COMPARATIVE ANALYSIS OF DIFFERENT ARTIFICIAL INTELLIGENCE TECHNIQUES TO REACTIVE POWER DISPATCH FOR IMPROVING VOLTAGE STABILITY

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Abstract: A power system engineer has to monitor and take adequate control action when the operating point reaches the limit of voltage stability with an increase in stress on the power system. Power system operator requires fast computations for operation and control under heavily loaded conditions to avoid voltage instability. So, it is significant to perform voltage stability analysis by optimal reactive power dispatch with Artificial Intelligence (AI) techniques. This paper presents application of Ant Colony Optimization (ACO) algorithm, Artificial Bee Colony (ABC) algorithm and BAT algorithm for Optimal Reactive Power Dispatch (ORPD) to enhance voltage stability. The proposed ACO, ABC and BAT algorithms are used to find the optimal settings of On-Load Tap Changing Transformers (OLTC), Generator excitation and Static VAR Compensators (SVC) and hence to minimize the sum of the squares of the voltage stability L– indices. By calculating system parameters like L-Index, voltage error/deviation and real power loss for the practical Extra High Voltage (EHV) Southern Region (SR) Indian 24 bus system, voltage profile is improved and voltage stability is enhanced. A comparative analysis is done with the Linear Programming (LP) for the given objective function to demonstrate the effectiveness of proposed ACO, ABC and BAT algorithms.

Key words: Ant Colony Optimization; Artificial Bee colony Algorithm; Bat algorithm; Linear Programming; Voltage Stability; L-Index; Optimal reactive power dispatch.

1. Introduction

Improving voltage profile and maintaining voltage stability are challenging tasks for today's power system engineers for the complex power systems which are highly non-linear with the objective of maximization of voltage stability. Several conventional [4, 6-8, 13] and AI techniques [15-16, 27-37] are available and applied for enhancing voltage stability by optimal reactive power dispatch. With increase in load, the problem of voltage stability, voltage collapses are adversely affecting the power system operation. In order to overcome voltage stability problems, several conventional and AI techniques have been considered by the researchers. K. R. C Mamandur and R. D Chenoweth [1] explained mathematical model of the optimal reactive power control problem for minimizing the real power loss and voltage profile improvement with linearized sensitivity between control and dependent variables. Mamandur K. R. C [2] demonstrated with LP technique for minimizing adjustments for the reactive power control variables required for under voltages, over voltages and VAR limits of the generator. Thukaram et al., [3] explained improved algorithm for optimum reactive power allocation in power system. A method for calculation of voltage magnitudes to detect voltage instabilities was proposed by Kessel and Glavitsch [4]. Qiu and Shahidehpour [5] explained a new method of LP for reducing system losses and to enhance voltage profile. Bansilal, D. Thukaram and K. Parthasarathy [6] proposed voltage stability improvement by optimal reactive power dispatch algorithm with base case and credible contingency condition. D. Thukaram et al., [7] developed a method to calculate voltage collapse proximity using LP method. E. Rezania and S.M. Shahidehpour [8] demonstrated application of conventional optimization technique like interior point method for the objective of real power loss minimization. D. Thukaram, G. Yesuratnam and C. Vyjayanthi [9] explained Voltage

Stability Criteria by optimal reactive power dispatch in a Large Power System with AC/DC including FACTS Devices. Dhadbanjan and Yesuratnam [10] applied conventional optimization technique like LP to obtain the near optimized values for control parameters like OLTC's, SVC's and Generator exciter settings for different objectives. Vaisakh and Kantharao [11] presented a differential evolution based approach for solving optimal reactive power dispatch for voltage stability enhancement. Ismail Musirin et al., [12] proposed ACO technique in economic power dispatch problems on IEEE 26-bus system with the aim of minimising the cost of generation. H.M.Soliman, E.H.E.Bayoumi and M.F.Hassan [13] proposed a technique based on the particle swarm approach to identify the parameters of a fixed structure lead compensator through the solution of a min-max problem while satisfying systems constraints for the design of power system stabilizer. D. Devaraj and J. Preetha Roselyn [14] explained enhancement of voltage stability by optimal reactive power dispatch using improved genetic algorithm on different IEEE test systems. Worawat Nakawiro and Istvan Erlich [15] explained a hybrid method for voltage stability for constrained ORPD with the objective of minimising energy loss using Artificial Neural Network and modified ACO. H.M.Soliman, Ehab H.E.Bayoumi and M.Awadallah [16] explained a design technique for reconfigurable fault-tolerant controllers acting on a flexible AC transmission system through the Kharitonov theorem and particle swarm optimization. Xin-She Yang [17] has developed a bio-inspired algorithm known as Bat algorithm in the year 2010 which is very efficient and explains about various applications. Kursat Ayan and Ulas Kilic [18] demonstrated the solution of optimal reactive power flow using ABC algorithm with the aim of reducing real power loss in the power system on different IEEE test systems. K. Rayudu [19] et al., presented an improved genetic algorithm approach for generator reactive power optimization. LP and Genetic Algorithm (GA) methods are explained by K. Rayudu [20] et al., to minimize power loss, enhance voltage stability and optimize generator reactive power. Sankalap Arora and Satvir Singh [21] proposed different AI techniques like Firefly algorithm, BAT and Cuckoo search algorithm to find optimal settings for the factors like success rate and minimum run time. S. Biswal et al., [22] applied Bat algorithm for optimal power dispatch for economic load dispatch problem for minimising operating cost of thermal power plant. Yuancheng Li, Yiliang Wang and Bin Li [23] presented hybrid ABC assisted differential evolution algorithm for optimal reactive power flow on different IEEE test systems. M. Rezaei Adaryani and A. Karami [24] reported ABC algorithm for solving multi-objective optimal power flow problem with different objective functions like convex and non-convex fuel costs, total emission costs etc. Md. Alimul Ahsan, S.M. Rakiul Islam and Bashudeb Chandra Ghosh [25] applied different search algorithms and AI techniques to locate and find the size of the FACTS devices. E. S. Ali [26] explained the usage of BAT search algorithm for finding optimal setting of power system stabilizers. Adis Alihodzic and Milan Tuba [27] proposed hybridized bat algorithm for global numerical optimization for standard benchmark functions for unconstrained optimization problem. Mustafa Servet Kiran and Ahmet Babalik [28] presented improved ABC algorithm for continuous optimization by considering bench mark functions as objective functions. Jagdish Chand Bansal et al., [29] reported optimal power flow using ABC algorithm with global and local neighbourhoods to find the optimal values of control variables. Ali Ghasemi, Khalil Valipour and Akbar Tohidi [30] demonstrated ORPD using a new multi objective strategy to find the feasible optimal solution for the multi objective ORPD problem selected. Ehab H.E. Bayoumi [31] Presented a new configuration of Static synchronous series compensator (SSSC) based on matrix converter for power flow control and reactive power compensation in transmission systems. The optimal parameters of power flow controller are achieved by using cooperative bacterial foraging optimization. Radial Distribution System (RDS) is considered for lessening of real power loss and voltage profile improvement using bat algorithm by optimizing position and sizing of distributed generation which is being demonstrated by Snigdha Rani Behera et al., [32]. B. Venkateswara Rao and G.V. Nagesh Kumar [33] explained optimal power flow by Bat search algorithm for generation reallocation using unified power flow controller with the aim of minimising real power loss. Alkın Yurtkuran and Erdal Emel [34] presented an adaptive ABC algorithm for global optimization, which employs six different search rules that have been used in the literature. Kursat Ayan, Ulas Kilic and Burhan Barakli [35] applied chaotic ABC algorithm based solution of security and transient stability constrained OPF on different IEEE test systems. K.Rayudu [36] et al., explained LP and GA methods for reducing real power loss on a practical southern region 24-node system. Mousa Marzband et al., [37] proposed real time

experimental implementation of optimum energy management system in standalone Micro grid by using multi-layer ACO.

This paper presents the application of ACO, ABC and BAT algorithms for ORPD with an objective of voltage stability enhancement using fast decoupled load flow method. System parameters like power loss, L-index and voltage error for an IEEE Equivalent practical EHV- Southern Region Indian 24 bus system is calculated. A comparative analysis is done for ACO, ABC and BAT algorithms with LP technique for the objective function considered.

2. Voltage stability analysis using L-index method

L - Index method is used to measure voltage stability of a power system. Assume a system where,
N = Total number of buses in the system,
G = Total number of generator buses,
S = Total number of SVC buses,
T = Total number of OLTC transformers.
The L-index is calculated from load flow analysis as,

$$L_j = \left| 1 - \sum_{i=1}^{G} F_{ji} \frac{V_i}{V_j} \right| \tag{1}$$

$$L_j = \left| 1 - \sum_{i=1}^{G} F_{ji} \frac{V_i}{V_j} \angle (\delta_i - \delta_j + \theta_{ji}) \right| \tag{2}$$

where, $j = G+1$, $G+2$... N .The values of F_{ji} are calculated from the Y_{bus} matrix as follows

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{bmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \tag{3}$$

where,

I_G = Current at generator buses (nodes),

I_L = Current at Load buses (nodes),

V_G = Voltage at generator buses (nodes),

V_L = Voltage at Load buses (nodes).

Rearranging equation (3) to obtain

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{bmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{bmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \tag{4}$$

where,

$F_{LG} = -\left[Y_{LL}\right]^{-1}\left[Y_{LG}\right]$ are the required values [7]. At the maximum power transfer condition, L_j values for all load buses will be close to unity, giving information that power system is nearer to voltage instability. And the voltage Stability margin is calculated as $(1 - L_j)$.

3. Mathematical modelling and analysis of reactive power optimization problem

The proposed objective function is given by

$$V_s = \sum_{j=G+1}^{N} L_j^2 \tag{5}$$

For this objective function, the system performance equations, showing the relationship between control and dependent variables are the constraints.

The control variables are, tap settings of the transformers (ΔT), excitation settings of generators (ΔV) and Static VAR Compensator (SVC) settings (ΔQ). The dependent variables are, generator reactive power output (ΔQ) and voltage magnitudes of all the load buses (ΔV).

The objective function mentioned in equation (5) can be modelled in general for optimization as a minimization function

$$f = \begin{bmatrix} C_1 & C_2 & .. & .. & C_k \end{bmatrix} X \tag{6}$$

subject to $b^{\min} \leq b = SX \leq b^{\max}$ (7)

and $X^{\min} \leq X \leq X^{\max}$ (8)

where

$\begin{bmatrix} C_1 & C_2 & .. & .. & C_k \end{bmatrix}$ is the row matrix of the sensitivity coefficients of the linearized objective function,

S is the linearized sensitivity matrix relating the dependent and control variables,

b is the column matrix of linearized dependent variables,

X is the column matrix of the linearized control variables,

$b^{\max}$ and $b^{\min}$ are the column matrices of the linearized upper and lower limits on the dependent variables,

$X^{\max}$ and $X^{\min}$ are the column matrices of linearized upper and lower limits on the control variables,

k is the number of control variables.

The control vector for incremental variables is defined as

$$X = \begin{bmatrix} \Delta T_1 & .. & \Delta T_T & \Delta V_1 & .. & \Delta V_G & \Delta Q_{G+1} & .. & \Delta Q_{G+S} \end{bmatrix}^T \tag{9}$$

$$b = \begin{bmatrix} \Delta Q_1 & .. & \Delta Q_G & \Delta V_{G+1} & .. & \Delta V_{G+S} & \Delta V_{G+S+1} & .. & \Delta V_N \end{bmatrix}^T \tag{10}$$

The upper and lower limits on both the control and dependent variables in linearized form are expressed as

$$X^{\max} = \begin{bmatrix} \Delta T_1^{\max} & .. & \Delta T_T^{\max} & \Delta V_1^{\max} & .. & \Delta V_G^{\max} & \Delta Q_{G+1}^{\max} & .. & \Delta Q_{G+S}^{\max} \end{bmatrix}^T \tag{11}$$

$$b^{\max} = \begin{bmatrix} \Delta Q_1^{\max} & .. & \Delta Q_G^{\max} & \Delta V_{G+1}^{\max} & .. & \Delta V_{G+S}^{\max} & \Delta V_{G+S+1}^{\max} & .. & \Delta V_N^{\max} \end{bmatrix} \tag{12}$$

$$X^{\min} = \begin{bmatrix} \Delta T_1^{\min} & .. & \Delta T_t^{\min} & \Delta V_1^{\min} & .. & \Delta V_G^{\min} & \Delta Q_{G+1}^{\min} & .. & \Delta Q_{G+S}^{\min} \end{bmatrix}^T \tag{13}$$

$$X^{\min} = \begin{bmatrix} \Delta T_1^{\min} & .. & \Delta T_t^{\min} & \Delta V_1^{\min} & .. & \Delta V_G^{\min} & \Delta Q_{G+1}^{\min} & .. & \Delta Q_{G+S}^{\min} \end{bmatrix}^T \tag{14}$$

where

$$\Delta T^{\max} = T^{\max} - T^{act}; \ \Delta T^{\min} = T^{\min} - T^{act}$$

$$\Delta Q^{\max} = Q^{\max} - Q^{act}; \ \Delta Q^{\min} = Q^{\min} - Q^{act}$$

$$\Delta V^{\max} = V^{\max} - V^{act}; \ \Delta V^{\min} = V^{\min} - V^{act}$$

4. Objective functions and constraints for the problem

The objective function given in equation (5) is given by

$$V_s = \sum_{j=G+1}^{N} L_j^2$$

Every optimization problem is modelled as follows

4.1. Load Flow Equality Constraints

Equality constraints at each node i, in the power system are active and reactive power functions, which are given by

$$P_i = P_{G_i} - P_{D_i} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos \delta_{ij} + B_{ij} \sin \delta_{ij}) \quad (15)$$

$$Q_i = Q_{G_i} - Q_{D_i} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (16)$$

where,

V_i, V_j = voltage magnitudes at buses i and j respectively

G_{ij}, B_{ij} = conductance and susceptance of the line i-j,

δ_{ij} = phase angle difference of voltage from bus i to j.

4.2. Inequality constraints

The inequality constraints exist for control variables as well as for dependent variables. The constraints for control variable and dependent variable are given as follows.

4.2.1 Control variable constraints

The maximum and minimum limits of the control variables are given by

$$\Delta V_{G_i}^{\min} \leq \Delta V_{G_i} \leq \Delta V_{G_i}^{\max} \quad (17)$$

$$\Delta T_i^{\min} \leq \Delta T_i \leq \Delta T_i^{\max} \quad (18)$$

$$\Delta Q_i^{\min} \leq \Delta Q_i \leq \Delta Q_i^{\max} \quad (19)$$

where,

V_{G_i} = Generator output voltage at bus i,

T_i = Transformer tap position at bus i,

Q_i = SVC setting position at bus i,

$V_{G_i}^{\min}$ = Minimum output voltage of Generator at bus i,

$V_{G_i}^{\max}$ = Maximum output voltage of Generator at bus i,

$T_i^{\min}$ = Minimum tap position of OLTC transformer at bus i,

$T_i^{\max}$ = Maximum tap position of OLTC transformer at bus i,

$Q_i^{\min}$ = Minimum value of SVC's at bus i and

$Q_i^{\max}$ = Maximum value of SVC's at bus i.

4.2.2 Dependent variable constraints

The dependent variable constraints are given by,

$$\Delta V_i^{\min} \leq \Delta V_i \leq \Delta V_i^{\max} \quad (20)$$

$$\Delta Q_{G_i}^{\min} \leq \Delta Q_{G_i} \leq \Delta Q_{G_i}^{\max} \quad (21)$$

where,

V_i = Voltage magnitude at load bus i,

Q_{G_i} = Reactive power at generator bus i,

$V_i^{\min}$ = Lower limit of load voltage i,

$V_i^{\max}$ = Upper limit of load voltage i,

$Q_{G_i}^{\min}$ = Lower limit of generator output of Reactive power i and

$Q_{G_i}^{\max}$ = Upper limit of generator output of Reactive power i.

4.3. System Parameters

The system parameters like V_{error} (V_e), $V_{stability}$ (ΣL^2) and Real Power loss (P_{Loss}) are given by the following equations:

$$V_e = \sum_{j=G+1}^{N} (V_j^d - V_j^a)^2 \quad (22)$$

$$Vs = \sum_{j=G+1}^{N} L_j^2 \quad (23)$$

$$P_{Loss} = \sum_{k=1}^{l} G_k \left[V_i^2 + V_j^2 - 2V_i V_j \cos(\delta_i - \delta_j) \right] \quad (24)$$

4.4. Reactive Power Output of the Generators

The reactive power 'Q' at generator bus 'i' is given by

$$Q_i = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin \delta_{ij} - B_{ij} \cos \delta_{ij}) \quad (25)$$

where,

V_i and V_j are the voltages at bus i and j,

G_k is conductance of kth transmission line,

l is total no. of transmission lines.

5. Calculation of Sensitivity matrix (S)

The total reactive power at all nodes in the entire power system can be changed, by changing tap settings of transformer and voltage magnitudes of all the buses in the system. The sensitivity matrix can be modelled as,

$$\begin{bmatrix} \Delta Q_g \\ \Delta Q_s \\ \Delta Q_r \end{bmatrix} = \begin{bmatrix} A_1 & A_2 & A_3 & A_4 \\ A_5 & A_6 & A_7 & A_8 \\ A_9 & A_{10} & A_{11} & A_{12} \end{bmatrix} \begin{bmatrix} \Delta T_m \\ \Delta V_g \\ \Delta V_s \\ \Delta V_r \end{bmatrix} \quad (26)$$

From equation (26), by transferring control and dependent variables to the right hand side and left hand side respectively, we obtain as

$$\begin{bmatrix} \Delta Q_g \\ \Delta V_s \\ \Delta V_r \end{bmatrix} = [S] \begin{bmatrix} \Delta T_m \\ \Delta V_g \\ \Delta Q_s \end{bmatrix} \quad (27)$$

where '**S**' is sensitivity matrix which correlates control and dependent variables.

6. Calculation of voltage stability objective function $\left(Vs = \sum_{j=G+1}^{N} L_j^2 \right)$ sensitivities with respect to control variables

From equations (2) and (5), voltage stability objective function V_s can be rewritten as,

$$V_s = \sum_{j=G+1}^{N} \left| 1 - \sum_{i=1}^{G} F_{ji} \frac{V_i}{V_j} \angle (\delta_i - \delta_j + \theta_{ji}) \right|^2 \quad (28)$$

Equation (28) can be modified as,

$$V_s = \sum_{j=G+1}^{N} \left(1 - \sum_{i=1}^{G} \frac{V_i}{V_j} c_{ji} \right)^2 + \left(\sum_{i=1}^{G} \frac{V_i}{V_j} d_{ji} \right)^2 \quad (29)$$

where

$c_{ji} = F_{ji}^r \cos(\delta_i - \delta_j) - F_{ji}^m \sin(\delta_i - \delta_j)$

$d_{ji} = F_{ji}^m \cos(\delta_i - \delta_j) + F_{ji}^r \sin(\delta_i - \delta_j)$

F_{ji}^r, F_{ji}^m are the real and imaginary parts of F_{ji}.

In order to calculate the sensitivities of the objective function with respect to control variables, the sensitivity of the objective function V_s, with respect to injected real and reactive powers at all buses of the power system need to be calculated foremost, excluding swing bus which is given by,

$$\begin{bmatrix} \dfrac{\partial V_S}{\partial \delta_2} \\ \vdots \\ \dfrac{\partial V_S}{\partial \delta_n} \end{bmatrix} = \begin{bmatrix} \dfrac{\partial P_2}{\partial \delta_2} & \cdots & \dfrac{\partial P_n}{\partial \delta_2} \\ \vdots & \vdots & \vdots \\ \dfrac{\partial P_2}{\partial \delta_n} & \cdots & \dfrac{\partial P_n}{\partial \delta_n} \end{bmatrix} \begin{bmatrix} \dfrac{\partial V_S}{\partial P_2} \\ \vdots \\ \dfrac{\partial V_S}{\partial P_n} \end{bmatrix} \quad (30)$$

$$\begin{bmatrix} \dfrac{\partial V_S}{\partial V_2} V_2 \\ \vdots \\ \dfrac{\partial V_S}{\partial V_n} V_n \end{bmatrix} = \begin{bmatrix} \dfrac{\partial Q_2}{\partial V_2} V_2 & \cdots & \dfrac{\partial Q_n}{\partial V_2} V_2 \\ \vdots & \vdots & \vdots \\ \dfrac{\partial Q_2}{\partial V_n} V_n & \cdots & \dfrac{\partial Q_n}{\partial V_n} V_n \end{bmatrix} \begin{bmatrix} \dfrac{\partial V_S}{\partial Q_2} \\ \vdots \\ \dfrac{\partial V_S}{\partial Q_n} \end{bmatrix} \quad (31)$$

By knowing the factors $\dfrac{\partial V_s}{\partial \delta}, \dfrac{\partial V_s}{\partial V}, \dfrac{\partial P}{\partial \delta}$ and $\dfrac{\partial Q}{\partial V}$ from equations (30) and (31), the sensitivities like $\dfrac{\partial V_s}{\partial Q_k}, \dfrac{\partial V_s}{\partial P_k}$, $k = 2$ to N can be calculated. From equations (30) and (31), the objective function sensitivities with respect to transformer tap settings and generator excitation voltages can be computed using the equations given by,

$$\frac{\partial V_S}{\partial T_{km}} = \frac{\partial V_S}{\partial P_k}\left(-\frac{\partial P_{km}}{\partial T_{km}}\right) + \frac{\partial V_S}{\partial Q_k}\left(-\frac{\partial Q_{km}}{\partial T_{km}}\right) + \frac{\partial V_S}{\partial P_m}\left(-\frac{\partial P_{mk}}{\partial T_{km}}\right) + \frac{\partial V_S}{\partial Q_m}\left(-\frac{\partial Q_{mk}}{\partial T_{km}}\right) \quad (32)$$

$$\frac{\partial V_S}{\partial V_k} = \frac{\partial V_S}{\partial Q_k} \frac{\partial Q_k}{\partial V_k} \quad (33)$$

Sensitivity of objective function with respect to the excitation of the swing bus generator can be computed as,

$$\frac{\partial V_S}{\partial V_1} = \sum_r \frac{\partial V_S}{\partial Q_r}\left(-\frac{\partial Q_r}{\partial V_1}\right) + \sum_{k=2}^{G} \frac{\partial V_S}{\partial Q_k} \frac{\partial Q_k}{\partial V_1} \quad (34)$$

where 'r' is the set of all the load buses connected to bus 1 and k = 2 to G. The values of $\dfrac{\partial V_S}{\partial P_k}, \dfrac{\partial V_S}{\partial Q_k}$ are obtained from equations (30, 31). The values of $\dfrac{\partial Q_r}{\partial V_1}$ are computed as,

$$\frac{\partial Q_r}{\partial V_1} = V_r \left(G_{r1} \sin \delta_r - B_{r1} \cos \delta_r \right) \quad (35)$$

and the values for $\dfrac{\partial Q_k}{\partial V_1}$, k = 2 to G are taken from equation (31). Objective function sensitivities with

respect to the switchable VAR compensators $\dfrac{\partial V_S}{\partial Q_{k+S}}$, k = 1, 2… S is obtained from the solution of equation (31).

7. Proposed Ant Colony Optimization (ACO) Algorithm

ACO algorithm is inspired by the behaviour of the real ant colonies used to solve combinatorial optimization problem. The following are the steps for ACO algorithm:

Initialize the no. of ants as 20, maximum iterations as 100, the parameters α = 0.1, β = 2 and evaporation constant ρ = 0.6.

Step 01. Generate the possible set of solutions containing the control variables which is given by $X_{ij} = (ub_i - lb_i) \times rand + lb_i$ (36)

ub_i = upper limits of ith control variables,

lb_i = lower limits of ith control variables.

Step 02. Each 'ant' selects the first node by generating random number based on uniform distribution, ranging from 1 to 100.

Step 03. Ant 'k' applies a probabilistic transition rule in order to decide which node to be visited next. The probabilistic transition rule is given as

$$P_{ij}^k(t) = \frac{\left[\tau_{ij}(t)\right]^\alpha \left[\eta_{ij}(t)\right]^\beta}{\sum_q \left[\tau_{iq}(t)\right]^\alpha \left[\eta_{iq}(t)\right]^\beta} \quad j \in N_i^k, q \in N_i^k \quad (37)$$

where τ_{ij} is Pheromone trail deposited between path i and j.

$\eta_{ij} = \dfrac{1}{d_{ij}}$, where d_{ij} is the distance of the path between i and j.

Step 04. Update the pheromone to the visited paths during the process. The amount of pheromones can be updated as

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \rho\Delta\tau_{ij} \quad (38)$$

where $\Delta\tau_{ij}$ is the incremental value of pheromone trail in the path. This local updating rule will shuffle the tours, so that the early nodes in the ant's tour may be explored later in other ant's tours.

Step 05. Check if ant visited all control variables or not. If not go to step 4 otherwise Step 7.

Step 06. Calculate the fitness value and select the best tour.

Step 07. Check for termination criteria if yes go to

Step 10; otherwise go to Step 03 after completing Step 09.

Step 08. Apply global updating rule. Only one ant is allowed to update the amount of pheromone which determines the best fitness. If all ants completed their tours, update the pheromones using equation

Step 09. $\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \varepsilon\tau_0$ (39)

where 'ε' is best path weighting constant [0 1], τ_0 is Pheromone trail in the best path.

Step 10. Print the results

8. Proposed Artificial Bee Colony (ABC) Algorithm

In ABC, each solution is called as food source of honey bees whose fitness is calculated in terms of quality of food source. In ABC, out of three groups of bees the number of employed and onlooker bees is equal. The following steps have been adopted for the ABC algorithm:

Step 01. Generate the possible set of solutions containing the control variables which is given by $X_{ij} = (ub_j - lb_j) \times rand + lb_j$ (40)

i = no of employed bees,
j = no of control variables,
ub = upper limits of control variables,
lb = lower limits of control variables.

Step 02. Evaluate the fitness values

Step 03. Update the solution using

$$V_{ij} = prob_i \times G_{ij} \quad (41)$$

$$G_{ij} = X_{ij} + (prob_i)(X_{gi} - X_{ij}) + \phi_{ij}(X_{r1ij} - X_{r2ij}) \quad (42)$$

$$prob_i = \frac{0.9 \times fitness_i}{\max fit} + 0.1 \quad (43)$$

X_{ij} = present position of ith bee,
X_{gj} = present best position,
X_{r1ij}, X_{r2ij} are two random positions,
$\emptyset_{ij}$ is a random number chosen from [-1 1],
fitness$_i$ is the fitness value for ith solution.
maxfit is the best fitness value from the possible set of solutions. After updating, apply greedy selection.

Step 04. Based on the probability value obtained from equation (43), the onlooker bees update the position using equation

$$V_{ij} = X_{ij} + \phi_{ij}(X_{ij} - X_{kj}) \quad (44)$$

and then apply greedy selection and obtain the best values.

Step 05. The abandoned food source is replaced by

randomly chosen food source and is given by equation (40).

Step 06. Check for termination criteria if no, go to Step 03, otherwise go to Step 07.

Step 07. Evaluate best solution and print the results.

9. Proposed BAT algorithm

In this section introduction to Bat algorithm and approach to Bat algorithm are explained.

9.1 Introduction

In this paper, a new metaheuristic method namely BAT algorithm based on the echolocation behaviour of bats is proposed. Bats fly randomly with velocity v_i, at position x_i with a fixed frequency, varying wavelength, λ and loudness A_0 to search for prey. They can adjust the rate of pulse emission $\begin{bmatrix} 0 & 1 \end{bmatrix}$. We assume that the loudness varies from a large positive A_0 to a minimum constant value A_{min}. In general, the frequency f in a range $\begin{bmatrix} f_{min} & f_{max} \end{bmatrix}$ corresponds to a range of wavelengths $\begin{bmatrix} \lambda_{min} & \lambda_{max} \end{bmatrix}$.

We can assume that $f \in \begin{bmatrix} 0 & f_{max} \end{bmatrix}$. The rate of pulse emission can be in the range of $\begin{bmatrix} 0 & 1 \end{bmatrix}$ where 0 means no pulses at all, and 1 means the maximum rate of pulse emission. We have to define how their positions x_i and velocities v_i are updated. The new solutions x_i^t and velocities v_i^t at time t are given by the frequency of the ith bat chosen using the equation,

$$f_i = f_{min} + \left(f_{max} - f_{min} \right) \beta_i \qquad (45)$$

where β (is a random number) $\in \begin{bmatrix} 0 & 1 \end{bmatrix}$.

The velocity of the ith bat is given by

$$v_i^t = v_i^{t-1} + (x_i^t - x_*) f_i \qquad (46)$$

x_*, the best position obtained till (t-1) iterations, x_i^t the position of the ith bat at last iteration v_i^{t-1}, Velocity of the ith bat in pervious iteration. The new position of the ith bat is calculated by using

$$x_{new} = x_{old} + \in A^t \qquad (47)$$

The best solution is updated in order to achieve exploration and is given by following equation

$$x_{new} = x_{old} + \in A^t \qquad (48)$$

A^t is average loudness of all the Bats at that iteration, $\in$ is random number between 0 to 1.
The loudness of the bat is updated as

$$A^{t+1} = \alpha A^t \qquad (49)$$

where $\alpha \in \begin{bmatrix} 0 & 1 \end{bmatrix}$.

The emission rate is updated by using

$$r_i^{t+1} = r_i^0 \left[1 - \exp(\gamma t) \right] \qquad (50)$$

r_i^0 is maximum emission rate, γ is positive real number which is chosen randomly.

9.2. Proposed approach using BAT algorithm

The following steps are involved in the BAT algorithm for the ORPD in the power system:

Step 01. Define objective function which is to be minimized.

Step 02. Initialize the bat population (x_i), velocity (v_i), pulse frequency (f), loudness (A) and emission rate (r) for each bat.

Step 03. Evaluate the initial fitness values and identify the best solution.

Step 04. Generate the new solution by adjusting frequency using equation (45) for each bat.

Step 05. Update the velocity and position for each bat using equations (46) and (47).

Step 06. Evaluate the fitness value using new positions of the bats and select the best solution.

Step 07. Is rand > emission rate (r)? If yes, select the solution among the best solutions and improve it using equation (48). If No, generate a new solution by flying randomly.

Step 08. Evaluate the fitness value and select the best solution.

Step 09. Is rand < loudness (A) and fitness is improved, If Yes accept the new solution and reduce the loudness (A) and increase emission rate (r) by using equations (49) and (50). If No, rank the bats and find the current best x^*.

Step 10. Check for termination criteria, if No go to Step 4 otherwise go to Step 11.

Step 11. Print result and stop.

10. Computational procedure for the enhancement of voltage stability by optimal reactive power dispatch with different AI techniques.

The following are the steps for different AI techniques applied to voltage stability enhancement.

Step 01. Read the system data for the proposed system.

Step 02. Run the load flow to calculate system parameters using equations (21), (23), and (24).

Step 03. Compute the upper and lower limits of the dependent and control variables using equations (17), (18) and (19).

Step 04. Compute the Sensitivity matrix (S) using equation (27).

Step 05. Calculate the objective function sensitivities (C) for the proposed objective function using equations (28) – (35).

Step 06. Solve the proposed linear optimization problem using upper bound LP technique and obtain the optimum changes in control settings.

Step 07. Execute the load flow with optimal settings of the control variables and evaluate the system parameters and generator reactive power output.

Step 08. Solve the proposed linear optimization problem by using ACO. Repeat Step 7 with the control settings obtained from ACO algorithm.

Step 09. Solve the proposed linear optimization problem by using ABC. Repeat Step 7 with the control settings obtained from ABC algorithm.

Step 10. Similarly solve the same optimization problem /objective function using BAT algorithm and obtain the optimal changes in the control settings.

Step 11. Repeat Step 7 with the optimum control settings obtained from BAT algorithm.

Step 12. Now compare the system parameters obtained from Step 7, Step 9 and Step 11.

Step 13. Print result.

11. Comparative analysis of LP, ACO, ABC and BAT algorithms

Analysis of typical set of results for a 24-node network is presented for the objective Vs for reactive power optimization. Table 1 gives the details of system size. Initially the control variable settings for transformer taps, excitation of all the generators and SVC's are 1.0, 1.0 and nil (0) respectively.

Table 1 System size

Power system components	24 bus system
No. of generators	4
No. of regulating transformers	7
No. of non-regulating transformers	4
No. of Transmission lines	27
P-Generation in MW	2850
P-Load in MW	2620
Q-Load in MVAR	980
No. of SVC buses	4

Four optimization techniques like LP, ACO, ABC and BAT algorithms are applied to solve ORPD problem. The initial control settings before running the load flow for all control variables, the optimal control settings obtained from the different optimizations algorithms for proposed objective are reported in Table 2. This system has fifteen control variables. They are seven transformers, four generators and four shunt VAR compensation devices at different buses. Using these control settings, system parameters and reactive power output of different generators are obtained by running fast decoupled load flow. All control variables are considered as continuous variables. However, in practice for discrete controllers the nearest rounded setting can be used.

Table 2 Comparison of controller settings for different algorithms of 24-node system

Control variables	Initial	LP	ACO	ABC	BAT
T_{16-5}	1.000	1.018	1.001	0.975	0.957
T_{22-13}	1.000	1.025	0.953	0.934	0.988
T_{18-10}	1.000	1.074	0.984	0.967	1.021
T_{19-6}	1.000	1.042	0.999	0.974	1.041
T_{23-9}	1.000	1.068	0.966	1.002	0.994
T_{20-7}	1.000	1.026	0.989	0.989	0.957
T_{14-8}	1.000	0.959	1.014	1.019	1.039
V_1	1.000	1.078	1.057	1.048	1.098
V_2	1.000	1.069	1.076	1.078	1.098
V_3	1.000	1.077	1.089	1.081	1.098
V_4	1.000	1.069	1.093	1.098	1.098
SVC_5	0.000	20.58	7.952	6.226	7.053
SVC_6	0.000	21.41	8.288	12.14	7.207
SVC_7	0.000	20.96	5.231	5.529	3.367
SVC_8	0.000	19.27	8.206	8.484	6.480

The results reported in Table 3 clearly indicate these voltages like V8, V13 and V14 are the most critical buses of the proposed power system. The voltage V8 of the power system improves from initial voltage of 0.7937 p.u to 0.9302 p.u in LP, to 1.0036 p.u in ACO, to 1.0188 p.u in ABC and to 1.0028 p.u in

proposed BAT technique for objective function Vs. The minimum voltage V13 of the system improves from initial voltage of 0.7905 p.u to 0.9218 p.u in LP, to 1.0009 p.u in ACO, to 1.0178 p.u in ABC and to 0.9988 p.u in BAT algorithm. The minimum voltage V14 of the system improves from initial voltage of 0.8285 p.u to 0.9279 p.u in LP, to 1.0420 p.u in ACO, to 1.0590 p.u in ABC and to 1.0677 p.u in BAT algorithm. The corresponding graph for the most critical load buses is shown in Fig. 1.

Table 3 Comparison of voltage magnitudes of all load buses of 24- node system

Bus No	Voltage magnitudes in p.u				
	Initial	*LP*	*ACO*	*ABC*	*BAT*
V_5	0.837	0.935	0.937	0.976	1.044
V_6	0.829	0.914	0.966	1.003	0.959
V_7	0.811	0.916	0.949	0.978	1.046
V_8	0.794	0.930	1.004	1.019	1.003
V_9	0.863	0.928	0.990	1.000	1.045
V_{10}	0.867	0.929	0.990	1.037	1.018
V_{11}	0.944	1.040	1.088	1.093	1.090
V_{12}	0.922	1.021	1.088	1.096	1.080
V_{13}	0.791	0.922	1.001	1.018	0.999
V_{14}	0.829	0.928	1.042	1.059	1.068
V_{15}	0.957	1.047	1.030	1.024	1.072
V_{16}	0.896	1.004	1.000	0.997	1.040
V_{17}	0.970	1.060	1.085	1.086	1.090
V_{18}	0.880	1.010	1.015	1.013	1.050
V_{19}	0.861	0.982	0.997	1.001	1.024
V_{20}	0.851	0.974	0.992	0.995	1.024
V_{21}	0.919	1.023	1.041	1.046	1.062
V_{22}	0.828	0.973	0.979	0.979	1.014
V_{23}	0.889	1.017	1.025	1.025	1.060
V_{24}	0.943	1.046	1.048	1.046	1.080

Fig. 1 shows voltage magnitudes for most critical load buses of 24-node system for the objective

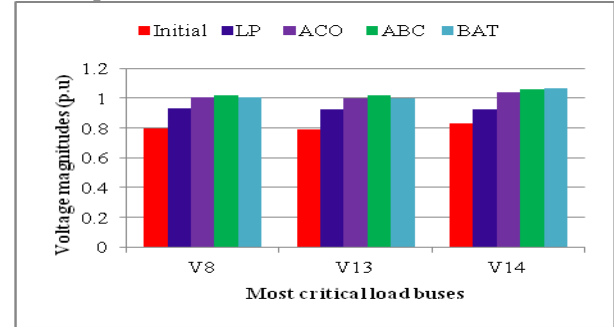function with LP, ACO, ABC and BAT optimization techniques.

Fig. 1. Voltage magnitude for most critical load buses for 24 - node system

Initial L-Index values at all selected buses and the corresponding L-Index values after optimization with LP, ACO, ABC and BAT techniques are indicated in Table 4 for the objective function considered. As reported in table 4, at most critical load bus V_8, L-index value decreases from initial value of 0.6329 to 0.4834 in LP, to 0.4298 in ACO, to 0.4246 in ABC and to 0.4069 in BAT algorithm. L-index value at V_{13} decreases from initial value of 0.6306 to 0.4825 in LP, to 0.4302 in ACO, to 0.4252 in ABC and to 0.4072 in BAT algorithm. L-index value at V_{14} decreases from initial value of 0.5376 to 0.4149 in LP, to 0.3715 in ACO, to 0.3674 in ABC and to 0.3488 in BAT algorithm. From these results it is obvious that there is a considerable improvement of L-Index values with the proposed ACO, ABC and BAT algorithms when compared with Conventional LP technique.

Table 4 Comparison of L-index values of all load buses for 24-node system

Bus No	L-Index values				
	Initial	*LP*	*ACO*	*ABC*	*BAT*
V_5	0.400	0.3523	0.315	0.306	0.275
V_6	0.466	0.3807	0.339	0.331	0.325
V_7	0.515	0.4161	0.373	0.365	0.340
V_8	0.633	0.4834	0.430	0.425	0.407
V_9	0.418	0.3484	0.307	0.306	0.257
V_{10}	0.395	0.3226	0.290	0.287	0.272
V_{11}	0.224	0.1812	0.169	0.169	0.159
V_{12}	0.301	0.2402	0.222	0.221	0.208
V_{13}	0.631	0.4825	0.430	0.425	0.407
V_{14}	0.538	0.4149	0.372	0.367	0.349
V_{15}	0.100	0.087	0.084	0.084	0.077
V_{16}	0.247	0.209	0.196	0.196	0.180
V_{17}	0.134	0.111	0.104	0.104	0.098
V_{18}	0.356	0.285	0.262	0.261	0.245
V_{19}	0.366	0.292	0.267	0.265	0.253

V_{20}	0.391	0.313	0.286	0.284	0.269
V_{21}	0.219	0.179	0.164	0.162	0.156
V_{22}	0.502	0.391	0.357	0.354	0.334
V_{23}	0.339	0.273	0.251	0.250	0.235
V_{24}	0.164	0.138	0.129	0.129	0.120

Fig. 2 shows the change in L-index values of most critical load buses for 24-node system for the objective function with four different optimization algorithms. These L-index values are corresponding to the most critical buses V_8, V_{13} and V_{14} of 24-node system. These graphs from Fig. 2 clearly indicate the effective improvement of stability by different algorithms and show the dominance of ACO, ABC and BAT algorithms. BAT algorithm shows satisfactory results over the other algorithms which are represented graphically in Fig. 2.
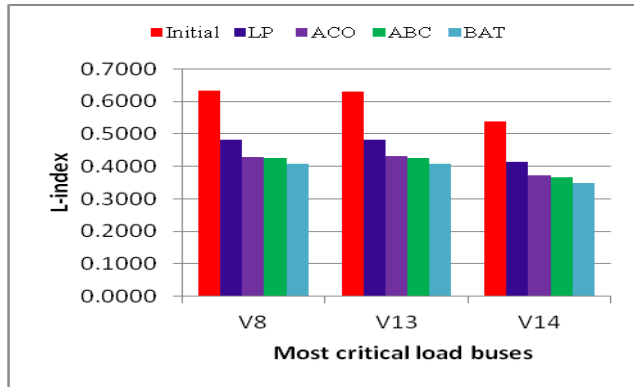

Fig. 2. L-index values of most critical load buses for 24 - node system

Table 5 indicates the change of system parameters with various optimization techniques for the 24-node power system. From the results reported in Table 5, it clearly indicates that the voltage deviation / error of the system decreases from initial value of 0.3744 to 0.0578 in LP, to 0.0388 in ACO, to 0.0379 in ABC and to 0.0598 p.u in BAT technique for the proposed objective function V_s. The $\sum L^2$ value of the system decreases from initial value of 3.1435 to 1.7939 in LP, to 1.6278 in ACO, to 1.2914 in ABC and to 1.4239 in BAT algorithm. Similarly, system power loss reduces from an initial value of 73.630 MW to 55.630 MW in LP, to 53.470 MW in ACO, to 53.30 MW in ABC and to 48.540 MW in BAT algorithm. These results clearly indicate the effectiveness and robustness of proposed ACO, ABC and BAT algorithms over the conventional LP technique. It is clear that the power loss reduction is much better with the proposed BAT algorithm as compared to the LP, ACO and ABC. The corresponding graph is

shown in Fig. 3.

Table 4 Comparison of system parameters of 24-node system for different algorithms

System Parameters	*Initial*	*LP*	*ACO*	*ABC*	*BAT*
Ve	0.374	0.058	0.039	0.038	0.06
$\sum L^2$	3.143	1.794	1.628	1.291	1.424
Ploss (MW)	73.63	55.63	53.47	53.3	48.54

Fig. 3 clearly shows variation of system parameters of 24-node system for various optimization techniques like LP, ACO, ABC and BAT algorithms.
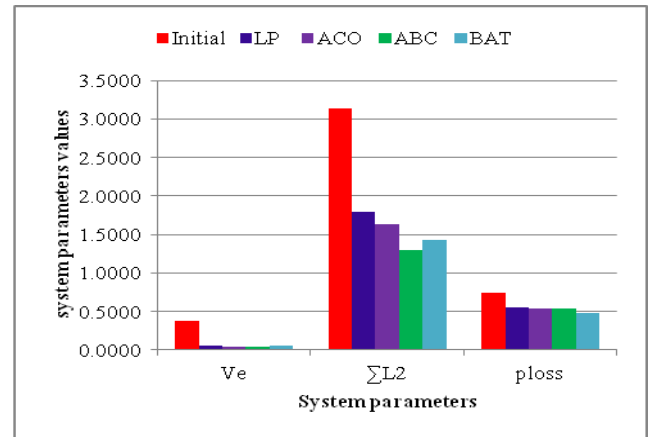

Fig. 3. System parameters for 24 - node system

Table 6 reports the comparison of reactive power outputs of generators for 24-node system for the objective function V_s with different Optimization techniques like LP, ACO, ABC and BAT Algorithm. From the results presented in Table 6, it is clear that the reactive power outputs of Generators, Q_1, Q_2, Q_3 and Q_4 for objective function V_s are improved much better with ACO, ABC and BAT algorithms than compared to LP. The corresponding graph is shown in Fig. 4.

Table 5 Comparison of reactive power outputs of Generators for 24-node system

Generator	Reactive power output (MVAR) values				
	Initial	objective function (Vs)			
		LP	*ACO*	*ABC*	*BAT*
Q_1	654.5	520.1	402.8	383.8	419.1
Q_2	73.00	35.11	-14.2	-23.9	-36.43
Q_3	279.8	171.3	175.7	185.9	91.73
Q_4	409.2	270.2	264.4	282.2	197.2

Fig. 4 shows change of reactive power output of

various Generators of 24 - node system with different optimization algorithms like LP, ACO, ABC and BAT. Satisfactory results are obtained for ACO, ABC and BAT algorithms. ACO, ABC and BAT algorithm offers considerable improvement in solving reactive power optimization problem. The reactive power output of generator Q_1 decreases from initial value of 654.55 MVAR to 520.16 MVAR in LP, to 402.82 MVAR in ACO, to 282.23 MVAR in ABC and to 419.06 MVAR in BAT algorithm for objective function V_s.
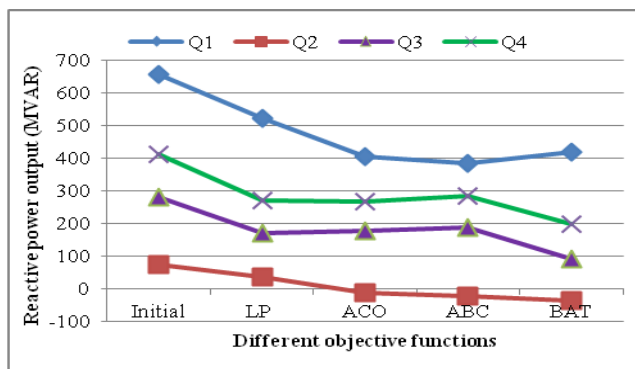

Fig. 4. Reactive power output of Generators for 24 - node system

12. Conclusions

In this paper, an approach for reactive power optimization is proposed with different algorithms like LP, ACO, ABC and BAT for the objective function V_s. The proposed algorithms are demonstrated to give encouraging results for the given loading conditions. Comparative analysis for the proposed objective function with different optimization techniques for 24-node power systems is presented for illustration purpose. Analysis of test system show that ACO, ABC and BAT algorithms are better compared to LP technique. The results obtained with all these algorithms are compared and the strength of the ACO, ABC and BAT algorithms over the other LP algorithm has been illustrated. The results obviously prove the effectiveness and robustness of the proposed ACO, ABC and BAT algorithms to solve the ORPD problem.

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