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Research Article

State Estimation and Volt-Var Control in Smart Distribution Grid

H. T. Hassan[Ȧ*], M. Rizwan[Ḃ], and M. S. Fakhar[Ȧ*]

[Ȧ]Department of Electrical Engineering, University of Lahore, State Lahore, Country Pakistan
[Ḃ]National Transmission and Dispatch Company, State Lahore, Country Pakistan

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Abstract

Distribution smart grid is very important part of the smart grid. Utilities use Distribution Management System (DMS) as supervisory control layer at the power system control centers. State Estimation (SE) and Volt-Var Control (VVC) are the prime applications of the DMS. In the modern DMS, SE is required for extensive monitoring and control of the entire distribution network. In the presence of Distributed Generators (DGs) such as solar, wind, micro turbines, fuel cells etc. to maintain voltage level in the prescribed limits and control of bidirectional flow of reactive power with minimized distribution power losses is a great challenge. Previously proposed methods to optimize SE and VVC presume that objective function equations are continuous and differentiable. However, the practical equipment installed in the distribution network i.e. on load tap changer transformers, DGs, voltage regulators etc. have nonlinear characteristics which result in nonlinear objective functions of SE and VVC. Moreover, the objective functions are discontinuous due to discontinuous tap changing of transformers. Therefore, the conventional methods cannot be applied to nonlinear optimization problems. To solve the nonlinear optimization problems, recently proposed heuristic algorithms are very effective. In this paper, Artificial Bee Colony (ABC) algorithm has been implemented to optimize SE and VVC applications.

Keywords: *DMS (Distributed Management System), SE (State Estimation), VVC (Volt-VAR control), ABC (Artificial Bee Colony)*

1. Introduction

Smart grid is the next generation power system. It's a modern electric power grid infrastructure for the improved conservation & energy efficiency, the revenue, reliability and security of the power system through automated control and modern communication technologies. The smart grid will also reduce the power outages & black outs, maintenance costs, peak hours demand, depletion of primary energy and carbon emission. However, there are great challenges for implementation of the smart grid concept. For example, integration of distributed energy resources has caused bidirectional flow of electric power in the system while the existing power systems were designed for unidirectional power flow. The existing power system is lack of communication capabilities while the smart grid infrastructure is full of enhanced sensing and advance ICT. Different applications of the modern smart grid are shown in figure 1.

Previously, the distribution networks used to be passive only i.e. they had only the load connected and no generation. But currently, the distribution networks are being transformed from passive into active networks due to integration of the distributed generators i.e. wind, photovoltaic, micro turbine etc. This means the distributor operators have to tackle the generation in the distribution networks as well. The connection of DGs in the distribution network imposes severe technical issues. If these issues are not properly handled, the integration of

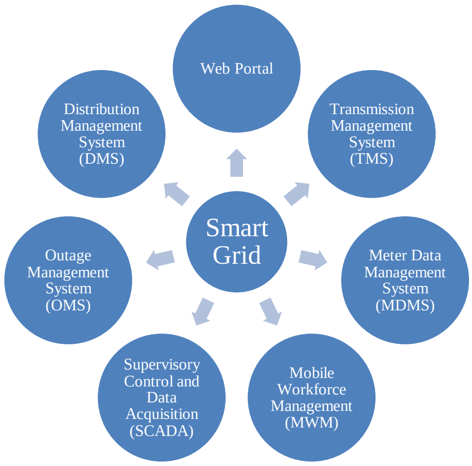

Figure 1: Smart Grid Applications

*Corresponding author **M. S. Fakhar** is working as Lecturer; **H. T. Hassan** as Associate Professor and **M. Rizwan** is working as Assistant Engineering

DGs costs a lot. The apposite management of the active distribution networks assists the distribution system operator to economically dispatch distributed generation, control of voltage regulators & load changing transformers and the management of the reactive power. A tremendous survey of the modern DMS has been conducted in (Ruh, Andersson, & Borer, 2007). According to survey, the main functions of DMS are:

- Base System Functions
- Applications

Base system functions correspond to the control of the distribution network such as intermingling with the system. The base system functions have further two subgroups namely Control Room Operation Management (CROM) & Supervisory Control and Data Acquisition (SCADA). CROM includes all the amenities offered to the distribution operator for example graphics system provided in the control room. On the other hand, applications assist the distribution system operator and the control system as well. Different functions of the modern DMS have been summarized in figure 2.

In the modern DMS, SE is required for extensive monitoring and control of the entire distribution network. This would, in return, provide effective operation of the system by determining operating point of the system and also provides high quality of services to the consumers. In distribution network, we have only limited number of measurements available i.e. measurements at the distribution grid and a few measurements of line currents or power injection at the feeder. These limited numbers of measurements do not serve the purpose of monitoring the whole distribution network as we require information from all nodes of the system. So what we do is, we estimate the system state on the basis of these limited numbers of measurements and the historical data available with the distribution companies (Baran & Kelley, 1994).

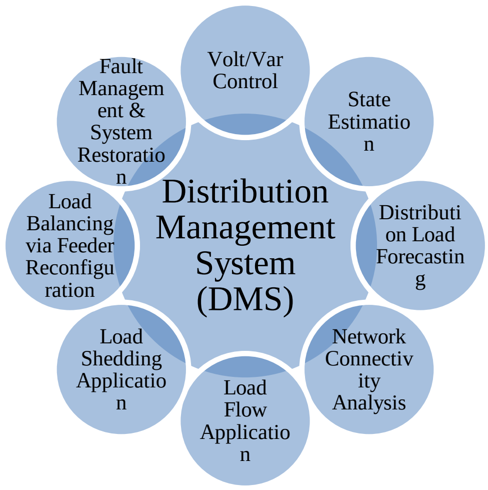

Figure 2: Functions of DMS

In estimating the system state, some parameters like impedance is given. Moreover, we consider the following assumptions to have the unique solution (Niknam, Ranjbar, Shirani, & Ostadi, 2005):

1) The status of the circuit breakers and the line isolators is known.
2) The load connected at each node and the values of distributed generations are known.
3) The values of voltage and the current are known at the distribution substation.
4) If the loads and the output of distributed generators are fixed, then the values of power factor and output are known.
5) If the loads and the output of distributed generators are variable, then the values of power factor, standard deviation and the average output are known.

Weighted least square (WLS) method is the basic tactic to solve the SE problem. WLS represents the statistical relations between the state variables and the measurements. Mathematically this relation can be expressed as follows:

$$\min f(x) = \sum_{i=1}^{n} w_i (z_i - h_i(X))^2 \qquad (1)$$

where

w_i = weight associated with each measurement variable i.

z_i = vector representing the measurement values.

h_i = state equations of measurements.

X = state variables inclusive of variable loads & DGs.

n = No. of measurements.

h (X) can be one of the following forms:

a. Branch current
b. Power injection
c. Load
d. Node voltage magnitude

In case, we have branch current as measurement then this current can be represented in the form of node voltages as

$$I_{lr,ij(abc)} + jI_{lx,ij(abc)} = \sum_{m=1}^{3} y_{ij(abc,m)}(V_{i,m} - V_{j,m}) \qquad (2)$$

where

$I_{lr,ij(abc)}$ = real part of the three phase currents between buses i & j and depends on the values of *Vi,m* and *Vj,m* which are the state variables in our case.

$I_{lx,ij(abc)}$ = imaginary part of the three phase currents between buses i & j and depends on the values of *Vi,m* and *Vj,m* which are the state variables in our case.

The relation between real & imaginary components of the currents and the state variable can be expressed as

$$h(x) = I_{l,abc} = \sqrt{I^2_{lr,ij(abc)}(x) + I^2_{lx,ij(abc)}(x)} \qquad (3)$$

Similarly if we have power flow as the measurement, then

$$h(x) = S^*_{ij,abc} = V^*_{i,abc} \sum_{m=1}^{3} y_{ij(abc,m)}(V_{i,m} - V_{j,m}) \qquad (4)$$

If the measurement is load, state equation would be

$$h(x) = S_{i,abc}^{*} = V_{i,abc}^{*} \sum_{j \in J} \sum_{m=1}^{3} y_{ij(abc,m)} (V_{i,m} - V_{j,m}) \quad (5)$$

In the last scenario state equation, in case of voltage as measurement at node i, would be

$$h(x) = V_{i,abc} \quad (6)$$

From equations (3), (4), (5) and (6) it is clear that all the measurements are nonlinear functions of the state variables except the voltage measurement.

Previously proposed methods for the distribution state estimation can be divided into two categories (Naka, Genji, Yura, & Fukuyama, 2003):

1. Statistical methods
2. Load adjustment methods

Statistical methods include the iterative convergence methods while load adjustment methods use sensitivity analysis. Methods belonging to both categories presume that the objective function equations are continuous and differentiable. However the practical equipment installed in the distribution network i.e. on load tap changer transformers, DGs, voltage regulators (VR) etc. have nonlinear characteristics which result in nonlinear objective function of distribution SE. Moreover, due to tap changing, the objective function becomes discontinuous as well. Therefore, the above mentioned conventional methods cannot be applied to the nonlinear distribution state estimation optimization problem. To solve the nonlinear optimization problems, recently proposed heuristic algorithms are very effective.

Among different applications of modern DMS, VVC is the most important one (Roytelman, Wee, & Lugtu, 1995). The utilities have some constraints regarding the voltage rise & drop along the feeders. For example the ANSI standard C84.1 defines the voltage limits as ±5% (Baran & Hsu, 1999). The voltage drop can be compensated in two different ways: Load Changing Transformers (LTCs) at the distribution substation and the VR installed in the distribution network. In the decentralized environment, we have three sources of reactive power i.e. centralized power plants, capacitor banks and the DGs. In VVC, we have to manipulate how much reactive power from each of the aforementioned three sources should be drawn so that the system requirements of reactive power are satisfied and losses of the system are also minimized.

Previously different techniques have been utilized by the researchers to solve the VVC problem. Roytelman et al. proposed an oriented discrete coordinate descent method for the distribution management system (Roytelman et al., 1995). Baran and Hsu introduced supervisory type control scheme to enhance the performance of VR and capacitor controllers (Baran & Hsu, 1999). Coordination between local controllers and centralized VVC has also been suggested by Roytelman and Ganesan (Roytelman & Ganesan, 2000). On the basis of dynamically changing system conditions, Borozan et al. have recommended supervisory controllers to coordinate the settings of regulating devices (Borozan, Baran, & Novosel, 2001). In all of the aforementioned techniques integration of the DGs has not been considered and also the nonlinear characteristics of the practical equipment in the distribution network have not been encountered. Niknam et al. analyzed the impact of DGs on VVC in the distribution network using genetic algorithm (Niknam, Ranjbar, & Shirani, 2003). Ant colony optimization (ACO) has been implemented by Nikmam et al. to control the voltage level and flow of reactive power in the DMS (Niknam et al., 2005).

Aucharyamet and Sirisumrannukul have suggested particle swarm optimization (PSO) to define optimal coordination among DGs, tap position of substation transformer and the capacitors (Auchariyamet & Sirisumrannukul, 2010).

Due to the nonlinear characteristics of the distribution network equipment, it's very difficult for the conventional optimization techniques to find an optimal solution. In this research work, ABC algorithm has been implemented to optimize the mixed integer non-linear optimization problem (MINLP) of VVC. ABC algorithm is a new heuristic optimization technique presented by Dervis Karaboga in 2005 (Karaboga, 2005). ABC algorithm was originally offered for unconstrained optimization problems. Then its later version was proposed for the constrained optimization problems. The results show that the performance of the ABC algorithm has outperformed the other optimization techniques. The algorithm can handle both the discrete (VR, transformer, capacitors) and continuous (DGs) state variables. Due to discrete/continuous variables and the nonlinear characteristics of distribution equipment, the VVC optimization problem has been transformed into MINLP.

The objective function of VVC is to minimize the total system real power losses subject to the system constraints. Mathematically, the objective function can be expressed as follows:

$$\min f(x) = \sum_{i=1}^{m} Ploss_i \quad (7)$$

where,

'm' is the number of branches.

Subject to the following system inequality constraints

Vi,min ≤ Vi ≤ Vi,max i=1,2,………N
Qci,min ≤ Qci ≤ Qci,max i=1.2,……....Nc
Qgi,min ≤ Qgi ≤ Qgi,max i=1,2,………Ng
Ti,t(min) ≤ Ti,t ≤ Ti,t(max) i=1,2,………Nt
Ti,vr(min) ≤ Ti,vr ≤ Ti,vr(max) i=1,2,………Nvr

where

Vi = bus voltage
Vi,min = minimum bus voltage
Vi,max = maximum bus voltage
Qc = reactive power from each capacitor bank
Qc,min = minimum reactive power from capacitor
Qc,max = maximum reactive power from capacitor
Qgi = reactive power from distributed generator
Qgi,min = minimum reactive power from distributed generator
Qgi,max = maximum reactive power from distributed generator
Ti,t = Tap position of transformer

Ti,t(min) = minimum tap position of transformer
Ti,t(max) = maximum tap position of transformer
Ti,vr = Tap position of voltage regulator (VR)
Ti,vr(min) = minimum tap position of VR
Ti,vr(max) = maximum tap position of VR
N = Number of buses
Nc = Number of capacitors
Ng = Number of distributed generators
Nt = Number of transformers
Nvr = Number of voltage regulators

2. Artificial Bee Colony Algorithm

A new heuristic research technique, Artificial Bee Colony (ABC) algorithm, has been presented by Dervis Karaboga in 2005 (Karaboga, 2005). ABC algorithm was originally offered for unconstrained optimization problems. Then its later version was proposed for the constrained optimization problems.

Three types of bees accomplish the colony of artificial bees i.e. employed bees, onlooker bees and scout bees. The employed bees correspond to one half of the size of colony of artificial bees and the onlooker bees correspond to the remaining second half. One employed bee is dispensed to only one food source (solution). It can also be narrated as the number of employed bees and the food sources (solutions) neighboring the hive are equal. Employed bees explore for food sources (solutions) haphazardly. After collecting the nectar, employed bees return to the hive and share information about the nectar with onlooker bees. As a result, the first onlooker bee selects best food source (solution) as per probability of the food source (solution), then second onlooker bee and so on. When an employed bee has visited *limit* times a food source (solution) and it's not working then this food source (solution) is abandoned and the employed bee is now called the scout bee. The scout bee explores entirely new food sources (Abu-Mouti & El-Hawary, 2011).

The onlooker bees calculate the probability p_i of selecting a foods source by the following equation:

$$p_i = \frac{fitness_i}{\sum_{i=1}^{Eb} fitness_i} \tag{8}$$

where Eb is the total number of solutions and $fitness_i$ is the fitness value of solution i. With the help of equation (8) the onlooker bees select good food sources (solutions) than bad ones.

Now one parameter of the first solution is randomly selected as per below equation:

Parameter2change = x * D (9)

Where, x is a randomly generated number and D is the number of parameters to be optimized.

Now a neighboring solution is selected as follows:

Neighbor = x * Food Number (10)

where x is a randomly generated number and Food Number is half of the colony size i.e. equal to number of employed bees.

The randomly selected Parameter2change is replaced by the New parameter using the same parameter of the randomly selected Neighbor as

$$x_{new} = x_{old} + w(x_{old} - x_{neighbor}) \tag{11}$$

w is a random number having value between [-1,1].

After the parameter has been changed, the objective function value of the new proposed solution is calculated and if it's improved than the previous one then we replace the previous solution with the new proposed solution. This procedure is repeated for all the solutions initialized and the best solution is memorized.

The *limit* parameter of the ABC algorithm defines the number of times each solution to be modified for the better result. If after *limit* number of trials, a solution does not improve then this solution is discarded and the associated employed bee is converted into scout bee. The new solution for the scout bee is initialized as per below equation:

solution = lb + u*(ub – lb) (12)

where ub is upper bound of the parameters and lb is the lower bound while u is a randomly generated number. The complete flowchart of the ABC algorithm is shown in figure 3.

3. Results and Discussion

In order to check the efficacy of the proposed ABC algorithm, IEEE 34-bus radial distribution test feeder has been selected as the bench mark system with slight modification (Kersting, 2001). Single line diagram (SLD) of the selected system is shown in figure 4. There are single phase, line to line and three phase connections. This test system has distributed load and spot load. The distributed load between any two buses has been converted into spot load by dividing the load equally on the both buses. There is one substation transformer and one distribution transformer between buses 20 & 21. We have two voltage regulators between buses 7-8 and 19-20. Three distributed generators of different types namely DG1, DG2 and DG3 have been integrated to see the effect of DGs on the distribution network. DG1 is micro turbine-CHP, DG2 is large wind turbine and DG3 is combustion turbine-CHP. Two variable capacitor banks C1 & C2 of 450Kvars each have been incorporated having discrete steps of 15Kvar to provide reactive power to the load. There are two variable loads L1 and L2 at buses 26 and 28 respectively.

The proposed ABC algorithm has been implemented in MATLAB 7.8.0 (R2009a) and run on Intel Core™ i3-2350M CPU @ 2.30GHz processor & 4GB RAM.

Table 1 shows the results for SE. It can be observed that the estimated values of the G2, G3, L1 and L2 are very close to the actual values. The results obtained using the proposed ABC algorithm have outperformed the Ant Colony Optimization (ACO), Neural Networks (NN) and Genetic Algorithm (GA) (Niknam et al., 2005). Now using these values of G2, G3, L1 and L2, we can estimate the remaining all nodes of the distribution network. As these SE values are very close to the actual values, so using the proposed ABC algorithm in SE application, we can monitor the whole distribution network at each and every node more precisely even if the numbers of available measurements are very limited.

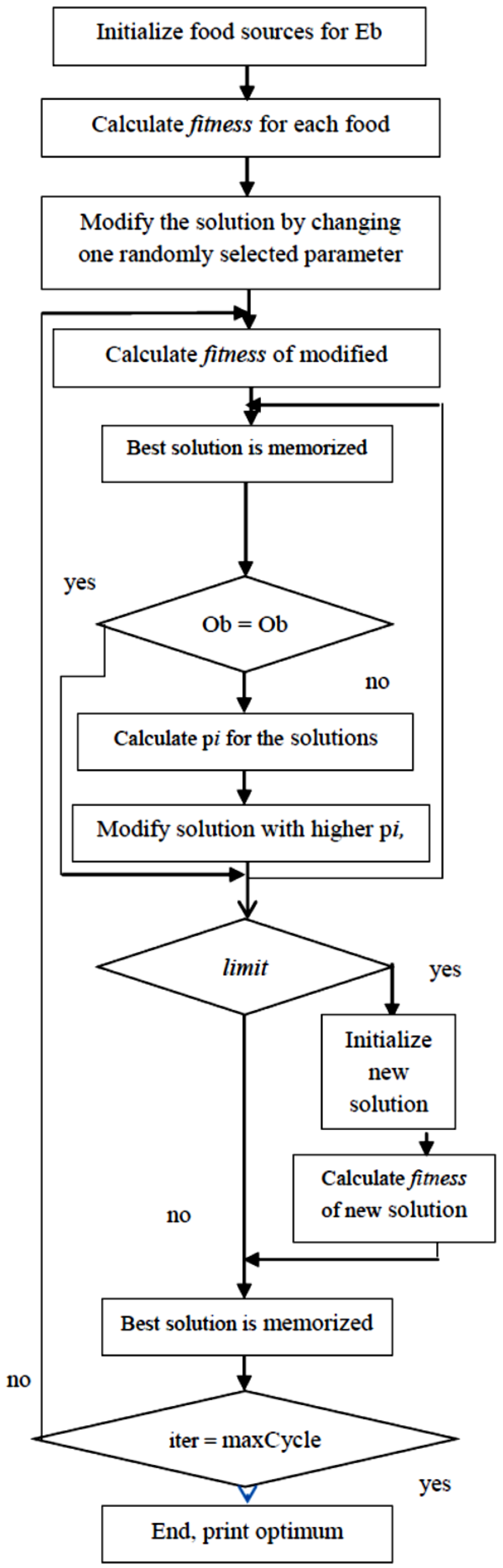

Figure 3: Flowchart of the Artificial Bee Colony

From figure 5, 6 and 7 voltage profile, flow of reactive current in the feeder and active power losses can be evaluated in both the cases when VVC application is "ON" and "OFF". The voltage falls below 0.95pu at buses 16-18 and 28-34 when VVC is "OFF" which is not permissible. After implementation of VVC, this violation of system voltage constraints is eliminated and voltages at most of the buses are close to 1.0pu. Also the VVC application assists to reduce the flow of reactive current in the feeder to a great extent as most of the reactive power is now being supplied locally by the DGs and the capacitors. This reduction of reactive current flow saves the massive capital investment required for expansion of transmission and distribution network in the case when even VVC is not properly utilized or it is "OFF". Moreover, active power losses have also been reduced substantially which results in increase of revenue for the utility.

Table 1 shows comparison of the results obtained using the proposed ABC algorithm with those obtained using ACO and GA (Niknam et al., 2005). It can be observed that the active power losses have been reduced significantly. Moreover, the execution time is also considerably low which makes it possible to implement the proposed algorithm in the real networks.

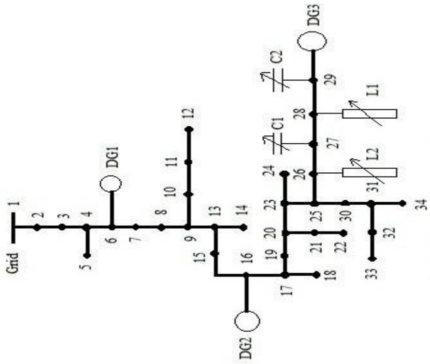

Figure 4: IEEE 34-Bus Radial Distribution Test Feeder

Table 1 State Estimation for CS=200 and MCN=50

CS = 200				MCN = 50			
Parameters	Min	Max	Average	Actual Value	ACO	NN	GA
G2	306.74	313.64	311.28	310	308.42	305.13	315.56
G3	515.13	522.82	519.13	520	523.95	522.39	517.63
L1	87.72	92.1	89.61	90	89	89.2	90.5
L2	72.74	76.03	74.27	75	75.21	74	76.4

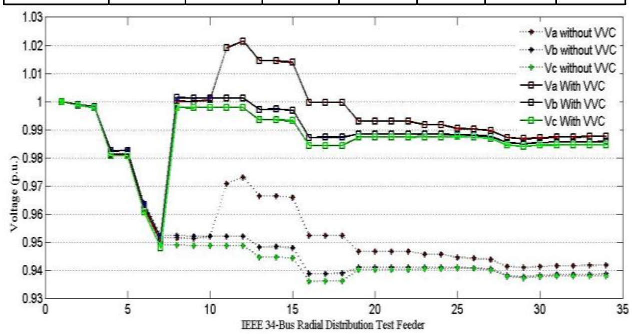

Figure 5: Voltage Profile augmentation due to VVC application

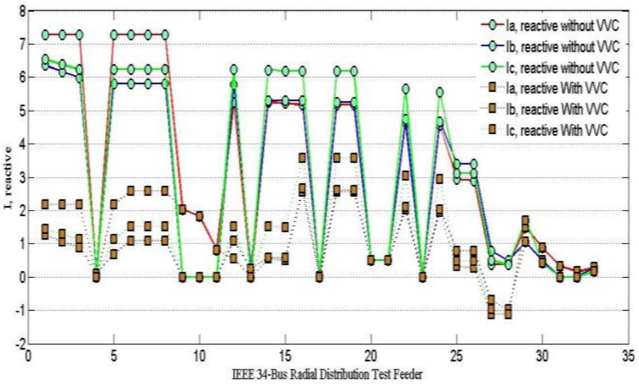

Figure 6: Decrease in reactive current flow due to VVC application

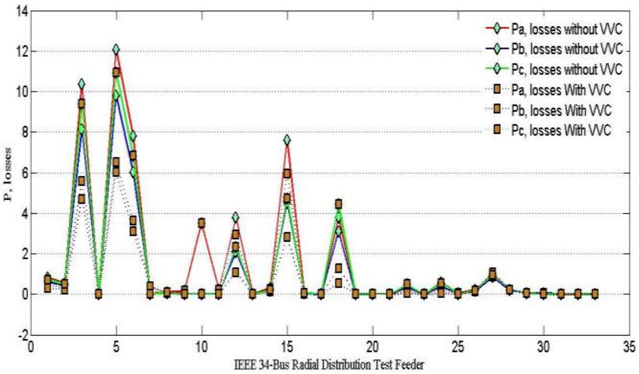

Figure 7: Active power losses reduction after implementation of VVC application

Table 2 Comparison of VVC Results with Previous Results

Parameters	ABC	ACO	GA
Losses (kW)	27.1978	45.23	50.23
Tap of VR1	5	3	2
Tap of VR2	0	2	4
Tap of Substation Transformer	0	0	1
Reactive Power of C1 (Kvar)	120	450	0
Reactive Power of C2 (Kvar)	75	0	0
Reactive Power of DG1 (Kvar)	40.56	11.4	29.65
Reactive Power of DG2 (Kvar)	96.21	174.5	253.23
Reactive Power of DG3 (Kvar)	323.28	40.2	437.22
Execution Time (sec)	45	200	700

4. Conclusion

In this paper, a new heuristic optimization technique ABC algorithm has been implemented to optimize SE and VVC applications of the modern DMS. Simulations have been conducted on IEEE 34-bus radial distribution test feeder with slight changes to integrate the DGs. The results obtained by using the proposed ABC algorithm have been compared with those obtained using ACO, NN and GA. The comparison shows that the performance of the ABC algorithm has outperformed the other well-known heuristic techniques. Moreover, other well-known heuristic techniques such as PSO, ACO, GA etc. have a number of parameters to be tuned to get optimized solution while the proposed ABC algorithm has only two parameters i.e. colony size and the maximum iteration number. Therefore, more efficient solution can be obtained in considerably lesser execution time which shows potential of ABC algorithm to solve complex problems.

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