Optimal Location of Static Synchronous Compensator (STATCOM) for IEEE 5-Bus Standard System Using Genetic Algorithm

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ABSTRACT

Heuristic approaches are traditionally applied to find the optimal size and optimal location of Flexible AC Transmission Systems (FACTS) devices in power systems. Genetic Algorithm (GA) technique has been applied to solve power engineering optimization problems giving better results than classical methods. This paper shows the application of GA for optimal sizing and allocation of a Static Compensator (STATCOM) in a power system. STATCOM devices used to increase transmission systems capacity and enhance voltage stability by regulate the voltages at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. IEEE 5-bus standard system is used as an example to illustrate the technique used. Results showed that the STATCOM was able to reduce the voltage deviation and the apparent power losses with minimum possible size of installation capacity for STATCOM devices. GA plays its own requirements by finding best location and best size of STATCOM devices.

Key words: facts, statcom, genetic algorithm.

الموقع الأمثل للمعوض التزامني الثابت لمنظومة IEEE ذات (5) عقدة القياسية بأستخدام الخوارزمية الجينية

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الخلاصة

النُهج الارشادية تطبق تقليديا لايجاد الحجم الامثل والموقع الامثل للاجهزة المرنة لنظام نقل التيار المتناوب (FACTS) في أنظمة القدرة. تقنية الخوارزمية الجينية (GA) طبقت لحل مشاكل هندسة الطاقة المثلى معطية نتائج أفضل من الطرق التقليدية. هذا البحث يوضح تطبيق (GA) لايجاد الموقع والحجم الامثل للمعوض التزامني الثابت (STATCOM) في نظام القدرة. يستعمل (STATCOM) لزيادة سعة أنظمة النقل وتحسين استقرارية الفولتية عن طريق تنظيم الفولتية عند الاطراف (الأحمال) بواسطة التحكم بمقدار القدرة غير الفعالة المحقونة أو الممتصة من منظومة القدرة. المنظومة الكهربائية ذات (5) عقدة القياسية لـ IEEE أستخدمت كمثال لتوضيح التقنية المستخدمة. أظهرت النتائج بأن الجهاز كان قادرا على تقليل أنحراف الفولتية وخسائر القدرة الظاهرية, مع أقل حجم ممكن للسعة التنصيبية لأجهزة (STATCOM). (GA) لعبت دورهم من خلال ايجاد الموقع الامثل والحجم الامثل لأجهزة (STATCOM).

الكلمات رئيسية: الاجهزة المرنة لنظام نقل التيار المتناوب, المعوض التزامني الثابت, الخوارزمية الجينية.

1. INTRODUCTION

Recently network blackouts related to voltage collapse tend to occur from lack of reactive power support in heavily stressed conditions, which are usually triggered by system faults. Reactive power has received less attention recently until the Great Blackout in August 2003 in the northeastern US, which showed that the reactive power in US power systems was not very well planned and managed, **Zhang, et al., 2006.**

Reactive power including its planning process had received tremendous interest after the 2003 Blackout from utilities, independent system operators, researchers, and the government. Power electronics based equipment, or flexible AC transmission systems (FACTS), provide proven technical solutions to voltage stability problems. Especially, due to the increasing need for fast response for power quality and voltage stability, the shunt dynamic Var compensators such as Static Var Compensators (SVC) and Static Synchronous Compensators (STATCOM) have become feasible alternatives to a fixed reactive source, and therefore have received intensive interests, **Meena, et al., 2013.**

The Static Synchronous Compensator (STATCOM) is a shunt device which employs one of the latest technologies of FACTS and power electronic switching devices in electric power transmission systems to control the voltage and power flow. The STATCOM regulates the voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When the system voltage is low, STATCOM generates reactive power and when the system voltage is high STATCOM absorbs reactive power. The purpose behind installing STATCOMs is crucial in deciding where to install them and the sufficient number and size of each STATCOM. The locations of STATCOMs have a significant impact on the power flow control performance.

In this paper, STATCOM was proposed to reduce the apparent power loss and solve voltage fall problem for the IEEE 5-bus standard system, this performance has been done by using minimum possible size of the reactive power injected or absorbed by the STATCOM devices, while satisfying the stability limits in order to reduce the estimated installation cost of STATCOM devices. The locations and sizes in MVAr of the STATCOM devices will be calculated by means of one of the optimization algorithm, namely, “Genetic Algorithm” (GA), **Salbi, 2014.**

GA is one of the commonly used methods to solve several optimization problems. GA can be used only for the types of problems where solutions can be represented by chromosome. GA starts by a randomly generated population of solutions, which will be improved through a repetitive application of mutation, crossover, and selection operators. Individual solutions are selected through a fitness-based process, where the more adapted solution is typically more likely to be selected.

2. STATIC SYNCHRONOUS COMPENSATOR (STATCOM)

STATCOM is a second generation FACTS device used for shunt reactive power compensation. The principle of STATCOM is the reactive power compensation where the reactive power and voltage magnitude of the system can be adjusted such as shown in **Fig. 1**. It consists of three paths: shunt (coupling) transformer, voltage source converter (VSC), and capacitor. The reactive power is distributed in the power system by the converter control **,Lin, et al., 2009.**

Where $V i \angle \theta i$: are the bus voltage and its phase angle of power system.

$V s \angle \theta\ s$: is the STATCOM voltage and its phase angle.

The SATCOM active P and reactive power Q are given in Eqs. (1) and (2).

$$P = \frac{V_s V_i}{X_s} \sin \delta \tag{1}$$

$$Q = \frac{{V_i}^2}{X_s} - \frac{V_s V_i}{X_s} \cos \delta \qquad (2)$$

Where *Xs:* is coupling transformer equivalent reactance

$$\delta = \theta s - \theta i \qquad (3)$$

The STATCOM is a combination of a voltage sourced converter and an inductive reactance and shunt connected to power system. The converter supplies leading current to the AC system if the converter output voltage *Vi* is made to lead the corresponding AC system voltage *VS*. Then it supplies reactive power to the AC system by capacitive operation. Conversely, the converter absorbs lagging current from the AC system; if the converter output voltage *Vi* is made to lag the AC system voltage *VS* then it absorbs reactive power to the AC system by inductive operation. If the output voltage is equal to the AC system voltage, the reactive power exchanges.

3. GENETIC ALGORITHM

Genetic algorithm (GA) is one of the evolutionary Algorithms search technique based on mechanism of natural selection and genetics. It searches several possible solutions simultaneously and do not require prior knowledge or special properties of the objective function, **Eseosa, et al., 2012.**

GA starts with initial random generation of population of binary string, calculates fitness values from the initial population, after which the selection, cross over and mutation are done until the best population is obtained. GA encodes the variables of the optimization function and runs a searching process that explores the searching space in parallel. The searching mechanism starts with an initial set of solutions generated randomly and called "*Population*". This initial set up solutions satisfies the equality and inequality constraints of the problem. Each individual solution in the population is called "*Chromosome*". The movement of the algorithm towards the global point is directed by fitness function evaluation of the chromosomes. GA uses the criteria of natural selection to evolve the chromosomes through successive iterations called "*Generations*". New chromosomes (offspring) are formed by crossover and/or mutation operators. And by continuous evaluation of each chromosome during each generation, and by using selection techniques, a new generation is formed. Typically GA consist of three phases,

(1) Generation
(2) Evaluation
(3) Genetic operation

3.1 Generation

In this phase number of chromosomes equal to population size is generated and each is of length equals to string length. The size of population is direct indication of effective representation of whole search space in one population. The population size affects both the ultimate performance and efficiency of GA. If it is too small it leads to local optimum solution. The selection of string length depends on the accuracy and resolution requirement of the optimization problem. The higher the string length, the better the accuracy and resolution. But this may lead to slow convergence.

3.2 Evaluation

In the evaluation phase, suitability of each of the solutions from the initial set as the solution of the optimization problem is determined. For this function called *"fitness function"* is defined.

This is used as a deterministic tool to evaluate the fitness of each chromosome. The optimization problem may be minimization or maximization type. In the case of maximization type, the fitness function can be a function of variables that bear direct proportionality relationship with the objective function **,Sivanandam, et al., 2008.**

For minimization type problems, fitness function can be function of variables that bear inverse proportionality relationship with the objective function or can be reciprocal of a function of variables with direct proportionality relationship with the objective function. In either case, fitness function is so selected that the most fit solution is the nearest to the global optimum point. The programmer of GA is allowed to use any fitness function that adheres to the above requirements. This flexibility with the GA is one of its fortes.

3.3 Genetic Operation

In this phase, the objective is the generation of new population from the existing population with the examination of fitness values of chromosomes and application of genetic operators. These genetic operators are *reproduction, crossover, and mutation.* This phase is carried out if we are not satisfied with the solution obtained earlier. The GA utilizes the notion of survival of the fittest by transferring the highly fit chromosomes to the next generation of strings and combining different strings to explore new search points.

i. Reproduction

Reproduction is simply an operator where by an old chromosome is copied into a Mating pool according to its fitness value. Highly fit chromosomes receive higher number of copies in the next generation. Copying chromosomes according to their fitness means that the chromosomes with a higher fitness value have higher probability of contributing one or more offspring in the next generation.

ii. Cross over

It is recombination operation. Here the gene information (information in a bit) contained in the two selected parents is utilized in certain fashion to generate two children who bear some of the useful characteristics of parents and expected to be more fit than parents.

Crossover is carried out using any of the following three methods:

(a)Simple or Single Point Crossover

(b) Multi point crossover

(c) Uniform crossover

iii. Mutation

This operator is capable of creation new genetic material in the population to maintain the population diversity.

It is nothing but random alteration of a bit value at a particular bit position in the chromosome.

Some programmers prefer to choose random mutation ‘or’ alternate bit mutation. *“Mutation Probability (Pm)”* is a parameter used to control the mutation. For each string a random number between ‘0’ and ‘1’ is generated and compared with the Pm. if it is less than Pm mutation is performed on the string. Sometimes mutation is performed bit-by-bit also instead of strings. These results in substantial increase in process time but performance of GA will not increase to the recognizable extent **,Gen, et al. 2008.**

So this is usually not preferred. Thus obviously mutation brings in some points from the regions of search space which otherwise may not be explored. Generally mutation probability will be in the range of 0.001 to 0.01. This concludes the description of Genetic Operators.

4. OBJECTIVE FUNCTIONS

Three objective functions were considered in this paper, which are the apparent power losses (operational efficiency), voltage deviation (system security and service quality) and minimum possible value of reactive power injected/absorbed by the STATCOM (economic benefits). These objective functions can be summarized as follows:

A. Apparent Power Losses

The apparent power loss of the transmission line is one of the essential objectives for the optimization problem in the electrical power system when it gathers the active and reactive components in one formula. Then the apparent power losses of the transmission lines are given as:

$$S_{losses} = \sum_{i=1}^{Nt}\left(\left| P_{si} - \mathrm{P_{ri}} \right| + j \left[\left| Q_{si} - \mathrm{Q_{ri}} \right| - \{Q_{si}^{ch} + Q_{ri}^{ch}\} \right] \right) \quad (4)$$

In which

$$Q_i^{ch} = V_i^2 \, \frac{B_i}{2} \quad (5)$$

Where S_{losses} are the apparent power losses in MVA. Nt is the number of transmission lines. P_{si} and P_{ri} are the sent and received active power of the line i, respectively. Q_{si} and $Q_{ri}$are the sent and received reactive power of the line i, respectively. Q_{si}^{ch} and Q_{ri}^{ch} are the sent and received charging reactive power of the line i, respectively. V_i is the voltage magnitude at bus *i*. B_i represents the susceptance of the π-model transmission line *i*, **Salbi, 2014.**

B. Voltage Deviation

The bus voltage is one of the most important security and service quality indexes. Therefore, minimizing the voltage drop will increase the system security. The voltage deviation of the system is given as, **Vedam, et al., 2009.**

$$V_D = \sum_{i=1}^{Nb} \frac{(V_{ref} - V_i)^2}{V_{ref}} \quad (6)$$

The reference voltages for generator (PV) bus are fixed, thus, the equation becomes:

$$V_D = \sum_{i=1}^{Nd} (V_{ref} - V_i)^2 \quad (7)$$

Where

V_D is the voltage deviation. V_{ref} is the reference voltage for bus *i*. V_i is the specified voltage magnitude at bus *i*. Nb is the number of buses. Nd is the number of load buses.

C. Minimum Possible Size of STATCOM in MVar

This objective states that the injected/absorbed reactive power in Mvar should be as minimum as possible to satisfy the optimization and load flow requirements, which will lead to getting a minimum size of STATCOM Min_{MVar} and so minimizing STATCOM initial cost.

Many different sizes and Standardized configurations of STATCOM are available and the may be used in bands such as: ±25MVar, ±35MVar, ±50MVar, ±100MVar, and above. These units can be configured as a fully parallel operating system. It is well known that the FACTS devices can be used to provide reactive power compensation.
Table 1 gives an idea about the estimated cost of various reactive power sources including all FACTS devices, **Mathur, et al., 2002.**

5. OTTIMIZATION OF MULTIOBJECTIVE FUNCTION

The optimization problem may have a singleobjective function or multi objective functions. The multiobjective optimization problem can be defined as the problem of finding a vector of decision variables that satisfies the constraints and optimizes a vector function whose elements represent the objective functions. Most of the real world problems involve more than one objective, making multiple conflicting objectives interesting to solve as multi objective optimization problems. Multiobjective problem can be formulated as **,Zitzler, 1999.**

Minimize

$$Y(x,u) = [f_1(x,u), \ldots \ldots, f_n(x,u)] \quad (8)$$

While satisfying

$$g(x,u) = [g_1(x,u), \ldots \ldots, g_{m1}(x,u)] = 0 \quad (9)$$

$$h(x,u) = [h_1(x,u), \ldots \ldots, h_{m2}(x,u)] \le 0 \quad (10)$$

Where:
n is the number of objectives required to minimize or maximize. m_1 and m_2 are the number of equality and inequality constraints, respectively.
Compared with the single objective problems, multiobjective problems are more difficult to solve, since there is no unique solution. There is a set of acceptable trade-off optimal solutions. This set is called Pareto front. The preferred solution, the one most desirable to the decision maker, is selected from the Pareto set **,Kong, et al., 2009.**
There are several methods that can be used to solve multiobjective problems using single objective approximations. The weighted sum method is used in this work to solve the Pareto front problem. Weighted sum method changes a weight multiplier among the objectives in the objective function to obtain the Pareto front. Then, the multiobjective optimization problem will take the following general form:

$$F(x,u) = w_1 f_1(x,u) + w_2 f_2(x,u) + \cdots + w_m f_m(x,u) \quad (11)$$

Where:

$$0 \le w_i \le 1 \quad (12)$$

$$\sum_{i=1}^{m} w_i = 1 \quad (13)$$

6. CASE STUDY

The Genetic algorithm technique will be implemented to find the fitness function solutions for the proposed cases as shown in **Fig. 2**. The aim is to find the best locations of the STATCOM devices as well as the value of injected or absorbed reactive power from each one to satisfy the minimum values for the three proposed objectives. Two operational case studies will be discussed and analyzed in details in this research to clarify the significance of the proposed STATCOM device including the location and the size. The algorithm will be applied on the IEEE 5-bus standard system, based on the location and the size results of STATCOM.
The proposed algorithm is restricted to the following parameters, **Salbi, 2014.**

- The number of STATCOM devices that will be installed is one for the case of IEEE 5-bus standard system.
- The maximum and minimum limits of STATCOM used is :
  $-25MVar \leq Q_{STATCOM} \leq +25MVar$
- The algorithm is appropriate that only one STATCOM device is allowed to be installed at nominated bus.
- The STATCOM devices can be installed only at load buses (PQ).The slack bus and (PV) buses are excluded.
- GA parameters for the two case studies are:
  Population size = 65
  Maximum number of generations = 80
  Cross over probability = 0.8
  Mutation probability = 0.003

7. RESULTS

Fig. 3 shows the single line diagram for the IEEE 5-bus standard system which contains (2) generators, (7) transmission lines, and (3) load buses. The real data for the IEEE 5-bus test system are given in **Table 2.** The number of STATCOM devices that can be used is $0 \leq N_{STATCOM} \leq 3$. Only one STATCOM device with maximum and minimum size limits of ±25 MVar was sufficient to satisfy the stability requirements. GA solves the multiobjective function with equal weights for all factors (S_{losses} , V_D, and Min_{MVar}). The results show that the STATCOM optimal location is at bus (4) with the size of (22.5806 MVar) as an injected reactive power to the system. Obviously, the voltage deviation and the apparent power losses are reduced when compared with the uncompensated system using the conventional Newton-Raphson power flow. **Table 3** shows the STATCOM location, the size of injected MVar, the estimated cost, and the comparison between V_D and S_{loss} for the two cases.
In the STATCOM localization problem, it was noticed that the algorithm found the solution after around 2 generations. Nevertheless, the number of generations in each case is set to be 80 to explore all search space and prevent the algorithm from falling in local minima. For this optimum case, the evolution of the best individual (minimum objective function value) for each generation of GA with the value of the fitness function is to be minimized which collect three objective functions as shown in **Fig.4**.
The bus voltage magnitudes for the two cases uncompensated (before installing STATCOM) and compensated (after installing STATCOM using GA) are illustrated in **Fig. 5.** From **Table 3** and **Fig. 5**, it can be seen that when the reactive power is injected by a STATCOM device in bus 4 (selected by GA), a better improvement in the network voltage level occurs with reducing the voltage deviation by 53.95%. Also the STATCOM effect is attained to reduce apparent power loss by 2.25%.

8. CONCLUSION

In this work, GA was proposed as an algorithm to find the best locations and sizes of STATCOM devices. The algorithm was applied to IEEE 5-bus standard system. The proposed algorithm was implemented using MatLab programming language. Three objectives were taken into account, namely, apparent power losses, voltage deviation, and minimum possible size in MVar injecting or absorbing by the proposed device of STATCOM. GA was used to solve the multiobjective optimization problem. The three objectives were combined in one objective function using weighting method. The application of the algorithm successfully found the optimum location and the size of STATCOM. STATCOM reduced the apparent power losses of the grid as well as enhanced voltage profile by reducing voltage deviation from its nominal value for all load nodes. The optimization algorithm was always restricted to the system voltage limits, STATCOM's proposed limits, generators reactive power limits, etc.

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NOMENCLATURE

Min_{Mvar}: minimum reactive power supplied by STATCOM
$N_{STATCOM}$: number of STATCOMs
P: active power
Q: reactive power
$Q_{STATCOM}$: reactive power of STATCOM
S_{losses}: apparent power losses
V_D: voltage deviation
V_s: ac bus voltage
V_i: STATCOM bus voltage
θs: phase angle of power system
θi: phase angle of STATCOM
Xs: coupling transformer equivalent reactance
Nt: number of transmission lines
Q_i^{ch}: charging reactive power of line *i*
B_i : susceptance of the π-model transmission line *i*
Nd: number of load buses
$F(x, u)$: multiobjective optimization function

Table1. Cost estimates for FACTS controllers.

Controller	Cost
Shunt Capacitor	8$US /Kvar
Conventional series capacitor	20$US /Kvar
SVC	40$US /Kvar – controlled part
TCSC	40$US /Kvar – controlled part
STATCOM	50$US /Kvar
UPFC series portion	50$US /Kw – series power flow
UPFC shunt portion	50$US /Kvar – controlled part

Table2. The input branch data for the IEEE 5-bus standard system.

From Bus	To Bus	R p.u.	X p.u.	B p.u.
1	2	0.02	0.06	0.06
1	3	0.08	0.24	0.05
2	3	0.06	0.18	0.04
2	4	0.06	0.18	0.04
2	5	0.04	0.12	0.03
3	4	0.01	0.03	0.02
4	5	0.08	0.24	0.05

Table3. Results of comparison between uncompensated and compensated cases.

Case	Voltage deviation V_D	Apparent power loss S_{loss}(MVA)	Bus location	Minimum injected size in MVar Min_{MVar}	Estimated cost ($\$\times 10^5$)
Uncompensated	0.0569	15.9568	—	—	—
Compensated *using one STATCOM*	0.0262	15.5975	4	22.5806	11.2903

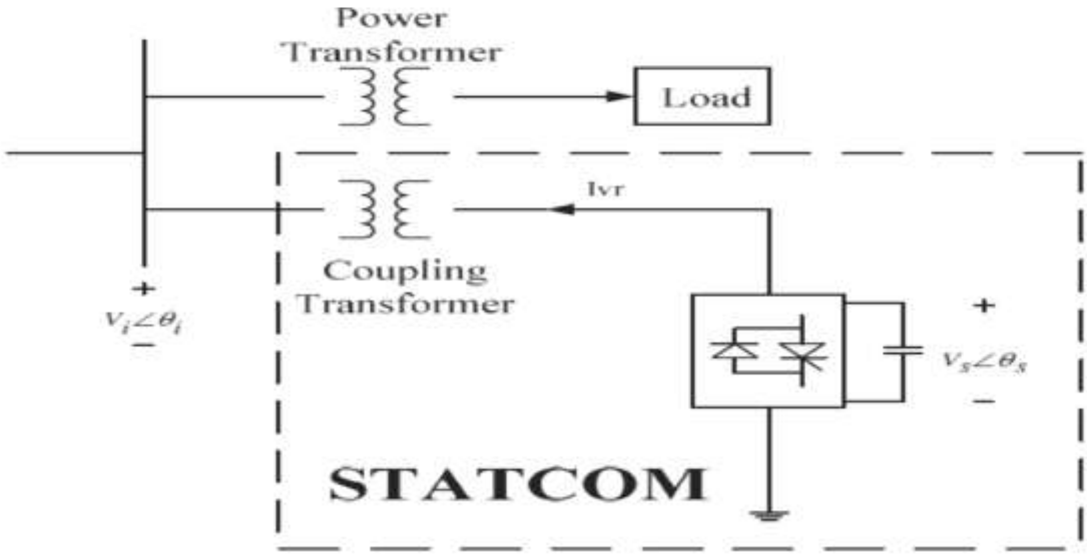

Figure 1. Block diagram of a typical STATCOM.

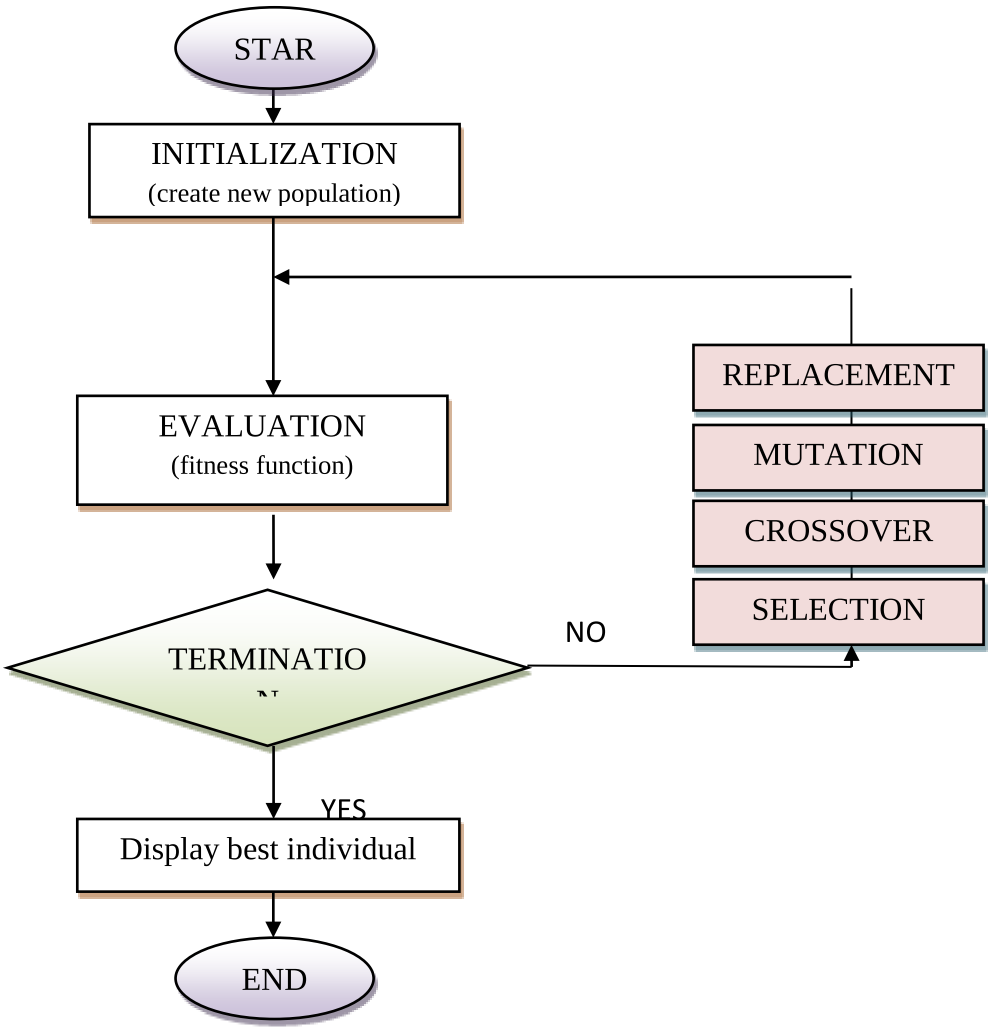

Figure 2. The proposed implemented Genetic Algorithm (GA).

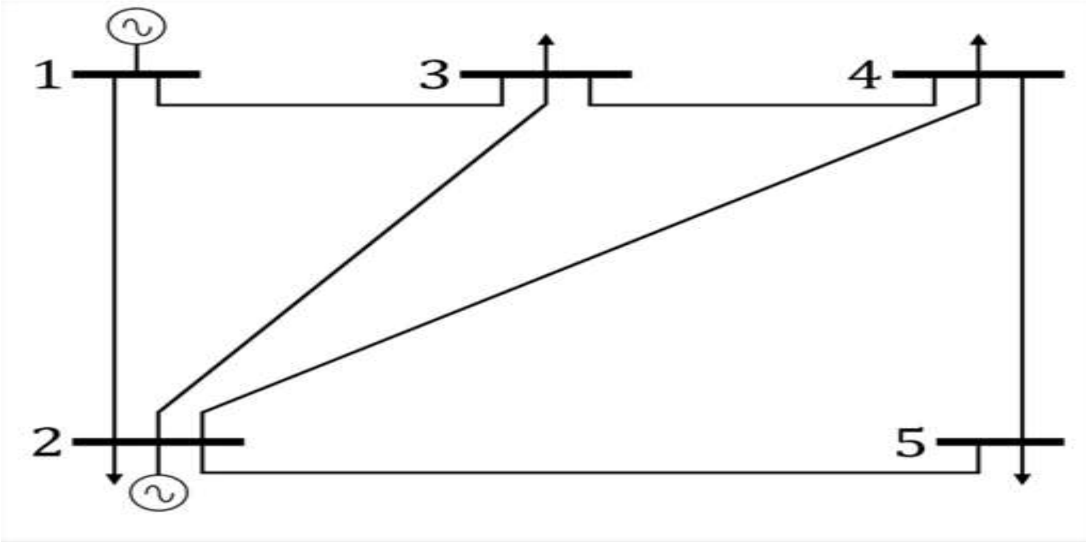

Figure 3. Single line diagram of IEEE 5-bus standard system.

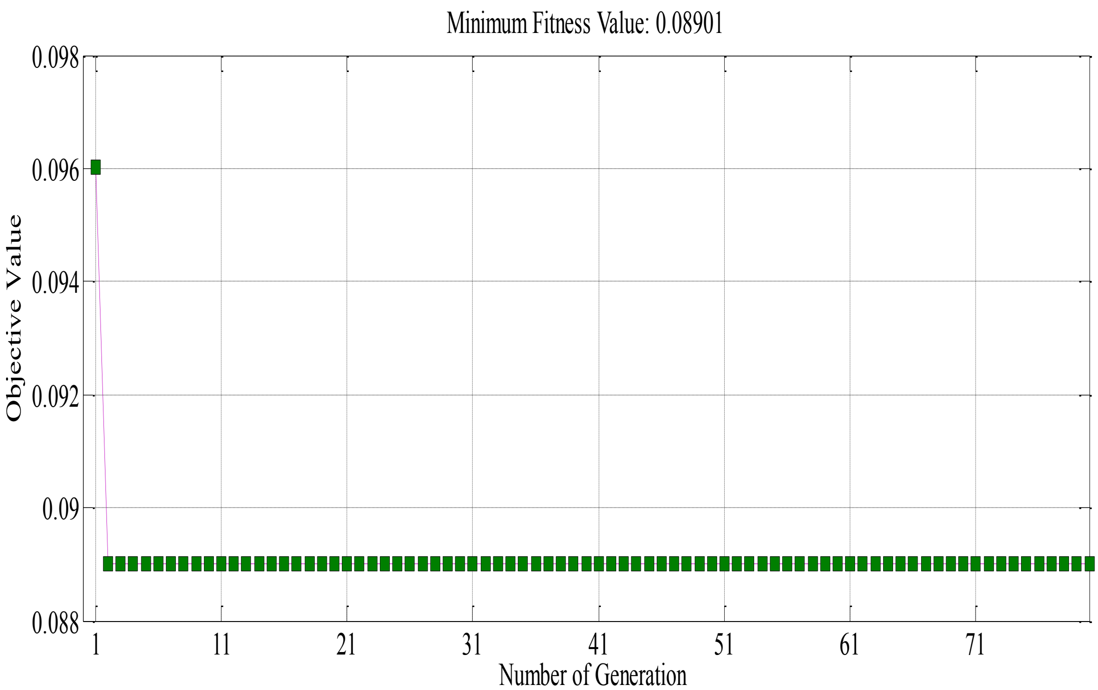

Figure 4. Best individual evolution for each generation in GA for IEEE 5-bus standard system.

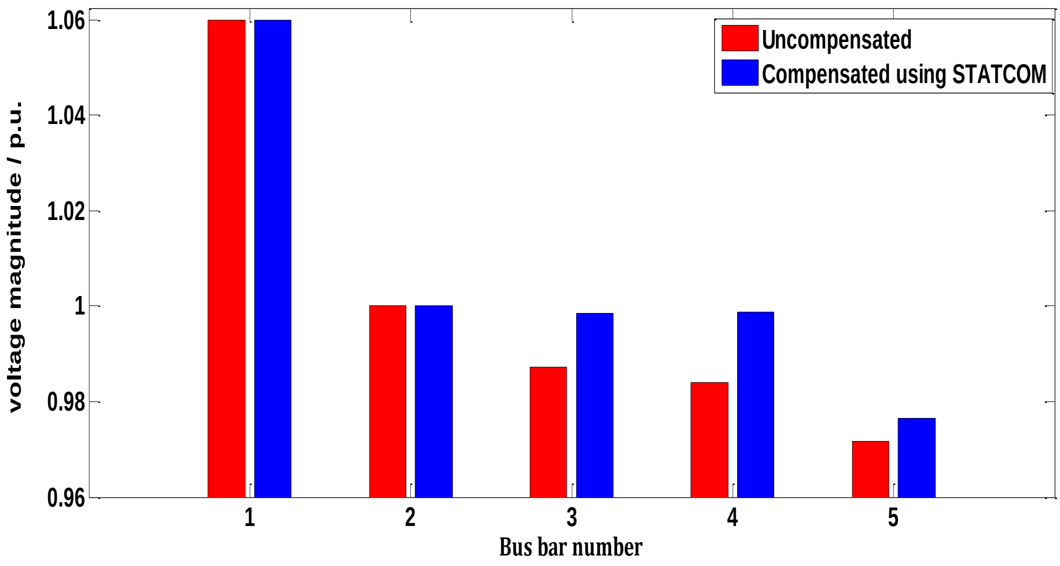

Figure 5. Bus voltage magnitudes before and after installing one STATCOM (in bus no.4) for IEEE 5-bus standard system.