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Novel simplified hourly energy flow models for photovoltaic power systems

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Abstract
This paper presents simplified energy flow models for photovoltaic (PV) power systems using MATLAB. Three types of PV power system are taken into consideration namely standalone PV systems, hybrid PV/wind systems and hybrid PV/Diesel systems. The logic of the energy flow for each PV power system is discussed first and then the MATLAB line codes for these models are provided and explained. The results prove the accuracy of the proposed models. Such models help modeling and sizing PV systems.

Keywords: PV system, sizing of PV system, modeling of PV systems

1. Introduction

Based on the fact that PV systems are clean, environment friendly and secure energy sources, the installation of PV systems has played an important role worldwide. However, the drawback of PV systems is the high capital cost compared with conventional energy sources. Currently, many research works are carried out focusing on the optimization of PV systems so that the number of PV modules, capacity of storage battery, capacity of inverter and PV array tilt angle can be optimally selected. the size and performance of PV systems strongly depend on meteorological variables such as solar energy, wind speed and ambient temperature and therefore, to optimize a PV system, extensive studies related to the meteorological variables have to be carried out [1,2].

The modeling of PV components such as PV module/array, battery, inverter and wind turbine plays important roles in optimizing PV systems. Research works related to PV system size optimization including PV system modeling can be found in [3-12]. In [3], the probabilistic approach is used to optimize PV systems by considering a probability function which is expressed as the probability of losing load (the case when the energy source is not able to fulfill the load demand) in terms of battery, PV array energy output and load demand. Therefore, the determination of an optimum storage battery is based on the reliability of the PV system, the optimum PV array size is calculated using the worst month method. In Europe, optimization of PV systems is done for three sites in which optimization considers PV array sizing curves derivation and minimum storage requirement in order to fulfill the desired load demand. The sizing curves of the PV array were helpful in calculating the PV array size based on the required energy production by the system [4]. To avoid any load interruption, the PV array size is designed based on the worst monthly average of solar energy. As for finding the minimum storage requirement, the same method for plotting sizing curves is used and the minimum storage requirement is calculated for each year of the used historical data. In [5], a PV system model has been developed to optimize its size based on a well-defined solar energy potential and load. The developed model contains models for PV array, storage battery and charge regulator. However, the optimization considers the combined minimum cost with minimum loss of load probability. In [6], optimization of PV systems in Delhi has been done using the loss of power supply probability. A defined load and daily solar energy has been used to calculate the loss of power supply probability. Then a sizing curve is generated based on the calculated loss of power supply probability. The number of PV modules and battery capacity are also evaluated based on the minimum cost. An analytical method for sizing PV systems based on the concept of loss of load probability has been also developed [7]. The method considers the standard deviation of the loss of load probability as well as annual number of system failures and the standard deviation of the annual number of failures. The optimization of the PV array tilt angle is also done so as to maximize the collected yield.

In the previous works, models for the PV components have been suggested in order to optimally design these systems, none of these works has presented an operational model for PV system in order to validate the suggested results. On the other hand some of the models proposed in the literature such as the works presented in [8-12] mainly focus on the output power of the PV array only, meanwhile, none of these models have considered the energy follow in the whole system. Based on this, this paper presents energy flow models for three types of PV systems, namely standalone PV systems, Hybrid PV/wind systems and hybrid PV/diesel system using MATLAB. The main objective of these models is to predict the performance of PV systems through a specific time period which helps validate PV system sizing techniques.

2. Energy Flow Modeling for standalone PV Power Systems

Modeling of standalone PV system, (SAPV) is very important in sizing system's energy sources. Therefore, many mathematical models have been described for SAPV systems. Figure 1 shows a typical PV system consisting of a PV module/array, power conditioner such as charge controller or maximum power point tracking controller (MPPT), batteries, inverter and load.

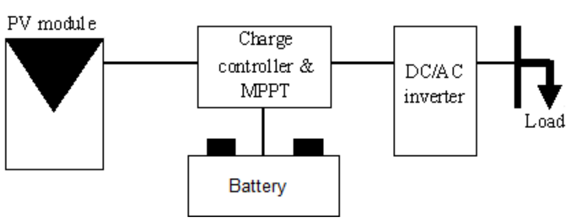

Figure 1 Typical PV system components

In general, a PV array collects energy form the sun and converts it to DC current. The DC current flows through a power conditioner to supply the load through an inverter. The daily output power produced by a PV module/ array is given by,

$$P_{PV}(t) = [P_{Peak}\left(\frac{G(t)}{G_{standard}}\right) - \alpha_T[Tc(t) - T_{standard}]] * \boldsymbol{\eta_{inv}} * \boldsymbol{\eta_{wire}} \quad (1)$$

where $G_{standard}$ and $T_{standard}$ are the standard test conditions for solar radiation and ambient temperature, respectively, and α_T is the temperature coefficient of the PV module power which can be obtained from the manufacturer datasheet. $\eta_{inv} and\, \eta_{wire}$ are the efficiencies of inverter and wires, respectively.

The temperature (Tc) in eq. (1) is the cell temperature. The cell temperature can be calculated by,

$$T_c(t) - T_{ambient}(t) = \frac{NOCT-20}{800} G(t) \quad (2)$$

where NOCT is the nominal operation cell temperature which is measured under 800 w/m^2 of solar radiation, 20 ^{o}C of ambient temperature and 1 m/s of wind speed.

The calculation of energy produced by the PV array (E_{PV}) depends on the time step of the weather data used . In other words if the input solar radiation data are hourly then the power produced by the PV array , $P_{PV}(t)$ is equal to PV energy production $E_{PV}(t)$. Meanwhile if the input data are daily solar energy then,

$$E_{PV}(t) = P_{PV}(t) * S \quad (3)$$

Where S is the day length which can be given by

$$\boldsymbol{S = \frac{2}{15}\, cos^{-1}(-\tan L \tan \delta)} \quad (4)$$

where L is the latitude and $\boldsymbol{\delta}$ is the angle of declination, given by

$$\boldsymbol{\delta = 23.45 \sin\left[\frac{360\,(284+N)}{365}\right]} \quad (5)$$

where N is the day number (the counts of days starting from the 1st of January, e.g, N for the 1st of February is 32.

As for the calculation of the inverter's conversion efficiency, Figure 2 shows an efficiency curve for a commercial inverter obtained from the manufacturer datasheet. The curve describes the inverter's efficiency in terms of input power and inverter rated power.

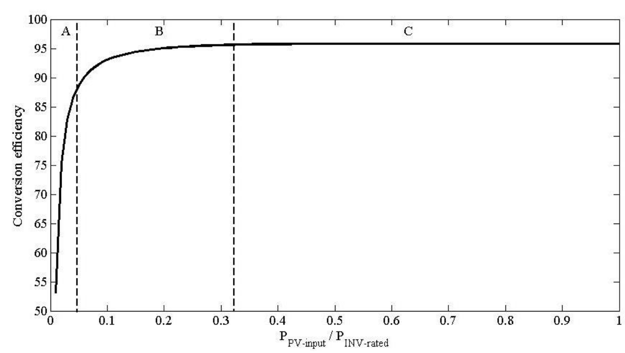

Figure 2 Typical efficiency curve of an inverter

The efficiency curve can be described by a power function as follows,

$$\begin{cases} \eta = c_1\left(\frac{P_{PV}}{P_{INV_R}}\right)^{c_2} + c_3 & \frac{P_{PV}}{P_{INV_R}} > 0 \\ \eta = 0 & \frac{P_{PV}}{P_{INV_R}} = 0 \end{cases}$$

(6)

where $P_{PV}\, and\, P_{INV_C}$ are the PV module is output power and inverter's rated power respectively while C1-C3 are the model coefficients. The MATLAB fitting tool can be used for calculating coefficients, C1-C3. Figure 3 shows the logic diagram for modeling standalone PV system.

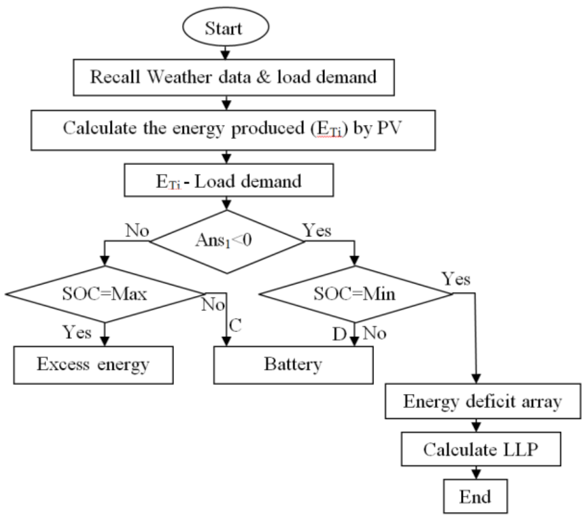

Figure 3 Logic diagram for modeling standalone PV system

The energy at the front end of a SAPV system or at the load side is given by,

$$E_{net}(t) = \sum_{i=1}^{366}(E_{PV}(t) - E_L(t)) \quad (7)$$

where E_L is the load energy demand.

The result of eq.(7) is either positive ($E_{PV} > E_L$) or negative ($E_{PV} < E_L$) . If the energy difference is positive then there is an excess in energy (EE), if negative then there will be an energy deficit (ED). The excess energy is stored in batteries in order to be used in case of energy deficit. Meanwhile, energy deficit can be defined as the disability of the PV array to provide power to the load at a specific time. Therefore, the energy flow across the battery can be expressed by,

$$E_{Battery}(t) = \begin{Bmatrix} E_{Battery}(t-1) * \boldsymbol{\eta_{inv}} * \boldsymbol{\eta_{wire}} * \boldsymbol{\eta_{discharging}} - E_L(t) & E_D < 0 \\ E_{Battery}(t-1) * \boldsymbol{\eta_{charging}} + E_{PV}(t) & E_D > 0 \\ E_{Battery}(t-1) & E_D = 0 \end{Bmatrix} \quad (8)$$

The first step in writing a MATLAB code for the described model above is to define the source file and the variables such as hourly solar radiation (G), hourly ambient temperature (T) and the hourly load demand (L). In addition to that some specification of the system needs to be defined such as the capacity of the PV array, the capacity of the storage battery, inverter rated power, the efficiency the PV module, the allowable depth of charge, the charging efficiency and the discharging efficiency as below (Appendix A), (Routine 2).

The simulation process starts by calculating the produced energy by the PV array, then the net energy (E_{net}) is calculated. The maximum state of charge of the battery (SOC) is given to the variable SOCi as an initial value. In addition to that, matrices are defined so as to contain the results of battery state of charge (SOCf), Damped energy (Dampf), and energy deficits (Deff) are initiated and defined (Appendix A), (Routine 3.1).

At this point a “For loop” is initiated to search the values of the E_{net} array. Then the energy difference is added to the variable SOCi. Here, if the result SOC is higher than SOCmax, the damped energy is calculated and stored in “Dampf” array. Meanwhile the ED is set zero and the battery state of charge does not change. This condition represents the case of the energy produced by the PV array and is higher than the energy demand .The battery is fully charged from the previous step (Appendix A), (Routine 3.2).

The second condition represents the case that the energy produced by the PV array and the battery together is lower than the energy required. Here the battery must stop supplying energy at the defined depth of discharge (DOD) level while the ED equals the un covered load demand. In addition to that, the damped energy here is equal to zero (Appendix A), (Routine 3.3).

The last condition represents the case that the energy produced by the PV array is lower than the load demand but the battery can cover the reaming load demand. In this case there is no damped nor deficit energy, while the battery state of charge equals the difference between the maximum SOC and supplied energy (Appendix A), (Routine 3.4).

Finally battery state of charge values, deficit and damped energy values are recalled and the loss of load probability is calculated (Appendix A), (Routine 3.5).

3. Energy Flow Modeling for hybrid PV/Wind Power Systems

Figure 4 shows a typical hybrid PV/wind system which consists of a PV array, a wind generator, a block of batteries, a DC-DC converter, an AC-DC converter and loads. The energy produced by the PV array and wind turbine is used to supply loads and charge a battery. Meanwhile the battery is used to supply the loads in the deficit time.

The output energy of the PV array was discussed in the previous section. Meanwhile, the output energy of the wind generator of a hybrid PV/wind system can be described as a function of wind speed as is illustrated in Figure 5.

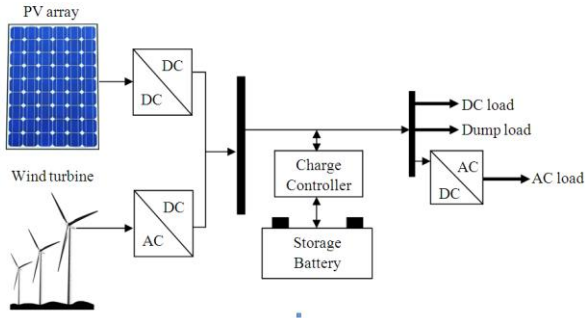

Figure 4 Typical components of a hybrid PV/Wind system

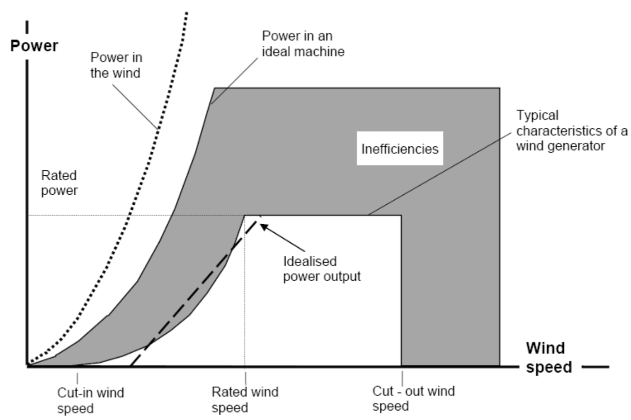

Figure 5 Wind turbine power characteristic curve

From the Figure the output power of a wind turbine can be described as follows

$$\begin{Bmatrix} 0, & V_{Cut\ out} < V < V_{cut\ in} \\ P_{rated}, & V = V_{rated} \\ P = f(V), & V_{cut\ in} < V < V_{rated} \end{Bmatrix} \quad (9)$$

The energy flow concept in a hybrid PV/Wind system is very close to the one in SAPV systems. The energy is generated by the wind turbine and the PV array in parallel and this energy is used to supply the loads (AC or DC) and charge the battery. Meanwhile, the battery supplies the loads in the deficit time. Moreover, a dump load is used to damp the excess energy in the system. Based on this the energy flow code is slightly different from the one for SAPV system. However, wind speed data as well as wind turbine model must be added to the first and second part of the code in Appendix A. Moreover, in the second part the energy difference equation will be as follows,

$$E_D(t) = \sum_{i=1}^{366}(E_{PV}(t) + E_W(t)) - E_L(t) \quad (10)$$

4. Energy Flow Modeling for hybrid PV/Diesel Power Systems

Figure 6 shows a hybrid PV/ diesel system. The system is supposed to have the PV array as a main source with a backup battery while the diesel generator is operated in deficit time. Here the deficit time is defined as the time in which the instantaneously produced energy from the PV array and battery is not enough to cover the load demand.

The coding of energy flow model for hybrid PV/diesel system is different from the hybrid PV/wind and SAPV systems. Figure 7 shows the logic diagram of coding the PV/diesel system.

The system first supplies the load as there is no diesel generator in the system. Meanwhile the diesel generator will be operated in the time that the energy produced by the PV array and the battery is not enough to cover the load demand. The first and the second parts of the energy flow model code is like the one for the SAPV system but the capacity of the used diesel generator (kWh/day) must be added to the first part. After that, a “For loop” is initiated to search the array of the “energy net” (E_{net}) values. The following part represents the case that the energy generated by the PV array is more than the load demand and consequently there is no generated energy neither by the diesel generator nor the battery. In addition, there is no energy deficit in this case while the energy to be damped equals to the difference between the energy generated by PV and the load demand (Appendix B), (Routine 2).

The second case is when the energy generated by the PV array and the battery is less than the energy demand. In this case, the diesel generator must cover the load demand which is not covered by the PV array and the battery. In addition to that, the diesel generator is used to charge the battery (Appendix B), (Routine 2.1).

At this point, there are three scenarios,

i. The first is that the diesel generator produced the maximum possible energy to supply the load and to charge the battery, while, the battery state of charge is less than or equal maximum state of charge (Appendix B), (Routine 2.2).
ii. The second scenario is the battery state of charge reach the maximum value and the diesel generator at this point must stop chagrining the battery (Appendix B), (Routine 2.3).
iii. In the third scenario, the diesel generator could not cover all the demanded energy by the load and it is consequently not able to charge the battery (Appendix B), (Routine 2.4).

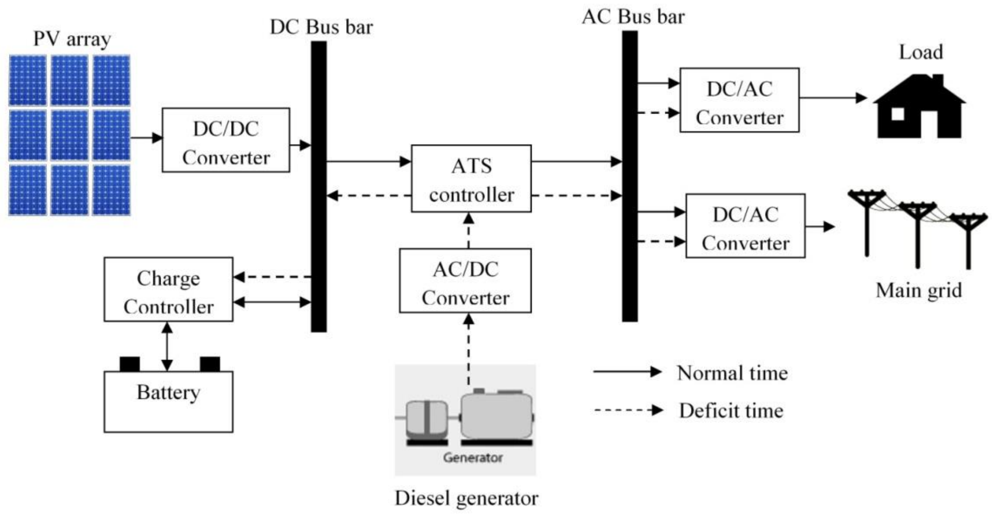

Figure 6 Hybrid PV/Diesel system configuration

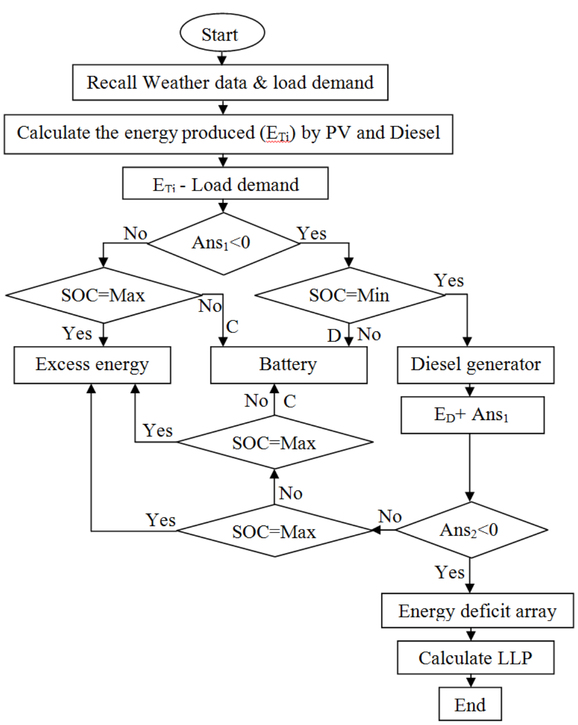

Figure 7 Coding logic diagram for PV/Diesel system

Finally, the following code represents the case that the battery is able to cover the load demand alone. Here the diesel generator is used to charge the battery as well. The diesel generator is supposed to keep the battery fully charged to be ready for deficit times. This is because the fact that the use of the energy stored in a battery is easier than operating a diesel generator since the diesel generator needs a start up time. Moreover, the frequent on/off states of a diesel generator affects its life time negatively. However, in this part also the SOC of the battery must be controlled in order not to exceed the allowable state of charge.

Eventually, four calculated values are stored in arrays. These values are the energy deficits, damped energy, battery SOC and energy produced by diesel generator. Here also the loss of load probability can be calculated to evaluate the reliability of the designed system (Appendix B), (Routine 3).

5. Results and discussion

To validate the proposed models, the average hourly load demand illustrated in Figure 8 is used with a daily energy demand of 7.68 kWh/day. This load is assumed to be supplied by a SAPV system and a PV/diesel system.

In this section, hourly averages of solar energy, ambient temperature, wind speed and load demand are used. These data are for the city of Kula Lumpur and provided by the Solar Energy Research Institute (SERI). Anyway, according to [13] a SAPV system consisting of a 3.1 kWp PV array and a 500 Ah/12 V battery is needed to supply the assumed load demand at 1% loss of load probability. Figure 9 shows the performance of the designed system through the first 1000 hours of the year.

Form the Figure, the produced energy by PV and battery are shown as well as the damped energy. The information about the damped energy is useful in estimating the needed dump load for the system.

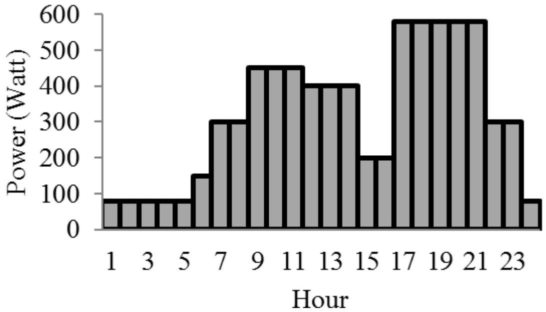

Figure 8 Theoretical load demand

However, the calculated loss of load probability is 0.6% which is close to the supposed (1%).

On the other hand a hybrid PV/ diesel system consisting of 2500 Wp PV array, 3 kVA diesel generator and a 580 Ah/12 V battery is needed to supply the assumed load demand at 1% loss of load probability according to [14]. Figure 10 shows the performance of the designed system for the first 1000 hours of the year. The first, third and fourth parts show the power generated by the PV array, battery and diesel generator respectively. Finally the calculated loss of load probability for the deigned system is 0.95 % which is also considered close to the supposed 1%.

The validation of the proposed models requires practical data for either a standalone PV system or a standalone hybrid PV/Diesel system. In addition to that, meteorological data and load demand measurements are required as well. Moreover, these systems must follow the same control strategy that described by proposed models. For example, we need to have a standalone PV system that powers the load and only use the battery in case of the lake of energy generated by PV. Currently in Alpen-Adria-Universtät Klagenfurt, Austria we do not have such a system installed in our field test. However such a system is installed at one of our research collaborator's field test. A photovoltaic system consisting of a 7 kWp PV array and a storage battery of 14.4 kWh is installed at Sohar University, Oman. Consequently, actual performance data have been requested for this system in order to be utilized in validating one of the proposed models. The validation results showed that the proposed model successfully predicted the system performance. However, the proposed model fails in predicting the system performance in abnormal meteorological condition such as dust deposition. Figure 11 shows an actual performance of the system in the month of January, 2013. In the first day the PV array was totally covered by dust. Meanwhile, the second and the third days are showing the system performance after being cleaned. From the figure it is very clear that the dust deposition significantly affected the power generation. On the hand Figure 12 shows the predicted performance by the proposed model for SAPV. Form the two figures, we can conclude that the proposed model can accurately predict the performance of the system subject to normal or predictable meteorological condition. In the meanwhile, the disadvantage of the proposed model is that it is not able to predict the performance of system when the PV panels are dirty. Anyway the overall prediction accuracy of the proposed model excluding the dusty day is 94.7% which is relatively good as compared to other models.

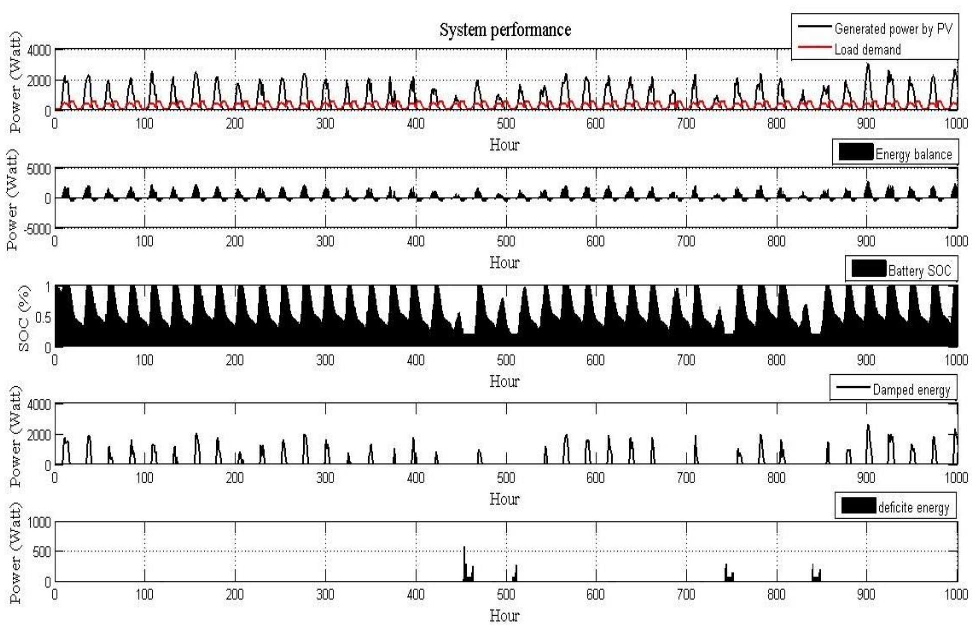

Figure 9 Performance of the designed SAPV system

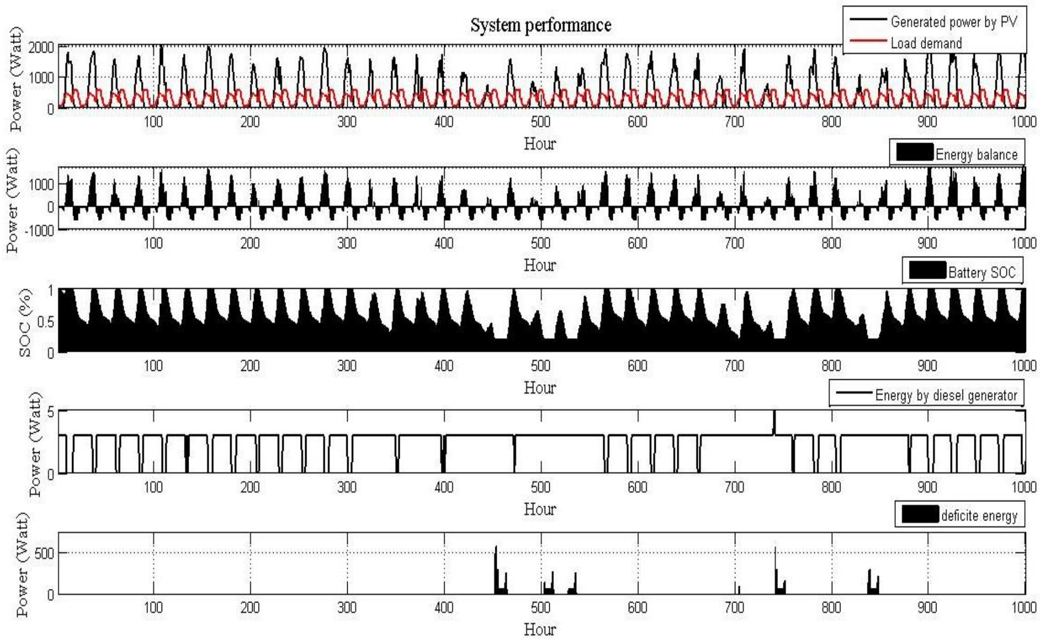

Figure 10 Performance of the designed hybrid PV/diesel system

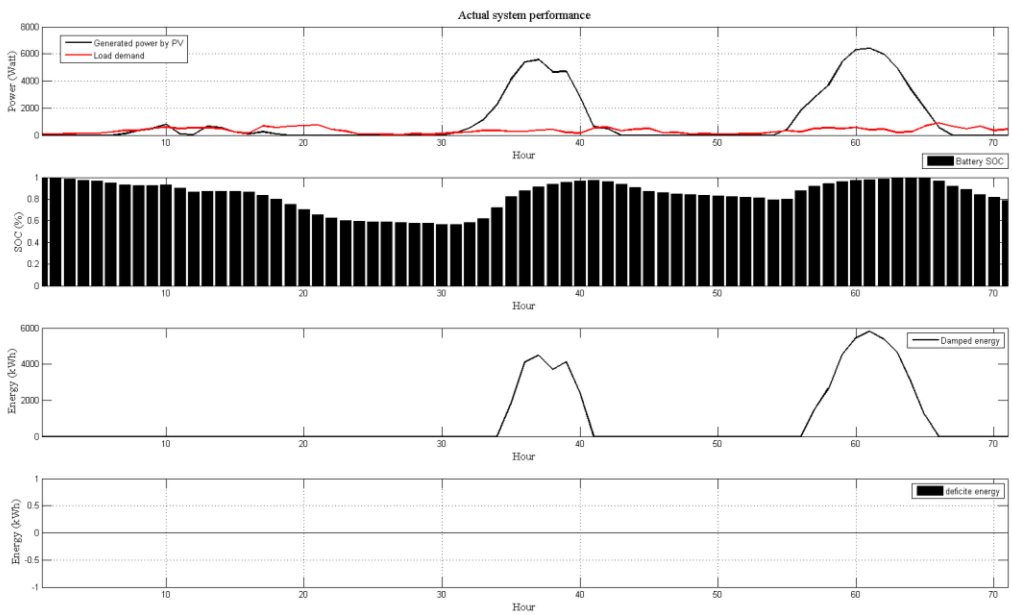

Figure 11 actual performance of a 7 kWp PV system installed at Sohar, Oman

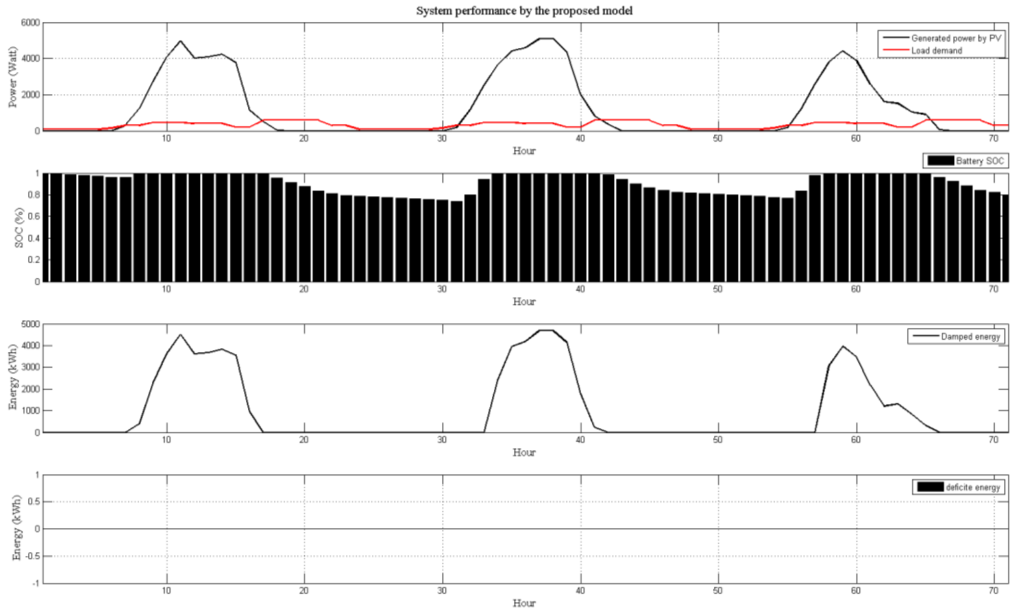

Figure 12 predicted performance of a 7 kWp PV system installed at Sohar Oman

6. Conclusion

Energy flow models for three types of PV power systems were proposed. These systems are SAPV systems, hybrid PV/wind systems and hybrid PV/diesel system. In this paper the energy flow logic was discussed first and then MATALB codes for these models were provided and explained. To validate the results two tests have been done for a SAPV system and hybrid PV/diesel system using real meteorological data and load demand. The results showed the validity of the proposed models. However, the proposed model fails in predicting the system performance in abnormal meteorological condition such as dust deposition. Such models help in modeling and sizing PV power systems

Acknowledgment

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Appendix A

```
%%(1)Data sources
fileName = 'hourly Weather Data.xls';
sheetName  = 'Site1';
G= xlsread(fileName, sheetName  , 'A1:A8761');
T= xlsread(fileName, sheetName  , 'B1:B8761');
L= xlsread(fileName, sheetName  , 'C1:C8761');
%%(2)System specifications
PV_Wp=2500;    % the capacity of the PV array
(Watt)
Battery_SOCmax= 1400; % battery capacity
kWh/day
PV_eff=0.16;  % efficiency of the PV module
V_B=12;     % voltage of the used battery
Inv_RP=2500   %inverter rated power
DOD=0.8;     %allowed depth of charge
Charge_eff=0.8; % charging eff
Alpha= .05;          % alpha
Wire_eff= 0.98;
SOCmin=SOCmax*(1-DOD)
 %%(3.1) Simualtion of the SAPV system
P_Ratio=(PV_Wp *(G/1000))/Inv_RP;
Inv_eff=97.644-(P_Ratio.*1.995)-
(0.445./P_Ratio);   %5KW
E_PV= ((PV_Wp*(G/1000))- (Alpha*(T-25)))*…
Wire_eff* Inv_eff;
E_net=EP_V-L;
SOCi=SOCmax
SOCf=[];
Deff=[];
Dampf=[];
%%(3.2)
for i=1:length(E_net);
```

```
SOC= ED+SOCi;
if (SOC > SOCmax)
    Dampi=SOC-SOCmax;
    Defi=0;
    SOCi=SOCmax;
%%(3.3)
elseif (SOC<SOCmin)
    SOCi=SOCmin;
    Defi=SOC-SOCmin;
    Dampi=0;
%%(3.4)
else
SOCi=SOC;
Defi=0;
Dampi=0;
end
%%(3.5)
SOCf=[SOCf; SOCi];
Deff=[Deff; Defi];
Dampf=[Dampf; Dampi];
end
SOCf;
Deff;
Dampf;
SOC_per=SOCf./SOCmax;
LLP_calculated=abs(sum(Deff))/(sum (L))
```

Appendix B

```
%%(2)
for i=1:length(E_net);
SOC= Net_E(i)+SOCi;
if (SOC > SOCmax)
    Dumpi=SOC-SOCmax;
    Defi=0;
    SOCi=SOCmax;
    E_Gen=0;
%%(2.1)
elseif (SOC<SOCmin)
    Old_Defi=(SOC-SOCmin)+E_Capacity;
    if (Old_Defi >=0)
    SOCi=SOCmin+Old_Defi;
%%(2.2)
if (SOCi<=SOCmax)
    Defi=0;
    Dumpi=0;
    E_Gen= abs(Old_Defi)+ (SOCi-SOCmin);
    SOCi=SOCmin+Old_Defi;
%%(2.3)
else
    Defi=0;
    Dumpi=0;
    E_Gen= abs(Old_Defi)+ (SOCi-SOCmin)- (SOCi-
SOCmax);
    SOCi=SOCmax;
    End
%%(2.4)
else
    SOCi=SOCmin;
    Defi=Old_Defi;
    Dumpi=0;
    E_Gen= E_Capacity;
    end
%%(3)
else
SOCi=SOC+ E_Capacity;
if (SOCi <= SOCmax)
Defi=0;
Dumpi=0;
E_Gen=E_Capacity;
SOCi=SOC+ E_Capacity;
else
Defi=0;
Dumpi=0;
E_Gen=E_Capacity- (SOCi-SOCmax);
SOCi=SOCmax;
end
end
SOCf=[SOCf; SOCi];
Deff=[Deff; Defi];
Dumpf=[Dumpf; Dumpi];
E_Geni=[E_Geni; E_Gen];
end
SOCf;
Deff;
Dumpf;
E_Geni;
SOC_per=SOCf./SOCmax;
LLP_calculated=abs(sum(Deff))/(Sum(L))
```

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