AN AIDED DESIGN ANALYSIS METHODOLOGY FOR OPTIMAL GRID–CONNECTED RESIDENTIAL PHOTOVOLTAIC SYSTEMS

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The evolution in the grid connected photovoltaic (PV) system design tools is not promoted compared to the great progress made in the PV material fabrication, and in the stand alone PV system development. So a more advanced examination is needed for each component of the PV array-utility grid chain, particularly the power conditioning unit, which is the key element in these systems. Success optimal operation of the whole system depends on the decision that a designer has to make for determination of the power conditioner parameters. This concerns in particular systems development and their control strategies, which depend completely on the available design tools and implantation techniques. In this paper a set of relatively simple decoupled modelling mathematical formulae, suitable for both frames DC and AC, are developed and investigated. These expressions are useful in sizing of the PV array and the conditioning unit parameters which allow determination of the minimum power to be recovered and the consequent modulation index. Expressions with their transformation techniques are validated followed by simulation and discussion of an optimum energetic case study.

**Key words:** grid connected PV systems, stand alone PV systems, maximum power point, load operating characteristics, inverter topologies

1 NOMENCLATURE

- \( A \): diode ideality factor
- \( k \): Boltzmann gas constant
- \( N_S \): total number of series cells (modules)
- \( T \): absolute temperature of the array
- \( q \): electron charge
- \( I_0 \): array reverse saturation current
- \( I_{PV} \): net delivered array output current
- \( T_L \): sunrise time
- \( T_C \): sunset time
- \( C_{noon} \): insolation at solar noon
- \( I_{PHnoon} \): array photo generated current at solar noon
- \( t \): solar time of the sunny day in hour
- \( Z \): AC side impedance (\( = R + j\omega L \))
- \( V_S \): inverter fundamental output voltage
- \( m \): amplitude modulation index (ratio)
- \( \delta \): load or power angle
- \( V_G \): grid voltage
- \( LOC \): load operating curve or characteristics
- \( MPP \): maximum power point
- \( MPPT \): maximum power point tracker
- \( c/c \): characteristics

2 INTRODUCTION

One of the most promising renewable energy technologies is the photovoltaic. There is a growing consensus that distributed photovoltaic systems which provide electricity at the point of use will be the first to reach widespread commercialisation [1]. The chief one, among these distributed applications, is single-phase grid connected PV power systems for dwellings (1–5 kW), [2].

In order to identify the critical parameters and target, the development or improvement of such systems needs a better knowledge of their performances. Herein, the analytical tools optimizing the system parameters are essentials; especially those which are simple and precise. Modelling grid connected PV systems with a set of simple and accurate expressions that look like those developed for stand alone PV systems (DC or AC) [3, 4, 5] will give them a growth ahead.

Grid connected PV systems operate in parallel with the local utility network at the power distribution level. Figure 1 shows a typical single-phase grid connected PV system, which can be either with or without transformer [6, 7]. In addition to the energy exchange between DC and AC frames, this configuration allows the consumer feeding, and decreasing the peak demand [8].

The determination of power conditioning parameters, referred to the DC or AC side (frame), that make the system operating successfully and optimally, is one of the important decisions that a grid connected PV system designer has to make. This concerns the hardware parts as well as the development and the control strategies, which depend completely on the available design analytical tools and implantation techniques. As an example, a poorly designed inverter MPPT algorithms may become lost in their search for the maximum power point.

Unfortunately, few authors have tackled this subject deeply. Maybe these problems are seen as manufacturers concern, who are developing their own techniques through
experience. In [9, 10] all the models are developed toward the stability analysis of power electronics based systems, while in [11] AC classical coupled models are used and a microcontroller-based circuitry is developed. In [12] a set is suggested of decoupled modelling expressions in the DC side for both inverter output current and power (load) angle but these expressions are knotty and need precision.

In this paper a set of relatively simple decoupled equations, suitable for system optimisation in both sides DC and AC, are developed and investigated. Moving of these expressions between both frames (AC and DC) is developed by using a straightforward transformation technique. The efficiency of this decoupled extended expressions appears in the optimum system design procedures, system performance predictions, evaluation, and in system verification [11]. Expressions with their transformation technique are validated through experimental outcomes obtained from [12], followed by simulation and discussion of an optimal energetic case study.

3 SYSTEM MODELLING

To determine the mathematical model of each element of the pervious chain, an equivalent circuit is used (Fig. 2) which is obtained under the following assumptions: the PV array is represented by “one-diode” model in which the shunt resistance is neglected, ripple current and voltage are neglected (high switching frequencies), \( R \) and \( L \) are the overall resistance (parasitic and inverter resistance) and filter inductance accounting for any other flux leakage, respectively, and the system is considered to be in the steady state.

3.1 Energy array model

The DC side model (Fig. 2), one-diode model, contains a current source \( I_{PH} \), one diode and a series resistance \( R_s \) which represents the total resistance of the array accounting that of wiring. The PV array (a solar cell as well) net output voltage at a given time is expressed as [6]:

\[
V_{PV} = \frac{AnskT}{q} \ln \left( \frac{I_{PH} - I_{PV} + I_0}{I_0} \right) - I_{PV}R_s.
\]

(1)

The array output power, which depends on the AC loop parameters, can be formulated as

\[
P_{PV} = \frac{AnskT}{q} \ln \left( \frac{I_{PH} - I_{PV} + I_0}{I_0} \right) I_{PV} - I_{PV}^2R_s.
\]

(2)

The maximum power point of the array at a given time can be obtained by differentiating equation (2) w.r.t. the current and equating to zero. The current at that point \( I_{mpp} \) can be found by solving

\[
I_{mpp} = I_{PH} - I_0 \exp \left( \frac{2I_{mpp}R_s}{ANsV_{th}} - \frac{I_{mpp}}{I_{PH} - I_{mpp} + I_0} \right) - 1
\]

(3)

where \( V_{th} = kT/q \); is the thermal voltage.

Having obtained \( I_{mpp} \), voltage \( V_{mpp} \) can be deduced from equation (1), and \( P_{mpp} \) from equation (2), which allows the calculation of the array maximum energy throughout one sunny day period

\[
E_{mpp} = \int_{T_L}^{T_C} P(t) dt.
\]

(4)

Manipulation of the previous equations throughout the sunny day period requires other two models: insulation model, \( C(t) \), and the photocurrent model \( I_{PH}(t) \), all as a function of solar time; here are these models [6]:

\[
C(T) = C_{noon} \sin \left[ 15(t - T_L) \right],
\]

(5)

\[
I_{PH}(t) = I_{PHnoon} \sin \left[ 15(t - T_L) \right].
\]

(6)
3.2 Classical Coupled model

By using Thevenin’s theorem, the load-grid equivalent circuit (a-b) is determined from the circuit modelling of the AC side as depicted in Fig. 3 and its phasor diagram is given in Fig. 4. The necessary formulae for this development are [6]:

\[
I_G = \frac{1}{2} \sqrt{V_S^2 + V_G^2 - 2V_SV_G \cos \delta}, \quad (7)
\]

\[
\tan(\theta) = \frac{RV_S \sin \delta - \omega L(V_S \cos \delta - V_G)}{(V_S \cos \delta - V_G)R + \omega LV_S \sin \delta}. \quad (8)
\]

Equations (7) and (8) have a great importance in the system design and performance prediction. Equation (7) represents the load curve (LC) in the AC side, indicating both rectification (AC-DC) and inversion (DC-AC) operations. The current phase angle is formulated by equation (4). It is observed that these equations are non-linear, coupled, and suitable only in the AC side. This is a topic for any designer dealing with both frames AC and DC.

3.3 Extended model

The development of this model requests a technique permitting conversion between DC and AC frames. The key of this conversion is to find a factor allowing the transition in both DC and AC directions. Having the previous hypotheses, and using the energy conservation theorem (DC power \( P_{PV} = AC \) apparent power \( S \)), [11], then

\[ P_{PV} = S. \quad (9) \]

The PWM inverter input and output voltages (current) are related by the amplitude modulation ratio \( (m) \). Thus, the expressions for these are

\[ V_S = \frac{m}{\sqrt{2}} V_{PV}, \quad (10) \]

\[ I_G = \frac{\sqrt{m}}{m} I_{PV}. \quad (11) \]

The generalized transformation technique is obtained using equations (10) and (11), where \( \frac{m}{\sqrt{2}} \) is the voltage transformation ratio and \( \frac{\sqrt{m}}{m} \) is the current transformation ratio in the transition from AC frame to DC frame.

By applying the previous transformation technique, the extended equations for any frame can be deduced easily. Since it is very suitable to study the system (sizing, performance prediction, etc) in the DC frame, it is more convenient to transfer the AC load model to the DC side; from this, equation (7) is transferred, giving:

\[ I_{GT} = \frac{m}{2\sqrt{2}} \sqrt{m^2 V_{PV}^2 + 2V_G^2 - 2\sqrt{2}m V_{PV} V_G \cos \delta}. \quad (12) \]

This equation gives the expression of the load operating characteristics (LOC) formula, which is a function of the DC voltage \( V_{PV} \) and the ‘secondary transformer’ or grid voltage \( V_G \), as well as embedding two control parameters \( (m \) and \( \delta \). To operate the system on the maximum power/energy point path (MP/E/PP) or to evaluate its performance, at least, these parameters should be determined.

The remarks, to come across from this, are: equation is coupled, and formed by mixer of AC and DC parameters. According to these remarks, it appears the importance of finding a new and relatively simple equations to deal with these requirements, and to solve other problems like the minimum injected power, transformer ratio selection, etc.

3.4 Decoupled extended model development

Equation (7) represents a non-linear equation, embedding both rectification and inversion, where \( m \) and \( \delta \) are two unknown control parameters. To solve it for the MP/E/PP and for the inversion case only, it is necessary to deduce another equation in the AC side, and obtaining the inversion part of this irrational function (eq. (7)). The obtained system of equations is the decoupled extended system.

3.4.1 Decoupled expressions in the AC side

First of all, the injected AC power into the grid is usually done with a unity power factor. The criterion for this condition is expressed, from equation (8), as:

\[ V_S = V_G/(\cos \delta - \frac{R}{X_L} \sin \delta). \quad (13) \]

In another way, the angle \( \delta \) can be expressed, from Fig. 4, as:

\[ \delta = \cos^{-1} \frac{V_G + I_G R}{V_S}. \quad (14) \]

Furthermore, substituting equation (14) into equation (7) after squaring it, and with some rearrangements, equation (15) can be obtained:

\[ Z^2 I_G^2 + 2RV_G I_G - (V_S^2 - V_G^2) = 0. \quad (15) \]

The positive root (DC/AC conversion) of this equation is:

\[ I_G = \frac{1}{2\sqrt{2}} \sqrt{R^2 + X_L^2 \left(1 - \frac{V_G^2}{V_S^2}\right) V_S - \frac{R}{Z^2} V_G}. \quad (16) \]

Equation (16) is the decoupled LOC in the AC side, which is a function of \( R, X_L, V_G \) and \( V_S \). This equation is suitable for many tasks such as studying the impact of the first three parameters on system behaviour, as well as optimizing the system operation (following MP/E/PP).
Comparing equations (19) and (21) with those deduced replacing $V_{verter}$ output voltage as a function in where $I$ is found by the same procedure from the equation (17),

$$I_G = \frac{1}{Z^2} \sqrt{R^2(1 - \sin^2 \delta) + X_L^2(1 - \cos^2 \delta) + 2RX \sin \delta \cos \delta V_S} - \frac{R}{Z^2} \left(\cos \delta - \frac{R}{X_L} \sin \delta\right) V_S. \quad (17)$$

Equations (13), (16), and (17) are suitable to carry out many studies (system sizing, performance evaluation, optimal design, etc), especially the optimal operation design and the analysis of the impact of different parameters on the system behaviour.

Next, the decoupled equation of $\delta$ in the AC side is:

$$\delta = \cos^{-1}\left[\frac{X_L^2 V_G}{Z^2 V_S} + \frac{R}{Z^2} \sqrt{R^2 + X_L^2(1 - \frac{V_G^2}{V_S^2})}\right]. \quad (18)$$

### 3.4.2 Decoupled expressions in the DC side

For many purposes, such as optimizing the system operation, sizing the PV array and the DC power conditioning parts, as well as studying the climatic effects on the performance of the system, it is convenient that equations (16), (17) and (18) should be transferred to the DC side, while equation (13) be adapted only. To do that, the transformation technique given by equations (10) and (11) is employed. Following are the LOC, $\delta$, and $V_G$ equations in DC side

$$I_{GT} = \frac{m^2}{2Z^2} \sqrt{R^2 + X_L^2(1 - \frac{2V_G^2}{m^2V_{PV}^2})} V_{PV} - \frac{mR}{Z^2} \sqrt{\frac{2}{\sqrt{2}}} V_G. \quad (19)$$

Equation of LOC, with parameter $\delta$ and without $V_G$, is found by the same procedure from the equation (17),

$$I_{GT} = \frac{m^2}{2Z^2} \times \sqrt{R^2(1 - \sin^2 \delta) + X_L^2(1 - \cos^2 \delta) + 2RX \sin \delta \cos \delta} V_{PV} - F \quad (20)$$

where $F = \frac{m^2}{2Z^2} \left(\cos \delta - \frac{R}{X_L} \sin \delta\right) V_{PV}.$

The adapted expression for phase angle $\delta$ of the inverter output voltage as a function in $V_{PV}$ is found by replacing $V_S$ with its equivalent expression, equation (10) into equation (15). So

$$\delta = \cos^{-1}\left[\frac{X_L^2 \sqrt{2} V_G}{Z^2 m V_{PV}} + \frac{R}{Z^2} \sqrt{R^2 + X_L^2(1 - \frac{2V_G^2}{m^2V_{PV}^2})}\right]. \quad (21)$$

Comparing equations (19) and (21) with those deduced in [11], we can say that these equations are analytically more accurate, relatively simple, and can be adapted for any on-line control for an optimal operation.

Concerning the minimum injected power problem, which is related to the transformer ratio selection, parameter $V_G$ should be expressed as a function of $V_{PV}$. Adaptation of equation (4) gives the answer to these requirements. So, the new form of equation (4), when it is written as a function of $V_{PV}$ according to expression (10), is

$$V_G = \frac{m}{\sqrt{2}} V_{PV} \left(\cos \delta - \frac{R}{X_L} \sin \delta\right). \quad (22)$$

This equation has the following important tasks: choosing the maximum value of $V_G$, determination of the minimum transformer ratio (for power conditioning unit with transformer), and recovering the minimum power possible under different climatic conditions. Notice that the sizing is made for $m$ optimal.

Finally, the expression for the daily injected energy ($E_I$) into the grid is deduced, using equations (10), (19), with the help of Fig. 4, as

$$E_I = \sqrt{2}m \int_{T_{noon}}^{T_{noon}} (V_{PV} I_{GT} \cos \delta - I_{GT}^2 R_G) dt \quad (23)$$

where $T_{noon}$ is the time at which the load just start extracting the useful power, which can be taken nearly equal $T_C$ (equal 6 am), and $R_G$ is the AC loop resistance transferred to the DC side (equal to $\frac{2}{m^2} R$).

### 3.5 Decoupled extended model verification

The extended expressions developed previously are to be verified by both calculation and experimentation. The main required reference conditions which have to be satisfied during these verifications are: power conservation theorem, approval of classical models, and approval of the set-up experimentation results in [11].

A 3 kW peak power demand, which can feed any residential type dwelling houses (low, medium and large efficient houses), is selected for the analytical verification. The PV array satisfying this peak demand has 3.112 kWp, configured as: two strings ($N_P = 2$), in each string there are 13 modules in series (appendix) connected to string inverters; which in principle, satisfies the approach followed in this verification. The experimental verification is carried out by using the measurements obtained from [11].

#### 3.5.1 Numerical verification

There are two sets of expressions to be verified; the first set concerns the extended expressions developed for the AC frame, while the second set concerns the transferred ones.

The verification of the decoupled extended AC expressions is done by using: $P_I = 2800$ W, $V_G = 220$ V, $R = 0.3 \Omega$, $L = 9$ mH, $m = 0.78$ and $V_S = 226.693$ V;
3.5.2 Experimental validation

In [11], an experiment was carried out to validate the effectiveness of an announced LOC expression, which is utterly different from the extended expression developed in this article. The experimental data used for the verification of $I_{GDC}$ are: $P_{DC} = 46.9$ W, $V_{DC} = 28.6$ V, $P_I = 44.2$ W, $V_G = 16$ V, $R = 0.3\, \Omega$, $L = 9$ mH, and $m = 0.9$.

While the one for $\delta$ verification is: $V_S = 30.2$ V, $\delta = 37^\circ$, $V_{DC} = 47.5$ V, and $m = 0.63$.

The results of our extended expressions (16, 19, 20 and 21) compared with the experimental analogous data are given in Table 2. It can be observed that the accuracy of the results obtained in this work is satisfactory.

Table 1. Numerical verification of the decoupled extended expressions.

<table>
<thead>
<tr>
<th>Equations</th>
<th>Results</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(7)</td>
<td>$I_G = 12.7373$ A</td>
<td>outcomes of a classical coupled model</td>
</tr>
<tr>
<td>(14)</td>
<td>$\delta = 9.1415^\circ$</td>
<td></td>
</tr>
<tr>
<td>(16)</td>
<td>$I_G = 12.7371$ A</td>
<td>equal to $P_I/V_G$ at unity power factor</td>
</tr>
<tr>
<td>(17)</td>
<td>$I_G(\delta) = 12.7372$ A</td>
<td>equal to that of equation (16)</td>
</tr>
<tr>
<td>(18)</td>
<td>$\delta = 9.1414^\circ$</td>
<td>the same result as that of (14)</td>
</tr>
<tr>
<td>(19)</td>
<td>$I_{GT} = 7.0198$ mA</td>
<td>results of the extended expressions in the DC side</td>
</tr>
<tr>
<td>(20)</td>
<td>$I_{GT}(\delta) = 7.0253$ A</td>
<td>(extended model)</td>
</tr>
</tbody>
</table>

Table 2. Experimental validation of the decoupled extended model.

<table>
<thead>
<tr>
<th>Frame and equations</th>
<th>Experience [11]</th>
<th>Results</th>
<th>Errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>equation (16)</td>
<td>$I_{GAC} = 4.40$ A</td>
<td>0.00 %</td>
</tr>
<tr>
<td>DC</td>
<td>equation (4), [11]</td>
<td>$I_{GAC} = 2.04$ A</td>
<td>53.64 %</td>
</tr>
<tr>
<td></td>
<td>equation (19)</td>
<td>$I_{GDC} = 1.6399$ A</td>
<td>2.31 %</td>
</tr>
<tr>
<td></td>
<td>equation (4), [11]</td>
<td>$I_{GDC} = 2.3490$ A</td>
<td>43.24 %</td>
</tr>
<tr>
<td></td>
<td>equation (21)</td>
<td>$\delta = 35^\circ$</td>
<td>4.32 %</td>
</tr>
</tbody>
</table>

with the values of (13) and (14) transferred to the DC side. The results given in Table 1 confirm the analytical exactness of equations (16), (17) and (18). Furthermore, the comparison of the results, given in Table 1, of the extended expressions with that of the DC referenced values, both in the DC frame; validate equations (19), (20) and (21).

As a final remark about the decoupled extended expressions, the energy conservation theorem, and the approval of classical models are hold for all extended expressions, in both DC and AC frames.

4 DECOUPLED MODEL INVESTIGATION

In this section, and by using the new extended expressions, the grid connected PV systems is examined in the same procedure like that of the stand alone PV systems, especially in characterization and sizing. The efficiency of each new extended expression is to be clarified by studying the impact of some key parameters, on the performance of the system; followed by exploiting these expressions to establish the control parameter paths for MP/E/PP operation.

4.1 Simulation and discussion in the AC frame

First of all, to show the disadvantages of the classical coupled models, equations (1) and (7) are plotted in the AC frame (equation (1) must be transferred to AC frame) for $m = 0.78$, $V_G = 236.56$ V and for a PV array given in the appendix. Figure 5 shows the possibility of two operating points (A and B) for the coupled model LOC; this is due to the characteristics of irrational functions. This problem was eliminated by using the decoupled equations (16) or (17) for $\delta$ equal $8.5^\circ$. It is observed from Fig. 6, curves obtained from equations (16) and (17), that

1. The similarity of the decoupled LOC curves to that of a Stand-Alone PV systems feeding an (R, L) impedance with some particularities.
2. Decoupled LOCs did not coincide with the inversion part of the coupled LOC, because of their parametric representation of the load (grid); presence or absence of parameters $V_G$ and $\delta$.

Influence of $R$ and $L$

Since converters, in general, particularly inverters in direct connected PV systems, exhibit negative impedance characteristic, which has detrimental consequences,
Influence of the angle $\delta$

Figure 7, drawn by using the decoupled equation (17), confirms the important task of the inverter output voltage phase angle $\delta$, with respect to the grid voltage, regarding the power transfer (current); for $\delta$ equal zero, there is no power transfer and injection into the grid.

4.2 Simulation and discussion in the DC frame

The effects of the modulation index $m$, which is not discussed in the previous section, because the AC frame is not suitable for that. The other parameter, which has not been discussed yet, is the selection of the maximum secondary grid voltage $V_G$ corresponding to the minimum PV power to extract.

The modulation index ($m$)

To make obvious the tasks of the modulation index let draw a family of load curves (equation 19) for a specified range of $m$, associated with that of the PV array as it is shown in Fig. 8; from which the MPP algorithm can detect all the maximum power points for values of $m$ located in the interval [0.725–0.808]. If there is an increase, for any circumstances, in parasitic parameters, the negative impedance effect increases as well; then the detection of MPP corresponds to the smallest value of $m$ which is not any more 0.725, but with a value greater than 0.725; thus the decrease in the range of $m$ should be carried out by the MPPT to compensate the delivered power diminution; therefore the detection of MPP for different climatic conditions are done in a narrow interval of $m$, which makes the search algorithm unstable. For this reason the minimisation of parasitic parameters in such systems (MPPT included in the inverter control system) is required.

Choice of $V_G$

This discussion concerns the module integrated, the module-oriented or the string self commutated inverters with line frequency transformers. Let take the last topology case, where the PV array structure is formed by one branch of four modules of Solarex MSX-120 at STC. The selection of $V_G$ puts together other intervening parameters (minimum transformer voltage ratio, lowest PV power to be recovered, maximum modulation index and minimum displacement angle $\delta$). Equations (13) and (20) can be used to proceed in these selections as follows: by taking $\delta_{\text{min}} = 0.1$ radian (normally known), and by the determination of the voltage corresponding to the minimum power to be recovered, (using equation (1)), equations (1) and (20) are solved to determine the maximum modulation index $M_{\text{max}}$; then $V_G$ is computed from equation (22); and finally the transformer ratio $N$ is obtained as $N = \frac{220}{V_G}$.

This procedure has given the following results: the minimum power to be recovered is 18.34 W, the computed corresponding voltage is 68.3 V, the solution of equations (1) and (20) gives the maximum modulation index $M_{\text{max}}$; thus $V_G$ is computed from equation (22); and finally the transformer ratio $N$ is found equal 39.6263 V. So, $V_G$ can be taken equals to 40 V, which is confirmed in Fig. 9, as well as in the experimentation results given in, [11, 12].

Maximum energetic law

In order to extract the MPP energy during a sunny day, the manner of specifying the control pair parameters $(m, \delta)^{\text{optimal}}$ law must be specified. The decoupling and transferring techniques let the optimisation procedure be achieved without using any numerical optimisation techniques (static or dynamic [6]). This pair is determined by using equations (19) and (22), solved separately, where
In addition to the previous two equations, equation set identified by (1) to (6) associated with equation (23) allows getting the variation paths of many parameters that optimising the operation of the grid connected PV system. Figs. 10 and 11 depict clearly the variations of most necessary parameters, in per unit (referred to the corresponding MPP values or to their maximum values) with respect to the solar time, especially the injected energy affected by the negative impedance aspect, which has a consequence of a diminution the efficiency to 96.67% and the injected energy by 104.7 W or 802 WH; and the control law paths \((m, \delta)_{\text{optimal}}\), permitting this operation.

As a guide line, here are some proposals concerning the grid connected PV applications and the suitable working frame: Grid connected PV system optimisation, PV array sizing, prediction of the parasitic parameters, system components sizing, and system performance evaluation are preferred to be done in the DC frame; while energy pattern (selling, buying and saving), impact of AC parameters on the system performance, and piecewise static model optimisation in the AC frame.
5 CONCLUSION

A simplified aided design analysis methodology for an optimal grid-connected residential photovoltaic system has been developed. A mathematical analysis was carried out on the power conditioning model, giving birth to an easy to use transformation technique, and straightforward expressions, especially that of the load operating curves LOC; where its efficacy was tested analytically, by simulation with other expressions, and experimentally.

In addition to this, other simple expressions are developed for sizing most parameters of the conditioner unit. Parameters effects are also clearly investigated. The proposed procedure to determine the minimum power to be recovered, the corresponding voltage and the consequent modulation index are important outcomes of the work. The manner of deducing the law for extracting and injecting the maximum power point energy is specified through the extended decoupled expressions. Finally a suggested guide line for a grid connected PV system study is given.

Appendix

The PV module, Solarex MSX-120, characteristics used for calculations and simulation at Standard Test Conditions (STC: 1000 W/m², AM 1.5, and 25 °C) are

- Open circuit voltage \( V_{oc} = 42.6 \text{ V} \);
- Rated power \( P_{mpp} = 120 \text{ W}_p \);
- Rated voltage \( V_{mpp} = 34.2 \text{ V} \);
- Rated current \( I_{mpp} = 3.5 \text{ A} \);
- Open circuit voltage \( V_{oc} = 42.6 \text{ V} \);
- Short circuit current \( I_{sc} = 3.8 \text{ A} \);
- Series resistance \( R_s = 0.71 \Omega \);
- Saturation current at \( 20 ^\circ \text{C} = 17 \text{ nA} \);
- Diode quality factor \( A = 1.2 \);
- Number of cells/module \( = 72 \);
- \( I_{sc} \) temperature coefficient \( \alpha = 6.0 \text{ mA/}^\circ \text{C} \);
- \( V_{oc} \) temperature coefficient \( \beta = -146 \text{ mV/}^\circ \text{C} \).

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