Case Study: Modelling and sizing stand-alone PV systems for powering mobile phone stations in Libya

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Abstract: A mobile telecommunication sector has experienced a rapid growth in Libya and Al-Madar Al-Jadid is one of largest companies providing services in this sector. Currently, PV systems are widely used for powering remote GSM communication stations in the country and number of Al-Madar Al-Jadid communication stations powered by such stand-alone PV systems was about 135 in 2009. A Simulink Matlab model was built to dynamically simulate the operation of the stand alone PV system powering one of Al Madar Al Jadid remote communication stations in desert conditions, taking into account variation of insolation and ambient temperature during a day. The results of mathematical modelling on the producible and produced power, charging and discharging battery power and the state of charge of the battery bank are in a good agreement with real experimental data recorded on the station with the use of a data-logger. Results obtained clearly indicated that the existing system, including PV panels and the electrical storage, is excessively large for the current electrical demand on the station and therefore could be reduced in the size by a factor of two.

Keywords: *Stand alone PV systems, Modeling stand alone PV systems, Powering mobile phone stations by stand alone PV systems.*

1. Introduction

The use of PV systems for powering remote communication stations is rapidly expanding in both developed and developing countries [1]. In Libya the photovoltaic power has been in use for the stations of communication networks since 1979. The use of the PV technology instead of diesel-generators reduces operational costs, since there is no need for fuel transportation, and is exhaust gas emissions (CO_2 and NO_x) free.

A typical PV system generally consist of an array of PV panels (a solar generator), an energy storage, which is very important for stand-alone systems, a power conversion system made of DC/DC converters and inverters, and an associated power flow control.

Dynamic modelling the operation and interaction of all system components, especially the PV generator and the electrical storage, is very important for the system assessment and its sizing. Mathematical models should be validated against the performance of the actual system in order to evaluate its accuracy and then can be used with a confidence to predict the overall performance of similar systems with different sizes. In this study, the PV generator and the electrical storage made of battery banks have been modelled in the Libyan environment using Simulink Matlab software and then the model results were compared to experimental data collected in one of Al-Madar Al-Jadid standalone communication stations.

2. Methodology

2.1. Modelling of the stand-alone PV system

The system model combines two sub-system models, the PV model and the battery storage system model, see *figure 1*. The model does not take into account the influence of air flow, due to its complexity, and calculates the DC output power of the PV array (P_{PV}) in watts as function of the solar irradiance, the PV cells temperature and the ambient temperature. The DC power output of the PV array is used as input data in the battery storage model. The battery model simulates a lead-acid battery bank and calculates the electricity flow for situations when batteries are charged or discharged and also the surplus and deficient power values.

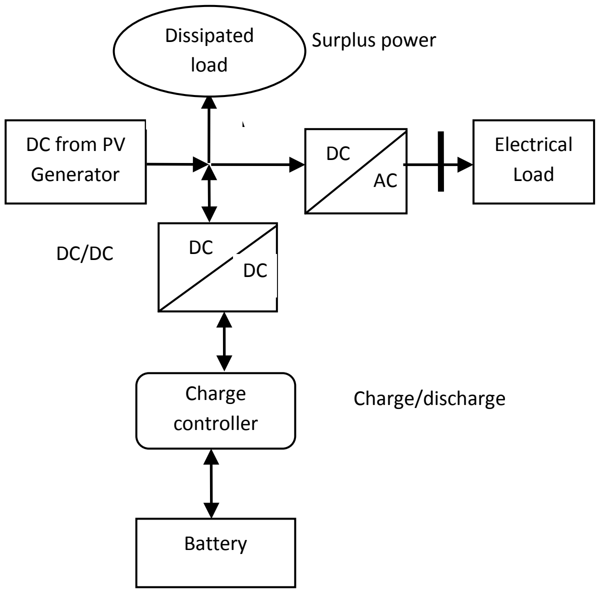

Fig. 1. The schematic of the electrical storage and electrical interface model

2.2. PV generator model

In order to achieve the best performance the PV modules must operate at the maximum power point (MPP). There are several methods to calculate DC power generated by the PV system and in this work this value was calculated as [2]:

$$\mathrm{P}_{PV} = \eta_g \times \mathrm{N} \times \mathrm{A}_m \times G_\mathrm{T}, \qquad (1)$$

where η_g is the instantaneous efficiency of the PV system, A_m is the area of a single PV module (m^2), G_T is the global irradiance incident on the titled plane (W/m^2) and N is the number of modules.

In the modelling it was assumed that connection and wiring losses and all other energy losses in the PV system are negligible.

The instantaneous efficiency of the PV generator is given as

$$\eta_g = \eta_r \times \eta_{TR}\left[1 - \mathrm{B}_\mathrm{T}\left(\mathrm{T}_c - \mathrm{T}_r\right)\right]. \qquad (2)$$

Here η_r is the PV generator reference efficiency, η_{TR} is the efficiency of the maximum power point tracker (MPPT), $\mathrm{T_c}$ is the solar cell temperature (°C), $\mathrm{T_r}$ is the solar cell reference temperature (°C) and $\mathrm{B_T}$ is the temperature coefficient, ranging from 0.004 to 0.006 per °C for a silicon cell.

The PV cell temperature is expressed as [3]:

$$\mathrm{T}_c = \mathrm{T}_a + G_\mathrm{T}\left(\frac{\tau \times \alpha}{U_L}\right), \qquad (3)$$

where T_a is the ambient temperature (°C), U_L is the overall heat loss coefficient (W/m^2 °C), τ and α is the transmittance and the absorbance coefficients, respectively, of the PV cell.

In this investigation the simplified mathematical model of the PV generator has been adopted in Simulink Matlab in order to calculate the DC power output and this model is based on the following equation [4]:

$$\mathrm{P}_{PV} = \eta_{\mathrm{PV}} \times S \times \mathrm{A}_{\mathrm{PV}} \left(1 + \sigma_T \left(\mathrm{T}_c - \mathrm{T}_{c\_ref}\right)\right) \times \eta_{MPP\_PV}, \quad (4)$$

where P_{PV} is the DC power output of the PV generator, S is the solar irradiance incident on the surface of the solar cell, η_{PV} is the efficiency of the PV generator, A_{PV} is the area of the PV modules, σ_T is the temperature coefficient, T_c is the solar cell temperature, T_{c_ref} is the reference solar cell temperature and η_{MPP_PV} is the efficiency of the MPP tracker.

The input data for the Simulink Matlab model consists of the irradiance, the ambient temperature, the temperature of the cell, the area of the modules and the reference solar cell temperature. The Simulink Matlab model simulates the PV generator when it is working at the MPP.

The temperature of the PV cells is a function of the weather conditions and the PV cells characteristics. The PV cell temperature (T_c) is given as [4]:

$$\mathrm{T}_c = \mathrm{T}_a + \frac{S}{S_{ref}} \times \left(\mathrm{T}_{c\_ref} - \mathrm{T}_{a\_ref}\right) \times \left(1 - \frac{\eta_{PV}}{0.9}\right), \quad (5)$$

where S_{ref} is the reference solar irradiance and T_{a_ref} is the reference ambient temperature.

2.3. Electrical storage system model

The battery storage system, shown in *figure 1*, has been adopted from [6]. It is relatively simple model but is sufficient to achieve the purpose of these investigations, which is evaluation of the power flow between the PV generator and the load and batteries and between batteries and load when it is necessary to compensate the shortage in the power production. The model is based on a time resolution of 60 minute to simulate the generated power, the load demand, the electrical storage and the power losses in the inverters and the power electronic equipment. The model is a generic and can simulate different sizes of the electrical storage system by changing the nominal voltage of the system V_B and the storage capacity C_O.

The nominal DC voltage output V_B of the battery in the model is set to be 48 V to match the battery used in the Al Madar Al Jadid telecommunication station. The storage capacity C_O of battery bank of PV system used in the stations of Al Madar Al Jadid is 5964 Ah. The state of charge SOC can be defined from documentation provided by the manufacturer. It is recommended not to discharge the battery completely in order to increase the life span of the battery and to avoid the very high drop of the battery voltage. Manufacturers commonly recommend the SOC from 20% to 80% of the storage capacity C_O. However, in this model, SOC_{max} and SOC_{min} are taken as 100% and 20% of C_O, respectively, to guarantee an acceptable battery's lifetime (i.e. SOC_{max}=5964 Ah and SOC_{min}= 4771.2 Ah). It is recommended in the provided technical documentation that the maximum allowable discharging current should be equal to C/5 and that the maximum charging current should be equal to C/10. Thus, in the battery bank the maximum allowable discharging current I_{Dmax} and the maximum allowable charging current I_{Cmax} are 1192.8 and 596.4 A, respectively.

Charging and discharging currents at any time (t) vary depending on the shortage or surplus in the available DC power from the PV generator, though, in order to ensure efficient performance of the battery, a charge controller limits these currents to the maximum and minimum amounts, I_{Dmax} and I_{Cmax}, respectively [5].

The surplus power P_+ at any time is the difference between the power of the PV generator (P_{PV}) and the electricity demand of the load P_{Load} at the same time [5]:

$$P_+ = P_{PV} - P_{Load}, \quad P_{PV} > P_D \tag{6}$$

where P_D is the electricity demand of the site at any time.

However, when the power produced by the PV generator P_{PV} is less than the demand, then a shortfall in power P_- can be calculated as follow:

$$P_- = P_{Load} - P_{PV}, \quad P_D > P_{PV} \tag{7}$$

The surplus power produced by the PV modules is used to charge the battery bank, unless it is already fully charged; the batteries charging current (I_{CO}) is limited by the charge controller to the maximum allowable charging current I_{Cmax} and SOC must be equal to or less than SOC_{max}. The charging current I_{CO} is calculated as [5]:

$$I_{co} = \frac{\left(P_+ \times \varepsilon_c \times \varepsilon_{B1}\right)}{V_B}, \tag{8}$$

where ε_C is the charge controller efficiency (it is constant and equal to 0.98 in the model) [5]; ε_{BI} is the AC/DC converter efficiency, though it varies insignificantly with the load, it is assumed to be constant at 0.9; V_B is the system and the batteries voltage and equals to 48 V.

In the event when the power required by the demand exceeds the generated power the current from the battery I_{DO} contributes to compensate this shortfall power. I_{DO} is

$$I_{DO} = \frac{P_-}{\left(V_B \times \varepsilon_C \times \varepsilon_{B2}\right)}, \tag{9}$$

Here ε_{B2} is the efficiency of the DC/AC converter or inverter [5].

The change in the battery capacity C_D with a period of time of Δt can be calculated as:

$$\Delta C = \left(I_C \times \Delta t\right) - C_D, \tag{10}$$

The battery state of charge SOC at any time *t* is calculated by the following equation:

$$SOC_t = SOC_{(t-1)} + \Delta C, \tag{11}$$

where $SOC_{(t-1)}$ is the battery's SOC at the time earlier than t, which is limited by the values of SOC_{min} and SOC_{max}.

The PV generator sources the load and charges the batteries during the day. In sunny periods, when the batteries are fully charged there will be more power produced than it is required. Therefore, the surplus power is dissipated in the Simulink model. The power demand supplied by the batteries at any time is calculated as [5]:

$$P_{batt} = I_D \times V_B \times \varepsilon_{B2} \times \varepsilon_C \qquad (12)$$

On the other hand, if there is surplus power P_+ and SOC = S OC_{max} or $I_{CO} > _{ICmax}$, the dissipated power P_{diss} will be determined as

$$P_{diss} = \left[\frac{I_{CO}}{\varepsilon_{B1} \times \varepsilon_C} - I_C\right] \times V_B \quad P_{diss} = \left[\frac{I_{CO}}{\varepsilon_{B1} \times \varepsilon_C} - I_C\right] \times V_B \text{ For } I_{CO} > I_C \qquad (13)$$

The model calculates the SOC for every minute taking into account the charging and discharging currents determined in equations 8 and 9, the maximum and minimum limits of the charge, SOC_{max} and SOC_{min}, respectively. The power drawn from the battery C_D at any time estimated by multiplying I_D by Δt in hours. However, the efficiency of discharge at high rates is considerably lower than 100%, so the accurate discharge efficiency can be calculated as [6]:

$$C_D = \frac{I_D \times \Delta t}{\alpha}, \quad C_D = \frac{I_D \times \Delta t}{\alpha}, \quad 0 \leq \alpha \geq 1 \;\; 0 \leq \alpha \leq 1 \qquad (14)$$

where α is the discharge efficiency determined as [5]:

$$\alpha = \frac{13.3 \times \ln\left(\frac{C_O}{I_D}\right) + 59.8}{100}, \quad 0 \leq \alpha \geq 1 \qquad (15)$$

It has been assumed in the model that the value of α cannot exceed the value w hich guarantees that the maximum charge removed from that battery at any time period Δt does not exceed the product ($I_D \cdot \Delta t$).

Although the same phenomenon is present during charging process, it does not significantly affect the efficiency of charging, especially with the charge current limited to C/10 (as highlighted earlier). So, such the effect has been neglected in the model. Consequently, the change in battery capacity C_D during any time period Δt is calculated as

$$\Delta C = \left(I_c - \Delta t\right) - C_D \qquad (16)$$

Thus, the battery SOC at any time t is calculated using the following equation:

$$SOC_t = SOC_{(t-1)} + \Delta C, \qquad (17)$$

Here $SOC_{(t-1)}$ is the battery's SOC at the time earlier than t and is limited by the values of SOCmin and SOCmax.

3. Experimental Part

Al Madar Al Jadid Company started using PV panels for power supply of stations in 2005, when 6 new stations were built in a r ural areas and the General Company of Electricity refused to power these new sites since some of them were away from the national grid and the grid network in the vicinity of others were not powerful enough. The PV systems were supplied and installed by Total Company using Ericsson a sub-contractor. The PV systems and batteries with the voltage of 24Vdc were used to power the stations directly without DC/AC conversion. Recently, the network of Al Madar Al Jadid Company has expanded to cover rural regions, oil company sites and roads in the desert area. A project to built 350 stations including 135 sites powered by PV panels, was developed and accepted in 2009. The new stations will have AC air conditioning, so it is necessary to use DC-AC inverters.

The GSM station which was chosen to be used for evaluation in this study is located in the vicinity of the main road connecting country's north and south parts and is about 50 km away from the national grid. The actual data used in this study is acquired at the location of the station using a laptop base data acquisition system. The data has been collected over three times periods, namely in January, April and July.

4. Results and discussion

During numerical investigations the average hourly performance of the PV system was modeled for three periods, namely January, April and July, and then the theoretical results were compared with the corresponding experimental data. The climatic conditions were taken from NACA collected data and the highest discrepancy between theoretical and experimental results was observed in modeling of operation in January period. Even so, the theoretical model provides acceptable accuracy in simulation the performance of the PV system.

The load entered into the Simulink Matlab model is an actual load for the real PV generator operating in Libyan winter conditions.

Although the solar radiation on a horizontal surface in winter, particularly, in January and December is not high, the solar radiation on an inclined surface is fair and at noon reaches the level of about $700W/m^2$. The high value of the geometric factor for January and December months causes an increase in the solar radiation on inclined surfaces.

Figure 2 illustrates the DC power that can be produced by the PV generator. Overall, the both theoretical and experimental curves have the same trend and the output power, which is represented by the area under the curves, is almost equal. The main difference is that the curve of the experimental output power is shifted in time and the PV system starts to generate power at about 8:30 am and not at 7.30 as predicted by simulations. This is because of satellite data on solar irradiance used in this study which is hourly data for a fixed period from 7:30 to 16:30 for 12 months of the year.

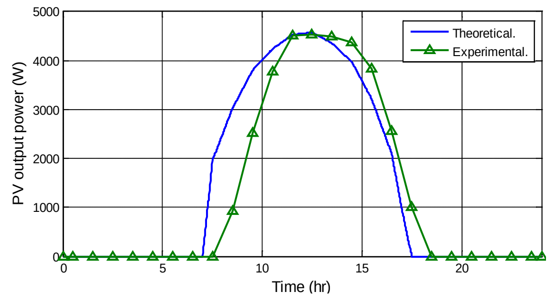

Fig. 2. Producible PV power

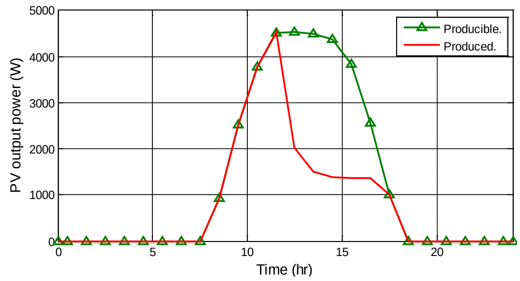

Fig. 3. Producible and produced PV power

Figure 3 shows the actual power produced by the PV generator and how much power is lost as a result of over sizing the PV system. The sum of the power consumed by the load and received by the electrical storage is about a half of the total producible power.

It can be seen in *figure 4* that the simulated battery charging curve is very similar to that of the experimental results. In both theory and experiment the batteries receive power as soon as it is started to be generated by the PV panels and it demonstrates that the power consumed by the load is very small compared to the power generated. On the other hand, the batteries are fully charged within few hours, because of the low power discharge, which is result in the huge capacity of the battery bank comparing with the load consumption. However, it can be observed from the experimental curve in *figure* 4 that the batteries charging is continued until the end of the day to compensate battery self-discharging process.

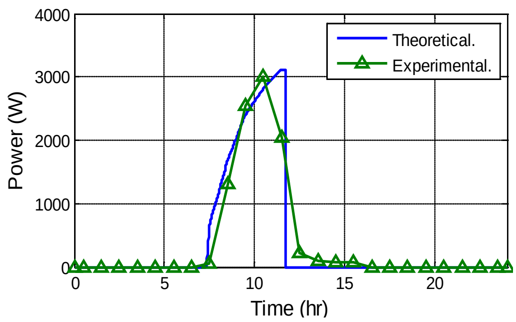

Fig. 4. Charging power

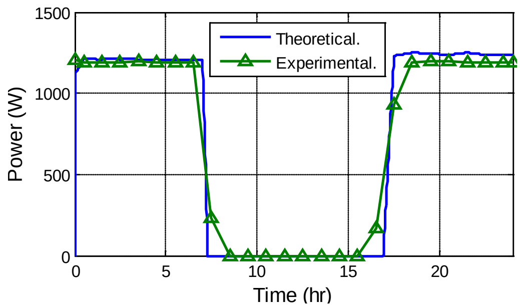

Fig. 5. Discharging power

Figure 5 presents the theoretical and experimental results on the battery discharging. As it can be seen from this figure, the curves are close, except at the beginning and the end of the day. Theoretically, the load is supplied either by the PV generator or the electrical storage; while in the real system, the shortage in the power from the PV generator is compensated by the power from the battery and this is reason for discrepancy between theoretical and experimental curves.

Figure 6 shows the SOC and processes of charging and discharging power in the summer period. It can be observed in this figure that, the batteries are fully charged within few hours, due to the small power drawn by the load during the night time. That emphasizes the excessive capacity of the battery bank compared with the load consumption.

As it is highlighted above, the power produced by the PV panels is disproportionately large when compared to the load consumption and the electrical storage. On the other hand, the capacity of the electrical storage is also very large with respect to the power consumed by the load. As a result, the deficit in the power is always zero. The dissipated power, which is represented by the red colour section in *figure 7*, is approximately two thirds of the total power that can be produced if the capacity of the battery bank is large enough, whereas the produced power, which is represented by the blue colour section, is only about one third of the total power.

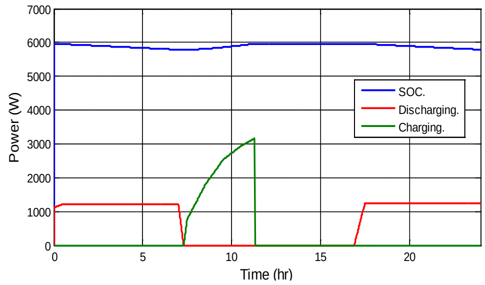

Fig. 6. State Of Charge of the battery bank

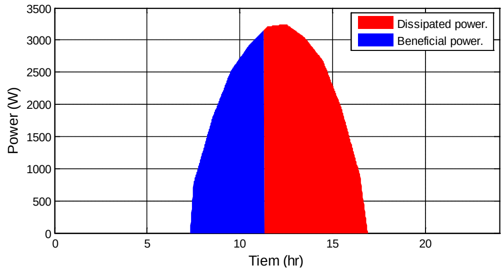

Fig. 7. The beneficial and the dissipated power

5. Conclusion

In this study the performance of standalone PV systems in telecommunication stations has been numerically evaluated. The simulation results illustrated that there is a considerable amount of the producible power is dissipated due to the over sized PV panels which can produce much more electricity than that could be stored in batteries bank. On other hand, the power drown from the battery bank at the normal rate is small and does not exceed 3% of the total stored power, which demonstrates the excessively large capacity of the electrical storage. Although zero solar radiation situations are very unlikely to have place such scenario taking place for 24 hours was simulated in order to calculate the power supplied by the battery and the SOC of the battery bank. The results from the simulation of such the scenario showed that only 10% of the total stored power is drawn from the battery in the winter, autumn and spring seasons, and in summer period this value is 11% of the total stored power. These results emphasize the large capacity of the battery bank. As a result of series calculations, it is found that the 60% of the existed PV modules area and 50% of the electrical storage capacity would be sufficient for powering the station. This would also result in significant reduction (by about 50%) of the capital cost of the PV system.

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