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Transmission Loss allocation with Optimal Power Flow using Gravitational Search Algorithm

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Abstract: In deregulated power systems, the transmission loss allocation plays a key role in planning and designing of the power system. In practice, these losses should be allocated to both generators and loads depending on the amount of contribution in the total power system losses. In this paper, a new methodology to optimally allocate the transmission losses to either generators or loads based on the power flow tracing methodology is presented. In this methodology, trace usage coefficients are formulated to allocate transmission losses. In real time, system operator tries to minimize the transmission losses to increase the security of the system. In this paper, for the sack of analysis, the formulated OPF problem with transmission losses as objective is solved while satisfying system constraints using gravitational search algorithm. The minimized transmission losses are then allocated to either generators or loads. The proposed methodology is tested on standard IEEE-30 bus and real time Indian-24 bus test systems with supporting numerical results.

Keywords: Transmission loss allocation, Power flow tracing, Optimal power flow, Trace usage coefficients

I. INTRODUCTION

Now a day, because of the open access environment, each of the loads has an advantage to use the power from the required generator. Due to this, the complexity of power system is increasing and sometimes leads to insecure condition such as system collapse. Similarly, the transmission losses in a system are increased drastically and the cost of this should be allocated to generators or loads based on the contractual agreements. To solve this, it is necessary to trace the power flow in a given system, to allocate the transmission losses to generators or loads based on the amount of generation or amount of the power consumed by the load.

Tracing of active power and reactive power are given. [1,2] as far as reactive flows are concerned, the lines are considered as sources or sinks; this is very different from the behavior of active power flows for which the lines are always simple 'carriers with losses'. In [3], a methodology for active power flow tracing is outlined; the authors say that such methodology is also suitable for reactive power tracing; but the applications only concern active power flow tracing. In the interconnected systems, power flows in the transmission lines in which how the power flow between generator/ loads and flows is given by sensitive analysis [4,5]. The tracing of power permits the system operator to incorporate the level of system usage for pricing the transmission services. It also helps to estimate some of the resources required in the form of ancillary services [6-8]. References [9-12] proposed power tracing algorithms.

In [13], a tracing algorithm is proposed which did not describe as to how to extend the same to cases where the reactive power flows from both ends of the line. The most famous scheme is tracing of electricity which simple and understandable to market participants. In [14], the matrix power series has been used to get inversion of upstream and downstream tracing distribution matrices giving some important inferences. In [15], an attempt was made to get relationship between the generator (or loads) and power flows by means of sensitivity analysis, that is by determining how the flow is influenced a change in a nodal generation/ demand in a particular line [16]. In [17,18], electricity tracing technique is proposed under the assumption that nodal inflows are shared proportionally between the nodal outflows, allowing one to trace the flow of electricity on interconnected network. With which, share of each generator in each line flow and load can be determined. Same concept was proposed in [19].

The loss compensation schemes to balance actual loss and recovered loss is employed by IGO [20]. The transmission loss compensation schemes considered as ancillary services are presented in [21-23]. The major factors in the locational spot pricing is transmission loss allocation amounting 3-5% of total generation [24]. In [25], an attempt is made that the difference between the sum of theoretically allocated losses and the actual system loss are reduced. In [26-32] the concept of distributed slack bus is introduced. In this method loses allocated to busses are exactly equal to actual loss which is given by ac power flow. Some meta-heuristic methods such as fast evolutionary programming (FEP) [33], particle swarm optimization (PSO) [34], hybrid quantum PSO (HQPSO) [35], and differential evolution (DE) [36], were applied to solve OPF problems with valve-point effects. Artificial bee colony (ABC) [37], artificial immune system (AIS)

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[38] and chaotic particle swarm optimization (CPSO) [39] were utilized in OPF problems with prohibited operating zones. For economic dispatch problems, evolutionary programming (EP) [40], real coded genetic algorithm (RCGA) [41] and time-varying acceleration coefficients PSO (TVAC-PSO) [42] were used. Differential harmony search (DHS) [43] and adaptive PSO (APSO) [44] were proposed to solve OPF problems.

Computational intelligent-based techniques, such as genetic algorithm (GA) [45], improved GA [46], real parameter GA [47], adaptive GA [48], evolutionary programming (EP) [49], particle swarm optimization(PSO) [50], hybrid PSO [51], bacterial foraging optimization(BFO) [52], differential evolution (DE) [53-55], seeker optimization algorithm (SOA) [56], gravitational search algorithm (GSA) [57], etc, have been applied for solving ORPD problem. These techniques have shown effectiveness in overcoming the disadvantages in traditional methods. Mainly, As far as researchers are concerned, PSO and DE are important techniques because they are efficient techniques. Even they are efficient methods; they attract local optima against global optima. Further, their searching performance depends on the appropriate parameter settings [58]. Premature convergence and local stagnation are frequently observed in many applications.

Gravitations search algorithm (GSA) is based on law of gravity and interaction with masses. In GSA, searcher agents are collection of masses and their interactions are based on Newton laws of gravity and motion. In this paper, to further improve the optimization performance of GSA, opposition-based learning is employed in opposition-based gravitational search algorithm (OGSA) for population initialization and also for generation jumping. In the present work, OGSA is applied for the solution of optimal reactive power dispatch (ORPD) of power systems. Traditionally, ORPD is defined as the minimization of active power transmission losses by controlling a number of control variables. ORPD is formulated as a non-linear constrained optimization problem with continuous and discrete variables. In this work OGSA is used to find the settings of control variables such as generator voltages, tap positions of tap changing transformers and amount of reactive power compensation to optimize certain objectives.

In [59], gravitational search has been discussed. Metaphor of gravitational interactions between masses based gravitational search algorithm is discussed. GSA is developed based theory of Newton's laws: every participle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

From the careful review of the literature, it is identified that, the transmission losses should be allocated to generators or loads based on the amount of the power generation or power consumption. For this, it is necessary to trace the power flow in a given system. In this paper, a new methodology based on power flow tracing is proposed. The power flow tracing in turn uses the proportional sharing principle. In this methodology, trace usage coefficients are formulated. In this paper, gravitational search algorithm is used to solve OPF problem with transmission loss as objective while satisfying system constraints. The minimized transmission losses are then allocated to generators or loads. The proposed methodology is tested on standard IEEE-30 bus and Indian-24 bus test systems.

II. OPF PROBLEM FORMULATION

In its general form, the OPF problem can be mathematically represented as

$$Minimize \quad f(x,u) \tag{1}$$

$$subjected \quad to \ g(x,u) = 0; \ h_{\min} \le h(x,u) \le h_{\max}$$
(2)

where

f(x,u) is the objective function

'x' is the vector of dependent variables

'u' is the vector of independent or control variables

g(x,u) represents equality constraints

h(x,u) represents inequality constraints.

The OPF solution determines a set of optimal variables to achieve a certain goal such as minimum generation cost, power loss etc., subjected to all the equality and inequality constraints. The dependent variables are slack bus active power, load bus voltage magnitudes and its angles, generators reactive powers and line flow limits. The independent variables consist of continuous and discrete variables. The continuous variables are active powers of all generators, except slack bus and generator voltages. The discrete variables are tap settings of regulating transformers and reactive power injections.

A. Transmission power loss (TPL)

The losses are calculated from the load flows. The power flow from ith bus to jth bus is given by Sij. and that for the power flow from jth bus to ith bus is given by Sji.

$$L_{ij} = S_{ij} + S_{ji} \text{ MW} \tag{3}$$

The total power loss bus system is given by

$$Ploss = \sum_{k=1}^{NTL} real(L_{ij}(k)) \text{ MW} \tag{4}$$

Where NTL is total number of transmission lines,

B. Equality constraints

The equality constraints represent the set of nonlinear power flow equations as

$$\sum_{i=1}^{N_G} P_{G_i} - P_D - P_L = 0 \tag{5}$$

$$\sum_{i=1}^{N_G} Q_{G_i} + Q_{sh} - Q_D - Q_L = 0 \tag{6}$$

where Pgi and Qgi are the active and reactive power generations of ith unit, Pd and Qd are the active and reactive load demands of the system, Qsh is the reactive power injection of the shunt compensator, PL and QL are the active and reactive power losses of the system.

C. Inequality constraints

The following are inequality constraints for OPF problem

Generator bus voltage limits:

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$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}; \qquad \forall i \in N_G$$

Active Power Generation limits:

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}; \qquad \forall i \in N_G$$

Transformers tap setting limits:

$$T_i^{\min} \le T_i \le T_i^{\max}; \qquad i = 1,2,\ldots,n_t$$

Capacitor reactive power generation limits:

$$Q_{Sh_i}^{\min} \le Q_{Sh_i} \le Q_{Sh_i}^{\max}; \quad i = 1,2,\ldots,n_C$$

Transmission line flow limit:

$$S_{l_i} \le S_{l_i}^{\max}; \qquad i = 1,2,\ldots,N_{line}$$

Reactive Power Generation limits:

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}; \qquad \forall i \in N_G$$

Bus voltage magnitude limits:

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1,2,\ldots,N_{load}$$

Where, total number of taps, n_C total number of VAr sources, N_{load} total number of VAr sources.

III. GRAVITATIONAL SEARCH ALGORITHM

In GSA, each mass (agent) has four specifications: position, inertial mass, active gravitational mass, and passive gravitational mass. The position of the mass corresponds to a solution of the problem, and its gravitational and inertial masses are determined using a fitness function [56, 57].In other words, each mass presents a solution, and the algorithm is navigated by properly adjusting the gravitational and inertia masses. By lapse of time, we expect that masses be attracted by the heaviest mass. This mass will present an optimum solution in the search space.The gravitational constant, *G*, is initialized at the beginning and will be reduced with time to control the search accuracy. In other words, *G* is a function of the initial value (*G*0) and time (*t*):

$$G(t) = G_0 * e^{\left(\frac{-\alpha t_i}{T}\right)} \tag{7}$$

where α is a constant,
t_i is the iteration number and
T is the total number of iterations.
Consider a system of N agents. The position of ith agent is defined as

$$X_i = (x_i^1, \ldots\ldots, x_i^d, \ldots\ldots, x_i^n) \qquad i = 1,2,3\ldots,N$$

For each position fitness function is evaluated.

A. Calculation of masses

Let fiti(t) be the fitness function of ith particle at tth iteration.
Now we introduce new variables worst(t) and best(t).
For a minimization problem, worst(t) and best(t) are defined as follows:

$$best(t) = \min_{j=1,2\ldots\ldots N} fit_j(t), \qquad worst(t) = \max_{j=1,2\ldots\ldots N} fit_j(t), \tag{8}$$

For a maximization problem, worst(t) and best(t) are defined as follows:

$$best(t) = \max_{j=1,2\ldots\ldots N} fit_j(t), \qquad worst(t) = \min_{j=1,2\ldots\ldots N} fit_j(t), \tag{9}$$

Gravitational and inertia masses are simply calculated by the fitness evaluation. A heavier mass means a more efficient agent. This means that better agents have higher attractions and walk more slowly. Assuming the equality of the gravitational and inertia mass, the values of masses are calculated using the map of fitness. We update the gravitational and inertial masses by the following equations:

$$M_{ai} = M_{pi} = M_{ii} = M_i$$
$$m_i(t) = \frac{fit_i(t) - worst(t)}{best(t) - worst(t)} \tag{10}$$
$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_i(t)}$$

B. Calculation of Force

For iteration t, we define the force acting on mass i from mass j as following

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t)M_{aj}(t)}{R_{ij} + \varepsilon}(x_j^d - x_i^d) \tag{11}$$

where *Maj* is the active gravitational mass related to agent *j*,
Mpi is the passive gravitational mass related to agent *i*,
G(*t*) is gravitational constant at iteration *t*,
ε is a small constant and
Rijis the Euclidian distance between two agents i and j given by

$$R_{ij}(t) = \| X_i(t), X_i(t) \|_2 \tag{12}$$

To give a stochastic characteristic to our algorithm, we suppose that the total force that acts on agent *i* in a dimension *d* be a randomly weighted sum of *d*th components of the forces exerted from other agents:

$$F_i^d(t) = \sum_{j=1, j\ne i}^{N} rand_i F_{ij}^d(t) \tag{13}$$

C. Calculation of Acceleration

Hence, by the law of motion, the acceleration of the agent at iteration t , and in direction d, is given as:

$$a_i^d = E_i^d(t) \times G(t) \tag{14}$$

Furthermore, the next velocity of an agent is considered as a fraction of its current velocity added to its acceleration. Therefore, its position and its velocity could be calculated as follows:

$$v_i^d(t+1) = rand_i \times v_i^d(t) + a_i^d(t)$$
$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \tag{15}$$

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IV. PROPOSED TRACE USAGE BASED LOSS ALLOCATION

A power flow procedure is used to calculate power loss in the system. It is desirable to take network loss effect of injection power at each node for calculating contribution of transmission loss by each generator and loss allocated to loads and loss allocations to both generators and loads. In this thesis, a tracing based usage coefficients are formulated to implement the loss allocation procedure to generators, loads and both. This methodology starts from a converged load flow solution. Result obtained from the load flow is utilized to further process in this existing methodology to allocate transmission losses to individual generators and individual loads.

A. Power flow tracing mechanism

Power flow tracing methodology [60] is normally used for calculating generator's share in line flows and loads. After finding generator's share in loads, traced-usage coefficients can be framed for the traced-usage methodology. In this section, procedure of power flow tracing and procedure to formation of traced-usage coefficients can be illustrated.

B. Mathematical modelling of proportional sharing principal

Consider a bus having two inflows and two outflows as it is convenient to analyze and shown in Fig.1.

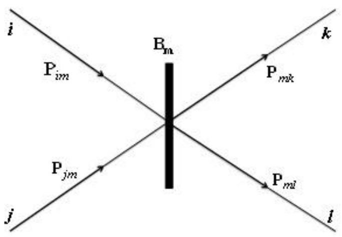

Fig.1. Proportional sharing principal at bus Bm

In Fig.1, Bm is the bus at which power flow tracing explanation is evaluated. i,j,k and l represents the buses which are connected to Bm through power lines. Pim and Pjm are power inflows to bus Bm. Pmk and Pml are power outflows from bus Bm.

The equations for outflows in terms of inflows can be expressed as

$$P_{mk} = \left(\frac{P_{im}}{P_{im}+Pjm} + \frac{P_{jm}}{P_{im}+Pjm}\right) P_{mk} \quad (16)$$

$$P_{ml} = \left(\frac{P_{im}}{P_{im}+Pjm} + \frac{P_{jm}}{P_{im}+Pjm}\right) P_{ml} \quad (17)$$

$$Q_{mk} = \left(\frac{Q_{im}}{Q_{im}+Qjm} + \frac{Q_{jm}}{Q_{im}+Qjm}\right) Q_{mk} \quad (18)$$

$$Q_{ml} = \left(\frac{Q_{im}}{Q_{im}+Qjm} + \frac{Q_{jm}}{Q_{im}+Qjm}\right) Q_{ml} \quad (19)$$

From these above four equations we can use only Eqn's (16) and (17), which are real or active power values. This paper deals with active power loss allocation only so that in this concept, the active power will be traced. Reactive power tracing and reactive power loss allocation is under future work.

C. Trace-Usage Coefficients

- T_{ij}^{α} is defined as the fraction of power received by the load at i[th] bus to the power generated at j[th] bus.
- T_{ij}^{β} is defined as the fraction of load power at j[th] bus supplied by the generation at the i[th] bus.

$$T_{ij}^{\alpha} = \frac{\text{Active power sharing of } i^{th} \text{ generator in } j^{th} \text{ Load}}{\text{Total active power generation of } i^{th} \text{generator}} \quad (20)$$

$$T_{ij}^{\beta} = \frac{\text{Active power sharing of } i^{th} \text{ generator in } j^{th} \text{ Load}}{\text{Total active power at } j^{th} \text{ load}} \quad (21)$$

These T_{ij}^{α} trace-usage coefficients are related to generators, rows indicates generators and columns indicates loads. It gives the details of how much of its generation transfers to loads.

These T_{ij}^{β} trace-usage coefficients are related to loads, rows indicates loads and columns indicates generators. It gives the details of how much of its load met by the generators.

D. Loss Allocation Procedure to Generators

Consider a power system network with NG generators and NB load (no of buses) connected through a transmission lines. This method separated the non-linear system loss into the sum of NB terms and similarly the sum of NG terms. The main difficulty arises in allocation of loss component to generators and loads because of non linear nature of the loss equation in which the combined set of all traced-usage coefficients interact through the load flow terms. Thus, the loss allocation depends on path and the traced-usage coefficients of generators and loads.

Consider the Generators set $G=G_1, G_2, G_3, \ldots G_{NG}$ and the load set $L=L_1, L_2, L_3, \ldots L_{NB}$.

An exact transmission loss formula using system parameters and bus injected powers is given [40] as follows

$$P_L = \sum_{i=1}^{NB} \sum_{j=1}^{NB} [A_{ij}(P_iP_j + Q_iQ_j) + B_{ij}(Q_iP_j - P_iQ_j)]$$

(22)

Where,

$$A_{ij} = \frac{R_{ij}}{|V_i||V_j|} cos(\delta_i - \delta_j);\ B_{ij} = \frac{R_{ij}}{|V_i||V_j|} sin(\delta_i - \delta_j) \quad (23)$$

P_L is the real power loss of the power system, S_i is the injected power at bus $S_i = P_i + jQ_i$, $Z_{ij} = R_{ij} + jX_{ij}$ and Z_{ij} is the i-j[th] element of Z_{bus}, V_i is the voltage magnitude of bus-i and δ_i is voltage phase angle of bus-i,

E. Loss allocation to generators

The injected real power at bus-i is given as

$$P_i = P_{Gi} - P_{Loadi}$$

Let T_{ij}^{α} be the traced-usage coefficient that is fraction of power generated at j[th] bus received by the load at i[th] bus.

The load at i[th] bus can be expressed as the sum of usage amounts from different generators that is

$$P_{Loadi} = \sum_{j=1}^{NG} T_{ij}^{\alpha} P_{Gj} \qquad where\ i = 1, 2, ..., NB$$

The injected real power can be modified by using above equation as follows

$$P_i = P_{Gi} - \sum_{j=1}^{NG} T_{ij}^{\alpha} P_{Gj} \qquad where\ i = 1, 2, ..., NB$$

The above equation can be rewritten as

$$P_i = \sum_{j=1}^{NG} T_{ij}^{\chi} P_{Gj} \qquad where\ i = 1, 2, ..., NB$$

where $T_{ij}^{\chi} = -T_{ij}^{\alpha}$ for $i \neq j$(non-generation buses); $T_{ij}^{\chi} = 1 - T_{ij}^{\alpha}$ for $i = j$ (generation buses).

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The injected powers at i[th] and j[th] bus can be given as

$$P_i = \sum_{p=1}^{NG} T_{ip}^{\chi} P_{Gp} \qquad where\ i = 1, 2, ..., NB \qquad (24)$$

$$P_j = \sum_{q=1}^{NG} T_{iq}^{\chi} P_{Gq} \qquad where\ i = 1, 2, ..., NB \qquad (25)$$

Rearrange the Eqn (22) as components of self power (active or reactive) and mutual-power components

$$P_L = \sum_{i=1}^{NB}\sum_{j=1}^{NB} [A_{ij}(P_iP_j) + B_{ij}(Q_iP_j - P_iQ_j)] + [A_{ij}Q_iQ_j]$$

(26)

The above Transmission loss Eqn (26) can be modified by using Eqn's (24) and (25) as follows as

$$P_L = \sum_{p=1}^{NG} \left\{ \left[\sum_{q=1}^{NG} \left(\sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} T_{pi}^{\chi} T_{qi}^{\chi} P_{Gp} P_{Gq} \right) \right] + \left[\sum_{i=1}^{NB}\sum_{j=1}^{NB} B_{ij} \left(T_{pj}^{\chi} Q_i - T_{pi}^{\chi} Q_j \right) P_{Gp} \right] + \left[\frac{P_{Gp}}{\sum_{p=1}^{NG} P_{Gp}} \sum_{i=1}^{NB}\sum_{j=1}^{NB} (A_{ij} Q_i Q_j) \right] \right\}$$

(27)

In the above equation the last term is observed that the active power loss caused because of interaction of reactive power injections and it is very small compared to total active power loss. Hence it is assumed that the loss contribution because of interaction of reactive power can be shared to the generators according to its generation.

The loss contribution component (Self Component) because of individual p[th] generator alone is expressed as

$$P_L^{(p,p)} = \sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} T_{pi}^{\chi} T_{qi}^{\chi} P_{Gp}^2 + \sum_{i=1}^{NB}\sum_{j=1}^{NB} B_{ij} \left(T_{pj}^{\chi} Q_i - T_{pi}^{\chi} Q_j \right) P_{Gp} + \frac{P_{Gp}}{\sum_{p=1}^{NG} P_{Gp}} \sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} Q_i Q_j$$

(28)

$P_L^{(p,p)}$ is part of total loss caused by p[th] generator that depends only on its generation.

The loss contribution component (Mutual Component) because of interaction of p[th] generator and q[th] generator is expressed as

$$P_L^{(p,q)} = \sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} \left(T_{pi}^{\chi} T_{qj}^{\chi} + T_{qi}^{\chi} T_{pj}^{\chi} \right) P_{Gp} P_{Gq}, \quad p \neq q$$

(29)

$P_L^{(p,q)}$ is part of total loss caused by interaction of p[th] generator and q[th] generator.

It is common practice that the above term can be allocated to each generator of pair (p,q) as half of the absolute value of $P_L^{(p,q)}$ rather than the total amount to individual generators.

$$P_L^p = P_L^{(p,p)} + \frac{1}{2} \sum_{q=1, q\neq p}^{NG} P_L^{(p,q)} \qquad (30)$$

The above procedure can be used for other generators to compute its loss contribution.

The total active power loss is

$$P_{Tloss} = \sum_{p=1}^{NG} P_L^p \qquad (31)$$

F. Loss allocation to loads

The injected real power at bus-i is given as

$$P_i = P_{Gi} - P_{Loadi} \qquad (32)$$

Let T_{ij}^{β} be the traced-usage coefficient that is fraction of power supplied by the generation at ith bus to the load power at jth bus.

The generation at ith bus can be expressed as the sum of usage amounts from different loads that is

$$P_{Gi} = \sum_{j=1}^{NB} T_{ij}^{\beta} P_{Load0j} \qquad where\ i = 1, 2, ..., NG$$

(33)

The injected powers at every bus can be rewritten as below by employ above Eqn's (32) and (33)

$$P_i = \sum_{j=1}^{NB} T_{ij}^{\beta} P_{Loadj} - P_{Loadi} \qquad where\ i = 1, 2, ..., NB$$

The above equation can be rewritten as

$$P_i = \sum_{j=1}^{NG} T_{ij}^{\eta} P_{Loadj} \qquad where\ i = 1, 2, ..., NB$$

(34)

where $T_{ij}^{\eta} = T_{ij}^{\beta}$ for $i \neq j$; $T_{ij}^{\eta} = T_{ij}^{\beta} - 1$ for i=j.

The injected powers at ith and jth bus can be given as

$$P_i = \sum_{p=1}^{NB} T_{ip}^{\eta} P_{Loadp} \qquad where\ i = 1, 2, ..., NB$$

(35)

$$P_j = \sum_{q=1}^{NB} T_{jq}^{\eta} P_{Loadq} \qquad where\ i = 1, 2, ..., NB$$

(36)

The above Transmission loss equation Eqn (22) can be modified by using equations Eq's (35) and (36) is follows as

$$P_L' = \sum_{p=1}^{NB} \left\{ \left[\sum_{q=1}^{NB} \left(\sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} T_{pi}^{\eta} T_{qi}^{\eta} P_{Loadp} P_{Loadq} \right) \right] + \left[\sum_{i=1}^{NB}\sum_{j=1}^{NB} B_{ij} \left(T_{pj}^{\eta} Q_i - T_{pi}^{\eta} Q_j \right) P_{Loadp} \right] + \left[\frac{P_{Loadp}}{\sum_{p=1}^{NB} P_{Loadp}} \sum_{i=1}^{NB}\sum_{j=1}^{NB} (A_{ij} Q_i Q_j) \right] \right\} \qquad (37)$$

In the above equation the last term is observed that the active power loss caused because of interaction of reactive power injections and it is very small compared to total active power loss. Hence it is assumed that the loss contribution because of interaction of reactive power can be shared to the Loads according to its Load capacity.

The loss contribution component (Self Component) because of individual pth load alone is expressed as

$$P_L'^{(p,p)} = \sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} T_{pi}^{\eta} T_{pj}^{\eta} P_{Loadp}^2 + \sum_{i=1}^{NB}\sum_{j=1}^{NB} B_{ij} \left(T_{pj}^{\eta} Q_i - T_{pi}^{\eta} Q_j \right) P_{Loadp} + \frac{P_{loadp}}{\sum_{p=1}^{NB} P_{Loadp}} \sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} Q_i Q_j$$

(38)

$P_L'^{(p,p)}$ is part of total loss caused by pth load that depends only on its load power value.

The loss contribution component (Mutual Component) because of interaction of pth load and qth load is expressed as

$$P_L'^{(p,q)} = \sum_{i=1}^{NB}\sum_{j=1}^{NB} A_{ij} \left(T_{pi}^{\eta} T_{qj}^{\eta} + T_{qi}^{\eta} T_{pj}^{\eta} \right) P_{Loadp} P_{Loadq}, \quad p \neq q$$

(39)

$P_L'^{(p,q)}$ is part of total loss caused by interaction of pth load and qth load.

The loss contribution of load at pth bus is given by adding the half of the amount of mutual loss component because of interaction of load-p and load-q to the self component.

$$P_L'^p = P_L'^{(p,p)} + \frac{1}{2} \sum_{q=1, q\neq p}^{NB} P_L'^{(p,q)} \qquad (40)$$

The above procedure can be used for other generators to compute its loss contribution.

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The total active power loss is

$$P'_{Tloss} = \sum_{p=1}^{NB} P'^{p}_{L} \tag{41}$$

V. RESULTS AND ANALYSIS

In this section, the analysis is performed on standard test systems such as IEEE-30 bus and Indian-24 bus systems.

A. Example-1

An IEEE-30 bus system with forty one transmission lines, four tap changing transformers and two shunt compensating devices is considered. For this system, there are eighteen control variables, which include active power generation and voltage magnitudes at six generating buses, tap settings of four tap changing transformers, reactive power compensated by two shunt compensators.

Initially, the transmission loss minimization problem formulated in section 2 is solved using the proposed GSA methodology and the corresponding optimal settings of the control variables are tabulated in Table.1. From this table, it is identified that, the total active power generation and consequently the total active power losses are decreased with GSA. In this case, all generators except slack generator are operating at its maximum limits due to which the total transmission losses are minimized is also observed. In the same way, the time taken for the execution is 30.9481 sec with GSA.

The convergence characteristics for the proposed method is shown in Fig.2. From this figure, it is observed that, the proposed method starts the iterative process with good initial value and reaches best final value in less number of iterations.

TABLE.1. OPF RESULTS WITH GSA FOR IEEE-30 BUS SYSTEM

S. No	Control parameters		With GSA
1	Real power Generation (MW)	P_{G1}	51.9567
		P_{G2}	80
		P_{G5}	50
		P_{G8}	35
		P_{G11}	29.7534
		P_{G13}	40
2	Generator voltages (p.u.)	V_{G1}	1.05
		V_{G2}	1.0459
		V_{G5}	1.0298
		V_{G8}	1.0331
		V_{G11}	1.05
		V_{G13}	1.0494
3	Transformer tap setting (p.u.)	T_{6-9}	1.1
		T_{6-10}	0.9
		T_{4-12}	1.0167
		T_{28-27}	0.9711
4	Shunt compensators (MVAr)	$Q_{C,10}$	5
		$Q_{C,24}$	16.424
5	Total generation (MW)		286.71
6	Total power loss (MW)		3.31
7	Time (sec)		30.9481

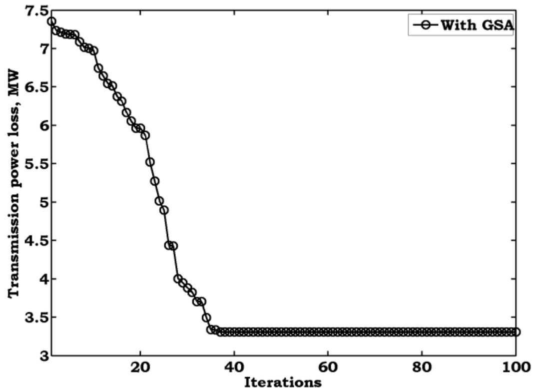

Fig.2. Convergence characteristics with GSA for IEEE-30 bus system

Further, the proposed method is validated with the existing methods and the corresponding information is given in Table.2. From this table, it is confirmed that, the proposed method gives better result when compared to existing methods.

TABLE.2. COMPARISON OF VARIOUS METHODS OF TRANSMISSION LOSS MINIMIZATION FOR IEEE-30 BUS SYSTEM

S. No	Method	Transmission losses (MW)	Time (Sec)
1	CPSO [49]	4.5615	138
2	DE [53]	4.555	NA
3	Proposed GSA	3.31	30.9481

After minimizing the transmission power losses in a given system using OPF, these losses should be allocated to either generators or loads. To perform this, procedure described in section 4 is used.

Loss allocation to generators:

Initially using the procedure given in section 4(E), the total losses obtained using GSA are allocated to generators alone. Here, from Table.1, the total losses are 3.31 MW with GSA are allocated to six generators which are connected at buses 1, 2, 5, 8, 11 and 13. The corresponding loss allocations are tabulated in Table.3. From this table, it is observed that, maximum losses are allocated to generator placed at bus-2 in both methods. This is because of the amount of generation is highest when compared to other generators. The graphical representation of loss allocations to all generators is shown in Fig.3.

TABLE.3. LOSS ALLOCATION WITH GSA TO GENERATORS FOR IEEE-30 BUS SYSTEM

S. No	Bus No	Loss allocation with GSA (MW)
1	1	1.1723
2	2	1.402
3	5	0.027
4	8	0.1501
5	11	0.2131
6	13	0.3455
Total power loss (MW)		3.31

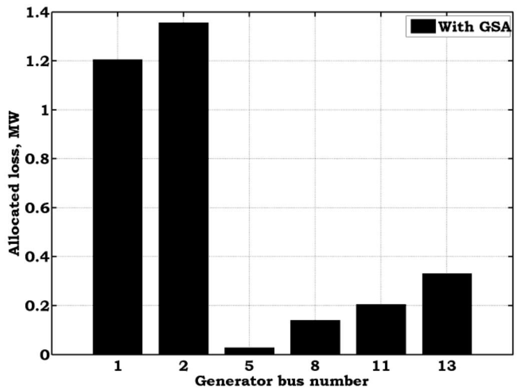

Fig.3. Variation of loss allocation with GSA to generators for IEEE-30 bus system

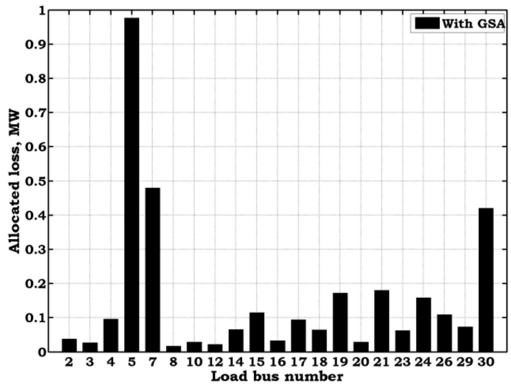

Fig..4. Variation of loss allocation with GSA to loads for IEEE-30 bus system

Loss allocation to loads:

The procedure described in section 4(F) is used to allocate losses among the loads. For this system, there are twenty one loads and respective loss allocations using existing and proposed methods are tabulated in Table.4. From this table, it is identified that, maximum losses are allocated to load at bus-5 as the amount of load at this bus is high i.e. 94.2 MW when compared to other buses. The minimum losses are allocated to load at bus-8 i.e. 30 MW, this is because of the availability of local generation. Hence, it very clear that, maximum amount of load at bus-8 is supplied from the generator at the same bus. The graphical representation of loss allocations to all loads is shown in Fig.4.

TABLE.4. LOSS ALLOCATION WITH GSA TO LOADS FOR IEEE-30 BUS SYSTEM

S. No	Bus No	Loss allocations with GSA (MW)
1	2	0.0381
2	3	0.0274
3	4	0.0951
4	5	0.9805
5	7	0.4796
6	8	0.0163
7	10	0.0307
8	12	0.0213
9	14	0.0656
10	15	0.1153
11	16	0.0321
12	17	0.0954
13	18	0.0655
14	19	0.1784
15	20	0.0309
16	21	0.1884
17	23	0.063
18	24	0.1654
19	26	0.1102
20	29	0.0706
21	30	0.4402
Total power loss (MW)		3.31

B. Example-2

A real time Indian-24 bus system with twenty seven transmission lines, four generating units is considered. For this system, there are eight control variables, which include active power generation and voltage magnitudes of four generating units.

Initially, the transmission loss minimization problem formulated in section 2 is solved using the proposed GSA methodology and the corresponding optimal settings of the control variables are tabulated in Table.5. It is also observed that, the total active power generation and consequently the total active power losses are decreased slightly with GSA. In the same way, the time taken for the execution is 27.9281 sec with GSA.

The convergence characteristics for the proposed and existing methods are shown in Fig.5. From this figure, it is observed that, the proposed method starts the iterative process with good initial value and reaches best final value in less number of iterations.

TABLE.5. OPF RESULTS WITH GSA FOR INDIAN-24 BUS SYSTEM

S. No	Parameter		With GSA
1	Real power generation (MW)	P_{G1}	524.4233
		P_{G2}	117.847
		P_{G3}	205.4282
		P_{G4}	431.1974
2	Generator voltages (p.u.)	V_{G1}	1.1
		V_{G2}	0.9952
		V_{G3}	1.0551
		V_{G4}	1.1
3	Total generation (MW)		1278.896
4	Total power loss (MW)		35.896
5	Time (sec)		27.9281

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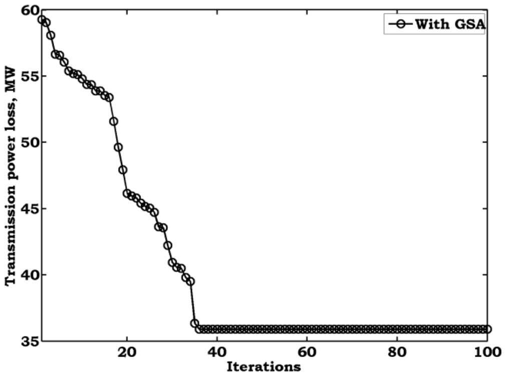

Fig.5 Convergence characteristics with GSA for Indian-24 bus system

After minimizing the transmission power losses in a given system using OPF, these losses should be allocated to either generators or loads. To perform this, procedure described in section 4 is used.

Loss allocation to generators:

Initially using the procedure given in section 4(E), the total losses obtained using GSA are allocated to generators alone. Here, from Table.5, the total losses are 35.896 MW with GSA are allocated to four generators which are connected at buses 1, 2, 3 and 4. The corresponding loss allocations are tabulated in Table.6. From this table, it is observed that, maximum losses are allocated to generator placed at bus-1. This is because of the amount of generation is highest when compared to other generators. The graphical representation of loss allocations to all generators is shown in Fig.6.

TABLE.6. LOSS ALLOCATION WITH GSA TO GENERATORS FOR INDIAN-24 BUS SYSTEM

S. No	Bus No	Loss allocations with GSA (MW)
1	1	17.9211
2	2	2.8372
3	3	4.2847
4	4	10.853
Total power loss (MW)		35.896

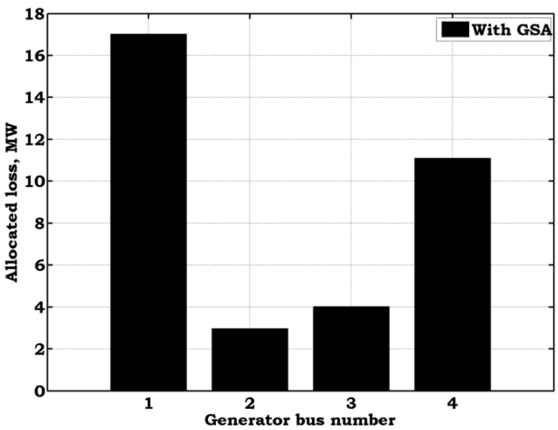

Fig.6 Variation of loss allocation with GSA to generators for Indian-24 bus system

Loss allocation to loads:

The procedure described in section 4(F) is used to allocate losses among the loads. For this system, there are fourteen loads and respective loss allocations using proposed method is tabulated in Table.7. From this table, it is identified that, maximum losses are allocated to load at bus-16 as the amount of load at this bus is high i.e. 230 MW when compared to other buses. The minimum losses are allocated to load at bus-11 i.e. 35 MW, this is because of the availability of local generation. Hence, it very clear that, maximum amount of load at bus-11 is supplied from the generator at the same bus. The graphical representation of loss allocations to all loads is shown in Fig.7.

TABLE.7. LOSS ALLOCATION WITH GSA TO LOADS FOR INDIAN-24 BUS SYSTEM

S. No	Bus No	Loss allocations with GSA (MW)
1	6	1.5336
2	7	6.3918
3	9	1.0702
4	10	3.3726
5	11	0.7265
6	12	0.926
7	13	4.0988
8	16	7.3069
9	17	1.9878
10	19	2.4692
11	20	1.2161
12	21	0.9486
13	23	1.5426
14	24	2.3053
Total power loss (MW)		35.896

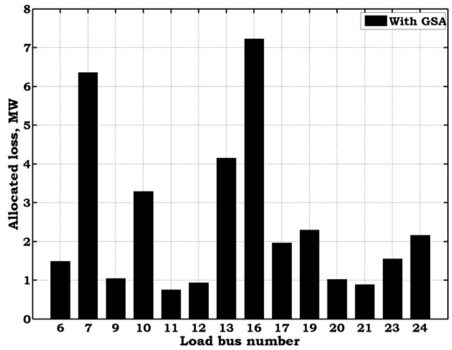

Fig.7. Variation of loss allocation with GSA to loads for Indian-24 bus system

VI. CONCLUSION

In this paper, gravitational search algorithm has been proposed to enhance the optimization technique performance in terms of convergence characteristics and computational time. Proposed OPF problem with transmission losses as an objective and is solved while satisfying equality and in-equality constraints. Finally the minimized power losses are allocated to generators or/and loads. It is finally observed that, with the proposed tracing based loss allocation mechanism, losses are allocated to generators or loads based on the amount of the generation and the amount of consumption. This is validated with proper explanations. The proposed GSA method is validated with some of the existing methods. Finally, it is summarized that, the proposed loss allocation methodology with the proposed GSA method yields good results on standard systems.

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