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Comparison of PSO and RCGA for Optimal Location of STATCOM for Improvement of Transient Stability of Power Systems

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In electrical power systems, reactive power compensation plays an important role in transient stability. Shunt flexible AC transmission system (FACTS) devices are being used in controlling the reactive power flow to the power network and, hence, the system voltage fluctuations and stability. Static synchronous compensator (STATCOM) is one of the shunt connected FACTS devices. The primary purpose of STATCOM is to support bus voltage by injecting (or absorbing) reactive power, but it is also capable of improving the power system stability. In this paper, an interconnected two-area test system with actual transmission line model is used to show the effectiveness of Particle Swarm Optimisation (PSO) and Real Coded Genetic Algorithms (RCGA) algorithms for determining the optimal location for power system stability improvement.

Keywords : *Transient Stability, STATCOM, Particle Swarm Optimisation, Real Coded genetic Algorithm , Actual Transmission Line Model*

1.0 INTRODUCTION

STATCOM or Static Synchronous Compensator is a shunt device which uses force-commutated power electronic devices to control power flow and improve transient stability on electrical power networks. It is also a member of the so-called Flexible AC Transmission System (FACTS) devices. The term Static Synchronous Compensator is derived from its capabilities and operating principle, which are similar to those of rotating synchronous compensators (i.e. generators), but with relatively faster operation. STATCOMs are typically applied in long distance transmission systems, power substations and heavy industries where voltage stability is the primary concern. STATCOM has the ability to provide more capacitive reactive power during faults, or when the system voltage drops abnormally, compared to SVC static var compensator. Transient stability of a power system refers to the ability of the system to reach a stable condition following a large disturbance in the network.

The first swing stability of the Power system is greatly influenced by the choice of different models of the transmission line. When the simplified model of transmission line (only reactance is considered and resistance and capacitance are neglected) is considered, the midpoint location of FACTS devices give maximum benefit of voltage support and transient stability. The transmission line losses affect the optimum location of STATCOM in long transmission lines.For long transmission lines, when the actual model of the line is considered, the results may deviate significantly from those found for the simplified model. With pre-defined direction of real power flow, the shunt FACTS devices need to be placed slightly off-centre towards the sending end for maximum

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benefit from the transient stability point of view. In this paper PSO (Particle Swarm Optimisation) and RCGA (Real Coded Genetic Algorithm) techniques are used to determine optimal location of STATCOM in a long transmission line for transient stability improvement.

2.0 TRANSIENT STABILITY OF POWER SYSTEM

Transient stability is mainly concerned with the ability of power systems to maintain synchronism when subjected to severe disturbances such as sudden change of load, Switching operations, Loss of generation and Fault. Following such sudden disturbances in the power system, rotor angular differences, rotor speeds, and power transfer undergo fast changes whose magnitudes are dependent upon the severity of the disturbances. For a large disturbance, changes in angular differences may be so large as to cause the machine to fall out of step. This type of instability is known as Transient Instability. Transient instability is a fast phenomenon, usually occurring within one second for a generator close to the cause of disturbance. In some cases, the system may be stable even with sustained fault; whereas in other cases system will be stable only if the fault is cleared with sufficient rapidity. Whether the system is stable on the occurrence of a fault depends not only on the system itself, but also on the type of fault, location of fault, clearing time and the method of clearing. Steady state stability is defined as the ability of a system to remain stable for small disturbances. The steady state stability limit is the maximum power that can be transferred by a machine to a receiving system without loss of synchronism. The transient stability limit is the maximum power that can be transmitted by a machine to a fault or a receiving system during a transient state without loss of synchronism. Transient stability limit is almost always lower than the steady state limit.

Each generator operates at the same synchronous speed and frequency while a delicate balance between the input mechanical power and output electrical power is maintained. The generators are also interconnected with each other and with the loads they supply via high voltage transmission line. Large disturbances like severe lightning strikes or loss of transmission line carrying bulk power due to overloading do occur on the power system. The physical phenomenon after any disturbance in the system will cause the imbalance between the mechanical power input to the generator and electrical power output of the generator. As a result, some of the generators will tend to speed up and some will tend to slow down. If, for a particular generator, this tendency is too great, it will no longer remain synchronous with the rest of the system and will be automatically disconnected from the system. The ability of power systems to survive the transition following a large disturbance and reach an acceptable operating condition is called transient stability. The imbalance in the generator electrical output power and mechanical input power is reflected in the change in the flows of power on transmission lines. As a result, there could be large oscillations in the flows on the transmission lines as generators try to overcome the imbalance and their output swing with respect to each other.

2.1 Critical Clearing Time

The critical clearing time (CCT) can be defined as the maximum time delay that can be allowed to clear a fault without loss of synchronization. The critical clearing angle is the maximum allowable change in the power angle before clearing the fault, without loss of synchronization. CCT is the principal criterion to transient stability assessment and every generator connected to the power system should have CCT longer than the operational time of circuit breaker in the power system. The calculated CCT for three-phase fault on nearest bus bar of individual generator will be sufficient to sustain transient stability of synchronous generator for all remaining types of fault in the more distant places in power system with times shorter than the CCT. Thus, if operational time of circuit breaker in the system is shorter than the smallest value of CCT (smallest CCT of individual generators in the power system), the occurrence of short-circuit in power system should not threaten transient stability of generators.

3.0 TWO-AREA POWER SYSTEM WITH STATCOM

A two area system consists of two single area systems , connected through a power line called the tie-line.Each area feeds its user pool, and the tie line allows electric power to flow between the areas. It is conveniently assumed that each control area can be represented by an equivalent turbine, generator and governor system [1].

Consider a two area system (area 1 and area 2), connected by a double circuit long transmission line as shown in Figure 1. The direction of real power flow is from area 1 to area 2. The system consists of two hydraulic generating units, one of 1400 MVA in one area and 700 MVA in the other. The generators are represented by a sixth-order model and both are equipped with hydraulic turbine and governor (HTG) and excitation system. The HTG represents a nonlinear hydraulic turbine model, a PID governor system, and a servomotor. The excitation system consists of a voltage regulator and DC exciter, without the exciter's saturation function.

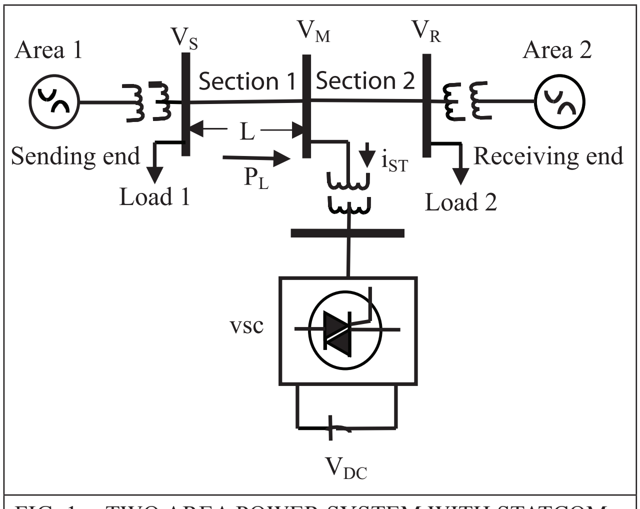


FIG. 1 TWO AREA POWER SYSTEM WITH STATCOM

The generators with output voltages of 13.8 kV are connected by a double circuit long 400 km transmission line through three-phase step-up transformers. The output voltage of transformer is 400 kV. The loads in each area are so chosen that the real power flow on the transmission line is always from area-1 to area-2. The STATCOM used for this model is a phasor model with a rating of ±200 MVA. The parameters of all the elements are given in Appendix. The transmission line is divided into two sections (section 1 and section 2) and 's' is the fraction of line length at which the FACTS device is placed. For a long transmission line of length L having a series impedance of z ohm/km and shunt admittance of y mho/km, the relationship between the sending-end and receiving-end quantities with A,B,C,D constants of the line can be written as

$$V_S = AV_R + BI_R \qquad ....(1)$$

$$I_S = CV_R + DI_R \qquad ....(2)$$

For the simplified model, where the line resistance and capacitance are neglected, both sending end power (PS)and receiving end power (PR) become maximum at power angle $\delta = 90°$. When a shunt FACTS device is connected to a long line to increase the power transfer capability,the above simplifications may provide erroneous results.[3] The active power flows at the sending end and receiving end for a long transmission line with distributed parameters can be written as

$$P_S = K_1\cos(\theta_B - \theta_A) - K_2 \cos(\theta_B + \delta) \qquad ....(3)$$

$$P_R = K_2 \cos(\theta_B - \delta) - K_3 \cos(\theta_B - \theta_A) \qquad ....(4)$$

where,

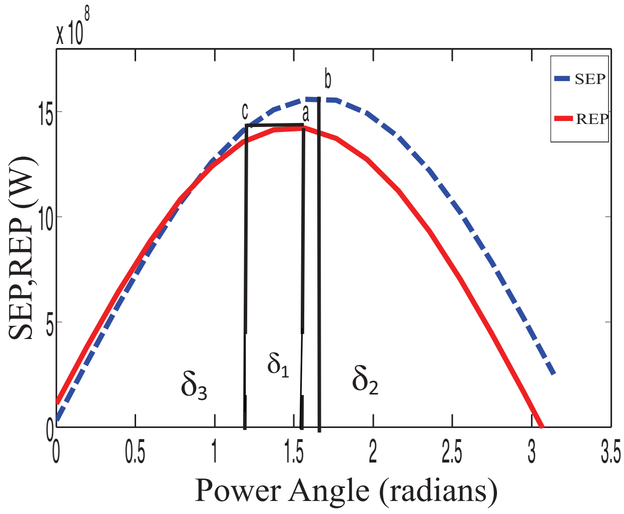
$K_1 = |A||V_S|^2/|B|$

$K_2 = |A||V_S||V_R|/|B|$, $K_3 = |A||V_R|/|B|$,

$A = |A| \angle\theta_A$, $B = |B|\angle\theta_B$, $V_R = |V_R|\angle 0$,

$V_S = |V_S|\angle\delta$

It is clear from Eq. (4) that the receiving-end real power P_R reaches the maximum value when the angle δ becomes θ_B. However, the sending-end real power P_S of Eq. (3) becomes maximum $\delta = (180 - \theta_B)$.



SEP--- Sending End Power

REP --- Receiving End Power

FIG. 2 SENDING-END AND RECEIVING-END POWER-ANGLE CHARACTERISTICS FOR ACTUAL LINE MODEL

The ABCD parameters of the 400 kV double circuit line and the values of K1, K2 and K3 are calculated. Then for various values of powerangles δ, the power-angle characteristic of the 400 kV Double circuit line using the actual line model without FACTS device is plotted using the equations (3) and (4) and is shown in Figure 2. It also represents the power angle characteristics of both line sections, if a large rating shunt FACTS device is placed at the centre. Assuming that the FACTS device does not absorb or deliver any active power, the receiving end power of section 1 must be equal to the sendingend power of section 2. If section 1 delivers the maximum power at its receiving end (point a), the corresponding sending end power of section 2 can be represented by the same power level (point c) and the total transmission angle at the maximum power point is δ = δ1 + δ3. Thus,the maximum power transfer capability of the system is limited by the maximum receiving end power of section 1.The shape of the power angle curve depends on the line length or fraction ‘s’. For lower values of s, the maximum receiving end power of section 1 increases, while the maximum sending end power of section 2 decreases.Thus point a in Figure 2 (b) moves upwards and point b goes downwards. Both the powers will be equal at a value s < 0.5 because of the losses in the line[1].

4.0 OPTIMAL LOCATION OF STATCOM IN LONG TRANSMISSION LINE

The power transfer capability and hence the transient stability of the system can be improved by locating STATCOM slightly off-centre towards the sending-end instead of the mid-point. For a given initial operating conditions, there will be an optimal location of STATCOM where the maximum sending-end power of section-1 is equal to the maximum receiving-end power of section-2. [6] From transient stability point of view, the value of maximum sending-end power is important as the power that can be drawn from generator terminals immediately after fault clearance influences the transient stability. Therefore, the objective function to maintain transient stability can be written in the following form:

Objective function

$$J = |\text{maximum}(\Delta\delta_1 - \Delta\delta_2)| \qquad ....(5)$$

where $\Delta\delta_1$ and $\Delta\delta_2$ are the rotor angle deviation following a disturbance of generators in areas 1 and 2, respectively, and $|\text{maximum}(\Delta\delta_1 - \Delta\delta_2)|$ is the absolute value of maximum rotor angle deviation difference of two areas. If $|\text{maximum}(\Delta\delta_1 - \Delta\delta_2)| < 180°$ the system is stable. For objective function calculation, the time-domain simulation of the nonlinear system model is carried out for the simulation period. PSO and RCGA techniques are employed to search for the location of STATCOM where the value of objective function is minimum. The problem constraints are the location bounds. Therefore, the design problem can be formulated as the following optimization problem:

$$\text{minimize } J \qquad ....(6)$$

subject to

$$L_{min} \le L \le L_{max} \qquad ....(7)$$

where L is the length of line section from the sending-end to the location of STATCOM. The following steps are to be followed to search for the optimal location of STATCOM to improve transient stability:

Step-1: Initially set the fault clearing time T_{FC} to a high value so that the system is unstable at all locations of STATCOM.

Step-2: Employ PSO or RCGA to minimize the objective function J

Step-3: Check for stability of the system.

Step-4: If the system is unstable, decrease T_{FC} by a small step and repeat from Step-2. Stop if the system is stable.

The system will be stable at $T_{FC} = T_{FCF}$ only if the STATCOM is placed at optimal location obtained by the above method and for $T_{FC}>T_{FCF}$ the system becomes unstable at all locations. [1][5]

5.0 PARTICLE SWARM OPTIMIZATION

PSO method is a population-based search algorithm where each individual is referred to as particle. Each particle in PSO flies through the search space with an adaptable velocity that is dynamically modified according to its own flying experience and also to the flying experience of the other particles. The position corresponding to the best fitness is known as pbest and the overall best out of all the particles in the population is called gbest.[4] The modified velocity and position of each particle can be calculated using the current velocity and the distance from the pbest$_j$, $_g$ to $_g$ best $_g$ as shown in the following formulas:

$$v_{j,g}^{(t+1)}=w_j v_{j,g}^{(t)}+c_1 r_1(pbest_{j,g}-x_{j,g}^{(t)}+ c_2 r_2(gbest_g-x_{j,g}^{(t)}) \quad ....(8)$$

$$x_{j,g}^{(t+1)} = x_{j,g}^{(t)} + v_{j,g}^{(t+1)} \quad ....(9)$$

$$W_j = w_{end} -(w_{end} - w_{start})^{\frac{i}{imax}} \quad ....(10)$$

with j = 1, 2, . . … n and g = 1,2,…..m, where n is the number of particles in a group;

m the number of members in a particle;

t the number of iterations (generations);

$v_{j,g}^{(t)}$ the velocity of particle j at iteration t,

$v_g^{min} \leq v_{j,g}^{(t)} \geq v_g^{max}$

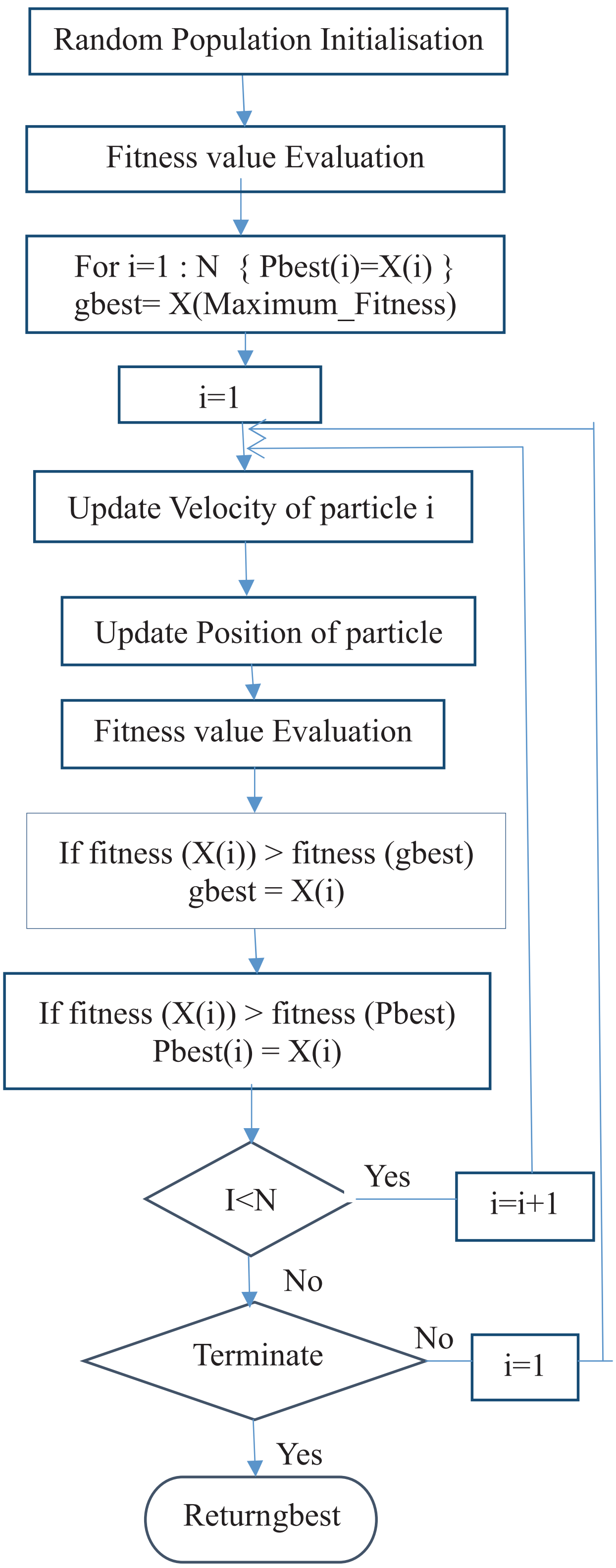


FIG. 3 PARTICLE SWARM OPTIMISATION ALGORITHM – FLOW CHART

w the inertia weight factor; c_1 and c_2 are the cognitive and social acceleration factors, respectively; r_1 and r_2 are the random numbers uniformly distributed in the range (0, 1); $x_{j,g}^{(t)}$ is the current position of particle j at iteration t;

The j-th particle in the swarm is represented by a g-dimensional vector $x_j=(x_{j,1}, x_{j,2},\ldots x_{j,g})$ and its rate of position change (velocity) is denoted by another g-dimensional vector $v_j=(v_{j,1}, v_{j,2},\ldots v_{j,g})$. The best previous position of the j-th particle vector $pbest_j = (pbest_{j,1}, pbest_{j,2}, \ldots ; pbest_{j,g})$. The index of best particle among all the particles in the group is represented by $gbest_g$. The flow chart of PSO is shown in Figure 3.

6.0 REAL CODED GENETIC ALGORITHM

Genetic algorithms(GAs) are general purpose search algorithms which use principles inspired by natural genetic populations to evolve solutions to problems . Each chromosome in the population has an associated fitness to determine which chromosomes are used to form new ones in thecompetition process,which is called selection. The new ones are created using genetic operators such as crossover and mutation. GAs have had a great measure of success in search and optimization problems. GAs based on real number representation are called *Real Coded GAs* (RCGAs). Genetic algorithms includes the following genetic operations.

6.1 Chromosome Representation

It is the initial pool of population and here real coded chromosome representation is used.

6.2 Selection function

To produce successive generations, selection of individuals plays a very significant role in a genetic algorithm. Here the natural selection method is employed which is based on the theory of survival of the fittest. Parents having high fitness values are chosen for the reproduction in each iteration.

6.3 Arithmetic Crossover

It is a reproduction operation which produces two complimentary linear combinations of the parents.

$$X' = r\ X + (1-r)\ Y \qquad ....(11)$$

$$Y' = r\ Y + (1-r)\ X \qquad ....(12)$$

Where r= random number U(0,1)

6.4 Non-Uniform Mutation

Non-Uniform mutation randomly selects one variable j and sets it equal to an non-uniform random number as follows

$$\begin{gathered} x_i{}' = x_i + (b_i - x_i)f(G) \quad if\ r_1 < 0.5, \\ x_i{}' = x_i + (a_i + x_i)f(G) \quad if\ r_1 \geq 0.5, \\ x_i' = x_i \ \ otherwise \end{gathered} \qquad ....(13)$$

Where

$$f(G) = (r_2(1 - G/G_{max}))^b \qquad ....(14)$$

r1, r2= uniform random numbers between 0 to 1

G=current generation

Gmax = maximum number of generations

b=shape factor

The flow chart of the RCGA optimisation method is shown in fig 4.

7.0 APPLICATION OF PSO AND RCGA TO DETERMINE OPTIMAL LOCATION

Initial power outputs of the generators chosen are P1 = 0.75 pu and P2 = 0.4 pu. The loads at the area-1 are 160MW and 200MVAR and those at area-2 are 1340MW and 500 MVAR. The reference voltage of STATCOM is set 1.0 pu. [1]

The pre-fault SEP and REP are 908 and 836 MW, respectively. A three-phase fault is applied at the sending-end bus at time t = 0.1 s. The original system is restored upon the clearance of the fault.

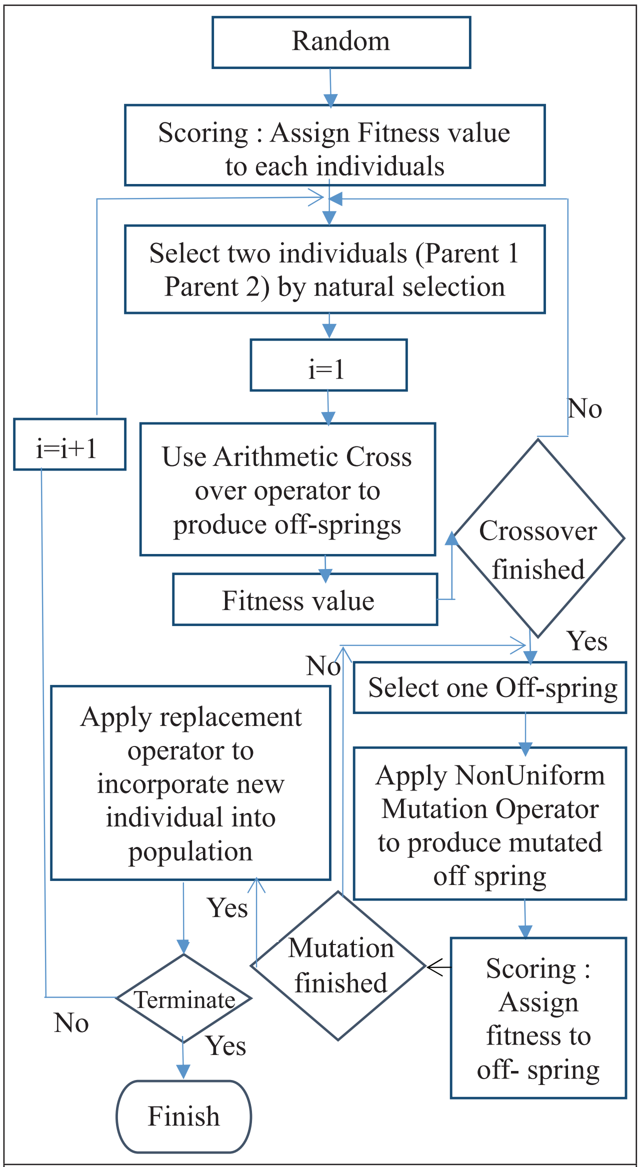


FIG. 4 REAL CODED GENETIC ALGORITHM – FLOW CHART

The optimal location of STATCOM is obtained employing PSO and RCGA algorithm. For the optimization of objective function given in Eq. (6), a matlab program for PSO and RCGA has been written wherein the particles are assumed as length L (location of STATCOM from the sending end of the transmission line) and ten uniformly distributed points are taken in the range of 0 to 400 km. In the programme, through commands, the simulation circuit is simulated for the simulation time of t_{sim}= 8 s for different locations of STATCOM and the wave forms of $\Delta\delta_1$ - $\Delta\delta_2$ is stored as an array from the measurement signals of the generators.

Then from the array, the value of objective function |maximum($\Delta\delta_1$- $\Delta\delta_2$)| is taken, based on which the particles velocity and pbest values are calculated using the PSO algorithm and While applying PSO technique, a number of parameters are required to be specified. An appropriate choice of the parameters affects the speed of convergence of the algorithm. Table 1 shows the parameters used in the present study for the PSO algorithm. In RCGA method each chromosome is assigned a fitness value and probability which is calculated as below

$$F(j) = \frac{1}{\max(\Delta\delta 1 - \Delta\delta 2)} \qquad .... (15)$$

$$P(j) = \frac{F(j)}{\Sigma F(j)} \qquad ....(16)$$

Two parents of high fitness values are selected for reproduction. Arithmetic cross over reproduction is applied on the two parents and two off spring chromosomes are computed. Among the two off spring the one with high fitness value is mutated using non-uniform mutation operator.[5] Then the chromosomes of high fitness values are selected for the next generation. The parameters used for RCGA are as given in Table 2.

After 100 iterations, all the ten particles are settling at an optimal point of L=180 km wherein the value of objective function is minimal.

TABLE 1

PARAMETERS USED FOR PSO ALGORITHM

PSO Parameters	**Value/Type**
Swarm Size	10
No. of Generations	50
C1, C2	2, 2
W_{start}, W_{end}	0.9, 0.4

TABLE 2

PARAMETERS USED FOR RCGA ALGORITHM

RCGA Parameters	**Value/Type**
Swarm Size	10
No. of Generations	50
Mutation Shape factor b	5

The optimal location of STATCOM is found to be at L = 180 km from the sending end and the corresponding highest critical fault clearing time T_{FCF} = 0.083 s by both of the optimization methods. To verify the obtained result, the above contingency (three-phase fault at sending-end at t = 0.1 s and cleared at t = 0.183 s) is simulated for different locations of STATCOM.

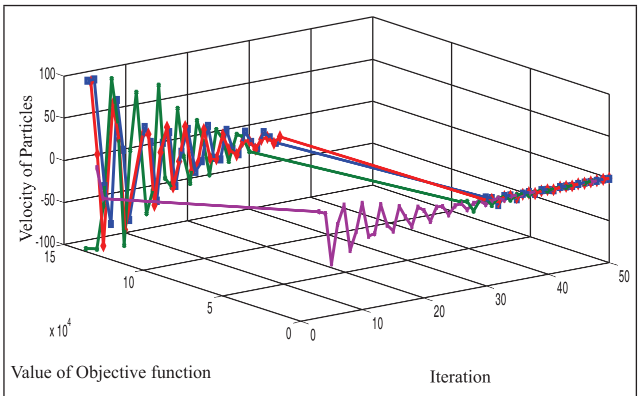


FIG. 5 CONVERGENCE OFOBJECTIVE FUNCTION FOROPTIMALLOCATION OFSTATCOMBY PSO

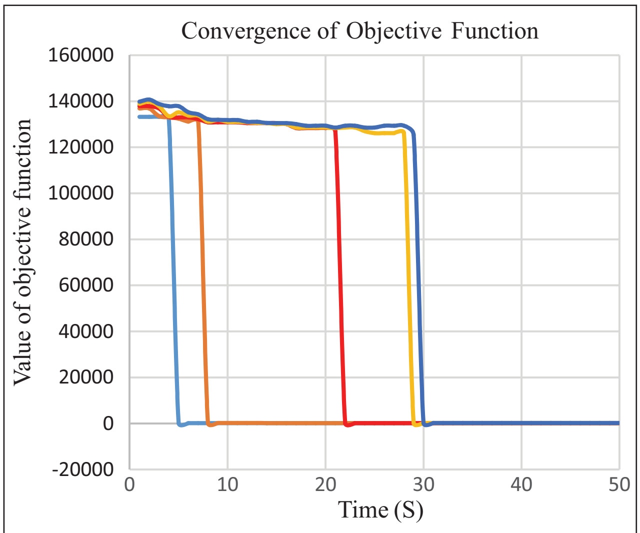


FIG. 6 CONVERGENCE OFOBJECTIVE FUNCTION FOROPTIMALLOCATION OFSTATCOMBY RCGA

Figure 7 shows the variation of rotor angle difference (δ1-δ2) for different locations of STATCOM which confirms that the system is stable for the given initial operating conditions and fault clearing time only if the STATCOM is placed at the optimal location (L = 180 km) and unstable at all other locations. The Convergence of the objective function by PSO and RCGA is as shown in Figure 5 and Figure 6.

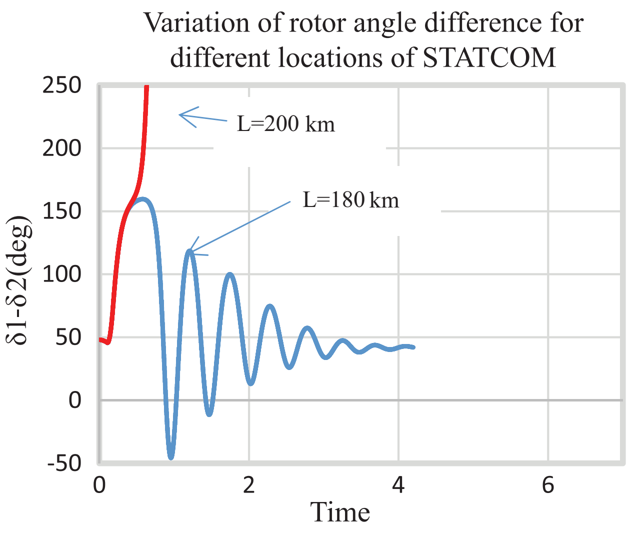


FIG. 7 VARIATION OF ROTOR ANGLE DIFFERENCE FOR DIFFERENT LOCATIONS OF STATCOM (TFC = 0.083 S AND SEP = 916 MW).

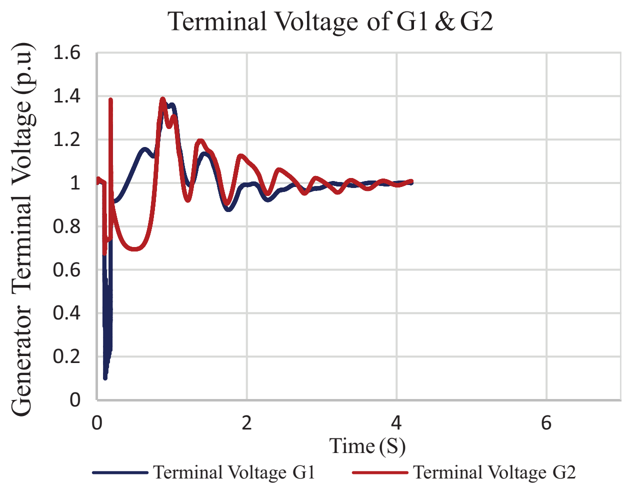


FIG. 8 TERMINAL VOLTAGE OF GENERATOR G1 AND G2 AT STABLE POINT

During the stable point location, the measured waveforms of the terminal voltages of generators, Active and Reactive power flow at the sending end and Reactive power supplied by the STATCOM are as shown in the Figures 8, 9 and 10 respectively.

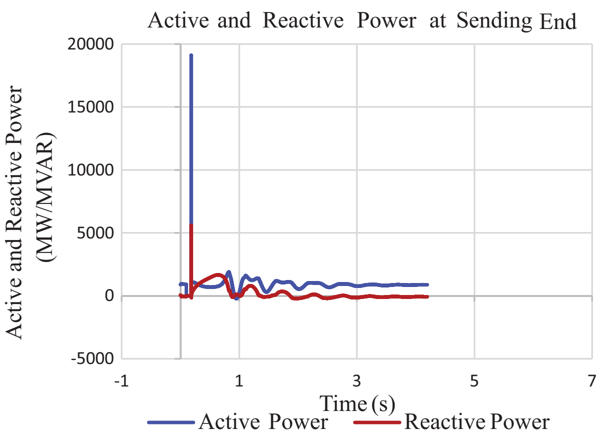


FIG. 9 ACTIVE AND REACTIVE POWER FLOW AT THE SENDING END OF THE TRANSMISSION LINE AT STABLE POINT

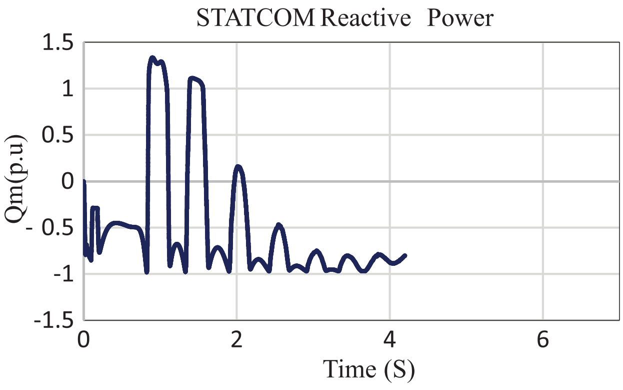


FIG. 10 REACTIVE POWER SUPPLIED BY THE STATCOM AT STABLE POINT

During unstalbe point voltages of generators, Active & Reactive power flow at the sending end and Reactive power supplied by STATCOM are as shown in the Figures 11, 12 & 13.

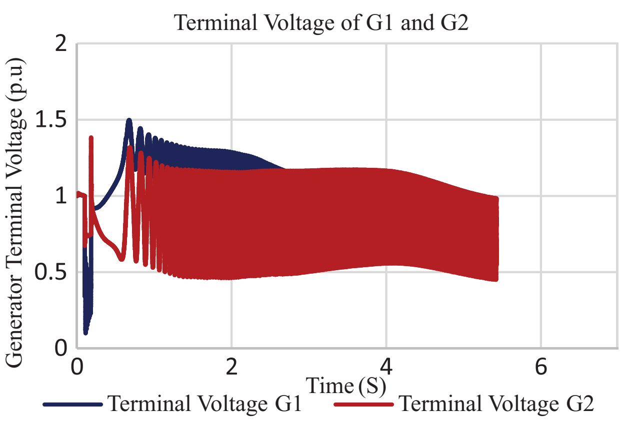


FIG. 11 TERMINAL VOLTAGE OF GENERATOR G1 AND G2 AT UNSTABLE POINT

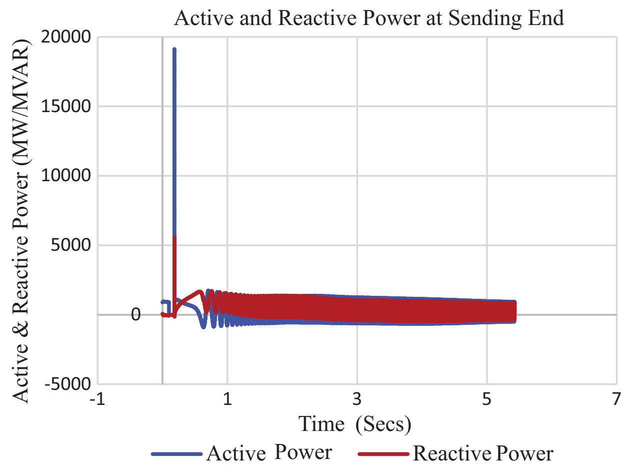


FIG. 12 ACTIVE AND REACTIVE POWER FLOW AT THE SENDING END OF THE TRANSMISSION LINE AT UNSTABLE POINT

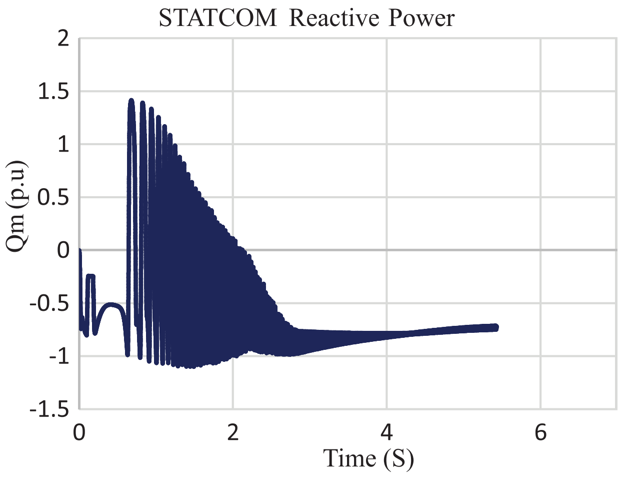


FIG. 13 REACTIVE POWER SUPPLIED BY THE STATCOM AT UN-STABLE POINT

Positive value of STATCOM reactive power indicates that the STATCOM operates in inductive region.

Both PSO and RCGA techniques are very effective in arriving at the global minimum of the optimal solution. However the PSO technique is slightly better in arriving at the exact solution and all the particles converges within less number of iterations compared to RCGA technique. Overall number of iteration and the total time taken for all the points to converge is more in case of RCGA technique. However in both the algorithms appropriate selection of control parameters are very important in arriving at the optimal solution.

The parameters of generators, transformers and transmission lines are as given in Annexure I.

8.0 CONCLUSION

1. In this simulation study by employing PSO and RCGA techniques, it is proved that the optimal location of STATCOM to improve transient stability in actual model of long transmission line is slightly off-centre towards the sending end.
2. It is proved that in order to utilise the existing transmission system effectively, the exact transmission line should be considered.
3. The performance of PSO is slightly better in terms of total execution time and number of iterations to arrive at the optimal solution.

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ANNEXURE I

Generator parameters:

M1 = 1400MVA, M2 = 700MVA, V = 13.8 kV, Xd = 1.305, Xd’= 0.296, Xd” = 0.255, Xq = 0.474, Xq” = 0.243, X1 = 0.18.

Transformer parameters:

T1 = 1400MVA, T2 = 700MVA, V=13.8/400 kV, R2 = 0.002, L2 = 0.12, Rm = 500 , Xm= 500 .

Transmission line parameters per km:

R1 = 0.068, R0 = 0.284, Rom=0.216L1 = 1.31 mH,L0 = 4.02mH, Lom=2.43 mHC1 = 8.85nF, C0 = 6.21nF, Com=-1.88 nF

Excitation Parameters :

Low pass filter time constant Tr=20x10-3s, Regulator gain Ka=200, Regulator Time Constant Ta= 0.001s, Damping filter gain Kf=0.001, Damping filter time constant Tf= 0.1s,

Hydraulic Turbine and Governor Parameters:

Servo motor Ka= 10/3; Ta=0.07, Gate opening limits [GminGmax]=[0.01 0.97518] p.u, Turbine Constant Tw=2.67