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Optimal Planning of Energy Storage Systems using Symbiotic Organisms Search Algorithm

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ABSTRACT

Energy storage systems, along with many capabilities in the grid, are costly technologies. Therefore, their economic issues should be also considered while they are used in the grid. In this paper, a method has been proposed that can be used to determine the location, power, and capacity of the energy storage systems with consideration of the technical and economic aspects, simultaneously. Technical goals of this method are improvement of voltage profile and loss reduction, while economic objectives are including reduction of investment cost, operation and maintenance cost of the energy storage system. The problem of optimization is solved with the symbiotic organisms search algorithm. The main advantage of this algorithm is the absence of specific regulatory parameters compared to other meta-heuristic algorithms. The proposed plan has been implemented safely. Safe performance is achieved by enforcing security constraints such as voltage and power balancing and constraints for the energy storage system, such as capacity of energy and power constraints, and amount of energy stored. The distributed generation used in this plan is wind power plant. The output of each turbine is determined by a linear model reliant on wind speed. The proposed method has been implemented on the IEEE 33 bus grid. The results demonstrate the efficiency and capability of the proposed method.

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I. INTRODUCTION

Nowadays, the penetration of distributed generation resources has increased dramatically. Advantages of using these resources include loss reduction, voltage regulation, improvement of reliability and reduction of greenhouse gases and environmental impacts[1]. In addition to these benefits, the use of distributed generation resources faces many problems. One of the major issues is the power quality reduction due to the fluctuating nature of these resources[2]. The variable power output of distributed generation resources causes oscillations in the voltage and frequency of the power grid. The use of energy storage systems is one of the solutions to solve this problem[3].

The first challenge in designing energy storage systems is to determine the optimal size and installation location of these systems in order to maximize their capabilities[4]. Reference[5], try to find the optimal location and capacity of energy storage systems in a grid, taking into account the grid-connected and islanding modes of operation, simultaneously. Reference[6] provides a method for determining the optimum energy storage capacity at a minimum cost to control the frequency in the grid in the islanding mode of operation. In[7], the problem of optimal battery design involves determining its location, capacity, and power to minimize the amount of objective function according to the technical consideration constraints. In[8], a method is proposed to allocate optimal site and size of the storage system in order to improve reliability in distribution grids. The goal is to optimize the energy storage systems in order to reduce the cost of energy not supplied, the investment cost and the operation cost of energy storage systems, simultaneously. In[9], a comparison is carried out based on the optimal design of different batteries in order to find the best choice for applications in the distribution grid. A method based on genetic algorithm is proposed to determine the capacity of storage systems in a grid in[10]. The main objective of this method is to find the power and energy capacity of the energy storage systems to minimize the operating cost of the grid. In this paper, an energy management method based on a fuzzy system is used to control the power output of the storage system.

Another paper that addresses the design of optimal energy storage systems is[11]. This paper presents a method by taking into account uncertainty for determining the optimum size and location of energy storage systems in a power grid with wind power resources. This uncertainty of the output power of the wind power resources is modeled by tree theory. In[12], a new stochastic design is proposed to determine the optimal battery capacity and year of installation in a grid in islanding mode of op-

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eration using battery energy diagram. Optimal decision making minimizes the expected costs during utilization years. The method presented in two steps is solved with the linear programming problem. The optimum values of battery energy and power is determined in the first stage and the optimal battery installation year is determined in the second stage.

Energy storage systems are divided into five categories including chemical, electrochemical, electrical, mechanical and thermal. Batteries are in the category of electrochemical storage systems. These systems convert chemical energy into electrical energy. The batteries are divided into two categories, primary battery and secondary batteries. In the first group, battery is un-rechargeable and in the secondary group, the battery is rechargeable[13]. One example of a rechargeable battery is vanadium battery, which is used in grid-scale applications. In this battery, unlike conventional batteries, that store energy in the electrodes, electrolytic solutions are responsible for storing of energy. This action will determine the power and energy capacity, separately. Although the battery has a relatively high investment cost and low energy density, the flexible battery discharge time, power, energy, along with long lifespan, encourage the usage of this type of battery[14].

The symbiotic organisms search (SOS) algorithm is a novel meta-heuristic algorithm for engineering design and numerical optimization. This algorithm simulates behavioral methods of coexistence between members of an ecosystem that uses these behaviors to survive. The main advantage of this algorithm is the absence of specific regulatory parameters compared to other meta-heuristic algorithms[15].

In this paper, the location, capacity of energy and power of the energy storage system are determined with the aim of improving the voltage profile and reducing loss in the presence of distributed generation resources. Due to the high investment cost of storage systems, the economic aspects of using these systems, such as investment costs, annual operation and maintenance cost during the design process, are considered in addition to technical aspects. The energy storage system used in this design is a vanadium battery. To solve the optimization problem, the symbiotic organisms search algorithm is used. The results obtained by using this algorithm are compared with the results obtained from the genetic and PSO algorithms to determine the efficiency of the above algorithm. The resource of the distributed generation used in this paper is a wind power plant consisting of several wind turbines. The output power of each turbine is determined by a linear model dependent on wind speed. Later, Section II explains the wind turbine model. In Section III, problem formulation, objective functions and the specified constraints are introduced. Section IV explains the SOS algorithm. Section V presents the results of the simulations carried out. Finally, Section VI is allocated to the conclusion.

II. WIND TURBINE MODEL

The wind turbine output power depends on wind speed and turbine characteristics. Therefore, the wind turbine output power P_{WT} can be modeled using (1)[16].

$$P_{WT} = \begin{cases} 0, & v < v_c \; or \; v > v_f \\ \alpha v^2 + \beta v + \gamma, & v_c \le v \le v_r \\ P_r, & v_r < v \le v_f \end{cases} \tag{1}$$

In this model, v is wind speed and P_r is the nominal turbine output. Also, v_r is the average amount of wind speed in which wind turbine production is equivalent to nominal power. v_c is the minimum wind speed, after which the turbine begins to generate power, and v_f is the maximum wind speed which then stops to maintain the turbine's health and prevent its overturning.

III. PROBLEM FORMULATION

A. The Objective Function

The optimization goals in this article are summarized as follows:

1. Improvement the voltage profile.
2. Reduction of losses.
3. Reduction of costs that are added to the grid due to the installation of the battery.

Consequently, the objective function consists of three parts as (2).

$$\text{objective function} = \min[F_1 + F_2 + F_3] \tag{2}$$

In this regard F_1, F_2, F_3 are the objective functions that are used to improve the voltage profile, reduction of loss and reduction of costs, respectively.

1. Voltage

The objective function is calculated to improve the voltage profile with (3). In (3), a desired voltage level, V_{level}, is considered, which is usually 1 pu Then the voltage of each bus is lowered from this desired level to indicate the voltage deviation.

$$F_1 = \sum_{j=1}^{24} \sum_{i=1}^{33} |V_{level} - V_i^j| \tag{3}$$

In this regard, V_i^j is the voltage of the i-th bus at j-th hour.

2. Power loss

The active power loss in each branch are obtained by (4):

$$P_{loss} = real[(V_i - V_j) \times I_n^*] \quad (4)$$

In this case, V_i is the voltage of bus i and I_n is the current of the branch n. Then, using (5), the total amount of loss is calculated in all branches.

$$F_2 = \sum_{j=1}^{24} \sum_{i=1}^{37} (P_i^{loss})_j \quad (5)$$

3. The cost of the energy storage system

A review over costs of energy storage systems, certifies that the cost of these systems is a function of their nominal power and energy. In order to verify the economical aspect of installation of energy storage systems, this paper takes into account the costs of investment, operation and maintenance[6].

The investment cost (IC) of an energy storage system is expressed in (6):

$$IC = PC \times P_{batt} + EC \times C_{batt} \quad (6)$$

In this case, P_{batt} (kW) is power and C_{batt} (kWh) is energy capacity and PC $(\$/kW)$ is power coefficient and EC $(\$/kWh)$ is energy coefficient of battery.

Costs related to the operation and maintenance (OC) of an energy storage system can be expressed as follows:

$$OC = CC \times P_{batt} + VC \times E_d \quad (7)$$

In Eq. (7), CC $(\$/kW/year)$ is the constant coefficient and VC $(\$/kWh/year)$ shows the variable coefficient for the cost of operation and maintenance. E_d $(kWh/year)$ is the annual discharged energy of the energy storage system.

The total cost of the battery (C_T) in the grid is the total cost of investment and the cost of operation and maintenance.

$$F_3 = C_T = IC + OC \quad (8)$$

Since, the unit of F_1 and F_2 functions are pu and unit of function F_3 is dollar, in order to equalize the units, the function F_3 is multiplied by a weighting factor.

B. Considered Constraints

1. Battery constraints

$$C_{batt}^{min} \leq C_{batt} \leq C_{batt}^{max} \quad (9)$$

$$P_{batt}^{min} \leq P_{batt} \leq P_{batt}^{max} \quad (10)$$

In Eq. (9), C_{batt} is the energy capacity of the battery in kWh. Also, C_{batt}^{min} is the minimum nominal energy capacity, and C_{batt}^{max} is the maximum nominal energy capacity which are equal to 1500 and 2000, respectively.

In Eq. (10), P_{batt} is the power of the battery in kW. Also, P_{batt}^{min} is the minimum nominal power and P_{batt}^{max} is the maximum nominal power that will be 300 and 500, respectively.

In each hour, the battery state of charge (SOC) should be update. For this purpose, (11) and (12), which are respectively used in charging and discharging modes, are utilized[17].

$$SOC^t = SOC^{t-1} + \frac{P_{batt}^t \times \Delta T \times \eta_c}{C_{batt}} \quad (11)$$

$$SOC^t = SOC^{t-1} - \frac{P_{batt}^t \times \frac{\Delta T}{\eta_d}}{C_{batt}} \quad (12)$$

In equations (11) and (12), η_c is charging efficiency and η_d is discharging efficiency which both are 70%. Also, the stored energy in the battery should be limited.

$$0 \leq E^t \leq \bar{E} \quad (13)$$

In Eq. (13), $\bar{E}$ is the capacity of battery energy.

2. Grid constraints

$$V_{min} \leq V_{b,t} \leq V_{max}, \ b = 1, 2, \cdots, 33 \quad (14)$$

In the Eq. (14), V_{min} is the minimum voltage and V_{max} is the maximum voltage of each bus with values of 0.9 and 1.1 pu, respectively.

$$P_{WT}^t + P_{Grid}^t = P_{batt}^t + P_{Load}^t + P_{loss}^t \quad (15)$$

In the Eq. (15), P_{WT}^t, the power of the wind turbine, P_{Grid}^t, grid power, P_{Load}^t, the load power and P_{loss}^t indicate the power loss per hour. The power of the battery will be negative during charging time, and positive at discharging time.

IV. SYMBIOTIC ORGANISMS SEARCH ALGORITHM

The symbiotic organisms search algorithm takes the form of interactions between organisms in nature. Because all creatures depend on other species for nutrition and survival, they rarely live alone. This relationship is based on dependence as a symbiotic. There are various symbiotic relationships in nature. A symbiotic relationship between the two species that benefits from both species is mutualism. The other symbiotic relationship between the two species is that one species benefits from other while this has no effect on the other species. This is known as commensalism. Another symbiotic relationship is parasitism which occurs between two species of which one species is beneficial and the other species are harmed.

The SOS algorithm, similar to all population-based algorithms, uses a number of candidate solutions to find the optimal solution. This algorithm begins with an initial population called the ecosystem. In the initial ecosystem, some members are randomly generated in search space. Each member presents a candidate's solution to the problem, which is related to the degree of compatibility, and indicates the degree of compliance with the target.

In this algorithm, three phases are used to generate new solution in the next iteration. These three phases are mutualism, commensalism and parasitism.

A. Mutualism Phase

X_i is the i-th member ecosystem and X_j is another member that is randomly chosen to interact with X_i. Both members are used in a mutualism relationship with the goal of increasing survival in an ecosystem. The new candidate's solutions for X_i and X_j are calculated based on the mutualism relationship between the members, (16) and (17) are modeled.

$$X_{inew} = X_i + rand\ (0,1) \times (X_{best} - MUTUAL\_VECTOR \times BF_1) \quad (16)$$

$$X_{jnew} = X_j + rand\ (0,1) \times (X_{best} - MUTUAL\_VECTOR \times BF_2) \quad (17)$$

$$MUTUAL\_VECTOR = \frac{X_i + X_j}{2} \quad (18)$$

In equations (16) and (17), $rand\ (0,1)$ is the vector of random numbers, and X_{best} is the member that has the highest degree of compliance with the ecosystem. Benefit factors (BF_1 and BF_2) randomly selected 1 or 2 indicate the benefit level of each member from the relationship. Finally, if the new compatibility value of members is more than the amount of compatibility in previous iterations, members will be updated.

B. Commensalism Phase

Similar to the mutualism phase, member X_j is randomly selected from the ecosystem for interacting with X_i. In this situation, the member X_i tries to benefit from the relationship. However, the member X_j will not benefit from this relationship and will not also be harmed. The answer to the new candidate X_i, which is calculated on the basis of the commensalism relation between the members X_i and X_j, is modeled in (19). The member X_j will be updated if the new compatibility value is greater than the compatibility level in previous iterations.

$$X_{inew} = X_i + rand\ (-1,1) \times (X_{best} - X_j) \quad (19)$$

C. Parasitism Phase

In this phase, the member X_i creates a parasitic-like parasite by creating an artificial parasite called the parasitic vector. Then the member X_j is randomly selected from the ecosystem and feeds the parasite vector as the host. Parasite vector attempts to replace the member X_j in the ecosystem. The compatibility degree of both members are calculated. If the parasite vector has a better compatibility degree, the member X_j will be destroyed and replaced by the ecosystem. If the X_j compatibility degree is better, X_j is no longer a parasite, and the parasite vector will not be able to survive in this ecosystem any more.

V. SIMULATION AND RESULTS

To investigate the proposed method, it is implemented on the standard IEEE 33 buses grid. This is performed as the study system. Fig. 1 shows this grid.

Information about this grid is presented in[18]. The grid includes a wind power plant with 180 turbines, which is considered as DG and connected to the bus 9. The rated power of each turbine is 20 kW and the rated capacity of the power plant is 3.6 MW. Wind turbine power is dependent on wind speed, Fig. 2 shows the wind speed at any hour of a day. The value of the parameters used in Eq. (1) including α, β and γ are respectively 0.144 kWs^2/m^2, -1.152 kWs/m and 2.268 kW.

By using (1) and the wind speed values shown in Fig. 2, the output of each wind turbine can be obtained. Fig. 3 shows the output power of the wind power plant over a period of 24 hours. Also, Fig. 4 shows the daily load curve connected to the grid.

The battery used in this grid is a vanadium and the characteristics of which are given in Table I. The goal is to find the optimal location for installation and besides determine the optimal capacity of the battery in the target grid in such a way that the objective function is optimized. In this paper, the symbiotic organisms search algorithm is used to obtain optimal solutions. Finally, the results are compared with well-known and successful algorithms, i.e., Genetic and PSO. The simulation is then carried out in four scenarios:

1. In the grid, only wind power plant (without storage system) is used.

2. In the grid, both wind power plant and optimized storage(optimizes with GA algorithm) are used.

3. In the grid, both wind power plant and optimized storage(optimizes with PSO algorithm) are used

TABLE I. Charactristics of vanadium battery[6]

Parameter	Efficiency (%)	VC ($/kW/year)	CC ($/kW/year)	EC ($/kWh)	PC ($/kW)
value	70	0	9	100	426

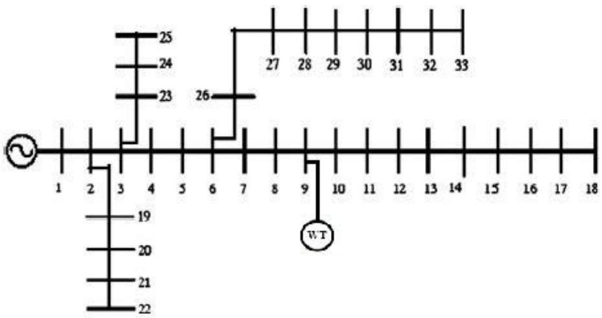

FIG. 1. IEEE standard 33 buses grid.

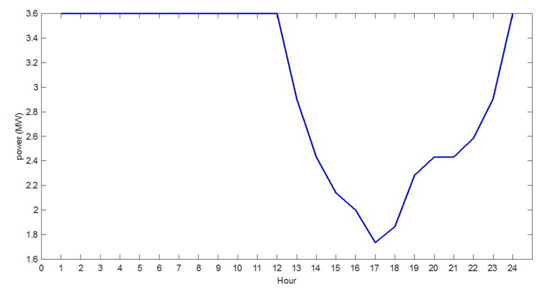

FIG. 3. Output power of the wind power plant.

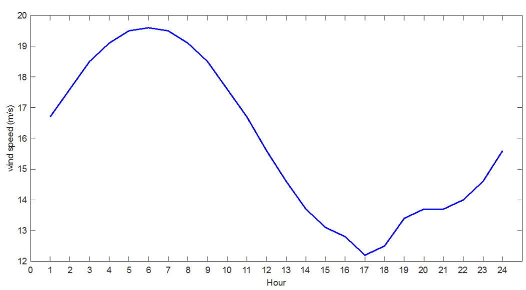

FIG. 2. Wind speed at each hour of a day.

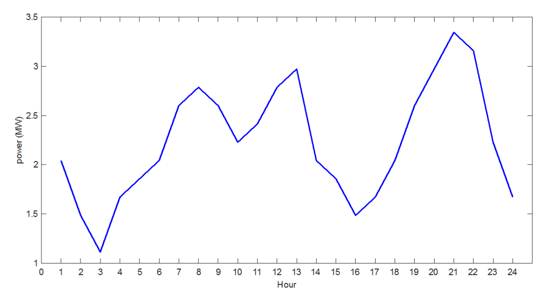

FIG. 4. Daily load curve connected to the grid.

4. In the grid, both wind power plant and optimized storage(optimizes with SOS algorithm) are used

First, simulation is performed to achieve the first two objectives, improvement of the voltage profile and reduction the loss. This is carried out without considering the economic considerations (the constraints of power and energy of battery are not considered). The results are presented in Table II.

The values of voltage deviation, loss, and cost are shown Table III.

Using the obtained values, it is shown that optimization of the voltage profile and loss is achieved to an acceptable level. But without considering the economic considerations, the capacity for the battery is not optimal and due to the high cost of buying and operating, a large cost is imposed to the grid. Therefore, third objective needs to be considered, namely as the reduction of costs in the objective function.

In the following, simulation is carried out by taking into account economic considerations and in order to optimize the three objective functions introduced in Section III. Table IV shows the location of installation, power capacity and energy capacity of battery.

Also, the value of the regulatory parameters related to each of the algorithms is given in Table V. The number of iterations for all algorithms is 200.

Table VI shows the values of voltage deviations in all buses and loss in the four scenarios in a day and the total cost of the energy storage system in one year. According to the results, the SOS algorithm generally provides better responses.

The grid loss are broken down every hour during the day for the mentioned scenarios in Fig. 5. The values of loss in each hour on the graph of scenario 1 differ from other graphs, it is due to the use of the battery. During the hours which the battery is being charged, the loss is reduced and during hours which the battery is discharged, the loss is increased. Also, the differences in values on the graphs of scenarios 2, 3, and 4 are due to alterations in the location, energy, and power provided for the battery in each algorithm.

In order to feed the load connected to the grid, we use three main resources which are included in the main grid, wind power plant, and battery. Fig. 6 shows the contribution of each resource in feeding the load. In this Figure, the blue diagram is the load curve connected to the grid. Also, yellow, green, and red columns are grid

TABLE II. Information of location and battery size

Algorithm used	Location of installation (number of bus)	Power capacity (kW)	Energy capacity (kWh)
SOS	15	511	1783
PSO	16	511	2006
GA	15	445	1786

TABLE III. Voltage deviation, loss and cost values in all scenarios

Scenario	Voltage deviation (pu)	Loss value (MW)	Cost value (dollar)
Scenario 1	11.39	3.52	-
Scenario 2	8.51	3.07	370375
Scenario 3	8.14	3.06	422885
Scenario 4	8.16	3.06	400585

power, battery power, and wind turbine output power, respectively.

Fig. 7, shows the grid bus voltage at the peak hour when the battery is in its discharge state. In this figure, four graphs are presented for each of the scenarios. The results show the efficiency of the energy storage system in improving the voltage profile.

The minimum value of voltage at all hours of the day for different scenarios is shown in Fig. 8. According to this figure, at moments in which the battery is in charge, this amount is less than the amount that is obtained when battery is not used. But at moments when the battery is in a discharge state, this amount is greater than the amount that is obtained when battery is not used.

VI. CONCLUSIONS

In this paper, the utilization of energy storage systems in the grid with the aim of improving the voltage profile and reducing loss in the presence of distributed generation resource with variable generation power is investigated. Since energy storage systems have a high investment, operating and maintenance cost, the economic aspects of their application are considered alongside technical aspects. Using the proposed method, optimal installation location, the optimal power and energy capacity of battery are determined. The SOS algorithm is used to optimize the objective function and forward-backward method is applied to calculate the load flow. The results show that the proposed method of optimal use of energy storage systems in compliance with the practical grid constraints, provides two technical and economic benefits. In the end, the results of the SOS algorithm are compared with the results of genetic and PSO algorithms and the advantages of each are discussed.

TABLE IV. Information of location and battery size

Algorithm used	Location of installation (number of bus)	Power capacity (kW)	Energy capacity (kWh)
SOS	18	304	1536
PSO	15	304	1568
GA	15	304	1551

TABLE V. Regulatory parameters related to each of the algorithms

Algorithm used	Parameter	Value
SOS	population	50
GA	population	50
	crossover	0.2
	mutation	0.6
PSO	population	50
	W	0.8
	C_1	1.5
	C_2	1.5

TABLE VI. Voltage deviation, loss and cost values in all scenarios

Scenario	Voltage deviation (pu)	Loss value (MW)	Cost value (dollar)
Scenario 1	11.39	3.52	-
Scenario 2	9.26	3.18	287340
Scenario 3	9.26	3.18	289040
Scenario 4	9.17	3.21	285840

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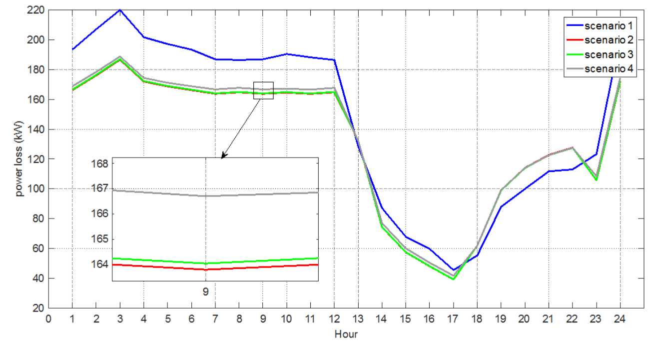

FIG. 5. Loss in each hour of day in all scenarios.

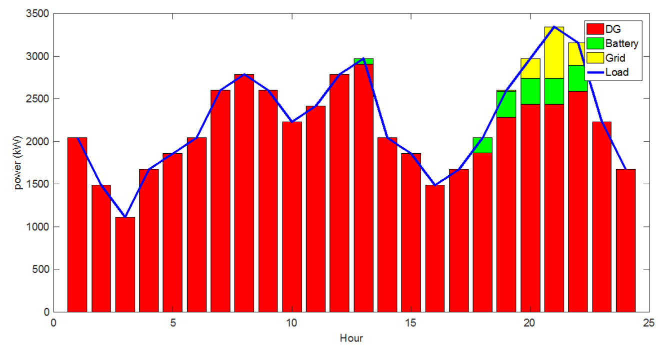

FIG. 6. Contribution of each resource in feeding the load.

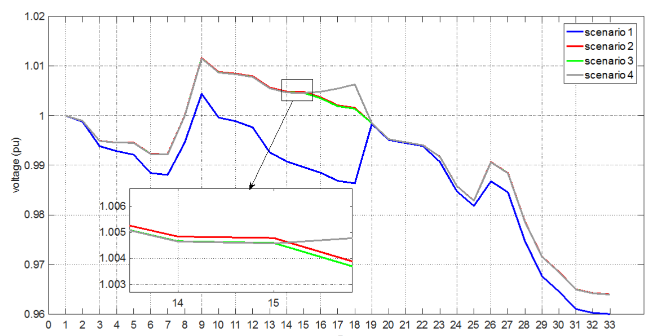

FIG. 7. Voltage of each bus at peak time in all scenarios.

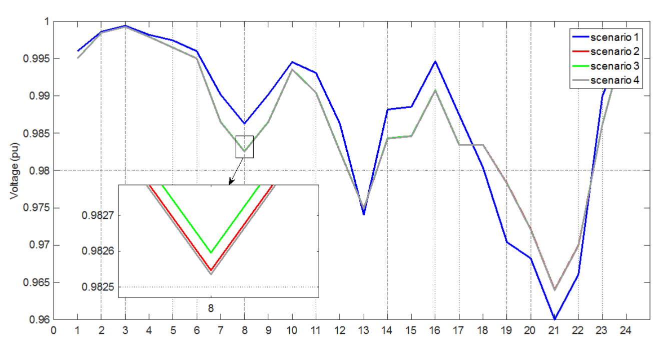

FIG. 8. Minimum value of voltage at all hours of the day for all scenarios.

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