JOURNAL OF MECHANICS OF CONTINUA AND MATHEMATICAL SCIENCES
www.journalimcms.org

ISSN (Online) : 2454 -7190 Vol.-15, No.-4, April (2020) pp 66-88 ISSN (Print) 0973-8975

OPTIMAL ALLOCATION OF FACTS DEVICES USING KINETIC GAS MOLECULAR OPTIMIZATION AND GREY WOLF OPTIMIZATION FOR IMPROVING VOLTAGE STABILITY

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https://doi.org/10.26782/jmcms.2020.04.00007

Abstract

Voltage instability is one of the major problems in the transmission line system it causes due to the dynamic load pattern and increasing load demand. Flexible AC transmission systems (FACTS) devices are used to maintain the voltage instability by controlling real and reactive power through the system. In transmission line system, the location and size of the FACTS devices are an important consideration to offer perfect real power flow in the bus system. In this paper, an optimal placement and sizing of the FACTS devices are carried out by combining the Kinetic Gas Molecular Optimization (KGMO) and Grey Wolf Optimization (GWO). There are three different FACTS devices are used in this research, such as Static VAR compensator (SVC), Thyristor Controlled Series Compensator (TCSC) and Unified Power Flow Controllers (UPFC). The objective functions considered for the proposed hybrid KGMO-GWO method are installation cost, Total Voltage Deviation (TVD), Line Loading (LL) and real power loss. Moreover, the optimal placement using the hybrid KGMO-GWO method is validated using IEEE 30 bus system. The performance of the hybrid KGMO-GWO method is analyzed by means of TVD, power loss, installation cost and line loading. Additionally, the hybrid KGMO-GWO method is compared with two existing technique named as QOCRO and hybrid KGMO-PSO. The TVD of the hybrid KGMO-GWO is 0.1007 p.u., it is less when compared to the QOCRO and hybrid KGMO-PSO.

Keywords: Flexible AC Transmission Systems, Grey Wolf Optimization, Kinetic Gas Molecular Optimization, Static VAR Compensator, Thyristor Controlled Series Compensator, Unified Power Flow Controllers.

I. Introduction

Nowadays, the constraints in the power system are increased due to the increase of electrical power demand. Thus leads to maximize the power flow instability, difficulty in power system operation and huge losses [V]. If a transmission line reaches the thermal limits, it leads to affect the energy security and the voltage collapse causes the blackout events. The consequences of huge blackouts result impacts on cost that depends on the interval of the outage and load types [VII]. Moreover, the generation units in the power system provides active power, but it fails to provide reactive power. Thus, the absence of the reactive power affects the performance of the transmission line system [VIII]. The aforesaid problems are minimized by using the FACTS devices in the transmission line system. FACTS devices are generally power electronics based converters that has the capacity to control the different electrical parameters in the power system network [II]. The FACTS device improves the voltage profile, minimizes the line losses and line loadings, delivers the reactive power support in the wide range of operating voltages and improving the stability of the system [XII].

The FACTS devices minimize the losses in high loaded lines by changing the voltage magnitude, impedance and phase angle. In addition, it enhances the stability and security of the power system at contingency situations [VI]. For different control objectives, the applications of FACTS devices are used that includes damping inter-area low-frequency oscillations, optimal power flow and voltage stability. However, the advantages due to the FACTS devices are mainly based on the device size, type, number and location at the transmission system. The main challenge in the transmission system is the identification of proper FACTS device size, type, number and location [IX] [XV]. The reactive power losses are controlled within a limit and it enhances the real power flow at the power system network, when the FACTS devices placed in the appropriate location [XIV]. The conventional algorithms used for the optimal allocation of FACTS devices are modified group searcher optimization [III], genetic algorithm [XIII] and particle swarm optimization [XI]. The major contributions of this research paper are given as follows:

- Three different FACTS devices, such as SVC, TCSC and UPFC are used to improve the voltage stability by controlling real and reactive power in the transmission line system.
- The integration of KGMO and GWO are used for optimal placement and sizing of the FACTS devices. In that KGMO has less computational complexity for FACTS device placement. Moreover, the GWO has better exploration and exploitation probability.
- The reactive power compensation and enhancement in power transfer capability are achieved by optimally placing the FACTS devices.

The organization of this research paper is given as follows: The literature survey about the recent techniques related to the optimal allocation of FACTS devices are described in section 2. The problem formulation and modelling of the FACTS devices are given in the section 3 and section 4 respectively. The description about the hybrid KGMO-GWO method for the optimal allocation and sizing of FACTS

devices using KGMO and GWO is described in section 5. The experimental results and comparative analysis of the hybrid KGMO-GWO method are given in the section 6. Finally, the conclusion is made in section 7.

II. Literature Survey

The literature survey about the recent researches related to the optimal allocation of FACTS devices are described in this section.

Dutta, S., Paul, S. and Roy, P.K [VI] presented the Quasi-Oppositional Chemical Reaction Optimization (QOCRO) to find the optimal allocation and size of the FACTS devices. Since, the QOCRO is the integration of the Quasi-Oppositional Based Learning (QOBL) in Chemical Reaction Optimization (CRO). There are two FACTS devices considered in this QOCRO based allocation such as SVC and TCSC. This QOCRO algorithm is validated in two different bus systems such as IEEE 14 bus and IEEE 30 bus system. The solution quality and convergence speed are enhanced by incorporating the QOBL and CRO. This system considers only three objective functions such as minimization of voltage deviation, real power loss and voltage stability index.

Hemachandra Reddy K, P. Ram Kishore Kumar Reddy and V. Ganesh [X] designed the hybrid optimization of KGMO and Particle Swarm Optimization (PSO) for optimal allocation of FACTS devices to avoid the RPD problem. In this work, three different FACTS are used, such as SVC, TCSC and UPFC. The hybrid KGMO-PSO algorithm is validated in the IEEE 30 bus system. The power loss and voltage deviation are minimized by optimally placing the FACTS devices at proper nodes. The PSO used in this KGMO-PSO is easily fall into local optima, when it used in the large dimensional space.

Safari, A., Bagheri, M. and Shayeghi, H [XVI] presented the Strength Pareto Multi-Objective Evolutionary Algorithm (SPMOEA) for optimal placement of TCSC and SVC. This SPMOEA algorithm considers three different objective functions such as reduction of real power losses, load voltage deviation and expansion of the static voltage stability margin. Here, two different bus systems are utilized to validate the SPMOEA that are IEEE 30-bus and IEEE 118-bus test systems. The real power loss and static voltage stability margin are enhanced by using this SPMOEA with three objective functions. This SPMOEA based optimal allocation fails to consider the generation cost of FACTS devices in its objective functions.

Sen, D., Ghatak, S.R. and Acharjee, P [IV] designed the hybrid algorithm by combining the CRO and Cuckoo Search Algorithm (CSA) to optimally allocate the SVC in the transmission system. There are various aspects considered for placing the SVC such as line loss reduction, voltage stability, power generation minimization, Return-On-Investment (ROI) time period and annual cost of power generation. This hybrid CSA-CRO based optimal placement of FACTS devices are analyzed in three bus system such as IEEE 14-bus, 30-bus and 57-bus transmission systems in heavily loaded condition. The total voltage deviation is not considered during the optimal allocation of SVC using hybrid CSA-CRO technique. For an effective transmission system, the voltage deviation should be considered to avoiding losses in the bus system.

Agrawal, R., Bharadwaj, S.K. and Kothari, D.P [I] presented three different optimization techniques such as Artificial Bee Colony (ABC), Teaching Learning Based Optimization (TLBO) and PSO for the optimal allocation of TCSC. Here, two different objective functions are considered in the optimization algorithms such as installation cost of TCSC and minimization of transmission loss. The optimal allocation using ABC, TLBO and PSO are validated in three bus systems such as the IEEE 14 bus, IEEE 30 bus and Indian 75 bus systems. The PSO and ABC provide less performance than the TLBO.

III. Problem Formulation

The hybrid KGMO-GWO is used for the optimal allocation of three FACTS devices such as SVC, TCSC and UPFC to solve the multi objective functions. The multi objective function includes generation cost, total voltage deviation, line loading and real power loss. The description of the multiple objective functions is given as follows:

Generation Cost

The generation cost is mainly depending on the active power and reactive power generation cost of the system. The active and generation power cost is expressed in the following equation (1) and (2) respectively.

$$Cost_a = \sum_{i=1}^{N_G} a_i P_{gi}^2 + b_i P_{gi} + c_i \quad (1)$$

$$Cost_r = \sum_{i=1}^{N_G} a_i Q_{gi}^2 + b_i Q_{gi} + c_i \quad (2)$$

Where, $Cost_a$ and $Cost_r$ are the active and generation power cost respectively; P_{gi} and Q_{gi} are the real and reactive power respectively. The cost coefficients are represented as a_i, b_i and c_i respectively.

Total Voltage Deviation

The total voltage deviation is generally a voltage gap among the reference voltage and bus voltage. If the system has less voltage gap, it results in less voltage deviation. The TVD is expressed in the following equation (3).

$$`TVD = \sum_{i=1}^{N_L} \left|(V_i - V_{ref})\right| \quad (3)$$

Where, amount of load bus is N_L; V_i and V_{ref} specifies the load bus voltage and reference voltage respectively.

Line Loading

The minimization of line loading is utilized to optimize the power flow within a limit and also it decreases the line overload in transmission system. The line loading decreases the power flow gap among the actual value and limit value that is expressed in the equation (4).

$$LL = \sum_{i=1}^{N_L} (P_{ij}(t) - P_{ijmax})^2 \quad (4)$$

Where P_{ij} and P_{ijmax} represents the power flow at each line and maximum power flow limit respectively.

Real Power Loss

The real and reactive powers are generated at the transmission line due to the transaction among the generator and demand node. The objective of reduction in real power loss (P_{loss}) at transmission line is expressed in the following equation (5).

$$P_{loss} = \sum_{i=1}^{L} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos(\delta_i - \delta_j)) \quad (5)$$

where, L specifies the total amount of transmission lines; the voltage magnitude in ith and jth bus are V_i and V_j respectively; the conductance of line i-j is G_{ij}; voltage angle of ith and jth bus are δ_i and δ_j respectively;

IV. Modelling of FACTS Devices

The FACTS devices are used in the transmission network to achieve the reliable, stable and secure power system network. Hence, it is essential to identify the proper allocation and size of the FACTS devices during the device placement.

SVC Modelling

Static VAR compensators is generally a static shunt VAR generator that has the capacity for controlling the specific parameters of power system network. Moreover, SVC is an integration of thyristor-controlled reactor and a thyristor switched capacitor which is shown in Figure 1. SVC is used to inject/absorb the reactive power for regulating the terminal voltage of the transmission network. The reactive power is injected to the system, when the load is highly inductive. Similarly, the reactive power is absorbed by the SVC, when the system has higher reactive power flow. The operation of SVC is more imperative to enhance of voltage profile. The reactive power is limited as follows -100 MVAR ≤ Q_{SVC}≤ 100 MVAR.

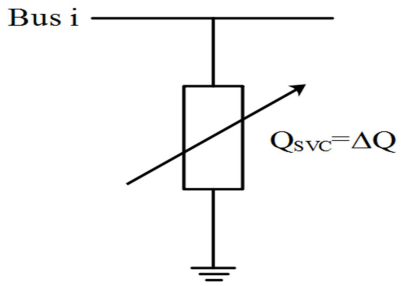

Fig. 1: Model of SVC in transmission line

The location of the SVC in node is expressed in the following equation (6).

$$\Delta Q = Q_{SVC} \quad (6)$$

Where, the size of SVC is represented as ΔQ. The Reactive Power Dispatch (RPD) issue with SVC placement is given as follows:

Cost Function of SVC

The SVC cost function is specified in the equation (7).

$$Cost - svc = 0.0003 \times s^2 - 0.305 \times s + 127.38 \quad (7)$$

Where, the functional limit of the FACTS device is represented as s.

TCSC Modelling

TCSC is generally a series-connected compensation device that has a series capacitor bank shunted by a thyristor controlled reactor. The capacitive or inductive reactance is included by the TCSC for modifying the effective series reactance of the transmission line. The TCSC placement in the network is used for continuous power control in the transmission line network. In the power system network, the TCSC controls the power flow and it has the capacity to eliminate the sub-synchronous resonance. Moreover, the TCSC improves the transient stability and damp outs the inter-area power oscillations. The model of the TCSC in a transmission line is shown in Figure 2.

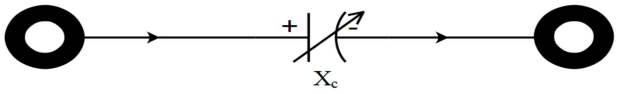

Fig. 2: Model of TCSC in transmission line

The location of the TCSC in node is expressed in the following equation (8).

$$X_{TCSC} = r_{TCSC}.X_{Line} \tag{8}$$

Where, the transmission line reactance is specified as X_{Line} and r_{TCSC} represents the coefficient that specifies the degree of composition by TCSC. The operating range of the TCSC is selected among the -0.8X_{Line} and 0.2X_{Line} for avoiding the overcompensation. The ideal position of the reactance is obtained by minimizing the reactance among the specified ranges. Additionally, the variable capacitance of the TCSC is adjusted based on the load requirement.

Cost Function of TCSC:

The TCSC cost function is specified in the equation (9).

$$Cost - \text{TCSC} = 0.0015 \times s^2 - 0.7130 \times s + 153.75 \tag{9}$$

UPFC Modelling

The UPFC device is the multipurpose FACTS controller that rapidly controls the impedance, phase angle, voltage, real and reactive power flow over the power system network. The modelling of UPFC is the combination of TCSC and SVC connected in the line/bus. Hence, the power flow in UPFC is severely based on the line reactance, phase angle and bus voltage. The schematic representation of the UPFC is given in the following Figure 3 and equation (10) expresses the power flow of the UPFC.

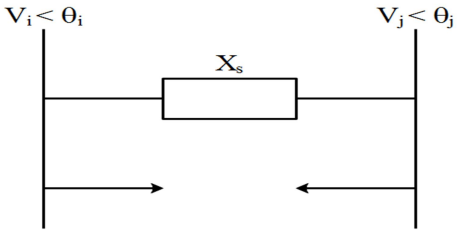

Fig. 3: Schematic representation of the UPFC

$$P_{ij} = \frac{V_i V_j}{X_{ij}} \sin(\delta_i - \delta_j) \tag{10}$$

If the UPFC is located between the node $i$and j, the admittance matrix adjusts the reactance. Besides, the reactance is equal to the X_s between two nodes and appropriate power insertion leads to change the jacobian matrix.

Cost Function of UPFC:

The UPFC cost function is specified in the equation (11).

$$Cost - \text{UPFC} = 0.0003 \times s^2 - 0.2691 \times s + 188.22 \tag{11}$$

V. Hybrid KGMO-GWO method

In this hybrid KGMO-GWO method, the combination of KGMO and GWO algorithms are used for the optimal allocation of FACTS devices. The hybrid KGMO-GWO based allocation has 5 major steps such as read system data, initialize the parameters, arrangement of FACTS devices, obtaining an optimal allocation from hybrid KGMO-GWO algorithm and validate the obtained position with base case value. There are three different FACTS devices are used in this hybrid KGMO-GWO method such as SVC, TCSC and UPFC. The detailed description about the SVC, TCSC and UPFC is already described in the Section 3. The flowchart of the hybrid KGMO-GWO method is shown in the Figure 4.

The overall process of the optimal allocation of FACTS devices using KGMO with GWO are given as follows:

Step 1: Initially, the parameters are selected for optimizing every molecule. In this work, there are five different scenarios are considered such as without FACTS devices, with SVC, with TCSC, with UPFC and with all FACTS devices. In without FACTS devices 19 parameters are selected that includes 9 shunt capacitor compensations, 6 generator bus voltages and 4 transformer tap settings. For SVC, the two more parameters such as SVC location and size are added along with above 19 parameters. For TCSC, the location and size of the TCSC are added along with above 19 parameters. For UPFC allocation, the location, voltage, angle and impedance are added along with the above 19 parameters of without FACTS devices. Finally, there are 27 parameters are considered in the scenario of with all FACTS devices which includes 19 parameters of without FACTS devices and the parameters from the SVC, TCSC and UPFC.

Step 2: Read the bus data and line data from the IEEE 30 bus system. The bus data has real and relative power values. Accordingly, the line data has resistance, impedance, susceptance and reactive power values.

Step 3: The random placement of FACTS devices is analyzed in IEEE 30 bus system. For this random placement, the load flow analysis is evaluated to know the performance of TVD and power loss.

Step 4: Subsequently, the fitness function for KGMO with GWO is evaluated for that particular line and bus data.

Step 5: From the evaluation, the best fitness value is evaluated and it is transferred to the IEEE 30 bus system. This fitness function based optimal allocation of FACTS devices are evaluated from the next iteration.

Step 6: The load flow analysis is validated with the hybrid KGMO-GWO method optimal allocation strategy for obtaining the optimum fitness values.

Step 7: In optimization algorithm, the best fitness value is calculated by using the random location of FACTS devices as input for the hybrid optimization. The optimum position and size of the FACTS devices are required for handling the power loss and voltage stability values.

Step 8: The FACTS devices are optimally located based on the fitness values from the combination of the KGMO and GWO algorithm. Additionally, the multi objectives are evaluated based on the optimum placement by the hybrid KGMO-GWO method. The multi objectives include TVD, power loss, line loading and cost of FACTS devices.

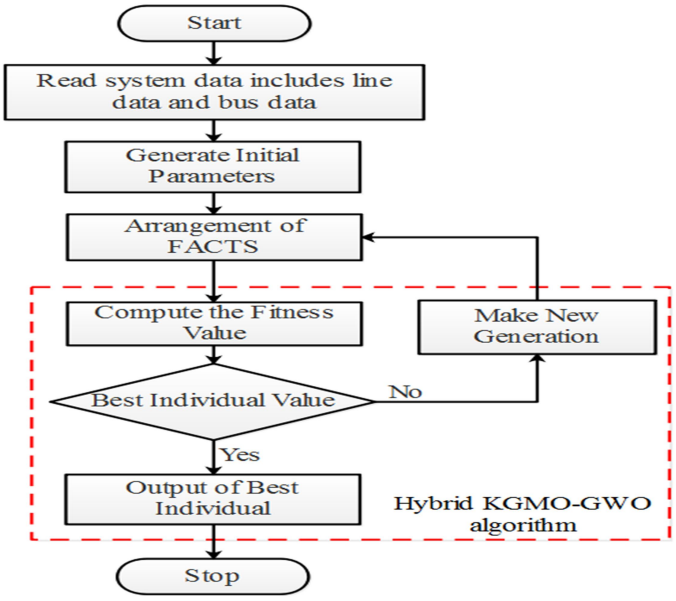

Fig. 4: Flowchart of the hybrid KGMO-GWO method

Data Collection from IEEE 30 Bus System

In this hybrid KGMO-GWO method, the line and bus data are collected from the IEEE 30 bus system. The line data contains resistance, impedance, susceptance and tap changing transformer. Additionally, the bus data has voltage, angle, real power, reactive power and its types (e.g. generator bus, load bus and slack bus). Based on this line and bus data, the optimal allocation of FACTS devices is optimized from the hybrid optimization method.

Optimal Placement of FACTS Devices using Hybrid Optimization Algorithm

In this hybrid KGMO-GWO method, two different optimization algorithm such as KGMO and GWO are used for optimizing the location of the FACTS devices. Then the FACTS devices such as SVC, TCSC and UPFC are placed in the IEEE 30 bus system based on the optimized locations from hybid optimization algorithm.

Kinetic Gas Molecular Optimization Algorithm

KGMO is generally a meta heuristic optimization algorithm that developed based on the gas molecules behavior. The particles of the KGMO is considered four different specifications such as position, kinetic energy, velocity and mass. The position and velocity of the gas molecule are calculated based on the kinetic energy. The inputs given to the KGMO are reactive power, real power, power loss and bus voltage. Moreover, the initial location and size of the FACTS devices are given along with the inputs that are randomly selected in the bus system. In this hybrid KGMO-GWO method, the inputs are considered as gas molecules.

Consider, the KGMO has *P*amount of particles and the location of the agent k in KGMO is specified in the following equation (12).

$$Z_j = \left(z_j^1, \ldots . z_j^d, \ldots z_j^p\right) for\ (j = 1,2, \ldots . P) \tag{12}$$

Where, z_j^p specifies the kth agent position at dth dimension.

Equation (13) provides the velocity of the agent k.

$$V_j = \left(v_j^1, \ldots . v_j^d, \ldots v_j^p\right) for\ (j = 1,2, \ldots . P) \tag{13}$$

Where, v_j^p specifies thek^{th} agent velocity at d^{th} dimension.

The motion of the gas molecules is depend on the Boltzmann distribution that specifies the velocity is directly proportional to the kinetic energy of the molecule. The equation (14) expresses the kinetic energy of the gas molecule.

$$k_j^d(r) = \frac{3}{2} PbT_j^d(r), K_j = \left(k_j^1, \ldots . k_j^d, \ldots . k_j^m\right) for\ (j = 1,2, \ldots . P) \tag{14}$$

Where, b is Boltzmann constant, T_j^d species the k^{th} agent temperature at dimension d and time r.

The equation (15) expresses the velocity of the gas molecule updated in each iteration

$$v_j^d(r+1) = T_j^d(r) w v_j^d(r) + E_1 rand_j(r)\left(gbest^d - z_j^d(r)\right) + E_2 rand_j(r)\left(pbest_j^d(r) - z_j^d(r)\right) \quad (15)$$

Where, the best previous location of j th gas molecule is $pbest_j = (pbest_j^1, pbest_j^2, \ldots . pbest_j^p)$ and best previous location for all gas molecule is $gbest_j = (gbest_j^1, gbest_j^2, \ldots . gbest_j^p)$. The inertia weight is w, uniform random variable is $rand_j$ and two acceleration coefficients are $E_1$and E_2.

Additionally, the position of the molecule is obtained based on the motion that is given in equation (16).

$$z_{r+1}^j = \frac{1}{2} a_j^d(r+1) r^2 + v_j^d(r+1) r + z_j^d(r) \quad (16)$$

Where, the agent k acceleration in dimension $d$is a_j^d.

The following equation (17) is used for determining the minimum fitness function.

$$pbest_j = f(z_j), \quad iff(z_j) < f(pbest_j)$$
$$gbest = f(z_j), \quad iff(z_j) < f(gbest) \quad (17)$$

Grey Wolf Optimization

GWO is generally inspired by leadership and hunting behavior of the grey wolves. The grey wolves are categorized into four levels based on the social dominant hierarchy such as alpha wolf (α), beta wolf (β), delta wolf (δ) and omega wolf (ω). The GWO is generally depends on the following assumptions: 1) The α, β and δ are denoted as optimum, 2nd optimum and 3rd optimum solution respectively. 2) The remaining level is supposed to be omega wolf (ω). 3) The three wolves such as alpha wolf, beta wolf and delta wolf are considered as optimum solution that has better information about the potential location of prey. The information about prey of those three wolves are better than the omega wolf. 4) the omega wolf follows the three best wolves. The global best position ($gbest$) from the KGMO is considered as location vector of prey. The process of GWO are given as follows:

Encircling prey

The equation (18) defines the encircling behavior of grey wolves.

$$Y^{t+1} = Y_p^t - B^t \times \left| D^t \times Y_p^t - Y^t \right| \quad (18)$$

Where, the prey's location vector is represented as Y_p^t; the coefficient vectors are B^t and D^t; the grey wolf's position vector is Y^t. The equation (19) and (20) are represented the coefficient vector of B^t and D^t respectively.

$$B^t = 2b^t rand_1 - b^t \quad (19)$$

$$D^t = 2rand_2 \quad (20)$$

Where, the exploration rate is specified as b^t. The $rand_1$ and$rand_2$ are represented the random vectors among 0 and 1. The exploration rate is linearly minimized from 2 to 0 over the number of iterations. The exploration rate is specified in the equation (21).

$$b_j^t = 2 - \frac{2t}{N_{max}} \tag{21}$$

Where, N_{max} specifies the maximum amount of iterations.

Hunting

The hunting process of the grey wolves are handled by the alpha wolf. The beta and delta wolf may also participate as guide for hunting at sometimes. Besides, it is very difficult to obtain the prey location in search space. The three wolves such as alpha wolf, beta wolf and delta wolf has better information about the potential location of prey. These prey locations are used to process the hunting behavior of grey wolves. The equation (22), (23) and (24) are used to stimulate the hunting process of the GWO.

$$Y_1 = Y_\alpha^t - B_1^t \times |D_1^t \times Y_\alpha^t - Y^t| \tag{22}$$

$$Y_2 = Y_\beta^t - B_2^t \times \left|D_2^t \times Y_\beta^t - Y^t\right| \tag{23}$$

$$Y_3 = Y_\delta^t - B_3^t \times \left|D_3^t \times Y_\delta^t - Y^t\right| \tag{24}$$

Where, the Y_α^t, Y_β^t andY_δ^t are the position of the alpha wolf, beta wolf and delta wolf respectively. The average state of the position obtained from the alpha wolf, beta wolf and delta wolf are given in equation (25). This average position gives the optimum position of the grey wolf.

$$Y^{t+1} = \frac{Y_1+Y_2+Y_3}{3} \tag{25}$$

Fitness Function Derivation

The fitness function used of the hybrid KGMO-GWO method is derived in this section. The expression for fitness function is given in the following equation (26).

$$f = \begin{cases} \max\,(V) \\ \min\,(Q_{load}, P_{load}, P_{loss}) \end{cases} \tag{26}$$

Where, Q_{load} and P_{load} represents the reactive and real power respectively. The equation (26) is used for an appropriate allocation and sizing of the FACTS devices. The placement of FACTS devices results power loss minimization and improvement in voltage profile.

Process of Optimal Allocation of FACTS Devices using KGMO and GWO

In this hybrid KGMO-GWO method, the GWO is integrated into the KGMO because of an appropriate exploration and exploitation probability of GWO. Moreover, the KGMO offers less computational complexity in large dimensional space. This hybrid KGMO-GWO results an optimal location and size for SVC, TCSC and UPFC in IEEE 30 bus system. The flowchart for the hybrid KGMO-GWO is given in the Figure 5.

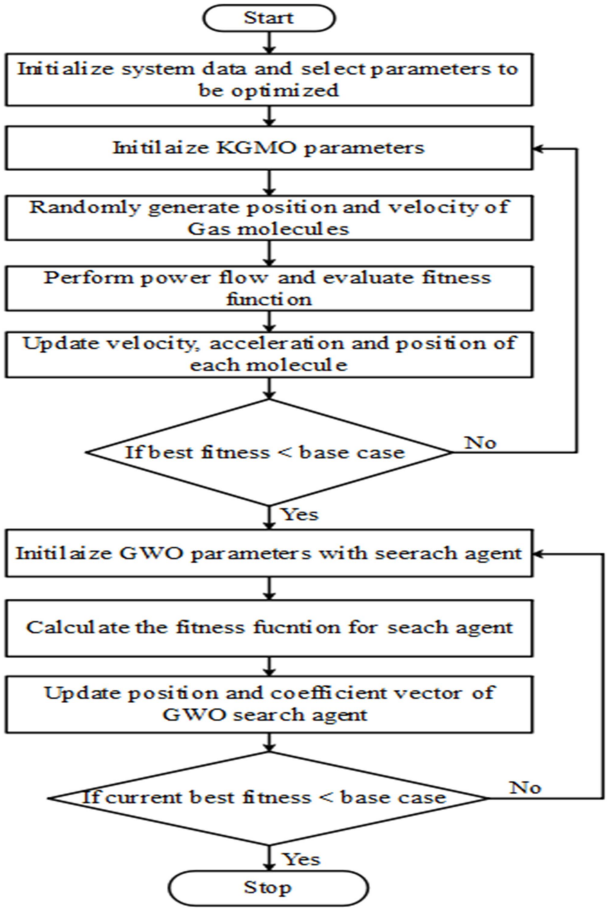

Fig. 5: Flowchart of hybrid KGMO-GWO

The hybrid KGMO-GWO based optimal allocation to eliminate the RPD issues are given in the following steps.

Step 1: Initially, the constraints are selected for optimal allocation of FACTS devices. The five cases considered in this hybrid KGMO-GWO method are given as follows:

1. Without FACTS devices
2. With SVC
3. With TCSC
4. With UPFC
5. With all FACTS devices

Step 2: The search space is determined by selecting *P*amount of molecules.

Step 3: Initialize the KGMO specifications such as iteration count, inertia weight, temperature, mass, Boltzmann constant and acceleration coefficients.

Step 4: Set initial velocity and position of the gas molecule for KGMO algorithm.

Step 5: Compute the kinetic energy, velocity and acceleration for each molecule.

Step 6: Based on the aforementioned values, the velocity of the gas molecules is updated.

Step 7: For updated position of gas molecules, the fitness functions are calculated that is described in the following section. Subsequently, define the personal and global best values of each gas molecule.

Step 8: The processed values from the KGMO such as location and size of FACTS devices are given as input to the GWO algorithm. Then GWO updates its own behavior of encircling prey and hunting.

Step 9: The optimum value is evaluated based on the fitness function derived for this hybrid optimization.

Step 10: The solution from the hybrid optimization is validated with the base case value. The base case has two different values such as power loss and total voltage deviation. If the values from the optimization is less than base case value, it considered as an optimal solution. Otherwise, the process of hybrid optimization starts again from Step 1.

Step 11: The hybrid optimization algorithm is terminated once the optimal solution is achieved for an adequate placement of FACTS devices.

VI. Results and Discussion

The experimental results and discussion of the hybrid KGMO-GWO method based optimal allocation of FACTS devices is explained in this section. The simulation of this hybrid KGMO-GWO method is carried out using MATLAB R2018a software that runs on a Windows 8 operating system with Intel core i3 processor and 4GB RAM. The FACTS device placement for resolving the multi objective problem is performed in the IEEE 30 bus system. The specifications of IEEE 30 bus system are mentioned in the Table 1.

Table 1:Specifications of the IEEE 30 bus system

Item	Details
Generators	6 buses {1, 2, 5, 8, 11, 13}
Transmission lines	41
Transformers	4 locations {6-9, 6-10, 4-12 and 27-28}
Shunt compensators	9 locations {10, 12, 15, 17, 20, 21, 23, 24 and 29}

Performance ASnalysis

The performance of the hybrid KGMO-GWO method is analyzed in terms TVD, power loss, line loading and cost of the devices. The performance analysis is carried out for five different scenarios that are given as follows:

1. In 1st scenario, the IEEE 30 bus system is evaluated without any devices.
2. In 2nd scenario, the IEEE 30 bus system is analyzed only with SVC.

3. In 3rd scenario, the IEEE 30 bus system is analyzed only with TCSC.

4. In 4th scenario, the IEEE 30 bus system is analyzed only with UPFC.

5. The last scenario considers the IEEE 30 bus system with all FACTS devices that includes SVC, TCSC and UPFC.

Table 2:Performance analysis for Scenario 1

Control Variables	Initial Values	Optimal Values
V1	1.0500	1.0439
V2	1.0400	1.0198
V5	1.0100	1.0099
V8	1.0100	1.0262
V11	1.0500	1.0296
V13	1.0500	1.0323
T11	1.0780	0.9541
T12	1.0690	1.0247
T15	1.0320	0.9943
T36	1.0680	0.9615
Qc10	0.0000	3.5583
Qc12	0.0000	2.8731
Qc13	0.0000	2.2694
Qc17	0.0000	2.6702
Qc20	0.0000	2.8385
Qc21	0.0000	2.7782
Qc23	0.0000	3.0416
Qc24	0.0000	3.1675
Qc29	0.0000	1.2411
TVD (p.u)	1.47	0.1915
Ploss (MW)	5.74	5.2343
LL	6.42	5.353

Table 2 shows the scenario 1 performance for the IEEE 30 bus system. In that case, there is no FACTS devices are considered for resolving the RPD problem. The value of TVD, P loss and LL for transmission system without FACTS devices are 0.1915 p.u, 5.2343 MW and 5.353 respectively. The fitness graph for scenario 1 is illustrated in the Figure 6.

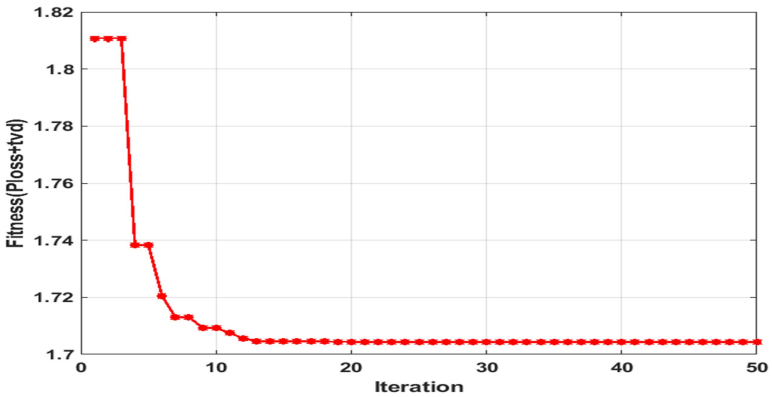

Fig. 6: Fitness function for scenario 1

Table 3:Performance analysis for Scenario 2

Control Variables	Initial Values	Optimal Values
V1	1.0500	1.0299
V2	1.0400	1.0390
V5	1.0100	1.0331
V8	1.0100	1.0087
V11	1.0500	1.0292
V13	1.0500	0.9909
T11	1.0780	0.9982
T12	1.0690	0.9928
T15	1.0320	0.9537
T36	1.0680	0.9801
Qc10	0.0000	2.1377
Qc12	0.0000	1.5403
Qc13	0.0000	2.2657
Qc17	0.0000	3.5854
Qc20	0.0000	3.0387
Qc21	0.0000	2.4162
Qc23	0.0000	3.1345
Qc24	0.0000	2.6004
Qc29	0.0000	2.4739
SVC location	15.0000	15.0000
SVC size	0.0000	0.2557

SVC cost ($/MVAR)	-	127.365
TVD (p.u)	1.47	0.1274
Ploss (MW)	5.74	4.5435
LL	6.42	3.9129

The scenario 2 performance analysis are given in the Table 3. The results of Table 3 are taken for the IEEE 30 bus system with only SVC. The value of TVD, Ploss, LL for scenario 2 is 0.1274 p.u, 4.5435 MW and 3.9129 respectively. The location and size of the SVC are 15 and 0.2557 respectively. Additionally, the cost of the SVC used in this scenario 2 is 127.365 $/MVAR. Table 3 concludes that TVD, Ploss, LL for scenario 2 is lesser than the scenario 1. Figure 7 illustrates the fitness function graph for Scenario 2.

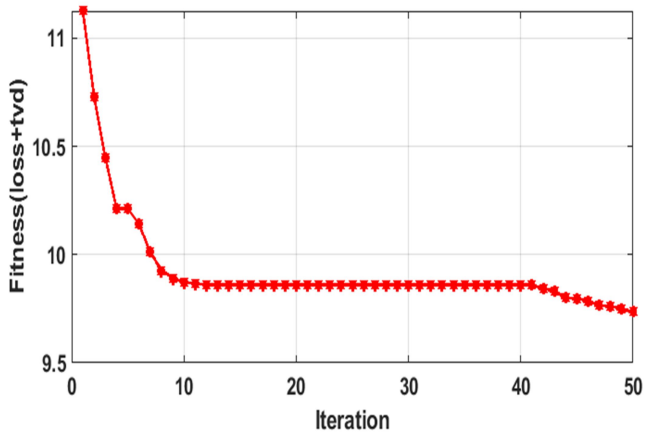

Fig. 7: Fitness function for scenario 2

Table 4:Performance analysis for Scenario 3

Control Variables	Initial Values	Optimal Values
V1	1.0500	0.9862
V2	1.0400	1.0644
V5	1.0100	1.0676
V8	1.0100	1.0289
V11	1.0500	1.0653
V13	1.0500	0.9691
T11	1.0780	1.0550
T12	1.0690	0.9000
T15	1.0320	0.9683
T36	1.0680	0.9690

Qc10	0.0000	2.9367
Qc12	0.0000	2.3654
Qc13	0.0000	5.0000
Qc17	0.0000	4.0393
Qc20	0.0000	2.4885
Qc21	0.0000	4.4321
Qc23	0.0000	0.0992
Qc24	0.0000	3.2304
Qc29	0.0000	2.4741
TCSC location	15.0000	16.0000
TCSC size	0.0000	0.137
TCSC cost ($/MVAR)	-	154.3736
TVD (p.u)	1.47	0.1077
Ploss (MW)	5.74	4.217
LL	6.42	4.9755

Table 4 shows the scenario 3 performance for IEEE 30 bus system. In that case, there is one FACTS device called TCSC is considered for resolving the RPD problem. The value of TVD, Ploss and LL for transmission system with TCSC are 0.1077 p.u, 4.217 MW and 4.9755 respectively. The location and size of the TCSC are 16 and 0.137 respectively. Furthermore, the cost of TCSC used in bus system is 154.3736 $/MVAR. The fitness graph for scenario 3 is illustrated in the Figure 8.

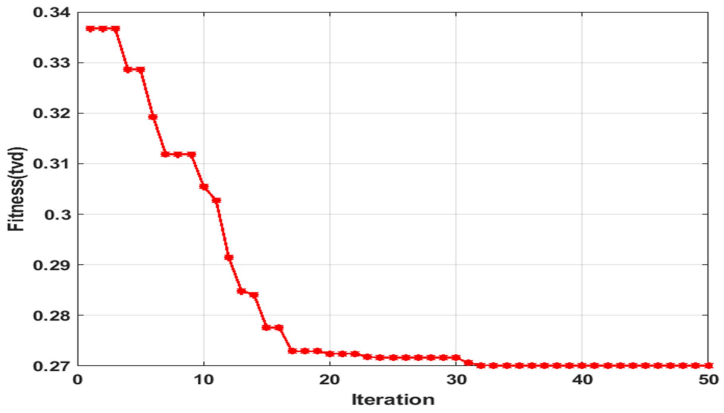

Fig. 8: Fitness function for scenario 3

Table 5:Performance analysis for Scenario 4

Control Variables	Initial Values	Optimal Values
V1	1.0500	1.0534
V2	1.0400	1.0650
V5	1.0100	1.0196
V8	1.0100	1.0479
V11	1.0500	1.0503
V13	1.0500	0.9788
T11	1.0780	0.9567
T12	1.0690	1.0540
T15	1.0320	0.9861
T36	1.0680	0.9970
Qc10	0.0000	1.9261
Qc12	0.0000	0.7125
Qc13	0.0000	0.2863
Qc17	0.0000	0.7656
Qc20	0.0000	3.2344
Qc21	0.0000	2.7643
Qc23	0.0000	2.3348
Qc24	0.0000	1.6346
Qc29	0.0000	3.0487
UPFC location	0.0000	27.0000
UPFC size	0.0000	0.9866
UPFC degree	0.0000	0.558
UPFC impedance	0.0000	0.1021
UPFC cost ($/MVAR)	-	187.7069
TVD (p.u)	1.47	0.1014
Ploss (MW)	5.74	3.940
LL	6.42	3.6168

The performance analysis of the scenario 4 (i.e., IEEE 30 bus system with only UPFC) is given in the Table 5. The value of TVD, Ploss, LL for scenario 4 is 0.1074 p.u, 3.940 MW and 3.6168 respectively. The location and size of the UPFC are 27 and 0.9866 respectively. Additionally, the cost of the UPFC used in this scenario 2 is 187.7069 $/MVAR. Table 5 concludes that TVD, Ploss for scenario 4 is lesser than the scenario 1 and scenario 2. Figure 9 illustrates the fitness function graph for Scenario 4.

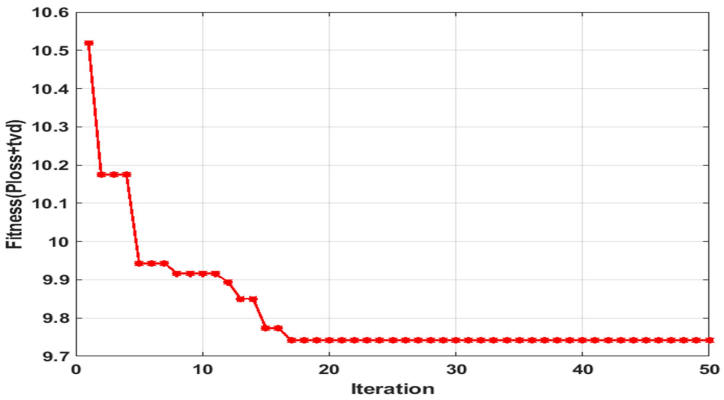

Fig. 9: Fitness function for scenario 4

Table 6:Performance analysis for Scenario 5

Control Variables	Initial Values	Optimal Values
V1	1.0500	0.9564
V2	1.0400	0.9770
V5	1.0100	1.0706
V8	1.0100	1.0251
V11	1.0500	0.9574
V13	1.0500	0.9951
T11	1.0780	0.9515
T12	1.0690	0.9684
T15	1.0320	1.0076
T36	1.0680	1.0236
Qc10	0.0000	0.6943
Qc12	0.0000	4.0131
Qc13	0.0000	2.6516
Qc17	0.0000	3.1690
Qc20	0.0000	1.4142
Qc21	0.0000	3.6634
Qc23	0.0000	2.1248
Qc24	0.0000	2.9427
Qc29	0.0000	1.9355
SVC location	0.0000	16.0000
SVC size	0.0000	41.2602

TCSC location	0.0000	25.0000
TCSC size	0.0000	0.974
UPFC location	0.0000	6.0000
UPFC size	0.0000	0.9943
UPFC degree	0.0000	0.3352
UPFC impedance	0.0000	0.64
SVC cost ($/MVAR)	-	129.1645
TCSC cost ($/MVAR)	-	152.7372
UPFC cost ($/MVAR)	-	187.8794
TVD (p.u)	1.47	0.1007
Ploss (MW)	5.74	3.6442
LL	6.42	4.1659

The performance analysis of scenario 5 is given in the Table 6 that is the results of IEEE 30 bus system with all FACTS devices that includes SVC, TCSC and UPFC. The value of TVD, Ploss, LL for scenario 6 is 0.1007 p.u, 3.6442 MW and 4.1659 respectively. The location of SVC, TCSC and UPFC are placed in the IEEE 30 bus system are 16, 25 and 6 respectively. The size of SVC, TCSC and UPFC optimized from the hybrid KGMO-GWO are 41.2602$/MVAR, 0.974$/MVAR and 0.9943$/MVAR respectively. Additionally, the cost of the SVC, TCSC and UPFC are used in this scenario 5 are 129.1645, 152.7372 and 187.8794$/MVAR respectively. From the Table 6 concludes that TVD, Ploss for scenario 5 is lesser than the scenario 1, scenario 2 and scenario 3. Figure 10 illustrates the fitness function graph for Scenario 5.

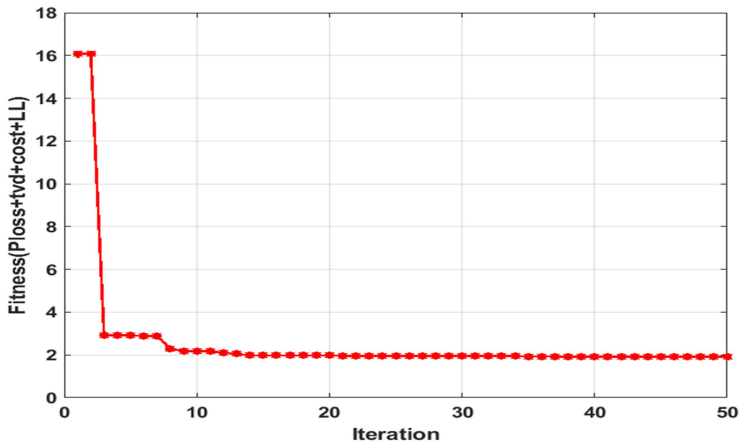

Fig. 10: Fitness function for scenario 5

Comparative Analysis

The performance of the hybrid KGMO-GWO method is compared with existing technique to know the effectiveness of the hybrid KGMO-GWO method. The comparison of the hybrid KGMO-GWO method is validated in terms of TVD and power loss. The existing techniques used for the comparison are QOCRO [VI] and hybrid KGMO-PSO [X]. Additionally, the comparative analysis of the hybrid KGMO-GWO method is validated for the IEEE 30 bus system. In [VI], the QOCRO algorithm is developed for obtaining the optimal positions of the TCSC and SVC. The hybrid optimization of KGMO and PSO is used to obtain the position and size of SVC, TCSC and UPFC [X].

Table 7:Comparative analysis of the hybrid KGMO-GWO method

Parameters	QOCRO [VI]	KGMO-PSO [X]	Hybrid KGMO-GWO
TVD (p.u)	0.1039	0.1167	0.1007
Ploss (MW)	-	3.8786	3.6442

Table 7 shows the comparative analysis of the hybrid KGMO-GWO method with QOCRO [VI] and hybrid KGMO-PSO [X]. From the table, its conclude that the hybrid KGMO-GWO method achieves less TVD and power loss compared to the QOCRO [VI] and hybrid KGMO-PSO [X]. For example, the TVD is 0.1007 p.u, that is less when compared to both the QOCRO [VI] and hybrid KGMO-PSO [X]. The QOCRO [VI] is fails to consider the generation cost and line loading during optimal placement of FACTS devices. Additionally, the PSO of hybrid KGMO-PSO [X] is insignificant for large dimensional space. But, the hybrid KGMO-GWO method considers four different objective functions namely generation cost, total voltage deviation, line loading and real power loss. Thus the hybrid KGMO-GWO provides significant results for optimal placement due to less computational complexity.

VII. Conclusion

In this research, an optimal placement and sizing of the FACTS devices are carried out using hybrid KGMO-GWO technique. The KGMO and GWO are used for the optimal placement due to the less computational complexity. The FACTS devices such as SVC, TCSC and UPFC are used to control the real and reactive power for improving the voltage stability of the transmission line system. The reactive power compensation, security improvement, power transfer capability enhancement and reliability are achieved by using the FACTS devices in transmission line system. The TVD and power loss of the hybrid KGMO-GWO method is less when compared to the QOCRO and hybrid KGMO-PSO. For the instance, the power loss of the hybrid KGMO-GWO method is 3.6442 MW, it is less when compared to the hybrid KGMO-PSO. Furthermore, an optimal allocation and sizing of FACTS devices can be analyzed in large bus systems like IEEE 39, IEEE 57 and IEEE 118 bus systems by using novel optimization algorithms.

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