and \( \mu_P \). However, the optimal decision is the highest membership value of \( \mu_D \). Thus, an optimal decision fuzzy set \( D \) can be designated as follows,

\[ \mu_D = \max \{\min[\mu_V, \mu_B, \mu_T, \mu_P]\} \]  

(2.70)

The above equation (2.70) combines the individual objective functions into single multi-objective function. In accordance with the set values of the membership functions, the individual membership functions for the respective objective function produces the value between 0 and 1. The min-max imperative of fuzzy shown in equation (2.70) produces the best configuration for respective iteration.

## 2.6 COMPUTATIONAL FLOWCHART

The reconfiguration scheme begins with finding the solution sets of the RDS. The total number of switches present in each set/loop is then calculated and applied as state variables for TLA. The selection of number of variables for TLA is the same as the number of sets/loops present in the distribution system. With the use of TLA, the optimal solution for the
reconfiguration is obtained. The real power loss, %THD, branch currents and bus voltages corresponding to the respective configuration is calculated using radial load flow and harmonic load flow. For every arrival of new configuration, the membership values and optimal decision fuzzy set are calculated $\mu_V$, $\mu_B$, $\mu_T$, $\mu_P$ and $\mu_D$. During this process, reconfiguration has been attempted only if the present configuration is better than the previous configuration. The final configuration has been arrived after a fixed number of iterations. The reconfiguration procedure based on hybrid FTLA is illustrated in the flowchart shown in Figure 2.3.

2.7 SIMULATION RESULTS

The effectiveness of the hybrid FTLA has been validated through two test distribution systems. The Test system 1 shown in Figure 2.4 is a 12.66kV system. It consists of 33 buses and five tie lines. The total load conditions are 3715kW and 2300kvar. The characteristic data of Test System 1 and Test System are taken from Wang and Cheng (2008). The characteristic data of Test system 1 is given in Table 2.1 and the branch current capacity of each line is assumed. The Test System 2 shown in Figure 2.5 is a balanced three-phase system with 11.4kV. It consists of 11 feeders, 83 normally closed switches and 13 normally open switches. Its characteristic data are given in Table 2.2 and the branch capacity is 600A and voltage limits are $V_{min}=0.9pu$ and $V_{max}=1.0pu$. 
Read Line data and Bus data of RDS

Run Radial Load Flow (RLF) get \( P_{\text{loss}} \), total iteration(N), \( \text{iter}=0, i=0, j=0, k=0, P_{\text{loss}}=0, NP \)

Identify no. of independent loops/variables (V) for TLBO

Initialize the population \( f(NP,V) \)

Find the best individual population

Evaluate the teaching factor

Produce the improved learners and produce the teachers

Find the best population with \( \mu_D \) and prepare the set of learners

Interaction phase of the learners

Is \( \text{iter}<N \)

Yes

\( \text{iter} = \text{iter} + 1 \)

No

End

Figure 2.3 Flowchart for Reconfiguration through hybrid FTLA
Figure 2.4 IEEE 33-bus distribution system (Test System 1)
Figure 2.5  The 83 bus Taiwan power company distribution system (Test System 2)
Table 2.1 Network data Test System 1

<table>
<thead>
<tr>
<th>Bus To Bus</th>
<th>Section resistance (ohm)</th>
<th>Section reactance (ohm)</th>
<th>End bus Real power (kW)</th>
<th>End bus Reactive power (kVAR)</th>
<th>Bus To Bus</th>
<th>Section resistance (ohm)</th>
<th>Section reactance (ohm)</th>
<th>End bus Real power (kW)</th>
<th>End bus Reactive power (kVAR)</th>
<th>Bus To Bus</th>
<th>Section resistance (ohm)</th>
<th>Section reactance (ohm)</th>
<th>End bus Real power (kW)</th>
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<td>60</td>
<td>13-14</td>
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<td>25-26</td>
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### Table 2.2 Network data Test System 2

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2.7.1 Optimal Reconfiguration under Normal Condition

In this section, optimization has been carried out by considering both the systems working under normal condition.

2.7.1.1 Test System 1

The proposed scheme has been tested on 33 bus RDS, which has 5 normally opened switches, 32 normally closed switches with 33 buses and it is assumed as balanced three-phase with 12.66kV. The corresponding power loss is 202.7kW. For the distorted voltage, harmonic-producing loads, namely fluorescent lighting, adjustable speed drives (ASD), and non-specific sources such as PCs, TVs, etc., were considered. A complete description of the system harmonics can be found in Abdelsalam et al (2010). The typical harmonic spectrum of these nonlinear loads is provided in Table 2.3.

Table 2.3 Harmonic current magnitudes as % of fundamental and phase angles with respect to voltage

<table>
<thead>
<tr>
<th>Harmonic Order</th>
<th>Adjustable Speed Drives (ASD)</th>
<th>Fluorescent Lighting (FL)</th>
<th>Non-specific Sources (NS)</th>
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<td></td>
<td>Magnitude in %</td>
<td>Angle in degrees</td>
<td>Magnitude in %</td>
</tr>
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<td>100</td>
<td>-1.45</td>
<td>100</td>
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<tr>
<td>3</td>
<td>84.6</td>
<td>-8.34</td>
<td>19.2</td>
</tr>
<tr>
<td>5</td>
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<td>7</td>
<td>47.8</td>
<td>-20.13</td>
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<tr>
<td>9</td>
<td>27.7</td>
<td>-29.02</td>
<td>1.4</td>
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<td>0.2</td>
<td>-27.91</td>
<td>0.9</td>
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<td>13</td>
<td>6.1</td>
<td>158.2</td>
<td>0.6</td>
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<td>15</td>
<td>4.2</td>
<td>122.3</td>
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All loads were treated as constant PQ spot loads for harmonic studies for the 33 bus RDS. Load composition in terms of harmonic sources is given in Table 2.4. After the successful executions of radial load flow and harmonic load flow, the initial configuration harmonic voltages with %THD is shown in Table 2.5. From the Table 2.5, it is observed that for the buses 18, 19, 20, 30, 31 and 32, %THD exceeds 3%.

**Table 2.4 Load composition in terms of harmonic sources of Test System 1**

<table>
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<tr>
<th>Bus No.</th>
<th>P in MW</th>
<th>Q in MVAR</th>
<th>% ASD</th>
<th>% FL</th>
<th>% NS</th>
<th>Bus No.</th>
<th>P in MW</th>
<th>Q in MVAR</th>
<th>% ASD</th>
<th>% FL</th>
<th>% NS</th>
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<td>10</td>
<td>65</td>
<td>17</td>
<td>0.09</td>
<td>0.04</td>
<td>10</td>
<td>20</td>
<td>70</td>
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<tr>
<td>2</td>
<td>0.09</td>
<td>0.04</td>
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<td>10</td>
<td>70</td>
<td>18</td>
<td>0.09</td>
<td>0.04</td>
<td>10</td>
<td>10</td>
<td>80</td>
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<td>0.08</td>
<td>15</td>
<td>15</td>
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<td>80</td>
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Table 2.5 Initial Configuration harmonic voltages at the buses of Test System 1

| Bus No. | $|V^{(3)}|$ | $|V^{(5)}|$ | $|V^{(7)}|$ | $|V^{(9)}|$ | $|V^{(11)}|$ | $|V^{(13)}|$ | $|V^{(15)}|$ | $|V|$ | % |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 0       | 0.0000  | 0.0000  | 0.0000  | 0.0000  | 0.0000  | 0.0000  | 1.0000  | 0.5055  |        |
| 1       | 0.00010 | 0.00012 | 0.00032 | 0.00030 | 0.00021 | 0.0001 | 0.9970  | 0.7190  |        |
| 2       | 0.00064 | 0.00081 | 0.00440 | 0.00017 | 0.00011 | 0.0006 | 0.9829  | 0.8880  |        |
| 3       | 0.00089 | 0.00112 | 0.00574 | 0.00025 | 0.00014 | 0.0008 | 0.9755  | 1.1194  |        |
| 4       | 0.00114 | 0.00144 | 0.00713 | 0.00034 | 0.00018 | 0.0001 | 0.9681  | 1.9298  |        |
| 5       | 0.00178 | 0.00225 | 0.01038 | 0.00054 | 0.00025 | 0.0017 | 0.9497  | 2.2522  |        |
| 6       | 0.00186 | 0.00235 | 0.01145 | 0.00055 | 0.00028 | 0.0017 | 0.9462  | 2.5402  |        |
| 7       | 0.00195 | 0.00248 | 0.01224 | 0.00055 | 0.00030 | 0.0018 | 0.9413  | 2.6221  |        |
| 8       | 0.00195 | 0.00251 | 0.01232 | 0.00054 | 0.00030 | 0.0018 | 0.9351  | 2.6804  |        |
| 9       | 0.00195 | 0.00254 | 0.01232 | 0.00054 | 0.00030 | 0.0018 | 0.9292  | 2.6891  |        |
| 10      | 0.00195 | 0.00255 | 0.01232 | 0.00054 | 0.00030 | 0.0019 | 0.9284  | 2.7215  |        |
| 11      | 0.00196 | 0.00257 | 0.01237 | 0.00054 | 0.00030 | 0.0019 | 0.9269  | 2.7680  |        |
| 12      | 0.00195 | 0.00261 | 0.01233 | 0.00054 | 0.00030 | 0.0019 | 0.9208  | 2.7906  |        |
| 13      | 0.00196 | 0.00263 | 0.01232 | 0.00054 | 0.00030 | 0.0019 | 0.9185  | 0.5055  |        |
| 14      | 0.00199 | 0.00267 | 0.01251 | 0.00055 | 0.00031 | 0.0019 | 0.9171  | 0.7190  |        |
| 15      | 0.00204 | 0.00275 | 0.01312 | 0.00057 | 0.00032 | 0.0020 | 0.9157  | 0.8880  |        |
| 16      | 0.00208 | 0.00285 | 0.01360 | 0.00060 | 0.00033 | 0.0020 | 0.9137  | 1.1194  |        |
| 17      | 0.00208 | 0.00287 | 0.01379 | 0.00060 | 0.00034 | 0.0020 | 0.9131  | 2.8741  |        |
| 18      | 0.00009 | 0.00011 | 0.00077 | 0.00003 | 0.00002 | 0.0001 | 0.9965  | 3.1216  |        |
| 19      | 0.00032 | 0.00042 | 0.00318 | 0.00006 | 0.00009 | 0.0003 | 0.9929  | 3.3411  |        |
| 20      | 0.00036 | 0.00048 | 0.00378 | 0.00007 | 0.00010 | 0.0004 | 0.9922  | 3.4234  |        |
| 21      | 0.00041 | 0.00053 | 0.00437 | 0.00007 | 0.00012 | 0.0004 | 0.9916  | 0.5063  |        |
| 22      | 0.00089 | 0.00111 | 0.00639 | 0.00022 | 0.00016 | 0.0008 | 0.9794  | 0.6073  |        |
| 23      | 0.00149 | 0.00185 | 0.01122 | 0.00034 | 0.00029 | 0.0014 | 0.9727  | 0.6512  |        |
| 24      | 0.00172 | 0.00210 | 0.01409 | 0.00036 | 0.00037 | 0.0016 | 0.9694  | 0.7022  |        |
| 25      | 0.00185 | 0.00234 | 0.01063 | 0.00058 | 0.00026 | 0.0017 | 0.9477  | 0.9669  |        |
| 26      | 0.00196 | 0.00248 | 0.01109 | 0.00063 | 0.00027 | 0.0018 | 0.9452  | 1.9715  |        |
| 27      | 0.00254 | 0.00322 | 0.01354 | 0.00087 | 0.00032 | 0.0024 | 0.9337  | 2.8342  |        |
| 28      | 0.00300 | 0.00381 | 0.01546 | 0.00105 | 0.00037 | 0.0028 | 0.9255  | 2.0176  |        |
| 29      | 0.00326 | 0.00414 | 0.01673 | 0.00114 | 0.00040 | 0.0031 | 0.9220  | 2.1733  |        |
| 30      | 0.00325 | 0.00415 | 0.01785 | 0.00118 | 0.00044 | 0.0031 | 0.9178  | 3.1466  |        |
| 31      | 0.00326 | 0.00417 | 0.01824 | 0.00119 | 0.00045 | 0.0031 | 0.9169  | 4.0949  |        |
| 32      | 0.00330 | 0.00420 | 0.01843 | 0.00119 | 0.00046 | 0.0031 | 0.9166  | 4.7789  |        |
For optimal restructuring, at first, the total number of loops present in the distribution system is identified. After categorizing the switches of each loop as based on close, open, permanently closed and temporary closed switches as described in Wang and Cheng (2008), the final solution sets are given as,

\[
L_1 = \{S_4, S_5, S_6, S_7, S_{20}, S_{19}, S_{33}\} \\
L_2 = \{S_8, S_9, S_{10}, S_{11}, S_{21}, S_{35}\} \\
L_3 = \{S_{12}, S_{13}, S_{14}, S_{34}\} \\
L_4 = \{S_{25}, S_{26}, S_{27}, S_{28}, S_{23}, S_{24}, S_{37}\} \\
L_5 = \{S_{15}, S_{16}, S_{17}, S_{32}, S_{31}, S_{30}, S_{29}, S_{36}\}
\]

(2.71)

From the above equation (2.71), it is clear that the Test system 1 has five loops (L_1, L_2, L_3, L_4 and L_5) and these loops have 7, 6, 4, 7 and 8 number of switches respectively. The hybrid FTLA algorithm has been proposed to identify the best set of open switches. As per hybrid FTLA, the number of courses offered is considered as five (i.e., the number of loops). For instance for the considered course L_1, if the value generated in any population is 3 then S_6 is the switch to be opened in the loop 1 and the similar process is continued for the rest of the courses for the populations. The initial population and their respective losses were calculated and stored. The generation size (P) and maximum iteration number (MAXIT) are assumed as 20 and 50 respectively. The best solutions with the fitness function (2.70) as multi-objective and its respective configuration have been stored at the end of iteration. The same process has been repeated for MAXIT. After the successful execution, the power loss is reduced, the branch currents and bus voltages were maintained within the limit and % THD has been reduced significantly compared with the initial configuration.
The proposed algorithm tunes for the optimized restructuring of the distribution system. The proposed method reduces the power loss from 202.67kW to 142.16kW, and maintains the bus voltages well above minimum value. Amongst four objectives, the power loss is the only parameter reduced in iterations and the other objectives only ensures the present iteration value does not violate the set value. Therefore, the convergence characteristic of the hybrid FTLA algorithm is represented through power loss in iteration which is shown in Figure 2.6. The final configuration branch currents and bus voltages are shown in Figure 2.7 and Figure 2.8 respectively. Also, the % THD of the buses before and after restructuring through the proposed algorithm is shown in Figure 2.9. From these figures, it is evident that the loss is minimized, branch currents are kept under limit, bus voltages are maintained under limit and % THD has been maintained less than 3%. The worst, average and best solutions through the proposed algorithm for the test system 1 are shown in Table 2.6.

![Figure 2.6 Convergence characteristic of the hybrid FTLA for Test System 1 under normal condition](image-url)
Figure 2.7 Final configuration branch currents of Test System 1 under normal condition as per hybrid FTLA

Figure 2.8 Final configuration bus voltages of Test System 1 under normal condition as per hybrid FTLA
The result summary without and with consideration of % THD is shown in the Table 2.7. From the table, it is clear that % saving is more without % THD consideration. Even though % saving is less with considering % THD as constraint, it ensures better quality of power supply which improves the life time of the equipments.

2.7.1.2 Test system 2

The proposed methodology has been tested with Test System 2 also. The characteristic data and system topology are shown in Table 2.2 and Figure 2.5 respectively. The system was considered under normal condition. The branch capacity is 600A and voltage limits are $V_{\text{min}}=0.9\text{pu}$ and $V_{\text{max}}=1.0\text{pu}$. The final solution sets for the 13 loops are identified. For FTLA, the courses offered have been considered as 13. Load composition in terms of harmonic sources, by referring Table 2.3, is assumed for all the load buses of the test system.
Table 2.6 Different Solutions received through FTLA for Test System 1

<table>
<thead>
<tr>
<th>Cases</th>
<th>Power Loss (kW)</th>
<th>Min. bus voltage (pu)</th>
<th>%THDmax</th>
<th>NFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst</td>
<td>154.59</td>
<td>0.9217</td>
<td>2.95</td>
<td>449</td>
</tr>
<tr>
<td>Average</td>
<td>149.16</td>
<td>0.9301</td>
<td>2.91</td>
<td>392</td>
</tr>
<tr>
<td>Best</td>
<td>142.16</td>
<td>0.9335</td>
<td>2.86</td>
<td>426</td>
</tr>
</tbody>
</table>

Table 2.7 Comparison of results with other methods in literature for Test System 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Initial Configuration</th>
<th>Optimal Restructuring without considering THD (only with linear loads)</th>
<th>Optimal Restructuring with considering THD (non-linear loads considered) (Proposed Algorithm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Loss (kW)</td>
<td>202.67</td>
<td>141.6</td>
<td>139.54</td>
</tr>
<tr>
<td>Min. bus Voltage (pu)</td>
<td>0.9130</td>
<td>0.9290</td>
<td>0.9378</td>
</tr>
<tr>
<td>THDmax (%)</td>
<td>4.77</td>
<td>3.67</td>
<td>3.25</td>
</tr>
<tr>
<td>%saving</td>
<td>-</td>
<td>30.13</td>
<td>31.14</td>
</tr>
<tr>
<td>Open Switches</td>
<td>S7, S9, S15, S32, S37</td>
<td>S7, S9, S14, S32, S37</td>
<td>S7, S9, S14, S32, S37</td>
</tr>
<tr>
<td>NFE</td>
<td>-</td>
<td>1127</td>
<td>783</td>
</tr>
</tbody>
</table>

FTLA identifies the optimal structure of the distribution system. The proposed method reduces the power loss from 542.56kW to 472.34kW, and maintains the bus voltages well above minimum value. The convergence characteristic of the hybrid FTLA algorithm is represented through power loss in iteration which is shown in Figure 2.10. The branch currents, bus voltages and % THD of the buses before and after restructuring through hybrid FTLA is shown in Figure 2.11, Figure 2.12 and Figure 2.13 respectively. From the
figures, it is understood that branch currents, bus voltages and %THD are maintained within the limit. The worst, average and best solutions through the proposed algorithm for the test system 2 are shown in Table 2.8.

The result summary without and with consideration of % THD is shown through the Table 2.9. From the Table 2.9, it is clear that the proposed method guarantees global optimum and maintains the % THD under the limit. Furthermore, it is clear from the table 2.9 that % saving is more without considering % THD as constraint. Even though % saving is less with % THD consideration, it ensures the better quality of power supply and improves the life time of the equipments.

Figure 2.10 Convergence characteristic of the hybrid FTLA for Test System 2 under normal condition
Figure 2.11  Final configuration branch currents of Test System 2 under normal condition as per hybrid FTLA

Figure 2.12  Final configuration bus voltages of Test System 2 under normal condition as per hybrid FTLA
Table 2.8 Different Solutions received through FTLA for Test System 2

<table>
<thead>
<tr>
<th>Cases</th>
<th>Power Loss (kW)</th>
<th>Min. bus voltage (pu)</th>
<th>%THDmax</th>
<th>NFE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst</td>
<td>483.44</td>
<td>0.9349</td>
<td>2.99</td>
<td>1311</td>
</tr>
<tr>
<td>Average</td>
<td>481.92</td>
<td>0.9381</td>
<td>2.98</td>
<td>1327</td>
</tr>
<tr>
<td>Best</td>
<td>472.34</td>
<td>0.9442</td>
<td>2.94</td>
<td>1208</td>
</tr>
</tbody>
</table>

Table 2.9 Comparison of results with other methods in literature for Test System 2

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Initial Configuration</th>
<th>Optimal Restructuring without considering THD</th>
<th>Optimal Restructuring with considering THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Loss (kW)</td>
<td>542.56</td>
<td>469.88</td>
<td>469.88</td>
</tr>
<tr>
<td>Min. bus Voltage (pu)</td>
<td>0.9285</td>
<td>0.9536</td>
<td>0.9536</td>
</tr>
<tr>
<td>THD max</td>
<td>6.51</td>
<td>5.87</td>
<td>5.87</td>
</tr>
<tr>
<td>Sl. No.</td>
<td>Start Bus</td>
<td>End Bus</td>
<td>Initial configuration Current in Amps.</td>
</tr>
<tr>
<td>--------</td>
<td>-----------</td>
<td>---------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>388.7269</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>11</td>
<td>296.1750</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>15</td>
<td>396.7751</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>25</td>
<td>245.9921</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>30</td>
<td>429.5862</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>43</td>
<td>118.8916</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>47</td>
<td>293.2296</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>56</td>
<td>162.1575</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>65</td>
<td>308.3686</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>73</td>
<td>167.6652</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>77</td>
<td>404.9000</td>
</tr>
</tbody>
</table>

The identified switches to be opened at the final configuration are $S_7$, $S_{13}$, $S_{33}$, $S_{39}$, $S_{41}$, $S_{55}$, $S_{62}$, $S_{69}$, $S_{83}$, $S_{86}$, $S_{89}$, $S_{90}$ and $S_{92}$.

2.7.2 Optimal Reconfiguration under Critical Load Condition

The robustness of the proposed algorithm was tested by keeping the test systems under critical load condition by modifying the load...
characteristics of the system. At first the critical buses are identified based on their voltage profile. The buses with least voltage profile are considered weaker buses. The loads are varied at the identified buses which makes the system to a critical condition. Then the system with the present state has been fed into the reconfiguration algorithm.

2.7.2.1 Test System 1

In this case, Test system 1 is overloaded by 2.5%, 5% and 10% from its initial condition. With the effect of overloading, the system loss increases from 202.66kW of base load condition to 213.76 kW, 225.21kW and 249.15kW at critical load condition respectively as given in Table 2.11. The system with the present state has been fed to the proposed reconfiguration algorithm with the intention of bringing the system into normal condition from critical. With the effective introduction of the algorithm the system has been reconfigured. In the resultant system, the power loss has been reduced from 213kW to 148.35kW, 225.21kW to 159.84kW and 249.15kW to 177.24kW which are shown in Figure 2.14, Figure 2.15 and Figure 2.16 respectively. The branch currents and bus voltages are maintained under limit. The branch currents and bus voltages under different critical condition are shown in figures from Figure 2.17 to Figure 2.22. The %THD after implementing proposed algorithm under different critical conditions is shown in Figure 2.23. It shows that none of the bus %THD beyond 3% value.
Figure 2.14 Power loss updates of Test System 1 under critical condition (2.5% overloaded) as per hybrid FTLA

Figure 2.15 Power loss updates of Test System 1 under critical condition (5% overloaded) as per hybrid FTLA
Figure 2.16 Power loss updates of Test System 1 under critical condition (10% overloaded) as per hybrid FTLA

Figure 2.17 Final configuration branch currents of Test System 1 under critical condition (2.5% overloaded) as per hybrid FTLA
Figure 2.18 Final configuration bus voltages of Test System 1 under critical condition (2.5% overloaded) as per hybrid FTLA

Figure 2.19 Final configuration branch currents of Test System 1 under critical condition (5% overloaded) as per hybrid FTLA
Figure 2.20 Final configuration bus voltages of Test System 1 under critical condition (5% overloaded) as per hybrid FTLA

Figure 2.21 Final configuration branch currents of Test System 1 under critical condition (10% overloaded) as per hybrid FTLA
Figure 2.22  Final configuration bus voltages of Test System 1 under critical condition (10% overloaded) as per hybrid FTLA

Figure 2.23  Final configuration %THD of Test System 1 under critical condition as per hybrid FTLA
2.7.2.2 Test System 2

In this case, Test system 2 is overloaded to 10%, 20% and 30% from its initial condition. With the effect of overloading, the system loss increases from 531.99kW of base load condition to 662.77kW, 796.48kW and 944.20kW at critical load condition respectively as given in Table 2.11.

The system with the present state has been fed to the proposed reconfiguration algorithm with the intention of bringing the system into normal condition from critical. With the effective introduction of the algorithm the system has been reconfigured. In the resultant system, the power loss has been reduced from 662.77kW to 582.19kW, 796.48kW to 699.14kW and 944.20kW to 823.72kW which is shown in Figure 2.24, Figure 2.25 and Figure 2.26 respectively. The branch currents and bus voltages are maintained under limit. The branch currents and bus voltages under different critical load condition cases are shown in figures from Figure 2.27 to Figure 2.32. Figure 2.33 shows the %THD after implementing proposed algorithm under different critical conditions and ensures none of the bus %THD beyond 3% value.

![Power loss updates of Test System 2 under critical condition (10% overloaded) as per hybrid FTLA](image)

**Figure 2.24** Power loss updates of Test System 2 under critical condition (10% overloaded) as per hybrid FTLA
Figure 2.25  Power loss updates of Test System 2 under critical condition (20% overloaded) as per hybrid FTLA

Figure 2.26  Power loss updates of Test System 2 under critical condition (30% overloaded) as per hybrid FTLA
Figure 2.27 Final configuration branch currents of Test System 2 under critical condition (10% overloaded) as per hybrid FTLA

Figure 2.28 Final configuration branch currents of Test System 2 under critical condition (20% overloaded) as per hybrid FTLA
Figure 2.29 Final configuration branch currents of Test System 2 under critical condition (30% overloaded) as per hybrid FTLA

Figure 2.30 Final configuration bus voltages of Test System 2 under critical condition (10% overloaded) as per hybrid FTLA
Figure 2.31  Final configuration bus voltages of Test System 2 under critical condition (20% overloaded) as per hybrid FTLA

Figure 2.32  Final configuration bus voltages of Test System 2 under critical condition (30% overloaded) as per hybrid FTLA
Table 2.11 summarizes the percentage of loss reduction from the initial configuration to the final configuration of the Test System 1 and Test System 2, under normal and faulted conditions. For Test system 1, 29.85%, 30.59%, 29.02% and 28.86% reduction of loss has been achieved under normal, and 2.5%, 5.0% and 10.0% overloaded conditions respectively from its initial configuration. Similarly, for test system 2, 11.21%, 12.15%, 12.22% and 12.76% reduction of loss has been achieved under normal and 10%, 20% and 30% overloaded conditions respectively from its initial configuration. Also reconfiguration has been done under three different critical loading conditions on both the test systems. For the resultant configurations, the other objectives such as bus voltages, branch currents and % THD are maintained within the limit as shown in Figure 2.17 to Figure 2.23 for Test System 1 and Figure 2.27 to Figure 2.33 for Test System 2.

2.8 CONCLUSION

Figure 2.33 Final configuration %THD of Test System 2 under critical condition as per hybrid FTLA
Table 2.11 Summary of Results through hybrid FTLA

<table>
<thead>
<tr>
<th>Cases Considered</th>
<th>Test System 1</th>
<th>Test System 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial Loss (kW)</td>
<td>Loss after applying algorithm (kW)</td>
</tr>
<tr>
<td>Normal Condition</td>
<td>202.66</td>
<td>142.16</td>
</tr>
<tr>
<td>Critical Load Condition -I</td>
<td>213.76</td>
<td>148.35</td>
</tr>
<tr>
<td>Critical Load Condition -II</td>
<td>225.21</td>
<td>159.84</td>
</tr>
<tr>
<td>Critical Load Condition -III</td>
<td>249.15</td>
<td>177.24</td>
</tr>
</tbody>
</table>

Thus, with the application of the hybrid FTLA reconfiguration algorithm, loss reduction was carried out subjected under operational constraints (radial structure), power flow constraints (branch currents and bus voltage limits) and power quality constraints (minimized %THD). Also, the proposed algorithm works under different loaded conditions (normal and critical load case) of RDS while obtaining global optimum.

This algorithm gets the benefit of Fuzzy (modifies constraints as multi objectives) and TLA (for optimization). The proper use of Fuzzy and TLA improves the efficiency in terms of reduced number of load flow executions, reduced computational executions and removal of unfeasible solutions in the search space. Most importantly, the test systems are designed with harmonic loads, which require the combination of radial load flow and harmonic load flow techniques to calculate the distribution system parameters. Though the proposed algorithm effectively handles optimal reconfiguration, the results must be compared with the other optimization procedures implemented for the distribution system.