Optimal Power Dispatch in Distribution Networks with PV Generation and Battery Storage

Jordan Radosavljević, Miloš Milovanović, Nebojša Arsić, Andrijana Jovanović, Bojan Perović and Jovan Vukašinović

***Abstract*—Numerous researchers in the last two decades have intensively dealt with various aspects of the integration of renewable energy sources (RES) into distribution networks (DNs). It has been shown that optimal planning and operation of RES can achieve positive effects, both in terms of technical performance of the system, and from the environmental and economic aspects. However, the uncontrollability and stochastic nature of wind speed and solar irradiance as the primary sources of RES remained their main shortcomings. The energy crisis that has been present lately imposes the need for much more flexible use of RES. This means finding technically efficient and economically acceptable solutions for energy storage, in order to fully exploit the potential of RES integrated into the system. This paper deals with the issues of the optimal operation and management of rechargeable batteries for energy storage in DNs with PV generation.**

***Index Terms*—Distribution networks, Renewable energy sources, Battery energy storage, Optimal power flow**

I. Introduction

In the last twenty years, we have witnessed the expansion of renewable energy sources (RES), primarily wind and solar photovoltaic (PV) power plants. The development and application of these technologies have several causes. First of all, it is the constant growth of the electricity consumption and need for new generation capacities. Another, no less important cause, is the ultimative request to limit the use thermal power plants in order to reduce global warming due to CO_2 emissions. In addition, the deregulation and liberalization of electricity market and preferential prices for green energy have contributed rapid growth of RES in the last two decades [1].

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Wind and solar technology is becoming cheaper year by year [2], which makes it widely available. There are wind and solar power plants with installed capacity of several hundred MW connected to the transmission network. In addition, there has long been a trend of building smaller so-called distributed energy sources from several kW to several MW, which are integrated into distribution networks (DNs).

A large number of papers have been written on the topic of the distributed energy sources. Various aspects in their planning, operation and control have been explored. It has been shown that optimal planning and control can maximize their positive effects, such as reducing power losses, improving voltage profiles, increasing the supply reliability in DNs, reducing greenhouse gas emissions, etc. However, the uncontrollability and stochastic nature of wind speed and solar irradiance as primary sources of RES remained their main shortcomings.

The energy crisis that has been present recently, imposes the need for much more flexible use of RES. This means finding (using) technically efficient and economically acceptable solutions for energy storage, in order to fully use the potential of RES integrated into the DN.

There is no way to directly store active electricity. There are more or less developed technologies and solutions for indirect storage of the electricity, i.e. converting the electricity into another type of the energy that can be stored in a certain medium. The energy stored in this way is, when necessary, converted back into the electricity, which is injected into the transmission or distribution system.

At the level of DNs, the battery energy storage systems (BESS) are imposed as a solution. For their application in DNs with significant penetration level of RES, type WT and PV, it is necessary to solve two questions beforehand. The first one refers to the optimal planning of the BESS, which includes the choice of capacity, rated power and location in the DN. The second one is the optimal exploitation, i.e. determination of the BESS operation mode in a given period of time, usually 24 h. This implies defining the charging/discharging regime, i.e. the time schedule and the charging/discharging power of the BESS in accordance with the adopted function that it should perform in the DN. These functions can be [3-7]: (i) providing energy management and optimal power flow for reducing the cost for electricity, minimizing power losses, and improving the power quality, (ii) enable/facilitate the

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realization of smart grids, (iii) meeting peak electrical load demands, (iv) increasing the reliability of power supply. The mode of operation of the BESS is determined taking into account variable load, as well as the variable and stochastic power of RES (PV and WT).

In essence, this is a problem of optimal power dispatch in DNs. Given the specificity of the BESS, i.e. the limitation related to the state of charge (SoC), which directly affects the battery status in the next time segment (charging/discharging and power level), the problem of optimal power dispatch must be observed in a certain (given) time horizon, usually a period of 24 hours. Therefore, the problem of optimal power dispatch becomes a dynamic problem on a certain time horizon. The solution of this problem is performed by time segments (e.g. from 1 to 24 h), where the solution in a given segment (t) is conditioned by the solution obtained for the previous segment (t-1).

This paper presents a two-stage procedure for optimal dispatch of active and reactive power in DNs with PV sources and BESS. In the first stage, the optimal active power dispatch in DN is determined, based on the classical model of dynamic economic dispatch with neglected power losses. The aim is minimizing costs for electricity from the source (upstream) grid. After that, the problem of optimal reactive power dispatch in DN is solved to minimize energy losses and voltage deviation.

II. Models of PV, Load and Battery Storage

A. PV Model

The power generated by a PV unit is dependent on the solar irradiance. Beta PDF is suitable to modeling the stochastic nature of the solar irradiance. The solar irradiance measurements are made available with the sampling time of 1-10 min. Therefore, the mean and standard deviation of the solar irradiance can be calculated from measured data which correspond to the certain time interval τ (e.g. 1 h). Based on the mean and standard deviation of the solar irradiance, the shape parameters of Beta PDF can be calculated [8].

To realize Beta PDF in discrete form, the time interval τ is divided into N_s states, where the corresponding solar irradiance and probability for each state ($g = 1 \div N_s$) can be calculated. The output power of PV is then estimated taking into account the probabilities of all solar irradiance states in the observed time interval, as explained in [8,9].

B. Load Model

It is assumed that the load diagram is the same for active and reactive power. The load is assumed to be a random variable following the same normal PDF within each hour of a given daily load diagram.

To realize the normal PDF load function, the hour t is divided into N_L states, and the corresponding loads and probabilities for each state ($g = 1{:}\ N_L$) are calculated.

The level of the load in the certain time segment t is determined based on the probability of all possible conditions within that hour [9].

C. BESS Model

The BESS model is conditioned by a continuous change in the state of charge (SoC). This means that the value of the SoC at a given time-hour (t) depends on its value in the previous time segment (t-Δt or t-1). Mathematically, this can be expressed as follows [10]:

$$SoC(t) = SoC(t - \Delta t) + \Delta SoC\,, \tag{1}$$

$$\Delta SoC = \frac{P_{bat}(t-1)\cdot \Delta t}{C_B}\,, \tag{2}$$

where C_B is the total capacity of the battery, Δt is the time segment (1 h), and P_{bat} is the power of the battery.

BESS mode means the time schedule and dynamics of charging/discharging of the battery during the considered time period (e.g. 24 h). The mode of the operation of the BESS in each time segment of the observed period is determined in accordance with the adopted function of the BESS in the DN. This can be, for example, minimizing the cost for electricity from the source grid, reducing peak loads, maximizing the use of the energy from RES to supply local loads in the DN, etc. The power of the BESS at time t depends on the adopted battery mode operation. At the same time, the following limits must be met:

$$-P_{bat,n} \le P_{bat}(t) \le P_{bat,n}\,, \tag{3}$$

$$SoC^{\min} \le SoC(t) \le SoC^{\max}\,, \tag{4}$$

where $SoC^{\min}$ and $SoC^{\max}$ are the predefined minimum and maximum charge levels, respectively, and $P_{bat,n}$ is the rated power of the BESS.

III. Optimal Active Power Dispatch

It seems that the minimization of the cost for electricity from the source grid is most appropriate function of BESS in the DN:

$$Cost = \sum_{t=1}^{24} P_g(t)\cdot C_{en}(t)\,, \tag{5}$$

where $P_g(t)$ is the active power from/to the source grid at the hour t, $C_{en}(t)$ is the electricity price in the hour t.

This means that during periods of the day when the electricity price is low, the BESS is used to store the energy from RES and the source grid, working in the charging mode. During periods of the day with a high price of the energy from the source grid, the BESS is used as an additional power source, i.e. it operates in the discharge mode. It is assumed that the electricity price from the source grid changes during the day according to a predetermined diagram, i.e. the electricity price is known in each time segment (hour) of the considered time period.

It is clear that in the charging mode BESS behaves as a

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load, and that according to the adopted reference directions the battery power is positive, and in the discharge mode BESS acts as a generator in the DN and the power P_{bat} is negative. In order to define the terms "high price" and "low price", it is assumed that the electricity price at a given time t is high if it is higher than the mean price in the observed time period (day), and that the electricity price at the given time t is small if it is less than the mean value of the electricity price in the considered period.

In order to define the charging/discharging power of the BESS, i.e. to define the value of $P_{bat}(t)$, the principle was adopted is that the greater difference in the energy price at a given moment t, $C_{en}(t)$, in relation to the mean electricity price during the day, it is also the higher power of the battery $P_{bat}(t)$ in relation to the rated power of the battery $P_{bat,n}$. Therefore, the BESS mode at the time t can be defined as follows:

$$P_{bat}(t)=\begin{cases}0 & \text{if} \quad SoC(t)=SoC_{\max} \\ & \text{and} \quad SoC(t)=SoC_{\max} \\ a_f(t)\cdot P_{bat,n} & \text{if} \quad C_{en}(t)\le C_{en,sr} \\ & \text{and} \quad SoC_{\min}\le SoC(t)<SoC_{\max} \\ 0 & \text{if} \quad C_{en}(t)>C_{en,sr} \\ & \text{and} \quad SoC(t)=SoC_{\min} \\ -a_f(t)\cdot P_{bat,n} & \text{if} \quad C_{en}(t)>C_{en,sr} \\ & \text{and} \quad SoC_{\min}<SoC(t)\le SoC_{\max}\end{cases} \tag{6}$$

where the coefficient a_f shows the difference in the electricity price at the time t from the mean value during the observed day:

$$a_f(t)=\frac{\left|C_{en}(t)-C_{en,mean}\right|}{C_{en,\max}}, \tag{7}$$

$C_{en,mean}$ and $C_{en,\max}$ are mean and maximum electricity price during the day, respectively.

The constraint related to the power balance in the DN for each time interval t, without considering power losses, can be expressed as folows:

$$P_g(t)=P_{load}(t)-P_{PV}(t)+P_{bat}(t), \tag{8}$$

where $P_{load}(t)$ is the total power of loads in the DN at the hour t, $P_{PV}(t)$ is the total power generation of PV sources at the hour t, while $P_{bat}(t)$ is the power of the BESS at the hour t determined according to (6).

The DN operating conditions are defined through the predicted daily load curve and PV source generation profile. In this model, the power losses in the DN are not taken into account, nor the cost of the BESS operation, and the cost of the PV generation.

IV. Optimal Distribution of Reactive Powers

PV sources and BESS are connected to the DN through three-phase inverters. Inverters have the ability to control the reactive power. Assuming that the rated power of the corresponding inverter is slightly higher (e.g. 10%) than the rated power of the PV source and BESS, it means that inverters can be used as an additional control resource in the DN. It is clear that the range of the reactive power is determined by the rated apparent power of the inverter and the active power that is transmitted through the inverter at a given moment. This can be expressed by the following relation [10]:

$$Q_{inv}^{\max}(t)=\pm\sqrt{S_{inv,n}^2-P_{PV}^2(t)}, \tag{9}$$

where $Q_{inv}^{\max}(t)$ is the maximum (minimum) reactive power of the inverter at the time t, $S_{inv,n}$ is the rated power of the inverter, and $P_{PV}(t)$ is the active power of the PV source at the time t. Equation (9) also applies to the BESS.

The optimal reactive power dispatch can be considered as a problem of determining the optimal values of the reactive powers of inverters with a certain objective function, such as minimizing power loss and/or voltage deviation in DN. Mathematically, this can be formulated as follows:

$$\min\ F(\mathbf{x},\mathbf{u}), \tag{10}$$

with constraints:

$$g(\mathbf{x},\mathbf{u})=0, \tag{11}$$

$$h(\mathbf{x},\mathbf{u})\le 0, \tag{12}$$

$$\mathbf{u}\in\mathbf{U}, \tag{13}$$

where $\mathbf{x}$ is the vector of dependent variables, $\mathbf{u}$ is the vector of control variables, and F is the objective function.

The vector of dependent variables $\mathbf{x}$ consists of the slack bus power (P_0), load bus voltages (V_L), and line loadings (S_l). On the other hand, the vector of control variables $\mathbf{u}$ consists of the inverters reactive powers (Q_{inv}), and slack bus voltage (V_0). The equality constraints (11) are the typical nonlinear power flow equations. Inequality constraints (12) are the functional operating constraints, such as: slack bus active power limits, load bus voltage limits, and branch flow limits. Constraints (13) define the feasibility region of the problem control variables, i.e. inverter reactive power limits, and slack bus voltage limits.

It is worth mentioning that the control variables are self-constrained. The inequality constraints of dependent variables are incorporated in the objective function (10) as quadratic penalty terms [11].

To solve this nonlinear optimization problem with constraints, a large number of classical and metaheuristic methods are available. In this paper, the hybrid metaheuristic method PSOS-CGSA was applied [12].

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V. Simulation Results

The proposed procedure was applied to a modified IEEE 69-bus test system [13]. Modification of the original IEEE 69-bus system is reflected in the fact that in buses 16 and 61, according to the results in [1], are connected PV sources, as shown in Fig. 1. Both PV sources have the same rated power of 1.8 MW, and they are connected to the network through inverters whose apparent powers are 10% higher than the rated powers of the PV sources. In the bus 4 is connected a BESS, rated power of 2 MW, and capacity of 8 MWh. The apparent power of the BESS converter is also 10% higher than the rated power of the BESS.

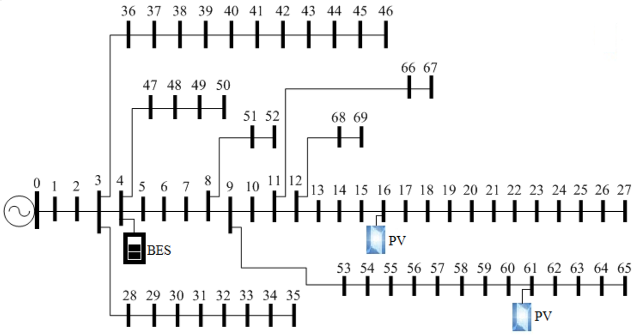

Fig. 1. Single-line diagram of the modified IEEE 69-bus test system.

It is assumed that all loads have the same daily load diagram, as shown in Fig. 2. The rated powers of loads are given in [13]. Also, it was adopted that the change of the solar irradiation is the same in the whole area of the DN, so that the powers of both PV sources change according to the same dynamics during the day, as in Fig. 2. The procedure for determining the optimal active power dispatch was carried out according to the algorithm described in Section III. The daily diagram of the change in the energy price from the source grid, expressed in p.u., is also shown in Fig. 2. The base energy price is 100 €/MWh [14]. It was adopted that SoC_{min} is 30%, SoC_{max} is 100%, and the initial state of charge is 30%.

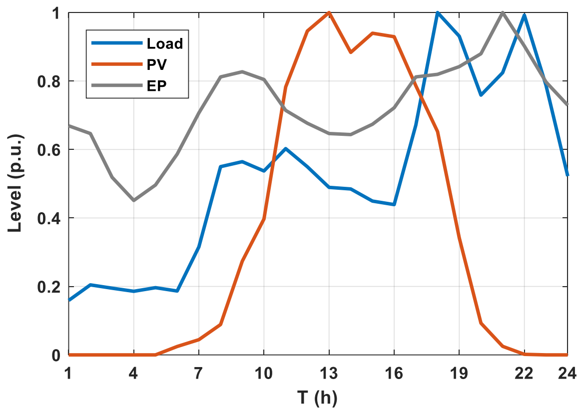

Fig. 2. Load, PV generation, and energy price (EP) profiles.

After determining the optimal active power dispatch, the procedure for determining the optimal reactive power dispatch was carried out for three types of the objective function, as follows:

- Case 1: Minimization of energy losses during the day
- Case 2: Minimization of load buses voltage deviation
- Case 3: Simultaneously minimization of energy losses and voltage deviation

It was adopted that the allowable voltage limits at load buses are from 0.95-1.05 p.u. The voltage magnitude at the slack bus is considered in the range 0.9 -1.1 p.u., whereas the reactive power limits of the inverters are changeable, according to (9).

A. Optimal Active Power Dispatch

In order to compare the results, the base case was adopted when PV sources are connected to the DN but there is no the BESS. Fig. 3 shows the costs for electricity from the source grid in the case when there is no the BESS and in the case when there is the BESS with the optimal active power dispatch obtained according to the algorithm described in Section III.

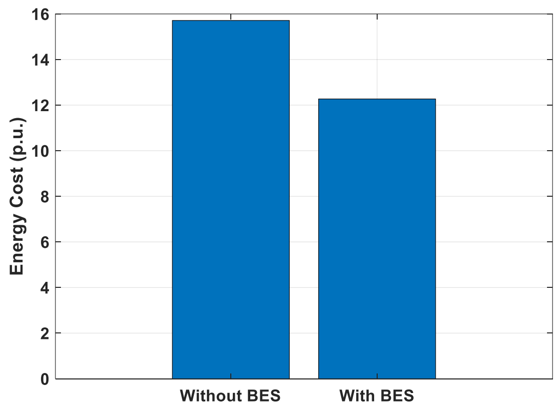

Fig. 3. Comparison of costs for energy purchased from the source grid.

As results of the optimal active power dispatch, daily diagrams of the active power and SoC of the BESS were obtained, as shown in Figs. 4 and 5, respectively.

Based on the results in Figure 3, it is clear that the integration of BESS and application of the proposed algorithm for optimal active power dispatch lead to a significant reduction in costs for electricity from the source grid. This conclusion is derived with the notation that the operating costs of the PV source and the BESS were not considered in this case.

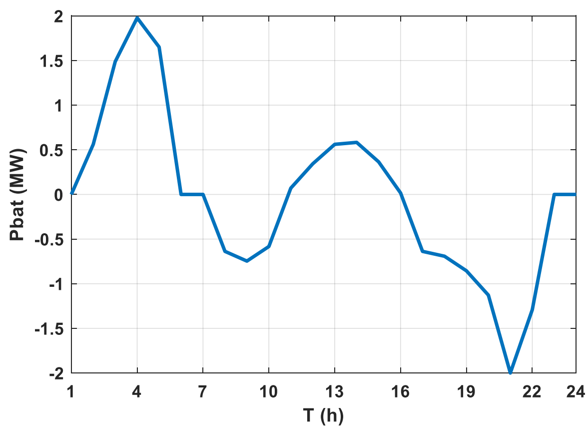

Fig. 4. The power change of the battery during the day.

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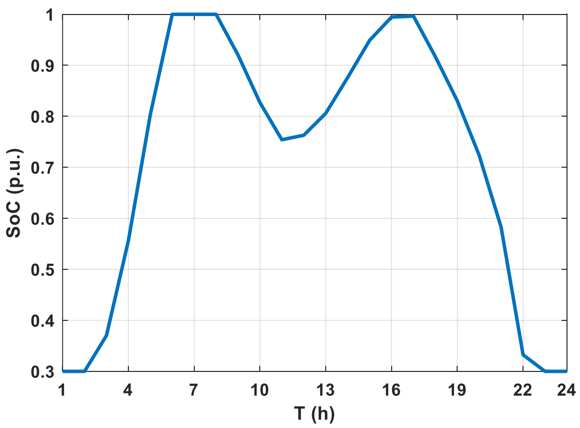

Fig. 5. The S_OC change of the battery during the day.

B. *Optimal Distribution of Reactive Powers*

The results of the optimal reactive power dispatch are given in Table I. The base case is taken when PV sources and BESS operate with unity power factor, and the slack bus voltage is equal to 1 p.u. The table shows the values of the active energy losses during the day (W_{loss}), the sum of voltage deviations at load buses during the day (ΔV_{pq}) and the maximum values of voltage deviations during the day in the whole DN. It is obvious that the proposed approach for the optimal reactive power dispatch in Case 1 achieves a significant reduction in energy losses, and in Case 2 a reduction in voltage deviations in the network. As expected, a compromise solution was obtained in Case 3. The optimal values of the control variables for Case 1 and Case 3 are shown in Figs. 6 and 7, respectively.

TABLE I
RESULTS OF THE OPTIMAL DISTRIBUTION OF REACTIVE POWERS

	Case			
	Base case	Case 1	Case 2	Case 3
W_{loss} (MWh)	2.33	2.04	2.93	2.15
sum(ΔV_{pq}) (p.u.)	22.60	57.19	16.88	19.78
max(ΔV_{pq}) (p.u.)	0.09	0.05	0.05	0.05

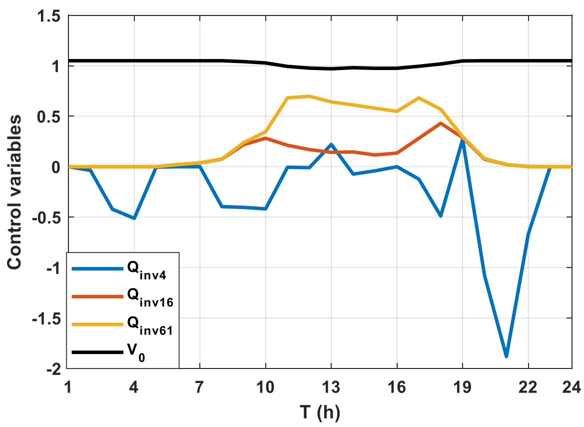

Fig. 6. Optimal values of control variables in Case 1.

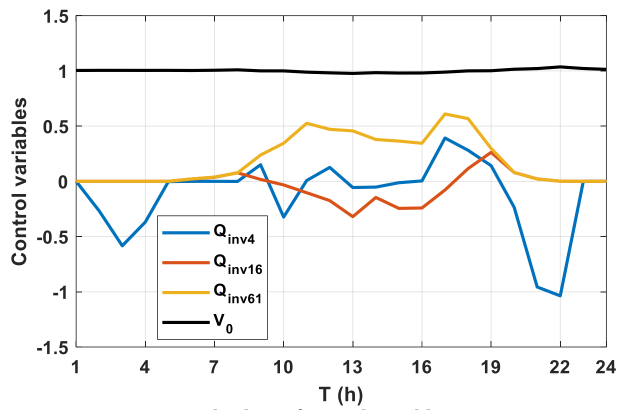

Fig. 7. Optimal values of control variables in Case 3.

The voltage profiles of the DN for the 24-hour period corresponding to the optimal active/reactive power dispatch for Cases 1-3 are shown in Figs. 8-10, respectively.

Based on these results, it can be seen a significant voltage deviation for Case 1 compared to the base case and Cases 2 and 3. This is a consequence of presenting loads with the constant power model; to minimizing the power losses in Case 1, control variables are optimized so that load voltages have higher values within the permissible limits to minimize branch currents, and thus power losses in the DN.

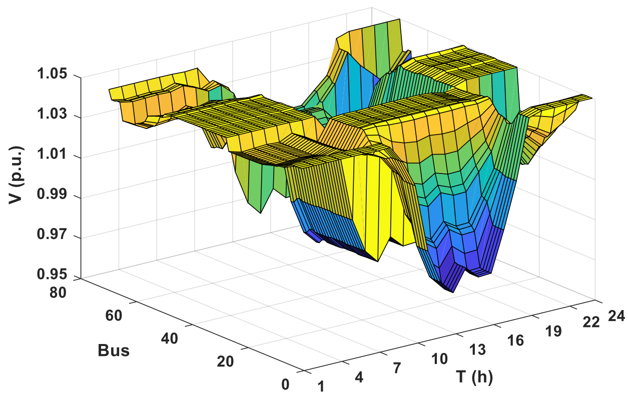

Fig. 8. Voltage profiles for Case 1.

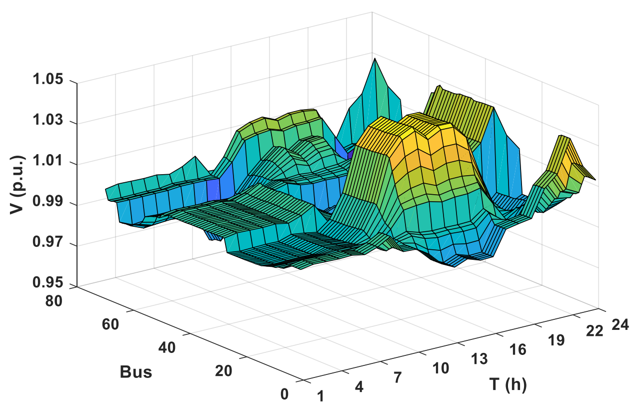

Fig. 9. Voltage profiles for Case 2.

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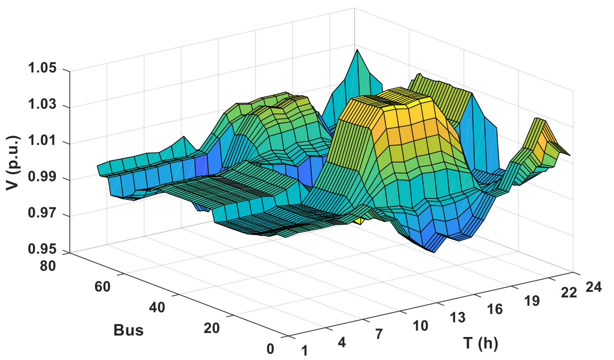

Fig. 10. Voltage profiles for Case 3.

VI. Conclusion

In this paper, a two-stage active/reactive power dispatch approach for DNs with high penetration of PV generation and BESS has been considered. The proposed procedure has been tested on the IEEE 69-bus test system with two PV sources and one BESS. The simulation results lead to conclusions that can be summarized as follows:

- Integration of BESS and application of proposed algorithm for optimal active power dispatch lead to a significant reduction in costs for electricity from the source grid. In this particular case, the results showed that it is possible to achieve a reduction in the energy cost by about 22%, compared with the base case without BESS.
- It has been shown that PV and BESS inverters can serve as additional control resources for reactive power. By applying the proposed algorithm for optimal reactive power dispatch, a significant reduction in active power losses and voltage deviations in DNs can be achieved. Specifically, in comparison with the base case, the solutions obtained by the proposed algorithm provide a reduction in energy losses of 12.45% for Case 1, and a reduction in voltage deviations of 25.31% for Case 2.

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