American Journal of Engineering Research (AJER)
e-ISSN : 2320-0847 p-ISSN : 2320-0936
Volume-03, Issue-11, pp-77-84
www.ajer.org
Research Paper Open Access

Genetic Algorithm Based Transmission Expansion Planning System

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ABSTRACT: *This paper presents an application of genetic algorithm (GA) to the solution of Static Transmission Expansion Planning (STEP) to determine the optimal number of transmission circuits required in each network corridor and their respective network adequacy while satisfying various economic and technical constraints. The uncertainties in generation and distribution networks as a result of power system deregulation cannot be modeled effectively using the conventional mathematical methods. GA, been a probabilistic based approach has the ability to resolve the transmission expansion planning problem in the face of such uncertainties. The model presented in this work will help in the identification of overloaded lines using Gauss Seidel (GS) load flow technique. Result from GS is then used as input in the GA simulation to show the extra lines needed to accommodate present load flow in the system. The model was tested on IEEE 14 – bus test network.The model developed and simulation results obtained may be useful in an electric power systems undergoing deregulation. Such is the case in Nigeria presently where the generation and distribution components are increasing significantly without any commensurate boost in the transmission sector. This leads to line overloads necessitating commensurate and immediate expansion of the grid.*

KEYWORDS: Deregulation, Gauss Seidel, Genetic algorithm, *Transmission expansion planning and System overload.*

I. INTRODUCTION

The basic principle of TEP is to minimize the network construction and operational costs while satisfying the requirement of delivering electric power safely and reliably to load centers along the planning horizon [1]. The expansion of a transmission network may include the construction of new overhead lines or underground cable in new corridors, and the upgrading of existing lines or cables in corridors already in use by increasing the number or the capacity of lines or cables, increasing the rated voltage, the improvement on the capacity and control equipment (FACTS, Capacitor banks etc.). In a more broad sense, one may also consider the introduction of generators in appropriate places to allow a better balance between generation and loads, and better use of the network, increasing the transmission capacity of the network.

From the stake-holders point of view, transmission expansion should attend the following targets [2].

- Encourage and facilitate competition among market participants;
- Provide non-discriminatory access to cheap generation for all consumers;
- Alleviate transmission congestion;
- Minimize the investment, the risk of investments and operation costs;
- Increase the reliability of the network;
- Increase the flexibility of system operation while reducing the network charges;
- Minimize the environmental impacts;
- Allow better voltage level regulation.

Even though the principles are quite simple, the complexity of the problem and the impact on society due to the heavy investments that have to be made, together with the costs incurred due to failures, make TEP on as a challenging issue. The following are some of the factors that distinguish TEP as a challenging field in power system analysis [2].

- Complexity of the problem; TEP is a complex problem because it has a mixed integer nonlinear programming nature. It is also a complex mathematical problem as it involves, typically, a large number of variables.

- Usually, heavy investments must be made. This kind of investments goes a long way to strain the economy of the country or region undergoing such expansion plans.

Transmission expansion planning addresses the problem of strengthening an existing transmission network to optimally serve a growing electricity market while satisfying a set of economic and technical constraints. Various techniques, including simulated annealing, tabu search, evolution strategies, greedy randomized adaptive search procedure (GRASP), probabilistic reliability criteria (PRC), and probabilistic load flow (PLF), have been used to study the problem [3] – [7]. It is difficult to obtain the optimal solution of a composite power considering the generators and transmission lines simultaneously in an actual system, and therefore, transmission expansion planning is usually performed after generation expansion planning.

This paper presents a method for determining the optimal number of transmission circuits required in each network corridor using genetic algorithm (GA). Gauss – siedel power flow algorithm was used to determine the line flows and voltage magnitudes in each network corridor and network bus respectively. The static transmission expansion planning (STEP) problem was formulated using a DC power flow model [8], [9].

This paper is organized as follows; Section II describes in details the Genetic Algorithm theory. Section IIIdescribes the mathematical modeling of the chosen solution method. Section IV describes the application of GA theory to solve transmission expansion planning, i.e. implementation. Section V shows the results obtained from the application of GA in transmission expansion planning. Section VI summarizes the conclusion of the work.

II. GENETIC ALGORITHM (GA)

The use of Genetic Algorithm for problem solving is not new. The pioneering work of J.H. Holland in the 1970's proved to be a significant contribution for scientific and engineering applications.

GA is inspired by the mechanism of natural selection, a biological process in which the stronger individuals are likely to be the winners in the competing environment. Here, GA uses the direct analogy of such natural evolution. It presumes that the potential solution of a problem is an individual and can be represented by a set of parameters.

Standard genetic algorithm is a random search method that can be used to solve non-linear system of equations and optimize complex problems. The base of this algorithm is the selection of individuals. It doesn't need a good initial estimation for sake of problem solution, In other words, the solution of a complex problem can be started with weak initial estimations and then be corrected in evolutionary process of fitness [10].

GA also combines various operators namely; selection, crossover, and mutation operators with the goal of finding the best solution to a problem. GA searches for this optimal solution until a specified termination criterion is met. A proto-typical GA consists of the following steps

- Generate initial generation
- Measure fitness
- Select a mating pool
- Mutate randomly selected member of the mating pool
- Pair the members of the mating pool.
- Perform crossover to obtain the new generation
- Iteration continues until some stopping condition is satisfied.

The Mutation operator selects one of existed integer numbers from the mating pool and then changes its value randomly. Reproduction operator, similar to standard form, reproduces each individual proportional to the value of its objective function. Therefore, the individuals which have better objective functions will be selected more probable than other chromosomes for the next population [15].

The selection operator selects the individual in the population for reproduction. The more fit the individual, the higher its probability of being selected for reproduction. The crossover operator involves theswapping of genetic material (bit-values) between the two parent strings. Based on predefined probability, known as crossover probability, an even number of individuals are chosen randomly. Each individuals (children) resulting from each crossover operation will now be subjected to the mutation operator in the final step to forming the new generation. The mutation operator enhances the ability of the GA to find a near optimal solution to a given problem by maintaining a sufficient level of genetic variety in the population, which is needed to make sure that the entire solution space is used in the search for the best solution.

In the context of TEP, the alternative expansion plans are referred to as the individuals. These individuals are what make up the mating pool as stated above. The power flows in the network together with other line flow constraints are all modeled mathematically and constitute part of the Algorithm [10], [11].

III. MATHEMATICAL MODELLING

In this section, the mathematical models as proposed in [8], [12] and [13] are outlined. It consists of a Power flow model and a static transmission expansion planning (STEP) model.

A. Power flow model

This provides a model of the nonlinear relationships among bus power injections, power demands, bus voltages and angles with the network constants providing the circuit parameters.

The power flow model provides information on the electrical performance of the lines with actual power flows in such lines. They also provide information about the line and transformer loads as well as losses throughout the system and voltages at different points in the system [12].

In developing power flow equations, a 3 – phase balanced system operation is assumed; hence per – phase analysis is utlized to obtain the necessary equations.

$$S_i \triangleq S_{Gi} - S_{Di} \qquad (1)$$

$$I_i = I_{Gi} - I_{Di} \qquad (2)$$

$$I_i = \sum_{k=1}^{n} Y_{ik} V_k \qquad (3)$$

$$S_i = V_i I_i^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* \qquad (4)$$

$$V_i \triangleq |V_i| e^{\angle V_i} = |V_i| e^{j\theta_{ik}} \qquad (5)$$

$$\theta_{ik} = \theta_i - \theta_k \qquad (6)$$

$$Y_{ik} \triangleq G_{ik} + jB_{ik} \qquad (7)$$

$$S_i = \sum_{k=1}^{n} |V_i| |V_k| (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) \qquad (8)$$

Resolving into real and imaginary parts we obtain

$$P_i = \sum_{k=1}^{n} |V_i| |V_k| (G_{ik} \cos\theta_{ik} + B_{ik} \sin\theta_{ik}) \qquad (9)$$

$$Q_i = \sum_{k=1}^{n} |V_i| |V_k| (G_{ik} \sin\theta_{ik} - B_{ik} \sin\theta_{ik}) \qquad (10)$$

Gauss – Siedel power flow modification was also adopted as highlighted in this section.

Recall from equation 4 that:

$$S_i = V_i I_i^* = V_i \sum_{k=1}^{n} Y_{ik}^* V_k^* \quad i = 1,2, \dots \dots \dots n$$

$$S_i^* = V_i^* \sum_{k=1}^{n} Y_{ik} V_k \quad i = 2,3, \dots \dots, n \qquad (11)$$

$$\frac{S_i^*}{V_i^*} = Y_{ii} V_i + \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k, \quad i = 2,3, \dots \dots \dots, n \qquad (12)$$

$$V_i = {}^{1}/_{Y_{ii}} \left[\frac{S_i^*}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k \right], i = 2,3, \dots \dots \dots, n \qquad (13)$$

$$V_i = {}^{1}/_{Y_{ii}} \left[\frac{(P_i^{sch} - jQ_i^{sch})}{V_i^*} - \sum_{\substack{k=1 \\ k \neq i}}^{n} Y_{ik} V_k \right], i = 2,3, \dots \dots n \qquad (14)$$

Where P_i^{sch} and Q_i^{sch} are the net real and reactive powers expressed in per-unit. Thus, for buses where real and reactive power are injected into the bus, such as generator buses, P_i^{sch} and Q_i^{sch} have positive values.For Load buses where real and reactive powers are flowing away from the bus, P_i^{sch} and Q_i^{sch} have negative values.

$$P_i = \Re \left\{ V_i^* \left[V_i Y_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} V_j \right] \right\} \quad j \neq i \qquad (15)$$

$$Q_i = \Im \left\{ V_i^* \left[V_i Y_{ii} + \sum_{\substack{j=1 \\ j \neq i}}^{n} Y_{ij} V_j \right] \right\} \quad j \neq i \qquad (16)$$

For the voltage controlled buses, the bus voltage must be equal to the specified voltage. Also, the maximum and minimum reactive powers at these buses are also specified and the value of $Q_i (for\ i = 1,2,3, \dots . n)$ must lie between these limits. [23], [24].

Thus, the conditions to be met are as follows:

1. $|V_i| = |V_i|_{spec}\ for\ i = 2,3, \dots \dots . n$
2. $Q_{i\,min} < Q_i < Q_{i\,max}\ for\ i = 2,3, \dots \dots . n$

If during any of the iterations, we find out that Q_i is outside the limits specified, Q_i is fixed at the minimum or the maximum value as the case may be and then the bus is treated as a PQ bus (load bus).

B. Static transmission expansion planning model

Generally, transmission expansion planning could be classified as static or dynamic. Static expansion determines where and how many new transmission lines should be added to the network up to the planning horizon [8]. Implicitly, we could infer the major goal of Static TEP is finding an appropriate number of new circuits that should be added to the transmission network.

The Static transmission expansion planning problem was formulated as follows using a DC power flow model [8], [9].

$$TC = \sum_{i,j\in\Omega} C_{ij} \times n_{ij} \qquad (17)$$

Where

TC: Construction cost of lines along the planning horizon

C_{ij}: Construction cost of each line in corridor$i - j$.

Equation 19 represents the construction cost of new lines which should be added to the network for delivering safe and reliable electric power to load centers over the planning horizon. Several constraints are also modeled in a mathematical representation to ensure that the mathematical solutions are in line with planning requirements. These constraints are stated in the following sections [8].

$$P_i = \sum_{j=1}^{NB} P_{ij} + d_i \, (i = 1,2, \dots \dots, NB), (\forall i, j \in \Omega)$$

(18)

Where, NB = total number of buses in the network

P_i &d_i: Generation and demand on bus i

P_{ij}: Power flow of each branch $i - j$

Equation is known as the Dc power flow node balance constraint.

Also,

$$P_{ij} = \gamma_{ij} \times \left(n_{ij}^0 + n_{ij}\right) \times \left(\theta_i - \theta_j\right) \qquad (19)$$

Where

γ_{ij}: Total Susceptance of circuits in corridor $i - j$

θ_i &θ_j : Voltage phase angles of buses i & j respectively

The power flow limit on the transmission line is modeled thus:

$$\left|P_{ij}\right| \leq Nl_{ij} \times P_{ij}^{max} \qquad (20)$$

$$Nl_{ij} = n_{ij}^0 + n_{ij} \qquad (21)$$

Where,

Nl_{ij}: Total number of circuits (new & existing) in corridor $i - j$

P_{ij}^{max}: Maximum power flow in corridor$i - j$.

By replacing P_{ij} and Nl_{ij} in equation 3.25 above with their respective expressions in equation 3.24 and 3.26 the following expression can be obtained

$$\left|\left(\theta_i - \theta_j\right)\right| \times \left|\gamma_{ij}\right| \leq P_{ij}^{max}$$

$$0 \leq n_{ij} \leq n_{ij}^{max}$$

Equation models the maximum number of lines that can be installed in each corridor of the network. Where, n_{ij}^{max} is the maximum number of constructible circuits in corridor $i - j$

IV. IMPLEMENTATION

The Gauss – Siedel power flow model was implemented using MATLAB. The flowchart used in implementing the Gauss – Siedel Power flow model is shown in Figure 1 and that of the Genetic algorithm is shown in Figure *2*.The output of the Gauss –Siedel load flow algorithm constitutes the input of the Genetic algorithm flowchart. The various blocks in the Genetic Algorithm flowchart are described in sectionII.

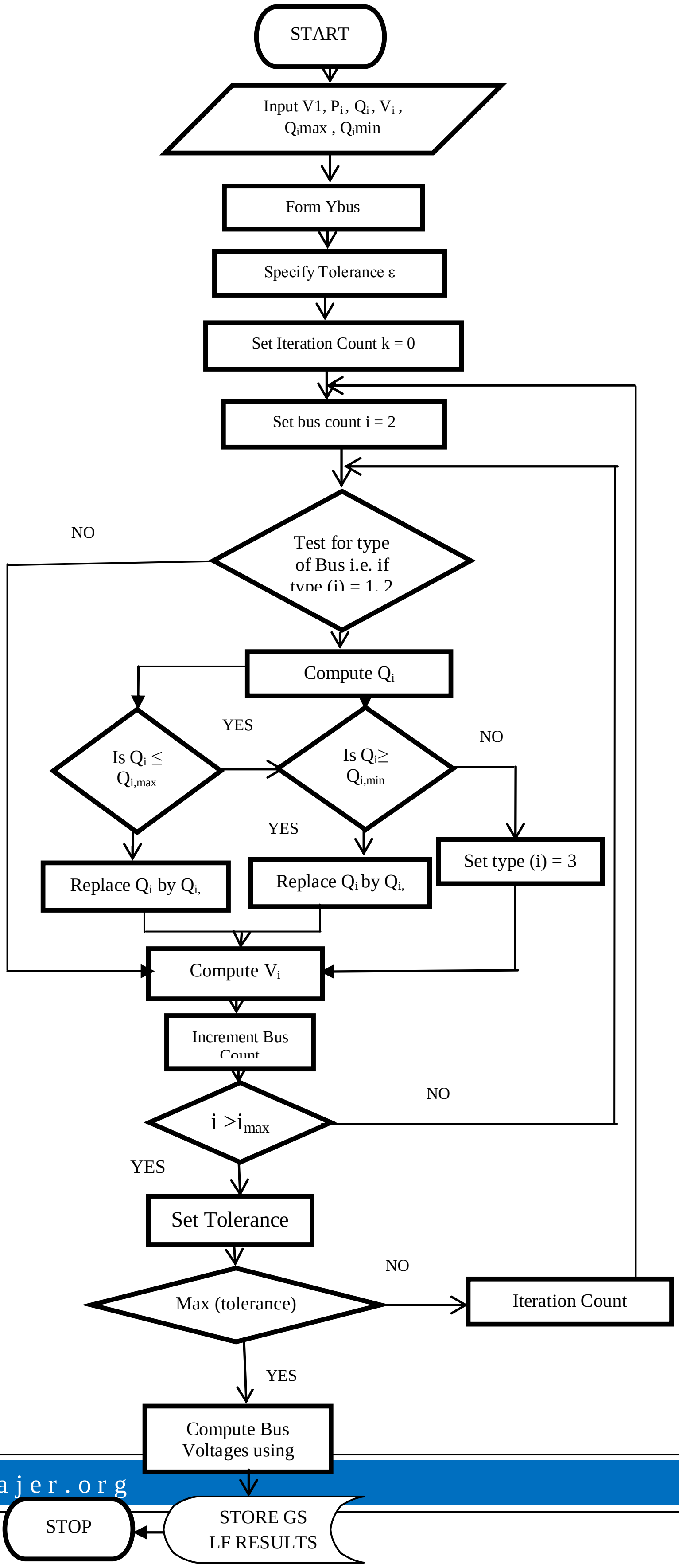
START
Input V1, P_i, Q_i, V_i, $Q_i$max, $Q_i$min
Form Ybus
Specify Tolerance ε
Set Iteration Count k = 0
Set bus count i = 2
NO
Test for type of Bus i.e. if type (i) = 1, 2
Compute Q_i
YES
NO
Is $Q_i \leq Q_{i,max}$
Is $Q_i \geq Q_{i,min}$
YES
Replace Q_i by $Q_{i,}$
Replace Q_i by $Q_{i,}$
Set type (i) = 3
Compute V_i
Increment Bus Count
NO
$i > i_{max}$
YES
Set Tolerance
NO
Max (tolerance)
Iteration Count
YES
Compute Bus Voltages using
STORE GS LF RESULTS
STOP

Fig 1 Gauss – Siedel (GS) Power Flowchart

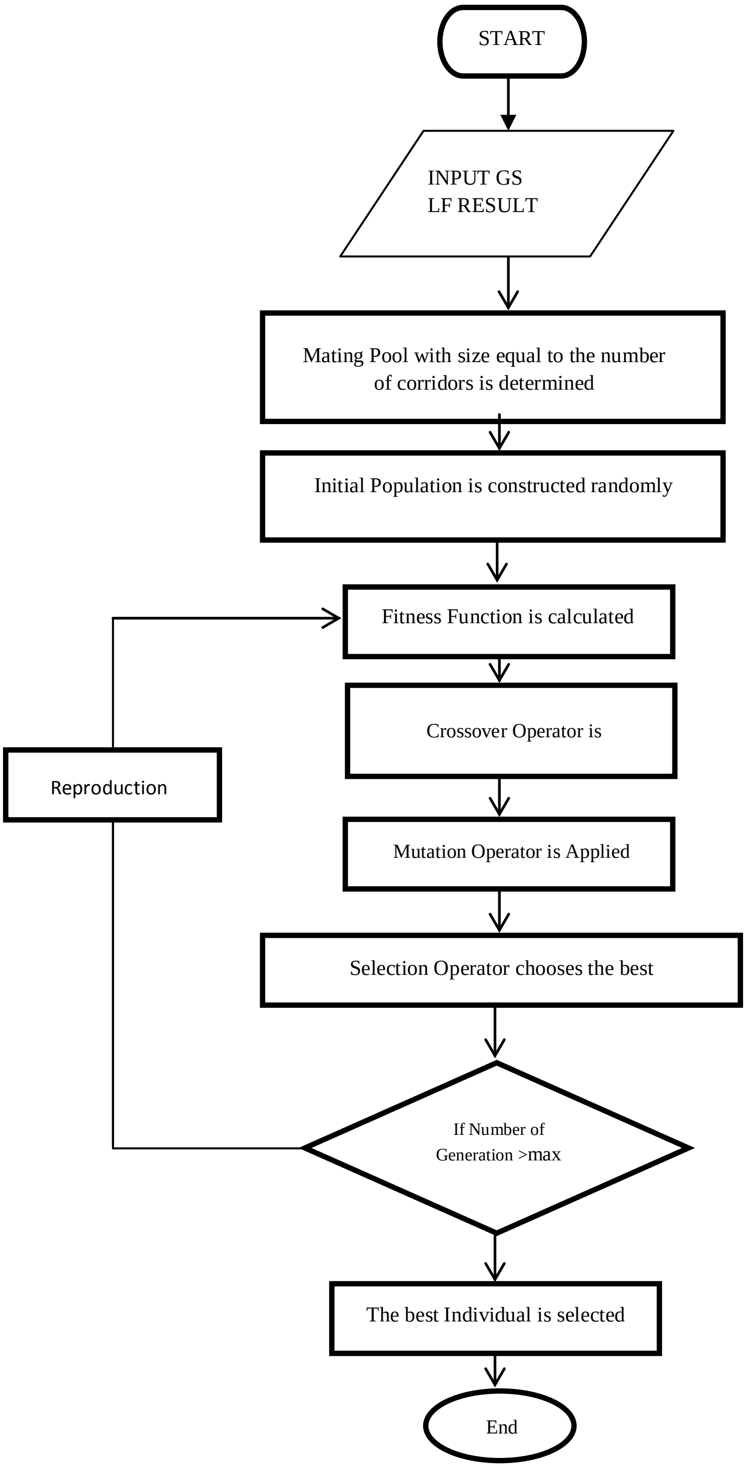

Fig. 2 Genetic Algorithm Flowchart

V. RESULTS AND DISCUSSION

IEEE 14 – bus network was used as a test system to demonstrate the effectiveness of the chosen method.The network data for the IEEE 14 – bus test network was gotten from [14].The voltage magnitude, voltage angle and line flow of the IEEE 14 – bus network as calculated are shown in tables I and II. Also, the optimal number of extra lines required in each network corridor as calculated is tabulated in Table III.

Table I: Voltage Magnitude And Voltage Angle

Bus Number	Voltage Magnitude(p.u.)	Voltage Angle
1.	1.0600	0
2.	1.0186	-4.6495
3.	1.0047	-13.0577
4.	0.9940	-10.2633
5.	0.9998	-8.7037
6.	0.9721	-15.0821
7.	0.9828	-13.8216
8.	1.0131	-13.8216
9.	0.9596	-15.7607
10.	0.9537	-15.9883
11.	0.9590	-15.6947
12.	0.9559	-16.1048
13.	0.9509	-16.1923
14.	0.9359	-17.1686

Table II: Line Flows

From Bus	To Bus	Line Flow (p.u.)
1	2	2.0220
1	5	2.8506
2	3	0
2	4	0
2	5	0.3277
3	4	0
4	5	0
4	7	0
4	9	0
5	6	0
6	11	0
6	12	0
6	13	0
7	8	0
7	9	0.6353
9	10	0.2140
9	14	0.1568
10	11	0.0373
12	13	0.0274
13	14	0

Table III: Number of New Circuits and Network Adequacy

S/NO	BRANCH	NEW CIRCUITS	NETWORK ADEQUACY (YEARS)
1.	1 – 2	4	6
2.	1 – 5	5	1
3.	2 – 5	0	5
4.	9 – 10	0	5

Table I and Table II show us the status of the network during the expansion year. A load growth coefficient of 1.07 was used to ascertain how the network would fare with yearly increase in demand. The transmission network adequacy is a measure of the length of time within which the transmission expansion plan would still be viable. The following can be inferred from the results so obtained:

- Line flow in branch 1 – 2 already exceeds the transmission capacity of the Line, thus the TEP proposes that 4 extra lines of the same capacity be constructed to relieve the already existing line in the branch. It also stipulates that the extra lines would become inadequate 6 years after expansion.
- Line flow of the line in corridor 1 – 5 also exceeds the transmission capacity of the line, much more than that of the line in corridor 1 – 2. Thus the TEP proposes that extra 5 lines of same capacity be constructed to relieve the already the congested line. However, the network adequacy of this plan is just 1 year. Improving the network adequacy would require an increase in the generation capacity, possibly in bus 2.
- Lines in corridors 2 – 5 and 9 – 10 both do not require extra lines; however the network adequacy of both lines is set at 5 years.

VI. CONCLUSION

This work addresses transmission system expansion planning using genetic algorithm. The number of transmission lines to decongest the branches and the corresponding network adequacy were both determined using this method. This work also provides a practical approach that could serve as a useful guide for the decision maker in selecting a reasonable expansion plan in the face of the prevalent circumstances.The model was also tested on IEEE 30 – bus network in order to ascertain the viability of the chosen methodology on diverse network models. They also suggest that transmission congestion occurs when actual or scheduled flows of electricity on a transmission lines are restricted below the level that grid users desire or when actual or scheduled flows exceeds the transmission capacity of the line.

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