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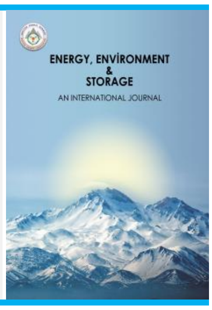

Determination of a New Performance Indicator for the Assessment of Stand-Alone PV System

Francis-Daniel MENGA[1*], Jorel landry OWONA[2], Oumarou DJOUBAIROU OUMAROU[3]

[1] National Committee for Development of Technologies (NCDT), Yaoundé, Cameroon, ORCID: 0000-0002-6165-0010
[2] National Committee for Development of Technologies (NCDT), Yaoundé, Cameroon, ORCID: 0009-0005-9245-2585
[3] National Committee for Development of Technologies (NCDT), Yaoundé, Cameroon, ORCID: 0009-0002-9058-1920

ABSTRACT. The use of stand-alone PV systems (*SAPV*) must be efficient and profitable for a better integration of solar energy in the global energy mix. However, the performance indicators that allow the evaluation of *SAPV* systems do not clearly inform us about the actual level of use of their sized and installed capacity. This article aims to determine a new performance indicator, called the theoretical power factor (*TPF*) by an original method based on the modelling of the *SAPV* system in the form of a matrix equation. The resolution of this matrix equation, makes it possible to bring out the reactive energy of the system during operation. A case study is presented and scenario I represents the case where the main elements are all assumed to operate at their rated capacity. scenario II represents the case were the rated capacity of storage system is reduced of 40%, scenario III represents the case were the rated current capacity of charge controller is reduced of 40%, and finally scenario IV represents the case were the rated power capacity of inverter is also reduced of 40%. The results obtained after implementation in the Spyder environment (python 5.1) show the effectiveness of *TPF* in the performance evaluation of *SAPV* systems. And also show how the *TPF* is substantially related to the capacity of each main element of the system. This being proved by the results obtained after the simulation of the four scenarios mentioned above. One can observe an increase in *TPF* of 0.1% in Scenario II during the period of low irradiance, and no change in *TPF* for the other scenarios in the same period. During the period of high irradiance, an increase in *TPF* of 17.9% is observed in scenario II and a decrease in *TPF* of 15.4% and 1.2% respectively in scenarios III and IV.

Keywords: Stand-Alone PV system, Performance indicators, Performance Ratio, Reactive energy, Theoretical power factor, Matrix model

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1. INTRODUCTION

Solar photovoltaic energy is a solution to the energy deficit observed in several developing countries. It is also a source of energy that helps to reduce the pollution caused by the use of fossil fuels. Solar energy conversion systems, also known as PV systems, are becoming increasingly popular in sub-Saharan Africa. Electricity from solar PV contribute at 3% of global electricity generation in the world and it is now the third-largest renewable electricity technology after hydro power and onshore wind [1]. Depending on the installation site and the intermittent nature of the solar energy source, these systems can be connected to an electrical distribution network or be associated with other energy sources (wind, diesel, etc.) to form hybrid sources. Or they can be combined with batteries to store electrical energy and form autonomous systems [2]. The choice of a PV configuration is usually based on technical, economic, social, environmental and political/legal criteria. In remote rural areas and some urban areas in sub-Saharan Africa, the choice is much more towards stand-alone PV systems with storage.

Stand-alone PV systems (SAPV) require good sizing. There are several sizing methods as presented in the articles [3], [4]. Due to the randomness of the solar energy source and the load profile, the reliability of stand-alone PV systems is questionable, regardless of the design method used. In the literature, several criteria for the reliability of PV systems can be distinguished [5].

The intermittency of the solar energy source, the variation in the load profile and the difficulty in obtaining certain technical and social environment data from the site where the system is to be installed, means that no sizing method is completely reliable. It is difficult to accurately design a PV system. In general, the mode of operation for which the system is designed is not always real (e.g., the power demand taken into account in the design calculations is variable in reality and can sometimes exceed the estimated power). It is therefore important to study the performance of a stand-alone PV system that has been designed.

[*]Corresponding author: danielmenga6@gmail.com

To assess the performance of SAPV system there are several types of indicators [5]–[8]. Among these indicators, the performance ratio (PR) is one of the most significant for evaluating the efficiency of the PV system. Specifically, the performance ratio is the ratio of the actual and theoretically possible energy outputs. It tells us about the electrical energy converted by PV solar panels and which is actually used by the load. And it is largely independent of the orientation of a PV plant and the incident solar irradiation on the PV plant. The performance ratio is a parameter that emerges in several studies concerning the performance evaluation of stand-alone and grid-connected PV systems [9]– [12].

However, the calculation of the performance ratio requires, for a given time, the actual consumption measurements of the load [13], [14]. This implies measurements on operational PV systems. such a performance ratio evaluation of a PV system would certainly be realistic but very expensive for a post-installation performance evaluation. there are also sizing software packages such as PVsyst, INSEL, TRNSYS, PVSOL, SOLARPRO [10] which can evaluate the performance ratio during the sizing of the PV system. But the software takes into account the estimated load consumption data. this makes the performance ratio calculation approximate and unrealistic for systems without a demand side management system.

The main problem with the performance ratio is that the size of the battery, charge controller and inverter does not clearly influence performance ratio value. This hiding the fact that the performance ratio can be caused by poor system sizing and poor storage management. The same performance ratio value can be obtained by two SAPV systems with different size of inverter, battery storage and charge controller.

In this work, the performance ratio of a stand-alone PV system is predicted just from the knowledge of the size of its components, the meteorological data and the electrical consumption data. The size of the different components of the system can therefore be varied to study their influence on the performances indicators (the conventional one and the new one). So, our objective is to determine a new reliability indicator thanks to an original method of calculation. This new reliability indicator is named the theoretical power factor (TPF). Which is obtained by considering the set (Charge Controller-battery-Inverter-Load) as a whole electrical receiver. and as with any electrical receiver its power factor can be determined. Two determine TPF an original method is developed and consists in modelling the PV Stand-Alone System as a matrix equation whose solution allows to calculate the TPF. The TPF is considered more as a new reliability indicator of the PV stand-alone system sized. In the same way as the Loss of Power Supply Probability (LPSP), the Loss of Load Probability (LOLP or LLP) and many others that each carry a specific information [4], [13].

To achieve our goal, the SAPV system will first be described. Then, an energy model of the SAPV system in matrix equation form, for the determination of the new reliability indicator will be developed. And the TPF will be calculated according the case study which will be presented. Finally, the results obtained by the implementation and simulation in an integrated development environment (SPYDER) will be presented before the conclusion.

2. MATERIALS AND METHODS

2.1 Description of the Stand-Alone PV system studied

The main components of the PV/Battery system are: The PV generator, the charge regulator (or charge controller), the batteries and the inverter. The PV generator produces the electrical energy for the load consumption. Batteries storage are used to store the excess electrical energy produced by the PV generator during the day. This energy is then consumed by the load at the night or when the generated energy by the solar panels is not enough (low sunlight) to respond to the load demand. The role of the charge controller is to ensure that the battery charging and discharging processes, are carried out, so that they are always in the correct operating conditions. It also permits to maximize the power of solar panels. The role of the inverter is to convert direct current (DC) into alternating current (AC). Since photovoltaic solar panels generate direct electricity current, and most of devices used in houses or in professional offices work with alternating current, this component is therefore for a particular importance in photovoltaic systems. Schematic representation of the studied system is given in Fig.1.

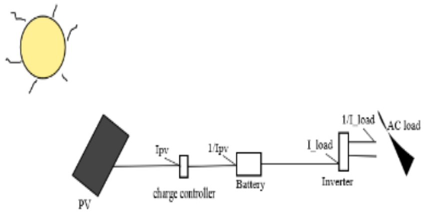

Fig. 1. Stand-Alone PV system

2.2 Performance Ratio PR

The performance ratio is a measure of the quality of a PV plant that is independent of location and it therefore often described as a quality factor. The performance ratio (PR) is stated as percent and describes the relationship between the actual and theoretical energy outputs of the PV plant. The closer the PR value determined for a PV plant approaches 100 %, the more efficiently the respective PV plant is operating. In real life, a value of 100 % cannot be achieved, as unavoidable losses always arise with the operation of the PV plant (e.g., thermal loss due to heating of the PV modules). High-performance PV plants can however reach a performance ratio of up to 80 %.
The Performance Ratio can be calculated either manually or automatically by software such as PVsyst. the formula of the PR is written [11]:

$$PR = \frac{E_{actual}}{E_{nominal}} = \frac{E_{actual}}{G_{period} * \eta_{STC} * A} \quad (1)$$

where $\boldsymbol{E_{actual}}$ is the actual reading of PV plant output in kW h, which is the energy consumed by the load side at the end of analysis period, $\boldsymbol{E_{nominal}}$ is the calculated nominal PV plant output, $\boldsymbol{G_{period}}$ is the solar radiation incident at the end analysis period, $\boldsymbol{A}$ the entire module surface, and η_{STC} is the nominal efficiency of the PV module under Standard Test Conditions) STC.

2.3 New performance indicator determination

The reliability indicator proposed in this work allows to determine over a given time the theoretical power factor (TPF) which is an average percentage of use of the SAPV system supplying a non-exhaustive and variable load. This indicator is determined through the matrix modelling of the SAPV system.

2.3.1 Modelling of SAPV system sized

The SAPV system is basically consists of PV modules, a charge controller or regulator, a storage device and inverter for AC appliances.
The model proposed here is developed by considering some of the following assumptions:

- The sized SAPV system can work perfectly without failure;
- The internal physical properties of each element of the system are neglected;
- The data considered are hourly average values.

Fig.1 shows the energy transfer from solar radiation to the load, through the components of the SAPV system. The model represents in the matrix equation form (A.X = B), the energy transfer from the PV generator to the load through the battery. Where A is a matrix of dimension $m \times n$ representing energy flow between each characteristic component of SAPV system and B is the column vector of dimension n representing the Energy and voltage state of each characteristic element during its operation. Solving this equation informs us about the balance between the energy generated by the system and the energy consumed by the load. It also informs us about the size of the system. Indeed, due to the variations in load and weather conditions, it is rare that the energy generated is equal to the energy consumed. Most of the time the system operates in an energy imbalance between supply and demand. It is in this latter case that the size of system is important.

Determination of the parameters of matrix A

The parameters of matrix A are determined according to an original logic, quite similar to the one used to determine the adjacency matrix in the graph theory [15]. By considering our SAPV system as an oriented graph in which the energy transit elements (PV generator, Charge Controller, battery, inverter and load) are nodes, the value of each edge connecting two nodes is determined by considering the following rules:

• When electrical energy flows from an active dipole to a passive dipole, the value of the edge is equivalent to the maximum current capable of flowing through the link between these two dipoles;

• And when the electrical energy flows from a passive dipole to an active dipole, the value of the edge is equivalent to the inverse of the maximum current capable of flowing through the link between these two dipoles.

So, one can write this:

$$A = \begin{bmatrix} 1 & I_{ccN} & 0 & 0 & 0 \\ 0 & 1 & 1/I_{ccN} & 0 & 0 \\ 0 & 0 & 1 & I_{invN} & 0 \\ 0 & 0 & 0 & 1 & 1/I_{invN} \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where I_{ccN} is the nominal current which can flow through the charge controller to the battery system and I_{invN} is the nominal current of inverter which can flow through the inverter to the load.

Determination of the parameters of vector B

B(t) is the column vector that provides information on the status of the characteristic parameters of each element of the SAPV system at each time *t* of a given period *T*. The PV generator, the battery and the load are characterized by their Energy level, while the charge controller and the inverter are characterized by their terminal voltage level. *B* vector at the specific time is given by this:

$$B = \begin{bmatrix} E_{pv} \\ V_{cc} \\ E_{bat} \\ V_{inv} \\ E_{load} \end{bmatrix} \quad (3)$$

Where E_{pv} is effective energy converted into electrical energy by the solar PV. It is written:

$$E_{pv} = G * A_{pv} * \eta_{pv} \quad (4)$$

G is the hourly global irradiance in (Wh/m^2). A_{pv} is the total array surface in (m^2) and η_{pv} is the photovoltaic panel efficiency. V_{cc} and V_{inv} are respectively the terminal voltage of charge controller and terminal voltage of inverter. E_{bat} is energy battery which is either stored or restored. It is given by this following equation:

$$E_{bat} = C_{bat} * V_{bat} \quad (5)$$

The instantaneous storage capacity of the batteries C_{bat} is given by:

$$C_{bat}(t) = C_{bat}(t-1) + (I_{PV} * \Delta t - I_{load} * \Delta t) \quad (6)$$

V_{bat} is the terminal voltage of batteries storage system.

I_{PV} is the PV current delivered by the generator for each time interval (Δt), here Δt =1 h.
This current is determined following this equation:

$$I_{PV} = \frac{E_{pv}}{V_{cc} * \Delta t} \quad (7)$$

I_{load} is current of load for each time interval. Determined by:

$$I_{load} = \frac{E_{load}}{V_{inv} * \Delta t} \quad (8)$$

With E_{load} which is the energy need at load for one hour.

2.3.2 *Theoretical Power Factor (TPF)*

TPF is the proposed performance indicator. Theoretical because there are some assumptions took into account for its determination. Cleary, it is an average percentage of system usage determined by solving the matrix equation $AX = B$ each time interval. The vector X is a solution obtained each time interval and whose first term X_1 corresponds to a reactive energy. This reactive energy is composed of the electrical energy produced by the PV generator that has not been consumed or stored, the energy difference between the maximum energy capacity of the charge controller and the energy that actually flows through it in each time interval and finally the energy difference between the maximum energy capacity of the inverter and the energy consumed by the load at a given time. these reactive energy components are losses related to the size of the system elements and the management method of the storage system. The following equation gives the TPF.

$$TPF = \frac{\sum_{i=1}^{nh} \sqrt{1 - \left(\frac{X_1[i]}{P_{pv,Peak} * \Delta t}\right)^2}}{nh} \quad (9)$$

$$TPF = \begin{cases} 0 \ \ if \ \ X_1[i] \geq \ P_{pv,Peak} * \Delta t \\ 1 \qquad if \qquad X_1[i] \ = \ 0 \end{cases} \quad (10)$$

where $P_{pv,Peak}$ is a nominal power of PV generator and nh is a number of the total hours of the given period.

It is important to note that, concerning the performance PV plant assessment, this performance indicator does not appear in the literature and especially not among the indicators proposed by the IEA PVPS Task 2 [7], [8].

2.4 Implementation data and strategy

The meteorological data (irradiance), constituting the important input parameters of the PV generator, is downloaded from the Helioclim-3 Archive Database of Solar Irradiation V5 (derived from satellite data) and meteorological data (MERRA-2/NASA and GFS/NCEP) for two periods of year (2020-02-01 to 2021-02-09 and 2020-08-08 to 2021-08-15) and for precise location of the Yaoundé, Cameroon. The energy demand is also a key input parameter for the simulation of the system. Fig. 2 shows the daily energy demand.

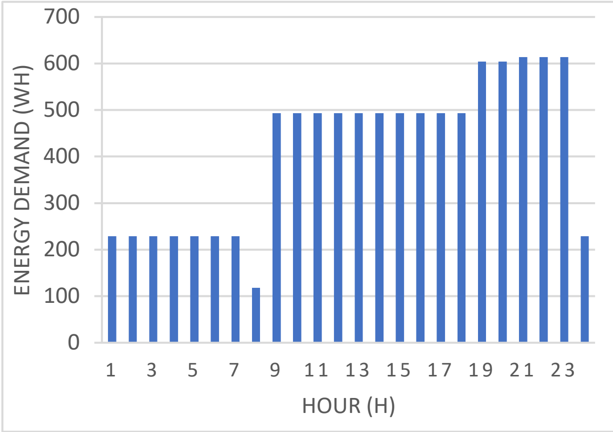

Fig. 2. Daily energy demand

In the defined operational strategy, the PV power production is determined for each time interval corresponding to the given meteorological data. The description of the strategy of the studied system, is given in Fig. 3.

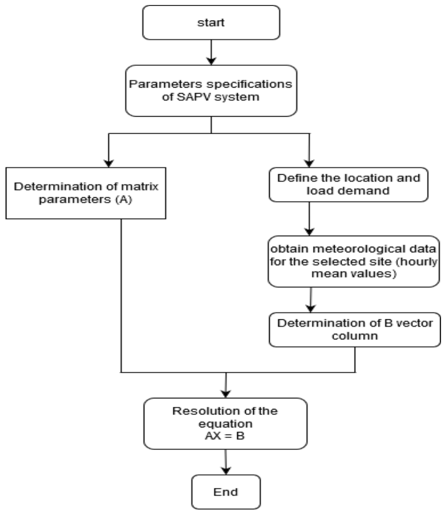

Fig. 3 Diagram of SAPV model implementation

Table 1. Parameters used for simulation

Designation	Value
Type of system	Stand-alone system
Nominal power of PV plant	3500 Wp
Nominal capacity of battery	1260 Ah
Total surface of PV plant	19.9 m^2
Allowable depth of discharge of batteries	80 %
Nominal power of inverter	635 W
Maximum current of charge controller	93 A
Batteries bank Voltage	26 V
Efficiency of conversion PV	15 %

To analyse the influence of the size of each element of the SAPV system. From the second scenario to the fourth scenario the size of an element (charge controller, battery and inverter) of the system will be reduced from 100% to 60% of their initial size as shown in table 2. The value

60% is a randomly chosen coefficient that has no particular meaning but will allow us to observe and analyse the values of the different performance indicators.

Table 2. simulation scenarios

	Scenarios			
	I	II	III	IV
Surface of PV plant (%)	100	100	100	100
Current of charge controller (%)	100	100	60	100
Capacity of Battery (%)	100	60	100	100
Capacity of inverter (%)	100	100	100	60

3. RESULTS AND DISCUSSION

The results obtained here after implementation and simulation in the Spyder environment (Python 5.1) allow, over a period of time, an analysis of the evolution of the reactive energy of the SAPV system in operation. Remembering that the reactive energy of the system, which is noted X1, is the first term of the solution vector X of the matrix equation of our system. The results obtained allow also to compare the performance indicators (Performance Ratio and Theoretical Power Factor) of the SAPV system between to different period of a year. One can finally observe the influence of the size of component systems on the performance indicators.

3.1 Analysis of the reactive energy evolution of the SAPV system during a period

Fig. 4 shows the evolution of the reactive energy and the energy produced by the PV generator during the August period. It can be seen that the reactive energy is positive and is very high. This reactive energy is more important during periods of low sunshine than during periods of high sunshine. This development indicates that the overall capacity of the SAPV system is low. This will be determined by the proposed performance indicator, the theoretical power factor (TPF) in Table 3. The period of August is generally a period of low irradiance in Yaoundé, Cameroon. This is most easily explained by the fact that the irradiance is low and the SAPV system is used below its nominal performance.

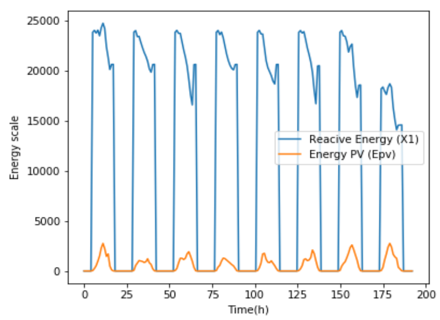

Fig. 4. Profile of reactive energy and PV energy produced

3.2 Comparison of the performance indicators for SAPV system according to two analysis periods

Simulation of scenario I is made for the nominal capacity of each component of SAPV system. Table 3 shows that, during periods of high irradiance the performance ratio (PR) decreases and the theoretical power factor (TPF) increases compared to the periods of low irradiance. a fairly predictable result because when the irradiance increases the energy converted by the PV panels also increases while the energy consumed remains the same. then the PR decreases.

However, when this PV energy increases the current also increases in the charge controller and the storage system is charging faster. This will be checked looking the final state of charge (SOC) of the battery which is 38% for the period of low irradiation against 84% in the period of high irradiation.

Table 3 Comparison of *PR* and *TPF* in nominal capacity of SAPV system

Performance Indicators	**Periods**	
	August period (Low irradiance)	February period (High irradiance)
PR	0.757	0.674
TPF	0.458	0.612

3.3 Influence of storage system capacity on the performance indicators

Simulation of scenario II is made to see the influence of the capacity of storage system on the performance indicators. One can observe from table 4 that, the capacity of the storage system does not influence the performance ratio (PR) of the system. But on the other hand, the reduction of this capacity increases the theoretical power factor. This result shows that the SAPV system can cover the requested energy efficiently with a much lower battery capacity than in the case of the first scenario.

Table 4 Comparison of *PR* and *TPF* with reduced capacity of storage system

Performance Indicators	**Periods**			
	Low irradiance		High irradiance	
	Scenario I	Scenario II	Scenario I	Scenario II
PR	0.757	0.757	0.674	0.674
TPF	0.458	0.459	0.612	0.791

3.4 Influence of charge controller current capacity on the performance indicators

Simulation of scenario III is made to see the influence of charge controller current capacity on the performance indicators. Looking at the table 5, one can see that the PR is not influenced by the reduction of charge controller current capacity in either case of low or high irradiance. But in other hand, the reduction of charge controller current capacity influences crucially in decreasing the theoretical power factor of SAPV system. This last observation can be justified by the fact that current will be stopped at the charge controller even when the irradiance is high. This will cause a low charging of storage system and therefore increase the reactive energy made more by the uncharged (or unused) capacity storage.

Table 5 Comparison of *PR* and *TPF* with reduction of charge controller current capacity

Performance Indicators	**Periods**			
	Low irradiance		High irradiance	
	Scenario I	Scenario III	Scenario I	Scenario III
PR	0.757	0.757	0.674	0.674
TPF	0.458	0.458	0.612	0.458

3.5 Influence of inverter power capacity on the performance indicators

Simulation of scenario IV is made to see the influence of inverter power capacity on the performance indicators. Looking at table 6, one can see that, if in the precedent scenarios the PR is not influenced by the charge controller current capacity and capacity of storage system of SAPV system, in this last scenario the reduction of the inverter power capacity influence clearly the PR. It can be justified by the fact the if the inverter capacity is limited, all the energy demand will not be covered.

The reduction of inverter power capacity has also decreased TPF, this can be justified by the fact that the huge energy which can be stored in the battery is not sufficiently used at the end. Because of the low energy demand. The SAPV system should be size well regarding the scale of energy demand.

Table 6 Comparison of *PR* and *TPF* with reduction inverter Power capacity

Performance Indicators	**Periods**			
	Low irradiance		High irradiance	
	Scenario I	Scenario IV	Scenario I	Scenario IV
PR	0.757	0.757	0.674	0.674
TPF	0.458	0.458	0.612	0.600

4. CONCLUSION

The locations far from electricity distribution networks and those suffering from poor electricity quality often resort to stand-alone PV systems (SAPV) which now appear to be the best solution for access to electricity. the sizing methods for these systems are not perfect. It is therefore possible to install a system that is not very suitable for use. Indicators proposed by the IEA PVPS Task 2, when they are well calculated, make it possible to attenuate the errors related to the sizing. But these indicators do not always tell us about the capacity of the installed SAPV system actually used.

It is in this way that we have developed a new performance indicator called the theoretical power factor (TPF), by an original method based on the modelling of the SAPV system in the form of a matrix equation. this indicator informs us about the reactive energy of the SAPV system. The reactive energy is this energy which was solicited and installed but which is not used at the end.

In this work, we have described the system studied, presented the performance indicator most used in the literature, calculated from a case study the performance indicators (the new one and the one most used in the literature). We have also analysed the evolution of the reactive energy for the case study and observed the influence of the capacity of each main element of the SAPV system on the proposed performance indicator TPF and on the conventional performance indicator PR. The reduction of 40% of the main element capacity of the SAPV system (storage system, charge controller and inverter) in each different scenario, makes it possible to observe during the period of low irradiance, an increase in TPF of 0.1% in Scenario II and no change in TPF in Scenarios III and IV. During the period of high irradiance, an increase in TPF of 17.9% is observed in scenario II and a decrease in TPF of 15.4% and 1.2% respectively in scenarios III and IV.

which leads to the conclusion that a low capacity of the charge controller or the inverter is not conducive to the optimal use of the SAPV system, especially since these are the main points of conversion of electrical energy. However, an appropriate value for the storage capacity is very favourable to the optimal use of the SAPV system because it is one of the most sensitive points in the design and operation of SAPV systems

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