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Reactive Power Management in Residential Feeders of Distribution Systems in Presence of Photovoltaic and Energy Storage Systems

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Abstract

In recent decades, due to the fast growth of electrical energy demand, researchers endeavor to find an appropriate replacement for conventional energy sources by investigating the modern ones. Today, renewable energy resources (RESs) are one of the most useful energy resources. The RESs are gaining developed countries attention due to their incredible advantages and this results in a significant increment in utilization of these energy sources especially in low voltage distribution systems (DSs) and among residential consumers. On the other hand, given the conventional configuration of most of the distribution networks, exceeded utilization of some RESs such as solar energy causes many issues and disturbances in utilization point of view. Voltage deviation is one of the most important issues in the DSs which can be happened due to the variable and unpredictable nature of RESs. Therefore, it seems that some specific methods are needed in order to overcome issues that come from inordinate presence rate of the RESs in recent years. This paper presents a new method for optimal reactive power management by proposing a new objective function and using inverter equipment of photovoltaic (PV) systems in coordination with energy storage system (ESS). In addition to improvement of the system voltage profile, by introducing a Hybrid PV System (HyPV), the system can be operated in islanded mode. In this paper, the Particle Swarm Optimization algorithm (PSO) is used for optimal reactive power management.

Keywords: *Renewable Energy, Voltage Profile, Inverter, Reactive Power Management, PSO Algorithm, Hybrid PV System.*

1. Introduction

Todays, given the worldwide electrical energy demand, despite the significant technological advances, in most centralized power plants, fossil fuels are still used in order to generate electricity. On the other hand, the fossil fuel resources are finite and also their consumption causes to produce large amounts of environmental pollutions. Therefore, in recent decades, research on new energy sources has expanded so fast in developed countries. Renewable Energy Resources (RESs) are the ideal kind of energy resources which are highly regarded especially in the last few decades. The RESs not only are devoid of all disadvantages of the fossil fuels such as pollution, finitude, high operation cost and etc. but also have many advantages include unlimited sources, high accessibility, efficient reliability, zero pollutant emission and low operation cost. These desirable benefits of RESs have brought them under many countries' spotlight. Solar energy is one of the most prevalent RESs that due to its worldwide availability, its usage is increasing day to day. Today, the solar energy is utilized in two common forms. First one is using the solar energy in form of centralized, large scale and far away from

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residential areas. In this case, the generated electricity is transmitted to the desirable regions via transmission lines. The second form is using the solar energy to produce electricity in near of the residential and commercial areas. This method which doesn't need immense investment cost to establish transmission lines and also prevent energy loss in long transmission lines is an economic and advantageous form to utilize solar energy optimally. Due to these reasons, in many developed countries, the green and unlimited solar energy is utilized by installing photovoltaic (PV) arrays on the roof of residential and commercial buildings.

Hence, the significant advantages of solar energy and its easy operation cause to increase its usage in different ways. For this reason, the capacity of installed PV systems until 2014 was reached to 177 GW [2] and also it is predicted that among different Distributed Energy Resources (DERs), the PV systems will have the most contribution in electricity generation until 2040 [9]. The PV systems advantages make it an attractive electrical energy source for residential consumers. So, many residential customers are interested in installing small PV arrays on their buildings roof for producing and selling electricity in level of low voltage DSs.

But given that many distribution systems (DSs) have configurations in accordance with the centralized and conventional electricity generation procedure. So they aren't still prepared for the presence of renewable and distributed energy sources and fast growth of these resources make the DS face with many problems and challenges. For instance, many DSs have radial configuration and often they were designed based on one direction power flow from upstream and high voltage network toward downstream and low voltage points. So high presence rate of PV systems and locally feeding electrical demand can make significant and considerable deviation in the DS voltage profile. The over-voltage issue is one of the most common issues related to the power quality which may be occurred in DSs include DERs.

Accordingly, using PV systems in large scales needs new management methods in the level of DSs in order to benefit effectively from RESs advantages. So by solving probable problems and issues, it will be possible to deliver electric power to consumers with the desired quality and continuously.

Therefore, in recent years, many kinds of research have been carried out for correction and regulation of DS voltage profile and in presence of DERs. In [3], a decentralized method is proposed to control voltage in DSs include inverter based DERs. In this method, despite the maximum usage of DERs capacity, the system voltage is always in the allowable range. The authors in [5] have recommended DERS as a reactive power generation sources to regulate DSs voltage profile. In [4], a method is presented for reactive power management using reactive power generation ability of DERs inverters in order to keep all phases' voltage in the allowable range and prevent voltage collapse which results in maintaining system stability.

In [7], by estimating the amount of available PV output and also considering the system configuration, the required capacity of the storage system is determined. As a result, a method is proposed for coordinated control of inverter and energy storage system (ESS) in order to aggregate several PV systems installed on the residential buildings' roof in DS. Authors in [8] introduced a hybrid PV system which can be operated in islanded mode by utilizing PV system and storing surplus energy. In the islanded mode, the system is separate from the upstream network.

In this paper, a small DS is considered which contains residential consumers which each of them has a PV system with an ESS. Then a method will be proposed for reactive power generation/absorption management using inverters of the PV systems in order to regulate voltage profile and store surplus electrical energy and use it at the proper time. In this method, through optimal utilization of the solar energy and the energy stored in the battery, the desired system can be operated separately. In the proposed method, Particle Swarm Optimization (PSO) approach is used for inverters' reactive power management and the required simulations are carried out in MATLAB software.

2. Methodology

In this research, a method is presented to correct and regulate voltage profile of a small DS that includes some residential buildings equipped with PVs and ESSs. In the presented method, it is assumed that the considered test power system can be operated independently and it is named Hybrid PV system (HyPV) which is operated in low voltage (LV) level. In another word, the independent operation is feasible only when the system energy demand can be met by using the PV outputs and the energy stored in the battery bank. In order to achieve this goal, it is essential to consider required practical constraints. Ensuring that the system voltage profile is within the allowable voltage range is one of the most critical constraints. Satisfying the voltage constraint guarantees quality of the energy delivered to consumers all over the day.

In this paper, the inverter's capability to supply reactive power is utilized in order to guarantee satisfying voltage constraint. In the proposed method, the voltage profile is regulated by generating/absorbing reactive power at under/over voltage situations. The maximum amount of reactive power which can be generated or absorbed depends on the inverter capacity and the PV's output power and is calculated based on equation (1), as can be seen in Fig. 1:

$$-\sqrt{S^2 - {P_{pv}}^2} \leq Q_{pv} \leq +\sqrt{S^2 - {P_{pv}}^2} \quad (1)$$

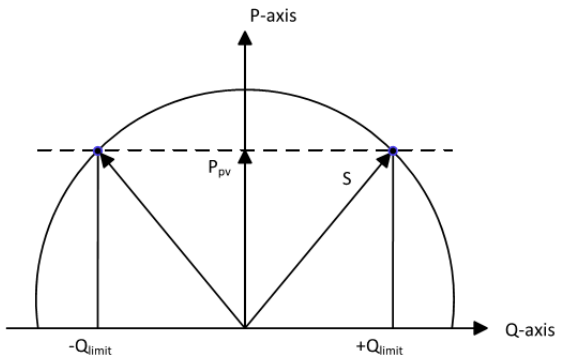

Figure 1: Maximum available reactive power by the inverter connected to PV system [10]

Where S is the capacity of the installed inverter, P_{pv} is the active power generated by PV and Q_{pv} is the reactive power generated/absorbed by the inverter. Maximum PV's output depends on the amount of available solar irradiation and PV's characteristic. So the maximum available amount of active power at each hour can be calculated as follows [1]:

$$P_{pv} = P_{stc} \times \left(\frac{G_c}{G_{stc}}\right) \times \left(1 + k \times (T_c - T_{stc})\right) \quad (2)$$

Where P_{stc} is the PV rated output power and P_{pv} is its actual output power. G_{stc} and G_c are amounts of the required solar irradiance to generate rated power in standard test condition (STC) and the irradiance of the current operating point, respectively. k is the power temperature coefficient, T_c is the PV temperature of operating point and T_{stc} is the temperature under STC.

2.1. Particle Swarm Optimization (PSO)

In this research, PSO approach is used to determine optimal amounts of the inverter's reactive power generation/absorption. PSO is one of the earliest introduced heuristic algorithms for solving complex optimization problems. This algorithm's mechanism is inspired by social behavior of some animal swarms such as birds flock, fish school and etc. PSO is a population-based optimization method which is modeled based on the swarm movement toward the leader member in order to find a better place [6]. Determining decision variables, defining a proper objective function and checking the practical constraints satisfactory to obtain feasible solutions are some essential points in using heuristic algorithms like PSO.

2.1.1. Decision variables

In this paper, amount of the reactive power generated/absorbed by the houses' inverters within the scheduling time interval are considered as decision variables. So decision variables matrix can be expressed as follow:

$$Q_{pv,H,T} = \begin{bmatrix} Q_{pv,1,1} & \cdots & Q_{pv,H,1} \\ \vdots & \ddots & \vdots \\ Q_{pv,1,T} & \cdots & Q_{pv,H,T} \end{bmatrix} \tag{3}$$

Where T is the scheduling time interval and H is the number of residential buildings within the HyPV system.

2.1.2. Objective function

Equation (4) shows the objective function is considered in this paper.

$$f = w_1 \times \sum_{t=1}^{T}\sum_{h=1}^{H}(V_{h,t} - V_i)^2 + w_2 \times \sum_{t=1}^{T}\sum_{h=1}^{H}|Q_{pv,h,t}| \tag{4}$$

Where $V_{h,t}$ is the voltage of house h at hour t, V_i is the target voltage and $Q_{pv,h,t}$ is generated/absorbed reactive power by the inverter of house h at hour t. w_1 and w_2 are weighting factors.
The first section of equation (4) is designed for voltage regulation of the residential buildings within the test system in order to keep system voltage in the allowable range. The second section is intended to minimize the amount of total reactive power generated/absorbed by the inverters in the test system. This part is designed to prevent early depreciation of the inverter equipment simultaneously. Through minimizing this part, the main goal, which is voltage regulation, will be achieved by utilizing minimum possible number of the required inverters.

2.1.3. Practical constraints

In most optimization problems, it is so important to define some technical constraints in order to make feasible the found solutions. In this paper, the following constraints are taken into account to verify the solutions which will be found by the optimization approach.

$$\sum_{h=1}^{H} P_{pv,h,t} + P_{Grid,t} + \sum_{h=1}^{H} P_{Bat,h,t} - \sum_{h=1}^{H} P_{L,h,t} = 0 \qquad \forall\, t \in T \tag{5}$$

$$V_{min} \le V_{h,t} \le V_{max} \qquad \forall\, t \in T \;\;\&\;\; \forall\, h \in H \tag{6}$$

$$-Q_{lim,h,t} \le Q_{pv,h,t} \le Q_{lim,h,t} \qquad \forall\, t \in T \;\;\&\;\; \forall\, h \in H \tag{7}$$

Where $P_{Grid,t}$ amount of the active power injected by the upstream network, $P_{L,h,t}$ is the demand of house h at hour t and $P_{Bat,h,t}$ is output of the battery installed in house h at hour t. Equation (5) guarantees power balance in the system and equations (6) and (7) are considered to ensure that buses voltage and generated/absorbed reactive power are within their allowable ranges. It is notable that $Q_{lim,h,t}$ can be calculated by equation (1).

2.2. Determining islanded operation time

In this paper, it is assumed that the under study test system is a HyPV system. A typical HyPV system includes PV and ESS units. It can be operated in either grid-connected mode or islanded mode and its operation mode is determined based on available solar energy [8]. Therefore, in our research, the system operation will be scheduled in such a way that in cases when the energy produced by the PV system plus the energy stored in the ESS are adequate to supply the system demand entirely, the system will be operated in islanded mode. Otherwise, the HyPV system will be connected to the upstream network and in this case, the system electrical demand is totally supplied by the power system. In cases when the solar energy is available during the grid-connected operation, it will be stored in each building's ESS and will be used at the proper time in order to prevent wasting solar energy. So, there are two possible amounts for PV output power in islanded mode [8]:

$$P_{pv} = \begin{cases} P_{mp} & \text{The battery isn't fully charged} \\ P_L & \text{The battery is fully charged} \end{cases}$$

Where P_{mp} is the maximum available active power that can be generated by the PV systems. Also amount of the active power supplied by the upstream network in two different HyPV operation modes is as follows:

$$P_{Grid} = \begin{cases} 0 & \text{Islanded mode} \\ P_L & \text{Connected mode} \end{cases}$$

2.3. The procedure of the proposed method

In this section, the steps of implementing the proposed method are explained.

Step 1: All required data such as numeric information of the under study test system, forecasted values of the electrical demand, available solar energy at the desired time interval and etc. are received.

Step 2: The available electrical energy is evaluated and compared by the electrical demand value.

Step 3: stand-alone operation of the HyPV system is scheduled.

Step 4: Charge/discharge plan of each residential building's ESS is scheduled.

Step 5: The power flow is calculated for each hour of the under study time interval. Then the hours that the voltage constraint isn't satisfied will be determined.

Step 6: Amount of the reactive power is generated/absorbed by the inverters will be scheduled using PSO approach on purpose of voltage regulation.

Step 7: power flow is calculated and in cases where any practical constraints isn't satisfied, step 6 will be repeated again.

Step 8: The results are displayed.

3. Results and discussion

The presented method is implemented in the test system is shown in Fig. 2. In the test system, all equipment of the residential buildings are connected to control center via communication links and can receive plans and send required data. In this research, it is assumed that the exactly forecasted data of the system demand is available for the future scheduling time interval. Also for simplicity, it is assumed that all houses have similar demand curves and it is shown in Fig. 3.

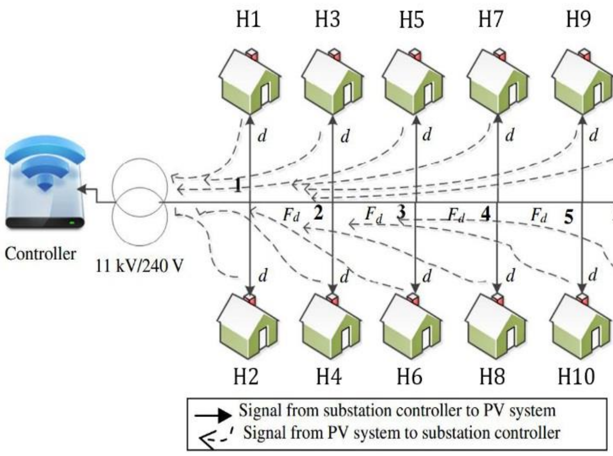

Figure 2: The test system [7]

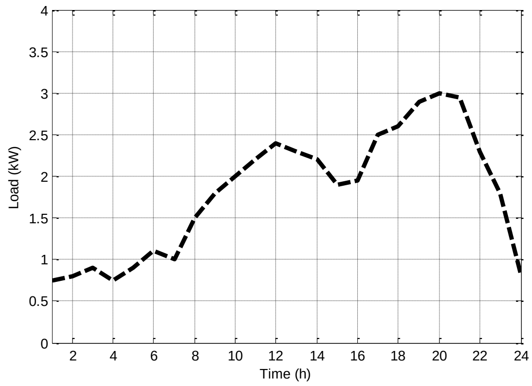

Figure 3: Electrical demand of each house

To demonstrate efficiency of the proposed method, two different sets of values are considered as available solar energy. The first set is values of solar irradiation at a summer day and the second one includes solar irradiation values on a winter day. The solar irradiation values of these two days are shown in Fig. 4.

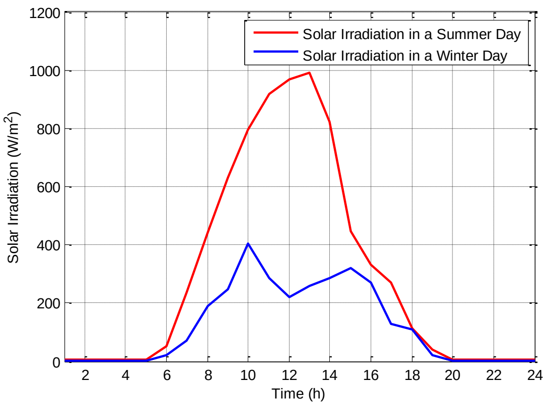

Figure 4: Solar energy of the two considered days

By considering the summer day's solar irradiation data, the buildings' voltage profile before regulating voltage by reactive power generation/absorption has been shown in Fig. 5. It is notable that the presented voltage profile has been obtained after determining ESS charge/discharge scheduling. In this paper, the allowable voltage range is considered [0.94 1.06] p.u. Therefore, given the solar irradiation data and the load curve are shown in Fig. 3 and Fig. 4, respectively, at hours with high irradiation values, the over-voltage issue will occur in the system. On the other hand, the voltage declines significantly at peak demand hours and exceeds the allowable voltage range. To solve these issues, it is so important to use voltage regulation schemes.

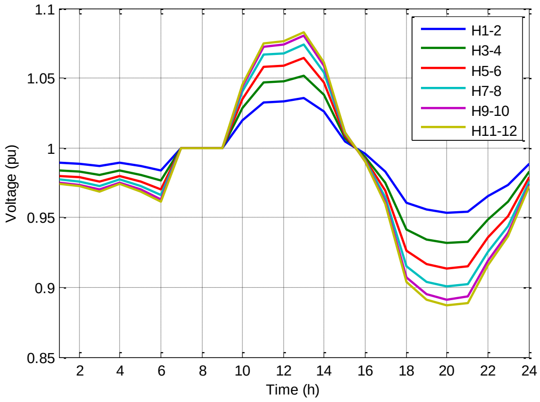

Figure 5: Summer day voltage profile before voltage regulation

By scheduling generated/absorbed reactive power by the inverters connected to the PV systems and performing the obtained optimal plan, the voltage profile will be regulated as shown in Fig. 6. Amount of the reactive power that is scheduled to be generated/absorbed by each house's inverter is shown in Fig. 7. As it can be seen in Fig. 7, in cases when it is needed to generate or absorb reactive power to improve the system voltage profile, the voltage regulation will be done by using the least possible amount of the available reactive power capacity. Also, it should be noted that in this figure, reactive power absorption is indicated by negative values and the positive values denote reactive power generation.

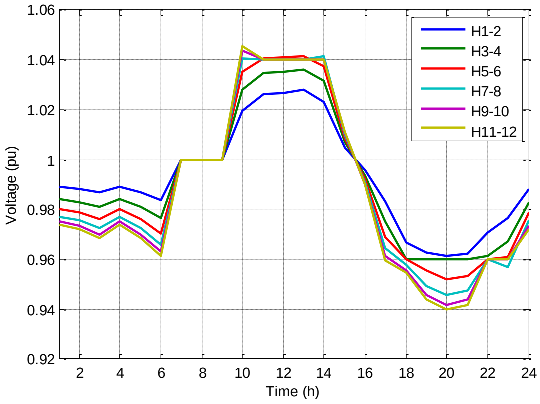

Figure 6: Summer day voltage profile after voltage regulation

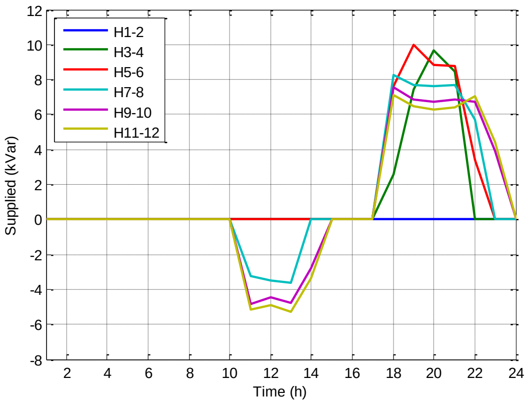

Figure 7: Scheduled plan for reactive power generation/absorption in the summer day

The scheduled operation of the HyPV system is shown in Fig. 8. This figure presents some useful information including the schedule of switching between grid-connected mode and islanded mode, amount of the energy stored in the battery at each hour and also amount of the energy charged/discharged into/from the battery at each hour of the day ahead. In the battery charge/discharge graph, positive (negative) value indicates charging (discharging) electric power. The grid mode graph declares the HyPV system operation state and in this graph, value 1 means that the HyPV system is connected to the upstream network and value 0 indicates islanded operation.

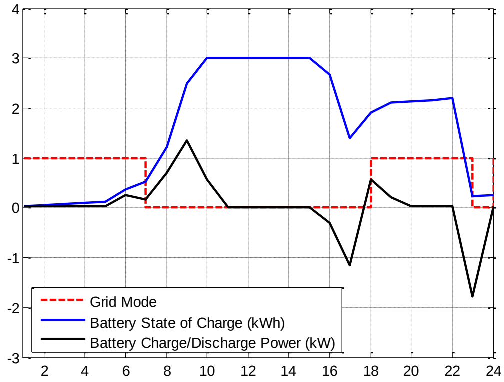

Figure 8: Scheduled plan for HyPV system operation in the summer day

As it can be seen in Fig. 8, by considering the available solar energy in the summer day (Fig. 4), when the solar irradiation reaches to its maximum amount between hours 7 and 15, the HyPV system is operated in islanded mode. At this time period, in addition to supplying electrical demand by using PV output, the surplus energy will be stored in the battery by utilizing its total capacity. Between hours 16 and 18, which the available solar energy is decreased, the houses' electrical demand is supplied by using the energy stored in batteries. When the solar energy declines significantly between hours 18 and 22, the HyPV system will be connected to the upstream network and the electrical load will be met by the power network entirely. At last hours of the day, which the electrical demand is decreased and the stored energy is enough to supply all houses' demand, once again the HyPV system operation mode will be switched to islanded mode.

On the other hand, by considering solar irradiation curve in the winter day and the same load curve which is shown in Fig. 3, voltage profile of the system houses, before performing voltage regulation plan, will be as Fig. 9. By scheduling inverters operation to generate/absorb reactive power with aim of voltage regulation, the system voltage profile will be improved as Fig. 10. Fig. 11 shows amount of generated reactive power by inverters at all hours of the day ahead. Fig. 12 declare the HyPV system operation mode, the energy stored in batteries and the amount of charged/discharged energy.

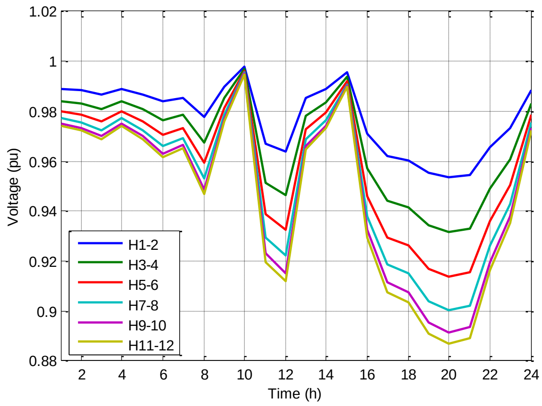

Figure 9: Winter day voltage profile before voltage regulation

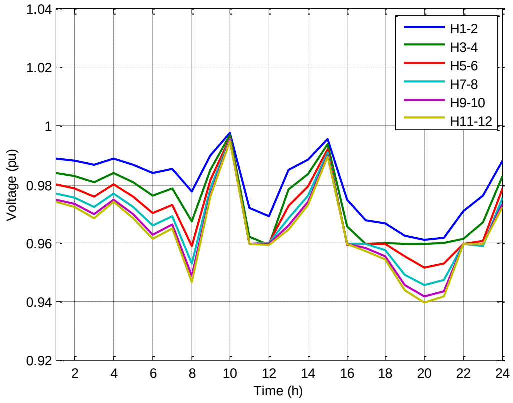

Figure 10: Winter day voltage profile after voltage regulation

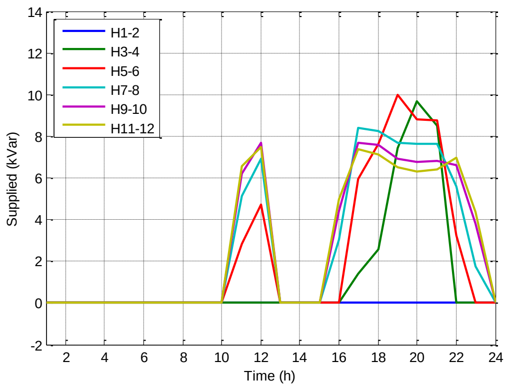

Figure 11: Scheduled plan for reactive power generation/absorption in the winter day

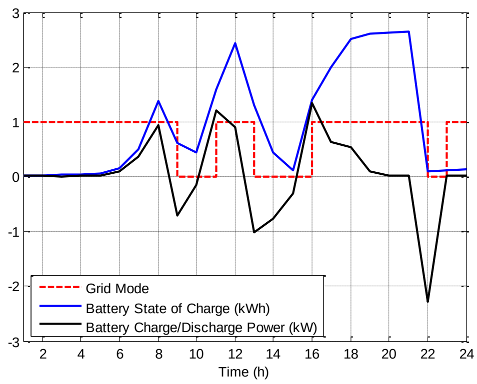

Figure 12: Scheduled plan for HyPV system operation in the summer day

As it can be seen in Fig. 9 and Fig. 10, due to the lower solar irradiation in comparison to the summer day, there isn't any over-voltage issue in the entire day. The HyPV system load is all supplied by the upstream network when it is operated in grid-connected mode and in this mode, the solar energy, if is available, will be stored in the batteries. So at this time period, the system demand is all fed from one end and this causes to occur under-voltage issue in houses in the end of the feeder. The amount of each house voltage violation depends on its load value. Therefore, when the system is utilized in grid-connected mode, more reactive power is needed to regulate voltage. This point is obviously noticeable in Fig. 11 and the system operation curve in Fig. 12. Also, it can be seen in Fig. 12 that in winter days, which the solar irradiation decreases significantly, the system demand can't be met only by using the PVs output. For this reason, more times of switching between grid-connected and islanded modes are needed in the winter days.

Conclusion

Todays, rate of RESs utilization is increasing rapidly; but using these energy sources, besides its significant advantages, has some drawbacks such as undesirable voltage violation, especially over-voltage issue at high solar irradiation hours. In this paper, a method is proposed to correct and regulate a HyPV system voltage profile. In the proposed method, by using PSO algorithm to schedule amount of inverters reactive power generation/absorption, the test system voltage profile is regulated. This procedure is carried out in such a way that the minimum possible amount of reactive power will be used to regulate the voltage profile within the allowable range. To demonstrate efficiency of the proposed method, two solar irradiation curves from two different days were taken into account and their features were investigated based on the numerical results. As a result, it is concluded that effectiveness of the presented HyPV system increases in days with high solar irradiation. But in winter days, due to the deficient available solar energy, the system operation mode will be switched frequently and this may cause some disturbances in the system from the dynamic point of view. On the other hand, this probable problem can be solved by considering some compensation schemes such as presenting spinning reserve service by the ESS and etc. that will be carried out in our future works.

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