Impact of Urban Photovoltaic Microgeneration in the Distribution Grid Using Three Phase Load Flow

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Abstract - Prompted by the need for clean energy sources, increasing numbers of photovoltaic generators are being connected to the distribution grid around the world. The urban photovoltaic microgeneration has recently been introduced in Portugal; increasing numbers of photovoltaic generators connected to distribution grid are expected in the future. It is, therefore, necessary to understand and quantify the impact that high penetrations of such generators may have on distribution grids. To achieve this goal, a three phase load flow algorithm is developed. This program provides the steady state analysis of any electric transmission network under all possible unbalanced conditions. The method of solution is the Newton-Raphson method. The results indicate that even at very high penetrations of PV, both the voltage profile and unbalances are small and unlikely to cause problems. Effects on network power flows and losses are also quantified and discussed.

I. INTRODUCTION

The scarce knowledge of the behavior of the low voltage grid (LV) subject to the introduction of microgenerators motivates this project. Keeping in mind that the low voltage grid is characterized by an unbalance of load, it is necessary to develop algorithms and three phase models, treating each phase individually. For that reason, this project revolves mainly around the development of models of the various components of a power system and the development of a methodology to solve the problem of a three phase load flow. Normally, for the study of large networks, the single phase load flow is optimized with relation of the complexity and precision of the results. So, the existing unbalances in the large systems are ignored. But, for the study of the smaller low voltage grids, the unbalance of the load can be more accentuated and may not be discarded. In this project, the three phase load flow is used to study the impact of the photovoltaic microgenerators (PV) in LV grids. The proposed algorithm to solve the three phase load flow consists of the Newton-Raphson method, due to its convergence conditions and convergence speed.

Some consequences of the microgenerators penetration in a LV grid can be anticipated, like the bus voltages rise and the reduction of load in cables. Any power injection causes an elevation in bus voltages where it is injected, a situation which should be analyzed and controlled to secure the voltage in its appropriate limits. The reduction of power flow in the cables causes a reduction of temperature and an increase of time of duration of these equipments.

The equipment of the power system can be three phase equipment or single phase equipment.

The PVs also have to be characterized and correctly modeled, in order to be inserted in a three phase load flow algorithm.

In this work, the impact of PVs in a distribution grid is also analyzed.
II. THREE PHASE MODELS

Power networks are composed by: rotating generators, three phase transformers, transmission lines, cables and loads. In this work, models of each of these elements are going to be developed taking in consideration the fact that these models can be described by a 6x6 dimension matrix, as represented in equation (1). The power system elements are modeled by a six terminals circuit, and the element \((i,k)\) of matrix (1) is the admittance linking the terminals \(i\) and \(k\).

\[ I_1 \begin{bmatrix} y_{11} & \cdots & y_{61} \\ \vdots & \ddots & \vdots \\ y_{61} & \cdots & y_{66} \end{bmatrix} V_1 \]

A. Synchronous machines

The models of the synchronous machines can be developed based upon the symmetrical impedances given by the manufactures of the machines:

\[ Z_{abc} = \begin{bmatrix} Z_0 + Z_a + Z_a & Z_1 + aZ_1 + a^2Z_1 & Z_2 + a^2Z_2 \\ Z_2 + Z_1 + aZ_1 & Z_0 + a^2Z_2 + aZ_2 & Z_1 + Z_0 + aZ_0 \\ Z_1 + aZ_1 + a^2Z_2 & Z_2 + a^2Z_2 + aZ_2 & Z_0 + Z_1 + aZ_1 \end{bmatrix} \]

(2)

Where \( \alpha = e^{\frac{2\pi}{3}} \) and \( Z_1, Z_2, Z_0 \) represent the positive, negative and homopolar impedances, respectively.

The model of the synchronous machines is easily obtained from equation(2). The matrix that represents the model of the synchronous machines is shown in (3)[1].

\[ \begin{bmatrix} I_{abc} \\ I_{abc} \end{bmatrix} = \begin{bmatrix} Z_{abc}^{-1} & -Z_{abc}^{-1} \\ -Z_{abc}^{-1} & Z_{abc}^{-1} \end{bmatrix} \begin{bmatrix} V_{abc} \\ V_{abc} \end{bmatrix} \]

(3)

In equations (3), busbars \( k \) and \( i \), represent the internal bus and the terminal bus of the generator, respectively. For that reason, the introduction of synchronous generators, implicaes an increase in the number of buses (the machines are modeled by an \( \text{emf} \) behind a impedance). These new busbars assume the particularity of being buses where voltages are balanced and form a positive sequence. This is because the rotor circuit of the machine spins at a constant speed and induces a positive sequence \( \text{emf} \) in stator phases.

All the generators are equipped with a voltage regulator that is also modeled in the three phase load flow algorithm. In this paper, it is assumed that this regulator measures the generator terminal bus voltages - bus \( i \), and acts on the rotor circuit in order to maintain the average of magnitude voltages at a specified value, as shown in (4):

\[ V_{reg} = \left( \frac{V_i^a + V_i^b + V_i^c}{3} \right) \]

B. Transmission Lines

The transmission lines are modeled through their series impedances and shunt admittances.

The voltage drop, for phase “a” is given by [1]:

\[ \Delta V_a = V_a - V_i^a = I_a (R_a + j\omega L_a - joL_w + R_i + j\omega L_i - joL_w) \]

(5)

The effects of ground currents and earth wire are included in calculation of the voltage drops. Developing similar equations for phases \( b \), \( c \) and for the earth wire, equations (6) are obtained.

\[ \begin{bmatrix} \Delta V_{abc} \\ \Delta V_g \end{bmatrix} = \begin{bmatrix} Z_A & Z_B \\ Z_C & Z_D \end{bmatrix} \begin{bmatrix} I_{abc} \\ I_g \end{bmatrix} \]

Assuming that the earth wire is at the same potential in the two extremities, \( \Delta V_g = 0 \),
it is possible to use the Kron’s reduction technique to reduce equation (6):

\[
[\Delta V_{abc}] = [Z_{abc}] [I_{abc}] 
\]

\[
Z_{abc} = Z_a - Z_a Z_D^{-1} Z_C 
\]

(7)

The shunt admittance of a transmission line can be determined by the same method that was used in the computation of the series impedance. The voltage between two electric conductors can be related to the charges, \( Q \), through the Maxwell coefficients:

\[
\begin{bmatrix}
V_{abc} \\
V_g
\end{bmatrix} =
\begin{bmatrix}
P_A & P_B & P_C \\
P_D & P_B & P_C
\end{bmatrix}
\begin{bmatrix}
Q_{abc} \\
Q_g
\end{bmatrix}
\]

(8)

Again equation (8) can be reduced using the Kron’s reduction technique:

\[
\begin{bmatrix}
V_{abc} \\
V_g
\end{bmatrix} = [P_{abc}] [Q_{abc}]
\]

(9)

\( P_{abc} = P_a - P_a P_b^{-1} P_c \)

The matrix of the shunt admittance is obtained from the Maxwell coefficients, by inverting matrix \([P_{abc}]\):

\[
[Y_{abc}] = j \omega [P_{abc}]^{-1}
\]

(10)

Knowing the series impedance and shunt admittance matrices, it is possible to obtain the model of the transmission lines, as shown in equations (11):

\[
\begin{bmatrix}
[I_{abc}] \\
[I_g]
\end{bmatrix} =
\begin{bmatrix}
[Z_{abc}^{-1}] + [Y_{abc}] / 2 & -[Z_{abc}^{-1}] \\
-[Z_{abc}^{-1}] & [Z_{abc}^{-1}] + [Y_{abc}] / 2
\end{bmatrix}
\begin{bmatrix}
[V_{abc}] \\
[V_g]
\end{bmatrix}
\]

(11)

C. Three phase cables

The three phase cables possess the same parameters of the transmission lines; however, the calculation method differs a little due to its cylindrical geometry. The series impedance composed by a resistance and a reactance is calculated in the following way: the resistance is obtained through the cross section, the length of the conductor and by the resistivity of the conductor at the temperature of service (in the worse case it will be of 70ºC). The self-induction coefficient and the mutual induction coefficient are calculated through (12) e (13) [3]:

\[
L = 2 \times 10^{-7} \times \ln \left( \frac{1}{GMR} \right) \left( \frac{H}{m} \right)
\]

(12)

\[
M = 2 \times 10^{-7} \times \ln \left( \frac{1}{d_{ik}^2} \right) \left( \frac{H}{m} \right)
\]

(13)

Where \( GMR = e^{-\frac{4}{a^2} \cdot r} \), \( r \) is the conductor radius and \( d_{ik} \) is the distance between the conductors.

Concerning the shunt admittance, the capacitance matrix is calculated on the basis of equations (14) and (15). [6], [7]

\[
C = C_0 + 3 \cdot C_c
\]

(14)

\[
C(F/m) = \frac{4 \pi \varepsilon}{\ln \left( \frac{3 \cdot (a^2 - s^2) \cdot s^2}{r_p^2 \cdot (a^6 + s^6)} \right)}
\]

(15)

\[
C_0(F/m) = \frac{2 \pi \varepsilon}{\ln \left( \frac{a^6 - s^6}{3 \cdot r_p \cdot s^2 \cdot a^3} \right)}
\]

where \( C_0 + 2 \cdot C_c \) are the diagonal elements and \(-C_c\) are the non-diagonal elements.

D. Three phase transformers

Three phase transformers can be represented by an ideal transformer with tap ratio \( m \) in series with the short circuit impedance. To represent the transformer in the phase coordinates, it is necessary first to represent the equivalent circuit in the symmetrical coordinates. Next, using the Fortescue transformation, the models are
transformed to phase coordinates, taking into account the type of winding connections [2].

Table 1: Transformer models

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Prim.</td>
<td>Sec.</td>
<td>Prim.</td>
</tr>
<tr>
<td>![Δ]</td>
<td>![Δ]</td>
<td>![Y₁]</td>
</tr>
<tr>
<td>![Δ]</td>
<td>![Δ]</td>
<td>![Y₂]</td>
</tr>
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<td>![Δ]</td>
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<td>![Y₁]</td>
</tr>
<tr>
<td>![Δ]</td>
<td>![Δ]</td>
<td>![Y₁]</td>
</tr>
</tbody>
</table>

Where \( y_i \) is the short circuit transformer admittance.

**E. Loads**

In a power system the constant impedance loads and the constant power loads can exist. The grounded wye constant power loads are modeled by a specified power. The grounded wye constant impedance loads are directly introduced on the global admittance matrix. For the other loads types, for example, delta connection loads, it is necessary to make some calculations in order to transform these loads to equivalent grounded wye loads.

### III. SINGLE PHASE MODELS

The single phase cables and the single phase transformers are two single phase elements examples that can be used in a power system.

The series impedance of single phase cables is modeled in the same way of the series impedance of three phase cables. The shunt admittance is determined knowing that the equivalent capacity of a single phase cable is given by [6], [7]:

\[
C(F/m) = \frac{2\pi \varepsilon}{\ln \left( \frac{2 \cdot (a^2 - s^2) \cdot s}{r_p \cdot (a^2 + s^2)} \right)}
\]

The capacity between a phase conductor and the reference conductor is given by [6], [7]:

\[
C_o(F/m) = \frac{2\pi \varepsilon}{\ln \left( \frac{a^4 - s^4}{2 \cdot r_p \cdot s \cdot a^2} \right)}
\]

The capacitance between the phase conductors may be computed through

\[
C = C_o + 2 \cdot C_e.
\]

So, the single phase cable model is represented by 2X2 matrix:

\[
\begin{bmatrix}
I_i^r \\
I_i^k
\end{bmatrix} =
\begin{bmatrix}
\frac{1}{Z_{cable}} + \frac{Y_{cable}}{2} & -\frac{1}{Z_{cable}} \\
-\frac{1}{Z_{cable}} & \frac{1}{Z_{cable}} + \frac{Y_{cable}}{2}
\end{bmatrix}
\begin{bmatrix}
V_i^r \\
V_i^k
\end{bmatrix}
\]

(18)

The single phase transformer is modeled by the 2X2 matrix, as presented in(19).
\[
\begin{bmatrix}
    I' \\
    I^k
\end{bmatrix} = \begin{bmatrix}
    y_{cc} & -y_{cc} \\
    -y_{cc} & y_{cc}
\end{bmatrix}
\begin{bmatrix}
    V' \\
    V^k
\end{bmatrix}
\] (19)

Where \( y_{cc} \) represents the transformer short-circuit admittance.

The 2X2 matrices must be transformed in 6X6 matrices, as presented in matrix(20), in order that they may be used in the three phase load power program.

\[
[Y] = \begin{bmatrix}
    y_{11} & 0 & 0 & y_{12} & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 \\
    y_{21} & 0 & 0 & y_{22} & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 \\
\end{bmatrix}
\] (20)

Matrix (20) models branches connecting two single phase buses. However, if the branch is connecting a single phase bus and a three phase bus, then the 6X6 matrix has the form:

\[
[Y] = \begin{bmatrix}
    y_{11} & 0 & 0 & y_{12}^a & y_{12}^b & y_{12}^c \\
    0 & 0 & 0 & 0 & 0 & 0 \\
    0 & 0 & 0 & 0 & 0 & 0 \\
    y_{21}^a & 0 & 0 & y_{22}^a & 0 & 0 \\
    y_{21}^b & 0 & 0 & y_{22}^b & 0 & 0 \\
    y_{21}^c & 0 & 0 & y_{22}^c & 0 & 0 \\
\end{bmatrix}
\] (21)

If connecting phase on three phase bus is phase \( a \), then \( y_{12}^b = y_{12}^c = y_{21}^b = y_{21}^c = y_{22}^b = y_{22}^c = 0 \); if connecting phase on three phase bus is phase \( b \), then \( y_{12}^a = y_{12}^c = y_{21}^a = y_{21}^c = y_{22}^a = y_{22}^c = 0 \), and, if connecting phase on three phase bus is phase \( c \), then \( y_{12}^a = y_{12}^b = y_{21}^a = y_{21}^b = y_{22}^a = y_{22}^b = 0 \).

**IV. NEWTON’S METHOD**

The goal of load flow program is to solve the equations for all busbars of a power system. In power system, the single phase buses and three phase buses can exist. The buses of a power system can be divided in two types: load buses or generation buses.

For all load buses (three phase buses) the equations (22) and (23) must be solved [1].

\[
P_p^i = V_p^i \sum_{k=1}^{n} V_{k}^{m} \left( G_{p}^{km} \cos(\theta_p^i - \theta_k^m) + B_{p}^{km} \sin(\theta_p^i - \theta_k^m) \right)
\] (22)

\[
Q_p^i = V_p^i \sum_{k=1}^{n} V_{k}^{m} \left( G_{p}^{km} \sin(\theta_p^i - \theta_k^m) - B_{p}^{km} \cos(\theta_p^i - \theta_k^m) \right)
\] (23)

The real power and reactive power on bus \( i \) and phase \( p \) were computed by these equations. The matrices \( G \) and \( B \) represent the real part and imaginary part of the global admittance matrix. This matrix is computed with the matrices that represent the model of power systems components.

For all generators (except the slack generator) the equations that specify the real power produced must be solved (24)

\[
P_{gen}^i = \sum_{m=1}^{n} \sum_{k=1}^{n} V_{m}^{n} \left( G_{m}^{nk} \cos(\theta_m^i - \theta_k^n) + B_{m}^{nk} \sin(\theta_m^i - \theta_k^n) \right)
\] (24)

For all terminal generator busbars, equation (25) must be solved.

\[
V_{reg}^i = \left( V_{a}^k + V_{b}^k + V_{c}^k \right) / 3
\] (25)

On single phase busbars, equations (26) and (27) must be solved in order to compute the real power and reactive power injected on these busbars.

\[
P_i = V_i \sum_{k=1}^{n} V_{k}^{m} \left( G_{i}^{km} \cos(\theta_i^k - \theta_k^m) + B_{i}^{km} \sin(\theta_i^k - \theta_k^m) \right) +
\]

\[
+ V_i \sum_{k=1}^{n} V_{k}^{m} \left( G_{i}^{km} \cos(\theta_i^k - \theta_k^m) - B_{i}^{km} \sin(\theta_i^k - \theta_k^m) \right)
\] (26)
\[ Q = V_i^0 \sum_{i=1}^{n_i} V_i^i (G_i^0 \sin(\theta_i^0 - \theta_i^0) - B_i^0 \cos(\theta_i^0 - \theta_i^0)) + \\
+ V_i^0 \sum_{i=1}^{n_i} V_i^i (G_i^0 \sin(\theta_i^0 - \theta_i^0) - B_i^0 \cos(\theta_i^0 - \theta_i^0)) \]

(27)

where \( n_{1\phi} \) represents the number of single phase busbars. The particular single phase involved is represented by the superscript \( p \).

In order to solve the three phase load flow equations, the Newton’s method was used. The Jacobian matrix is showed in equation (28).

\[
\begin{bmatrix}
\Delta P \\
\Delta P^{pm} \\
\Delta Q \\
\Delta V^{ref}
\end{bmatrix} = \begin{bmatrix}
\end{bmatrix} 
\begin{bmatrix}
\Delta \theta \\
\Delta \theta^{pm} \\
\Delta \theta \\
\Delta \theta^{ref}
\end{bmatrix}
\] (28)

The matrix coefficients are the partial derivatives of all the equations.

The left hand side vector is computed through the difference between the specified values and the computed values with estimated values for the state variables. The state variable values must be updated in order to decrease the error between specified and computed values. (28).

\[
\begin{bmatrix}
\Delta P \\
\Delta P^{pm} \\
\Delta Q \\
\Delta V^{ref}
\end{bmatrix} = \begin{bmatrix}
\end{bmatrix} 
\begin{bmatrix}
\Delta \theta \\
\Delta \theta^{pm} \\
\Delta \theta \\
\Delta \theta^{ref}
\end{bmatrix}
\] (28)

The state variables are updated through the computation of right hand side vector (incremental values vector).

Sometimes, because the reactive power generation limits, the specified voltage regulation value is not possible to realize. If a generator reaches its reactive power limit, then, the voltage regulation equation must be removed. The generator internal bus voltage magnitude must be computed from equations (33).

\[
[A] = \left[ V_j \right] \left[ Z_{abc} \right]^{-1}
\] (29)

\[
[\Phi]^* = \begin{bmatrix}
e^{-j\theta_a} \\
e^{-j(\theta_a - 2\pi/3)} \\
e^{-j(\theta_a + 2\pi/3)}
\end{bmatrix}
\] (30)

\[
[\alpha] = \text{imag} \left( [A]\left[ \Phi^* \right]^T \right)
\] (31)

\[
[\beta] = \text{imag} \left( [A]\left[ \Phi_j \right]^T \right)
\] (32)

\[
\begin{bmatrix}
V_{int}^t \\
Q_{prod}^a \\
Q_{prod}^b \\
Q_{prod}^c
\end{bmatrix} = \begin{bmatrix}
\alpha^a & -1 & 0 & 0 \\
\alpha^b & 0 & -1 & 0 \\
\alpha^c & 0 & 0 & -1
\end{bmatrix}^{-1} \begin{bmatrix}
\beta^a \\
\beta^b \\
\beta^c \\
Q_{prod}
\end{bmatrix}
\] (33)

In these equations the terminal bus voltage is represented by \( V_j \) and \( \theta_a \) represents the internal bus voltage phase on phase \( a \).

V. PHOTOVOLTAIC ARRAYS MODEL

The photovoltaic cells present an I- V characteristic as shown in figure 1 [4].

This curve can be represented through equation (34) [4]:

\[
I = I_s - I_0 \left( e^{V_{oc}/kT} - 1 \right)
\] (34)

Where:

\[
I_s = I_{sc} = \frac{G}{G_c} \frac{V_{oc}}{I_{sc}} (35)
\]
\[ I_o = I_o^r \left( \frac{T}{T^r} \right)^3 \cdot e^{\frac{\varepsilon q}{m' k T} \left( \frac{1}{T^r} - \frac{1}{T} \right)} \] (36)

\[ m = \frac{V_{\text{max}}^r - V_{\text{oc}}^r}{k \cdot T^r \ln \left( 1 - \frac{I_{\text{max}}^r}{I_{\text{sc}}^r} \right)} \] (37)

$q$ - Electron charge;
$T$ - Cell temperature;
$K$ - Boltzman constant;
$\varepsilon$ – Band gap energy;
$G$ – Solar radiation;
$m'$ - relation between “m” and the number of series connected cells.

In these equations the superscript “r” refers to standard test conditions parameters, while the subscripts “sc”, “oc”, “max” refer to short-circuit, open-circuit and maximum power point (MPP) variables, respectively.

Normally, the MPP is the photovoltaic array working point. Thus, it is necessary to know both voltage and current values on MPP. The MPP voltage can be computed through equation (38)[4].

\[ \frac{V_{\text{max}}^q}{e^{m' k T}} = \frac{I_s + 1}{I_o^r + V_{\text{max}}^r - \frac{q}{m' k T}} \] (38)

Due to the non-linearity, equation (38) must be solved using an iterative algorithm, as Gauss’ or Newton’s method. The current and power on MPP are then easily computed through (34) and by the relation $P_{\text{max}} = V_{\text{max}} \cdot I_{\text{max}}$, respectively.

Due to the inverter modulation limits, the voltage on PV array can be either imposed by the low voltage grid (if the modulation limits are violated), or by the chopper MPPT (if the modulation limits are not violated). The MPPT imposes the MPP voltage on PV array terminal bus. However, if the modulation limits are violated, the PV array terminal bus voltage is computed through equation (39) [5].

\[ V_{DC} = \sqrt{2} \times V_{AC}^{(1)} \] (39)

In this equation, the first harmonic RMS value of AC voltage is denoted by $V_{AC}^{(1)}$.

Equation (39) implies that the PV array terminal bus voltage is not the MPP voltage. So, in these conditions, the PV array does not produce its maximum power.

**VI. RESULTS**

The results of three phase load flow program are presented in the figures bellow. The ambient conditions and the load power are changed each simulation.

A. $G=1000W/m^2$; $T = 35^\circ C$; Pow: 100% (Máx)

These ambient conditions allow the PV systems to produce nearly its maximum power. The power system is on peak load conditions.

The following figures show, sequentially, as a function of the number of installed PV arrays:

1) Unbalance;
2) Three phase real power on MV/LV transformer;
3) Three phase reactive power on MV/LV transformer;
4) Real power losses;
5) Reactive power losses;
6) Voltage magnitude on bus 60.
B. G = 1000 W/m²; T = 35ºC; Pow: 25%

The ambient conditions are the same as for simulation A, but the load power is now 25% of the peak load. The relevant results are about the real and reactive power losses (figure 3).

C. G = 800 W/m²; T = 25ºC; Pow: 70%

Low power on phase b

The loads connected on phase b change to 10% of its nominal value. This implies the decreasing of the power flow on phase b of the MV/LV transformer (2nd graph – green line). The simulation results are presented in figure 4.

1) Unbalance;
2) Three phase real power flow on secondary winding of transformer;
3) Three phase reactive power flow on secondary winding of transformer;

D. Real power flow on MV/LV transformer in summer day and winter day.

In this case, there are 19 PV systems installed in LV grid. The load power, solar radiation and ambient temperature change on a 24 hours period. The simulation results on three different conditions are presented in figure 5:

1) Without PV systems installed (blue line)
2) With 19 PV systems installed and in a summer day (red line);
3) With 19 PV systems installed and in a winter day (green line);
VII. CONCLUSIONS

From the results analysis, it is possible to conclude that the unbalance conditions do not change much with the PV systems installation. The voltage rise has very low values, maximum 2 Volt.

If the voltage on the MV bus is largely unbalanced without PV systems installed, then, the PV systems installation do not contribute to balance the power network. However, if the PV systems are installed systematically on the more loaded phases, (phase a and phase c), then, the unbalance tends to decrease.

In the studied situations, the unbalance never assumes critical values. Comparing the studied unbalances with the maximum unbalance, it is possible to conclude that the studied unbalances are not very significant.

If the LV grid is in peak load power conditions, then, the real power losses are more sensitive concerning the number of installed PV systems. This occurs because the losses are proportional to the square current, and the PV systems decrease the cables current. On the last simulation, it is possible to observe that the peak power does not change by increasing PV systems penetration. However, in hotter countries, where peak loads are often caused by air conditioned, the peak power reduction could be expected.

REFERENCES