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Investigation of Power Saving and Optimal Placement of Energy Storage Units in Active Distribution Network with reference to Conservation Voltage Reduction and Contingent Load Configuration

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Abstract: The uncertain and intermittent nature of renewable Distributed Generation (DG) components have significant effects on the operation of power system networks causing power quality issues which also reduce the system's stability. The deployment of Battery Energy Storage Systems (BESS) being the best solution to sustain system stability and power loss minimization. However, the optimal locations and sizes affect the losses of the distribution system and the stochastic loads greatly affect the dynamic stability of the system. The main objective is to determine the bus stops with minimal loss and adequate potential. With the help of optimization techniques like the Genetic Algorithm (GA) and Ant Colony Optimization Algorithms (ACOA), this study aims to find the most efficient placement and size for a BESS, taking into account the power loss reduction afforded by the conservation voltage reduction (CVR) and contingent load (CL) design. The purpose of this work is to find the minimum power loss for the system that still satisfies the equality and inequality requirements. The CVR reduces power consumption relative to load voltage sensitivity via voltage minimization, which in turn improves power balance at the dynamic power scale and, ultimately, grid stability. In order to achieve the best possible decrease in power dissipations and to increase the dynamic stability under unpredictable loads, this research analyzes the optimum capacity and allocation of the DGs in a 33-bus test system. The suggested method is tested against other output and compared to a simulation generated using m-file Matlab code.

Keywords: *Battery Energy Storage Systems (BESS), Distributed Generation (DG), Genetic Algorithm (GA), conservation voltage reduction (CVR), Ant Colony Optimization Algorithms (ACOA) and Contingent load (CL).*

1. Introduction

In recent years, the development of renewable energy sources has been spurred by rising worldwide concern about environmental concerns, particularly the burning of fossil fuels. Keeping the voltage of power system networks stable has become much more difficult as a result of the widespread adoption of renewable energy sources, which has resulted in a dramatic rise in both power consumption and greenhouse gas emissions. This has forced many utilities to investigate new approach like smart metering, energy efficient designs, demand-based management, demand based response and CVR for energy and demand saving. Among them, CVR is the most effectual path to maintain feeder voltage in the bottom range of the permissible limit [1]. By decreasing voltage on the distribution network, CVR method minimizes maximum demand, losses thereby realizing the efficient energy savings [2, 3].The basic principle of CVR operation is minimizing end-use voltage within standard potential limits to lessen peak demand alongside making ample energy savings at minimal cost without disturbing consumer appliances. CVR is an efficient method of diminishing the power consumption which is the consequent effect of decrease in of feeder voltage and possibly overall energy consumption [4]. CVR and Volt-VAR Optimization (VVO) are two methodology used to reduce power in a controlled way by minimizing the voltages on the DS. The first method called open loop controlled No voltage feedback technique reduces the voltage by making use of capacitors, load tap changers and line compensators. The second method termed closed loop control voltage feedback VVO control advanced control methodology to reduce the potential is to use SCADA and the AMI [5-6]. It is important to employ different load models and examine the combinations in simulation in order to attain a better assessment. Using mathematical representations, the authors of [7-9] demonstrate how active power, reactive power, and load feed voltage are all interconnected to characterize load behavior on distribution networks. In 1973, Electric Power Network in the United States conducted a CVR-based

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test[10]. Subsequently, other utilities, including Northeast Utilities (NU), South California Edison (SCE), etc., conducted CVR tests and obtained significant data showing power savings associated with the voltage drop [11–17]. The CVR goal is attained in [18] by formulating a linear least-squares problem and optimizing using a linearly estimated link between voltage changes and the operations of voltage regulating devices.

The interactions between CVR and general DG resources, namely, residential solar photovoltaic (PV), have been investigated in [19-21]. It is established that DG based sources can level voltage curves alongside the feeders for intense voltage reduction. The application of the CVR technique can compensate a deterioration of the voltage profiles along the network having capacitor banks to make up the voltage drop along very long lines. When utilities survive voltage management by combining CVR with reactive power management concurrently, which could be referred to as VVO. As the reactive power flow affects the voltages, management control and performance of operating a power system, VVO concentrates on circuit-level operations and minimizes energy losses by reducing reactive power flow along the distribution circuit. Based on the preset control rules, the controller will operate when open loop control is applied to CVR, as there no link is amongst substations and control devices, the system is intact to dynamic load variations [22].

VVC, SCADA, AMI based VVC with CVR aids in numerous control purposes viz., minimization of loss and enhancing the power factor. Presently, many utilities prepared the closed loop based VVC for the DS and functioned in CVR model to overcome the issues faced by power utilities [23-25]. Methods for gauging CVR effects may be classified as either comparative, regression, synthesis, or simulation-based. To calculate the CVR factor, a comparison-based technique is presented in [26]. The lack of a suitable control group is a weakness of this technique. The loads in the regression method are created as a linear function of the impact variables [27, 28]. But authors try to explain the load series are proven to be obviously non-linear function of exogenic variable. During the previous decade, the non-model grounded optimization approaches are widely employed owing to their exceptional global search features.

The non-linear performances of loads may be approximated, thanks to recent developments in non-linear type regression methods like artificial neural network (ANN) and support vector regression (SVR) [29–31]. In order to predict the nature of utility and associated savings, we use an artificial neural network (ANN) model that takes into account the day, time, and temperature to analyze the performance of CVR and its impact on power decreasing. As a result, the CVR load management modeling is enhanced. Better solutions for OPF issues in future DN are provided by the authors of [32], who used PSO to improve the voltage profile of DG.

In order to reduce power loss, enhance the voltage profile, and provide dynamic stability during CL configurations, this study proposes using a CVR approach in conjunction with an ACO and GA optimization methodology for advanced distribution management system platforms. The IEEE 33-bus test feeder confirmed the accuracy of the planned method. To demonstrate the value of the proposed method, we conduct a comprehensive analysis of IEEE-based 33-bus RDN. The findings are provided to prove the efficacy of the CVR and the optimization technique, for which a number of CL compositions were derived into consideration in order to actualize the CVR impact. Simulation findings comparing the two approaches with the CVR method under stochastic loads in terms of power loss, voltage profile, and dynamic stability are shown. The results show that both algorithms are very effective and can even compete with one another. The goal of this study is to compare the strengths and weaknesses of GA and ACO algorithms for properly designing and assigning DG units, with the goal of enhancing the dynamic stability of power system networks.

2. Problem Statement and Objective Function of BESS Placement

(A) System Description

The suitable method for network losses calculation has to be employed with respect to distribution network's planned load's characteristics as to define the active power losses of the distribution network during distribution network DG planning,. The distribution network's power losses will vary with the addition of BESS, and the impact of that modification is prejudiced by the allocation and size of the BESS to the grid. In this section, the optimal placement of energy storage units is mathematically modelled, the optimization algorithm is utilized for ideal sizing and location of BESS. In addition, CVR method is employed to establish the dynamic stability of the system with contingent load configuration. Figure 1 depicts a single line diagram of IEEE standard 33-bus radial network under consideration. In the 33 bus system considered, the total of 6 DG units with 4 PV and 2 wind systems. PV solar systems are placed at 3,9,16 and 25 where wind system is placed at 7 and 13th bus each of capacity 100kW.

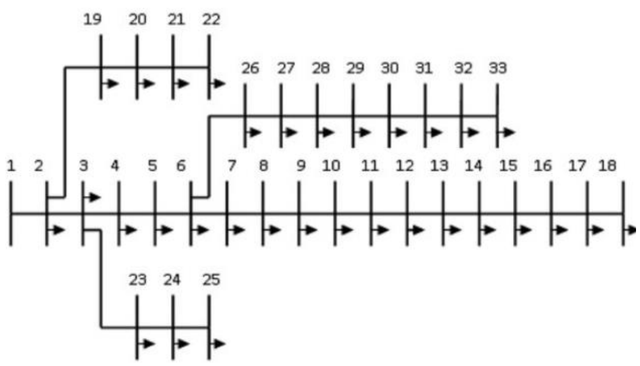

Fig. 1 33-bus Test system

Figure 2 shows a simple design for the Wind, PV and BESS-equipped distribution system. In this study, wind systems, solar systems, BESS, and loads are the three basic models that are integrated alongside distribution network. The ever-changing nature of solar PV arrangements and wind, which have a straight effect on the system stability between demand and generation, is being the major set-back. To supply or store electrical power as needed, BESS deployment is widely accepted under these conditions. By placing wind turbines, solar photovoltaic arrays, and battery energy storage systems (BESSs) in close proximity to load centers, DN current flow can be reduced. However, with the right BESS allocation into DN, distributed system power losses could be drastically cut. CVR and CL setup work together to minimize power loss and improve dynamic stability.

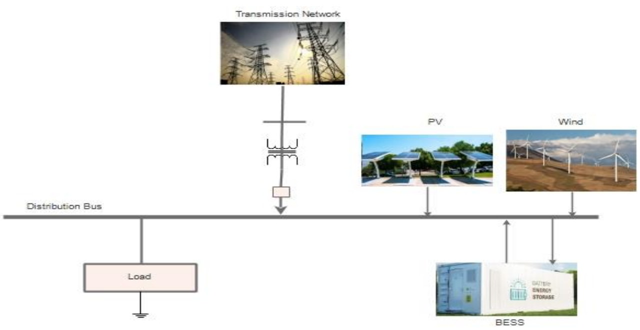

Fig. 2 Basic Structure of Distribution System with Wind, PV and BESS

(B) CVR Concept and CL configuration

CVR method works on the principle of demand minimization and peak trimming to attain the energy saving by minimizing the voltage without actually affecting the consumers sa as to improve the dynamic stability. It is put into action by lowering the grid voltage which ultimately lessens the energy utilization with respect to load voltage sensitivity. Hence, it causes the instant equity in the energy consumption at dynamic time scale thereby improving the grid stability. The CVR utilization through different time is illustrated in Figure.3.

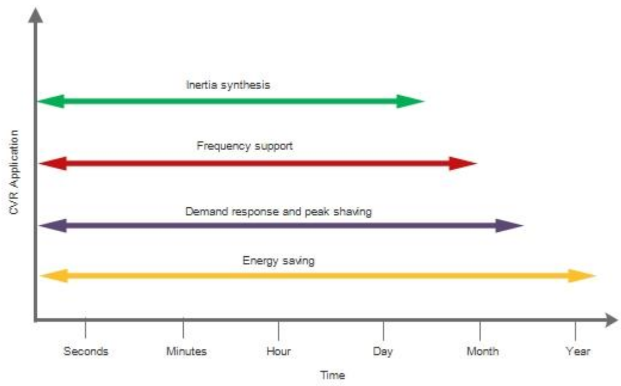

Fig. 3 Utilization of CVR vs. Time

The CVR is defined by equ. (1)

$$CVR^f = \frac{\Delta E\%}{\Delta v\%} \quad (1)$$

Where ΔE *and* Δv are the percentage of total energy saved as a result of the feeder voltage drop. There are frequent shifts in the load arrangement. Therefore, the proposed CVR approach may not be adequately validated in the fixed load situation. As a result, the dependent load arrangement is used, in which various loads are separated into categories according to their voltage requirements, with larger voltage going to industrial, residential, and commercial users. CVR factor is then calculated by allocating consumers who are preoccupied with different categories in the following way:

$$CVR^f = R * CVR^f_{,,R} + C * CVR^{f,}_{c} + I * CVR^f_{,I} \quad (2)$$

where R ($CVR^f_{,R}$), I($CVR^{f}_{,I}$), C($CVR^{f,}_{c}$), indicates the coefficients of CVR which denotes the load portion of the residential, industrial & commercial categories, correspondingly.

$$P_{li} = P_{ni}\left(\frac{v_i}{v_n}\right)^{k_p} \quad (3)$$

$$Q_{li} = Q_{ni}\left(\frac{v_i}{v_n}\right)^{k_q} \quad (4)$$

Where v_i and v_n - *i*th bus voltage and rated voltage of the system; P_{li} , P_{ni} –active power and load for ith bus; Q_{li}, Q_{ni} - reactive power and reactive load for ith bus; *Kp*,*Kq* represents the exponential parameters.

(C) Objective Function Formulation

As demonstrated in Eq. 5, the objective function for the mathematical modelling of the BESS placement optimization problem is to minimalize active power losses in the DG system. Voltage and line thermal limits constraints are the inequality constraints for the problem being studied.

$$P_l = \mathrm{Re}\left\{\sum_{t=1}^{N}\left(\frac{|V_t^s - V_t^r|}{Z_t}\right)^2 R_t\right\} \quad (5)$$

Location and generating capacity of the DG unit are key considerations. The ranges of these two deciding factors are shown as boundary values in Eq. 6.

$$P_i^{min} \le |P_i| \le P_i^{max} \quad (6)$$

The inequalities that must be satisfied in order to solve this optimization problem are shown in Eq. 7. As shown in Eq. 7, voltage restrictions require that the magnitude of a node's voltage be between the lowest voltage (Vmin) and the maximum voltage (Vmax).

$$V_k^{min} \le |V_k| \le V_k^{max} \quad (7)$$

The current via any line "k" must be less than the maximum current capacity of this branch, imax, as determined by Eq.8.

$$|i_k| \le i_k^{max} \quad (8)$$

The BESS constraint is defined by (9)

$$E_{BESSt+1}^{\tau} = \sum_{t=1}^{T}\left(E_0 + \Delta t \,.\, P_{BESS,t}^{\tau} - \left|P_{BESS,t}^{\tau}\right| .\eta_c .\Delta t - E_{BESS,t}^{\tau} .\eta_l .\Delta t\right) \quad (9)$$

Here,

P_l – Active power losses in the network.

N– Total number of lines in the network.

V_t^s – sending end node voltage of line t.

V_t^r– receving end node voltage of line t.

Z_t– impedance of line t.

R_t – resistance of line t.

P_i^{min} – Mimimum value of active power generated in DG i.

P_i – Active power generated in the DG i.

P_i^{max} – Maximum value of active power generated in DG i.

V_k^{min} – minimum value of bus potential of bus k

V_k – bus potential of bus k

V_k^{max} – maximum value of bus potential of bus k

i_k– current flowing through the line k.

i_k^{max}– maximum value of current flowing through the line k.

3. Optimization Techniques Suggested for the System

(A) Genetic Algorithm (GA)

The number of fundamental optimization operations and parameters, are generally included in GA design , which each necessitate a unique setting subject to envisioned optimization problem [20]. These factors greatly have impact on the accuracy of output of proposed GA and processing time. Henceforth, they are picked carefully. The basic GA processes that generate a new set of solutions (Xi) via crossover and mutation are called "population crossover" and "population mutation," respectively. Probabilities for the above parameters govern these processes. The crossover operation comes after the selection operation and involves choosing two random potential solutions (U_m, U_n) from the current generation (G_k). There is a maximum (U_{max}) and minimum limit to the potential solution (U_{min}).

As demonstrated in the equations (10) and (11), the crossover operation aims to provide 2 new solutions (U_{md}, U_{nd}) that are superior to their initial solutions for the following generation (G_{k+1}). However, the GA might become trapped in local minima or local maxima, necessitating a special operation to get it out of its rut. Since and are both random values between 0 and 1, the mutation process will carry out this duty as illustrated in the equations (12) and (13). Figure 4 depicts the flowchart representation of a simple GA method.

$$U_{md} = U_m + \tau(U_m - U_n) \quad (10)$$

$$U_{nd} = U_n + \tau(U_n - U_m) \quad (11)$$

$$U_{md} = U_{md} + \delta(U_{max} - U_{min}) \quad (12)$$

$$U_{nd} = U_{nd} + \delta(U_{max} - U_{min}) \quad (13)$$

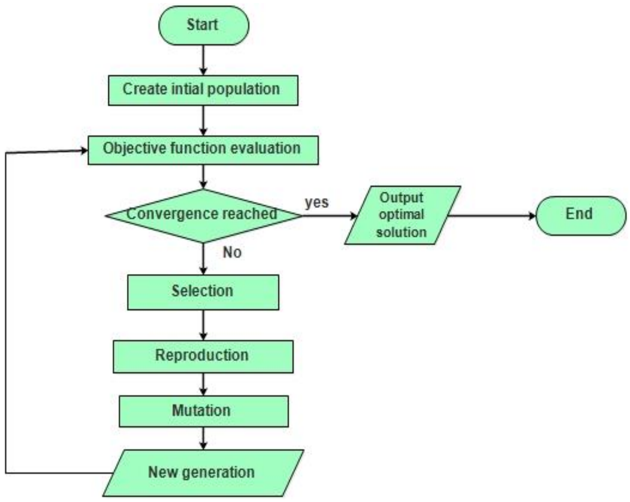

Fig. 4 Flowchart of GA Algorithm

(B) Ant Colony Optimization Algorithm (ACOA)

The foraging habits of several kinds of ants serve as a model for the ACOA's methods of operation. These ants spread pheromone around the ground to locate a perfect track that will help maintain group harmony as they follow it. Making a matrix with all the currents and voltages is the first step in using the ant colony method in reality. The right amount of ants are then selected. In the end, we settled on using two ants. Each ant begins its trip by picking an initial circumstance at random. Each ant starts in a different phase and progresses through them all at random. ACOA rose as a result of ants' foraging efforts. Researchers suggest that ants normally choose the shortest route between the food and the ant's home because ants construct pheromone trails that allow them to interact with one another and exchange information about food pathways. When hungry, ant colonies frequently start their hunt by following random paths. During their first trips, ants left behind persistent concentration traces that could be traced back to their travels throughout time. Due of the higher track density on shorter paths, they are better able to determine the quickest route to their next meal [23].

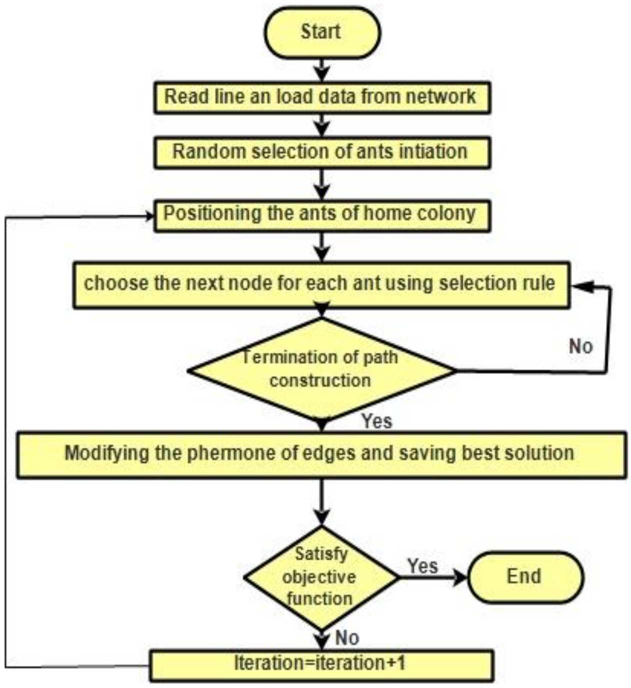

Fig. 5 ACOA Algorithm Flowchart

The primary flowchart for the suggested ACOA algorithm is shown in Figure 5. ACOA solves tedious optimization problems by utilizing the swarm of artificial ants. On the other hand, ACOA algorithms have a feature that makes it possible to distribute processing power over a large number of relatively small creatures, such as fake ants, that communicate with one another.

4. Results and Discussion

The methodologies proposed were used to the positioning of DG units in the MATLAB environment, namely the IEEE 33-bus distribution test system shown in figure 1. Four solar photovoltaic (PV) systems and two wind systems, each with a capacity of 100 kW, are selected at random and installed at the bus locations 3, 9, 16, and 25 along the distribution network. Position of the wind generators for buses 7 and 13. We present and verify the findings. Both the GA and ACOA algorithms decide where and how big DG units should be placed.

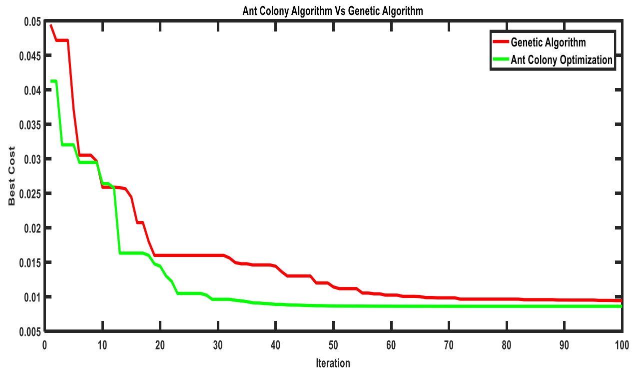

Fig. 6 Cost Function for GA and ACOA techniques

The suggested GA and ACOA algorithms are implemented on IEEE-33 bus system. The performance metrics are presented in Figures 6 to 12. Number of repetitions are done to determine the best cost function, as seen in figure 6 with BESS. It is clear from the figure.6 that the ACOA is not as much of costly than the GA method. The voltage before and after BESS placement is illustrated in Figure 7 by both methods. All 33 bus system actual and reactive power losses are shown in Figures 8 through 10. Figures 8 show the power losses for GA and ACOA methods before and after the placement of BESS.

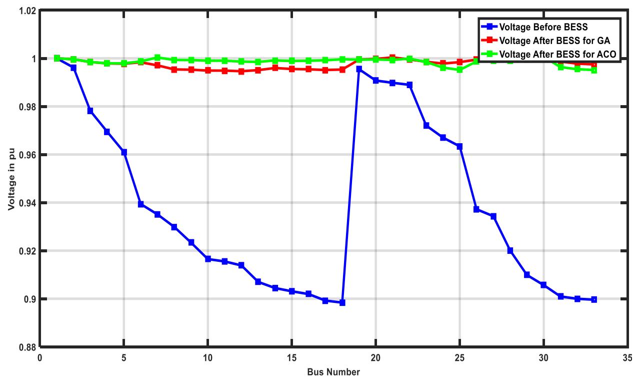

Fig. 7 Evaluation of GA and ACOA p.u. Voltage with and without BESS

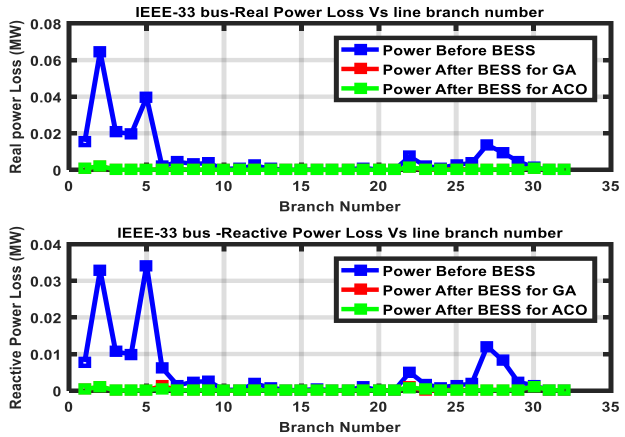

Fig. 8 Power losses for GA and ACOA methods with and without BESS

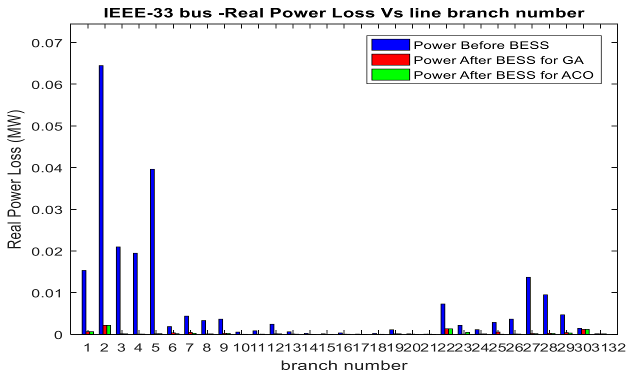

Fig. 9 GA and ACOA Real power losses with and without BESS

The active power losses for the two algorithms demonstrated in this research before and after placement of the BESS and presented in Figure 8. Similarly, the reactive power losses for the two algorithms utilized in this paper before and after placement of the BESS is shown in figure 9. It is obvious that the proposed ACOA algorithm has lower losses while compared to the other method.

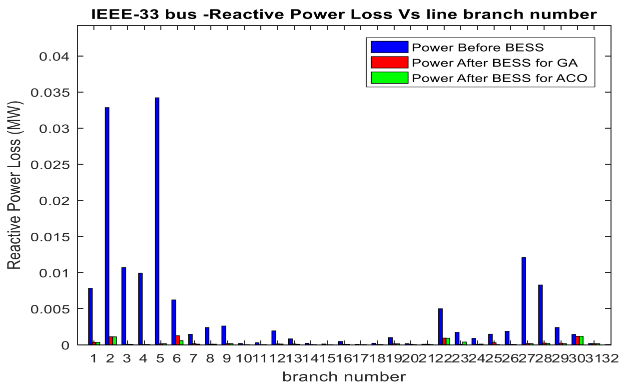

Fig. 10 GA and ACOA reactive power losses with and without BESS

Figure 11 depicts the optimum BESS size and position according to the recommended ACOA technique, while Figure 12 depicts the same information according to the suggested GA methodology.

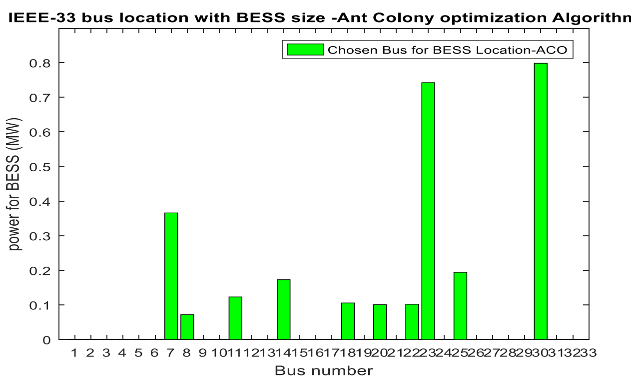

Fig. 11 ACOA method- BESS location and power

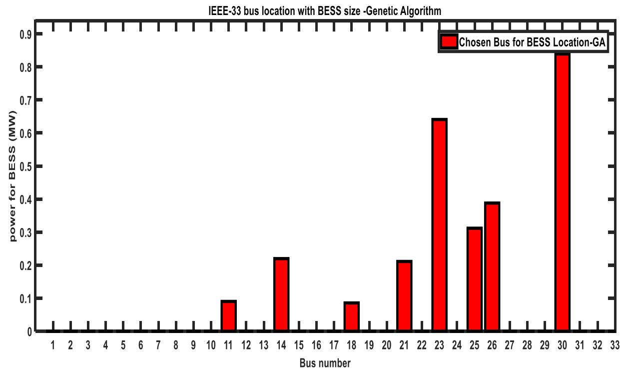

Fig. 12 GA method- BESS location and power

To compare CVR effects, the system is simulated with and without CVR. Figures 13–17 illustrate voltage, actual and reactive load, and power loss with and without CVR. Figure.13 shows that all distribution feeder voltage profiles decline. Figures 14 and 15 demonstrate the 33-bus system's actual and reactive load without CVR. Figures 16 and 17 show real and reactive power losses without CVR. Figures 18 and 19 show yearly PV and wind generation. Figures 20 and 21 show hourly wind and PV production. Figure 22 shows 24-hour average power production, wind, PV, and BESS charging and discharging.

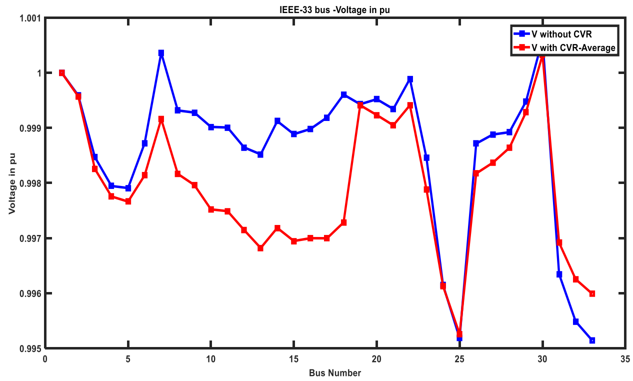

Fig. 13 Voltage profile with and without CVR

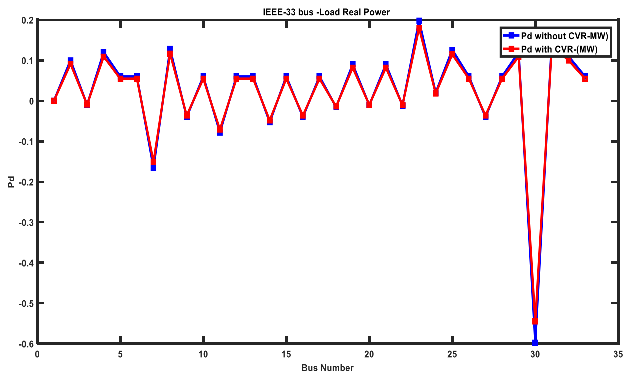

Fig. 14 Real load power with and without CVR

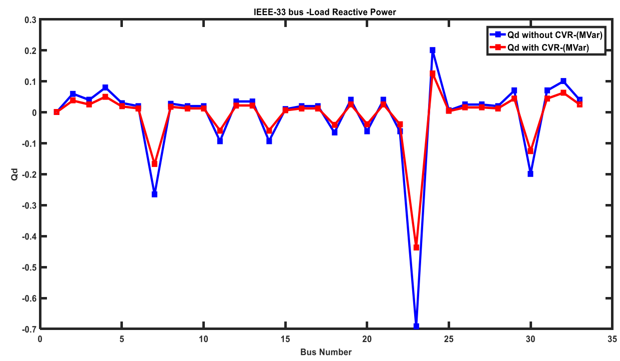

Fig. 15 Reactive load power with and without CVR

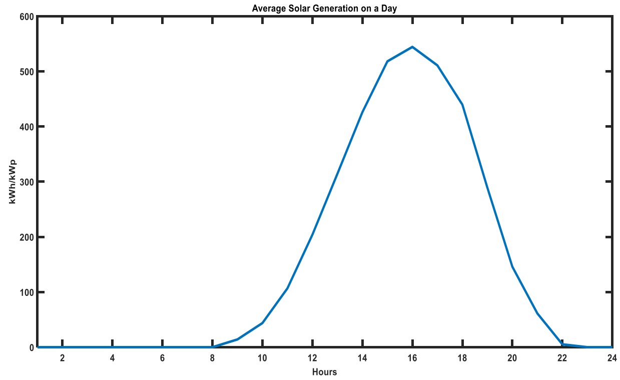

Fig. 19 Hourly Solar Power Genration

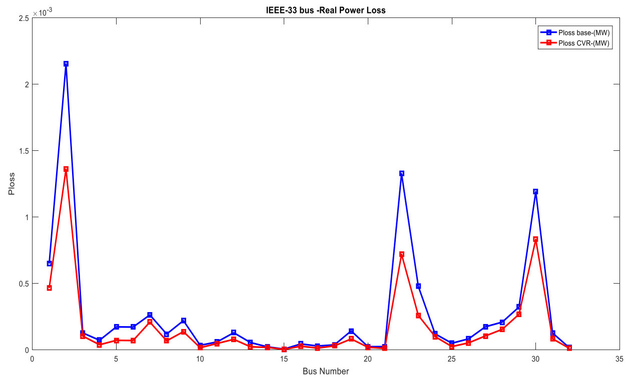

Fig. 16 Real power loss with and without CVR

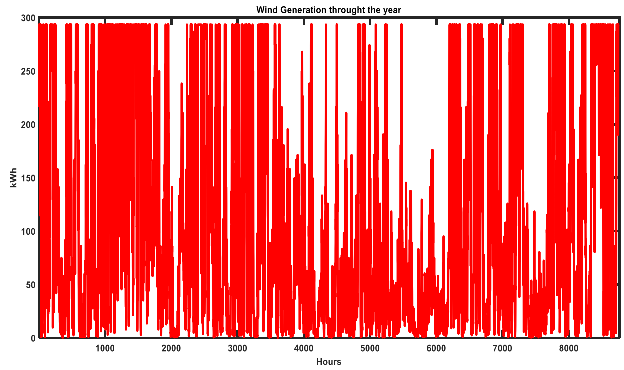

Fig. 20 Yearly wind Power Genration

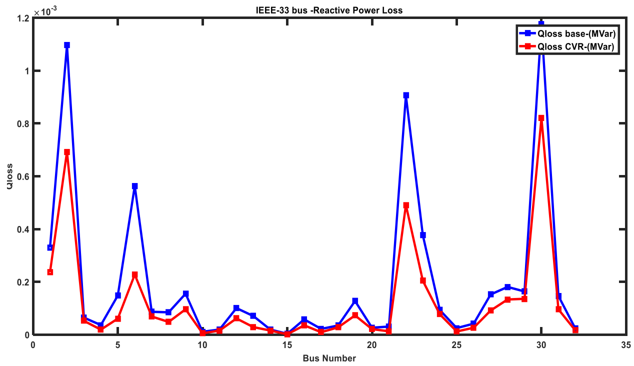

Fig. 17 Reactive power loss with and without CVR

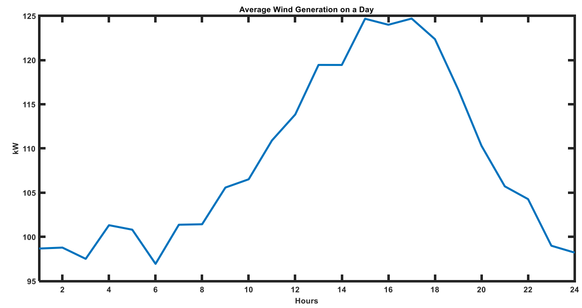

Fig. 21 Hourly wind Power Genration

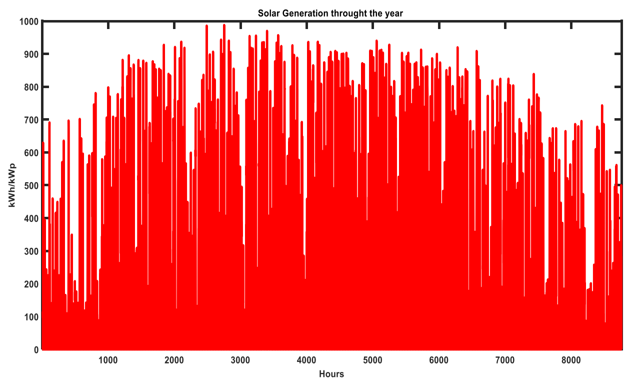

Fig. 18 Yearly Solar Power Genration

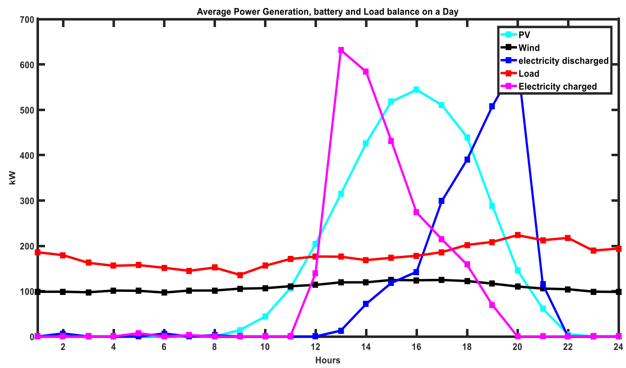

Fig. 22 Hourly Energy management profile

Table 1. Operation results comparison -Voltage

V without CVR in pu	0.99861
V with CVR-Residential Load in pu	0.99802

V with CVR-commercial Load in pu	0.99841
V with CVR-Industrial Load in pu	0.99733

Table 2. Operation results comparison – Power loss

Ploss without CVR in MW	0.0086117
Ploss CVR-Residential Load in MW	0.0054022
Ploss_CVR-commercial Load in MW	0.0054427
Ploss_CVR-Industrial Load in MW	0.0056523

Table 3. Improvement in Power Loss compared to without CVR

Ploss_CVR-Residential Load in %	37.2693
Ploss_CVR-commercial Load in %	36.7991
Ploss_CVR-Industrial Load in %	34.3652

Table 4. Improvement in Load capacity compared to without CVR

Improvement in Load Demand_CVR-Residential Load in %	10.3929
Improvement in Load Demand_CVR-commercial Load in %	14.6383
Improvement in Load Demand_CVR-Industrial Load in %	1.8813

Table 5. kp and kq denote the exponential parameters for active and reactive powers- load model

Residential Load	kp=1.04	kq=4.19
commercial Load	kp=1.5	kq=3.15
Industrial Load	kp=0.18	kq=6.00

In Tables 1-5, presents the results of operational parameters voltage, power loss and load demand for fixed and stochastic load configurations. Table 1 provides the voltage (pu) for both fixed and CL configuration. It is evident that the voltage is comparatively lesser when CL composition is considered with CVR for industrial load; concurrently, the CVR factor is higher. Table 2 and 3 presents the power losses with and without CVR.It is observed that in most cases the energy saving goal can be fulfilled. The power losses are minimized upto 3% with CVR. In peak load condition, the CVR factors are higher resulting in the BESS as a suitable unit for voltage regulation. The Table 4 represents the load demand with and without CVR and the exponential parameters for active and reactive power are presented in Figure.5.

5. Conclusion

This research integrates CVR and BESS impacts to better determine where and how much of a BESS should be installed in an IEEE 33 bus system with a random load configuration. In order to properly size and implement BESS in radial electrical distribution networks, this research proposes a set of guidelines. The different load configuration models classify the allocation BESS as a speculative optimization problem. These adjustments aim to reduce BESS's yearly operating costs due to energy loss by using GA and ACOA optimization approaches. The installation of CVR on BESS achieves the large power saving, as seen and shown by the findings. It also sums up BES's suitability for voltage management through load demand reduction of 9%. The utility is able to deal with the increasing load demand issue and achieve dynamic stability thanks to the combined usage of CVR and battery, which results in considerable energy savings. Matlab m-files are used to efficiently build the suggested algorithms for calculating the correct BESS size, positioning, and loss reduction. The IEEE-33 bus test system is validated with the help of ACOA and GA. Results are examined, researched, and judged based on their output parameters. The results are shown with the conclusions obtained. It follows that the proposed technique reduces power losses more effectively than the GA method. When composing CL, the CVR approach achieves dynamic stability.

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