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PREDICTION OF ANNUAL ENERGY PRODUCTION FROM PV STRING UNDER MISMATCH CONDITION DUE TO LONG-TERM DEGRADATION*

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Abstract. *Reduction of long-term degradation effects represents a long-time challenge in photovoltaic (PV) manufacturing industry. Modelling of long-term degradation types and their impact on maximum power of PV systems have been analysed in this article. Brief guidelines for PV cell-based modelling of PV systems have been illustrated. Special study case, PV string consisting of 12 PV modules, has been modelled in order to determine degradation and mismatch power losses. Modified methodology for prediction of annual energy production from PV string, based on horizontal irradiation and ambient temperature experimental measurements at the location of Belgrade, has been developed. Coefficient named "degradation factor" has been introduced to include and validate degradation power losses. Economic considerations have indicated evident money income reduction, as a consequence of lower annual energy production related to long-term degradation.*

Key words: *PV string, energy production, long-term degradation, degradation factor, mismatch losses*

1. INTRODUCTION

Precise determination of annual energy production from PV systems is very difficult to achieve, mostly due to variable operating conditions (irradiation and ambient temperature) [1]. Electricity production is closely related to conversion efficiency, which represents one of the most important parameters when discussing PV systems [2]. The new materials are being constantly developed with purpose of increasing conversion efficiency and mitigating degradation effects. According to research, presented in [3], organic materials with PV properties have proved to be one of the most promising solutions. Meanwhile, conventional silicon materials remain the most widely used in field applications.

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Conventional methods for prediction of energy production from PV systems usually use hourly-averaged horizontal irradiation and ambient temperature measurements for specific locations [4-6]. One of their main shortcomings is neglecting of long-term degradations related to encapsulating material, e.g. delamination, discoloration and corrosion. According to various research results [7-12], it has been found that long-term degradation effects can often reduce PV system's power up to 15-20% during lifetime exploitation period.

This article is organized as follows. The second chapter covers basic facts related to most common types of long-term degradation. In the third chapter, modelling guidelines for PV systems and degradation types are presented. PV module degradation effects, under variable irradiation and temperature condition, have been analysed with results presented in the fourth chapter. The fifth chapter presents study case dedicated to PV string power reduction due to long-term degradation. Modified methodology for prediction of annual energy production from PV string and financial income, based on introduction of degradation factor, has been investigated in sixth chapter. Valuable conclusions are pointed out in final chapter.

2. Long-term Degradation of PV systems

Degradation represents a gradual deterioration of PV system components caused by real operating conditions in the field. Affected PV modules can continue to generate electricity, although produced energy can be significantly reduced. According to manufacturers, it is common practise to identify PV module as degraded when its maximum power reduces below 80% of the initial value.

Long-term degradation of PV systems is related to encapsulation material deterioration and its effects could be observed on the surfaces of PV cells during exploitation period. Ethylene vinyl acetate (EVA) is recognized, over the decades, as one of the best encapsulation materials for PV cells. As a consequence, nearly 80% of PV modules, produced around the world, are encapsulated by EVA [7]. Typical long-term degradation types of PV cells, related to EVA, are: delamination, discoloration and corrosion. Characteristic field examples of PV cells affected by long-term degradation types are shown in Fig.1 [8].

(a) (b) (c)

Fig. 1 Typical long-term degradations of PV cells [8]:
(a) Delamination; (b) Discoloration; (c) Corrosion

2.1. Delamination

Glass, EVA and PV material are tightly affixed (laminated) in normal PV cells. If some of the mentioned layers is damaged it could lead to delamination development. Delamination represents separation between the different layers within the PV cells and it is usually followed by the penetration of moisture and corrosion. The most common PV cell's surface area affected is located around busbars, as can be seen in Fig.1.a. This type of degradation is observed in more than 50% of installed PV modules according to research [9].

2.2. Discoloration

Ultra-violet radiation, followed by high degree of humidity and environment temperature, is recognized as the main cause of discoloration. Discoloration is the most common type of long-term degradation represented by electro-chemical process in which PV material changes colour, usually from light yellow to brown (Fig. 1.b). According to research papers [10] and [11], discoloration can reduce PV cell's short-circuit current up to 15%.

2.3. Corrosion

The main reason for corrosion occurrence in PV cells is moisture penetration. Corrosion damages metal parts and contacts of PV cells (Fig.1.c), which leads to PV cell's series resistance increase. Based on the results of accelerated corrosion tests, it has been found that probability of corrosion occurrence is related to oxygen presence in silicon layers of PV cell [12].

3. PV SYSTEM MODELLING

In order to precisely determine degradation and mismatch power losses in PV systems, it is essential to use PV cell-based modelling [1]. For proper calculation of degradation effects on PV systems it is necessary to model functionality between generated power and specific ambient conditions. It is a common practice to model I-V curve with irradiation and temperature as controllable primary input variables. One-diode MATLAB-based model of PV cell has been created by using recommendations from [13]. Corresponding PV module and cell models are used throughout previous research and series of related publications [14-16]. Future PV modelling research will include the cooling effect of wind on PV cell temperature [17]. Regarding mismatch effect due to long-term degradation it can be assumed that wind conditions are uniform at the relatively small surface of PV string.

Low irradiation effects have been included in modelling process by threatening of PV cell's series resistance, parallel resistance and diode ideality factor, as functions of irradiation and operating temperature, with corresponding analytical expressions recommended in literature [18-20].

PV module modelling has been realized by using MATLAB/Simulink software [21]. The chosen PV module ZDNY -250P60 250Wp [22] consists of 60 polycrystalline Suntellite 156M PV cells with electrical data for Standard Test Conditions (STC) presented in Table 1.

PV string model consists of 12 PV modules with maximum installed power of 2.995 kW. Similar types of PV systems are often used on the roofs of households in urban environments. PV system modelling procedure is presented in Fig.2. PV modules within PV string are enumerated with numbers 1-12.

Table 1 STC electrical data of Suntellite 156M PV cell and PV module

Suntellite PV	PV cell	PV module
Efficiency [%]	17.00-17.19	17.00
P_{MPP} [W]	4.16	249.61
V_{MPP} [V]	0.531	31.84
I_{MPP} [A]	7.834	7.84
V_{OC} [V]	0.63	37.78
I_{SC} [A]	8.35	8.35
FF [%]	79.08	79.12

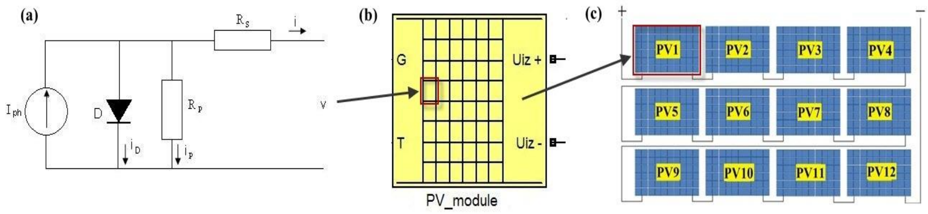

Fig. 2 PV system modelling procedure: (a) One-diode PV cell model; (b) 60-cell PV module model; (c) 12-module PV string model

3.1. Long-term degradation modelling

In order to analyse long-term degradation effects on reduction of PV string power, it is mandatory to establish relation between degradation mechanisms and PV cell's parameters. As delamination, discoloration and corrosion are impossible to predict precisely, their modelling is limited on approximate relations resulting from field observations and statistical analysis of experimentally obtained data.

According to experimental research results [8], delamination reduces PV module's short-circuit current I_{SC}, while its effects on open-circuit voltage V_{OC} can be neglected. Based on experimentally obtained data for characteristic PV module, several modelling cases are defined:

1. Case 0 - Del 0 - no delamination - $I_{SC} = I_{SC\text{-}(STC)}$.
2. Case 1 - Del 1 - limited area around PV cells' busbars affected - $I_{SC} = 0.95 \times I_{SC\text{-}(STC)}$ (5% decrease).
3. Case 2 - Del 2 - limited area around small cracks in PV module's surface - $I_{SC} = 0.92 \times I_{SC\text{-}(STC)}$ (8% decrease).

Based on statistical analyses and experimental field data obtained in temperate climate zone [23], it has been found that discoloration also can be modelled as reduction of I_{SC}, the following cases are defined:

1. Case 0 - Dis 0 - no discoloration - $I_{SC} = I_{SC\text{-}(STC)}$.
2. Case 1 - Dis 1 - bright colours present on less than 50% of PV module's surface - $I_{SC} = 0.9473 \times I_{SC\text{-}(STC)}$ (5.27% decrease).
3. Case 2 - Dis 2 - bright colours present on more than 50% of PV module's surface - $I_{SC} = 0.9137 \times I_{SC\text{-}(STC)}$ (8.63% decrease).
4. Case 3 - Dis 3 - dark colours present on less than 50% of PV module's surface - $I_{SC} = 0.9088 \times I_{SC\text{-}(STC)}$ (9.12% decrease).

Regarding corrosion modelling of PV modules, according to same experimental results, as in the case of discoloration [23], PV module's series resistance R_S has been identified as key parameter. Corrosion manifests as increase of R_S. The following modelling cases are defined:

1. Case 0 - Cor 0 - no corrosion.
2. Case 1- Cor 1 - bright colour corrosion on metal parts of PV module - $R_S = 1.65 \times R_{S\text{-}(STC)}$ (65% increase).
3. Case 2 - Cor 2 - bright colour corrosion on metal parts and terminals of PV module - $R_S = 2.2 \times R_{S\text{-}(STC)}$ (120% increase).
4. Case 3 - Cor 3 - dark colour corrosion on metal parts and terminals of PV module - $R_S = 4.3 \times R_{S\text{-}(STC)}$ (330% increase).

4. PV MODULE DEGRADATION EFFECTS UNDER VARIABLE IRRADIATION AND TEMPERATURE CONDITION

In real-time field conditions PV systems are operating under hourly-based irradiation and temperature variations. It is of mandatory importance to determine long-term degradation effects under variable irradiation and temperature conditions. By using earlier defined long-term degradation modelling cases, PV module maximum power is observed for ambient temperature and irradiation ranges: -5°C - 35°C; 200 W/m^2 - 1000 W/m^2, respectively. Ambient temperature values have been varied with constant irradiation condition 800 W/m^2. Similarly, irradiation values have been varied with constant ambient temperature condition -8.75°C (PV cells' operating temperature 25°C). Corresponding results are presented in Fig.3.

By analysing graphs from Fig.3, the several observations can be made:

- Delamination and discoloration preserve approximate linear correlation between PV module's maximum power (P_m) and both ambient temperature (T) and irradiation (I), while corrosion inserts slightly nonlinear components.
- In the case of T variations, P_m curve slopes remain approximately constant in delamination and discoloration analysis. As a consequence, differences between P_m for all modelling cases (del0, del1, del2 and dis0, dis1, dis2, dis3) remain approximately constant.
- In the case of I variations, P_m curve slopes slightly change in delamination and discoloration analysis, which leads to important conclusion: for higher irradiation values, differences between P_m for all considered modelling cases (del0, del1, del2 and dis0, dis1, dis2, dis3) are also higher.
- Regarding the corrosion effects, it can be seen from Fig.3.c that modelling case cor3 significantly differ from other cases in terms of P_m curve slope for variable T condition. For variable I condition, P_m value differences between different modelling cases of corrosion are lower than the corresponding cases of delamination and discoloration.
- Degradation losses related to delamination and discoloration maintain approximately equal values in whole analysed T and I ranges, while corrosion losses nonlinearly increase with T and I values increasing (Fig.3.d). It can be concluded that delamination and discoloration losses are approximately unaffected by variation of T and I.

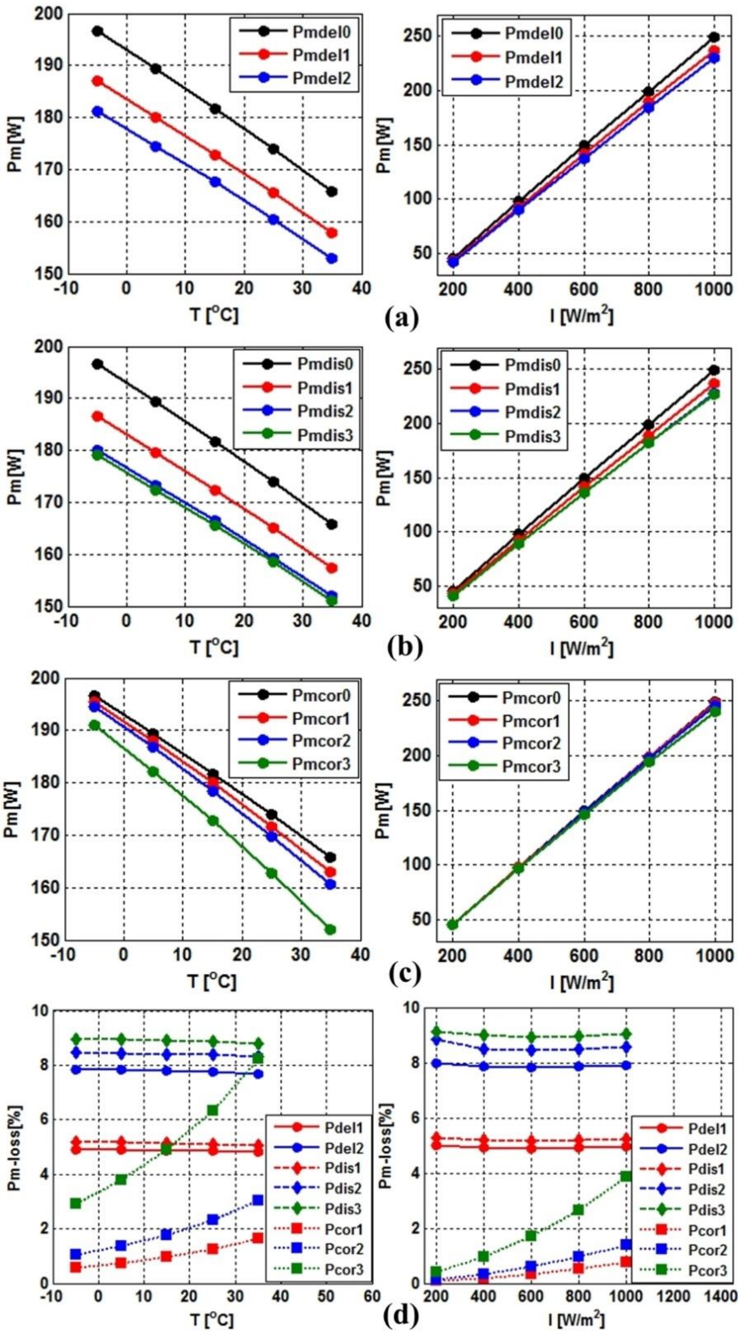

Fig. 3 PV module maximum power and degradation losses under variable temperature and irradiation condition: (a) delamination; (b) discoloration; (c) corrosion; (d) power losses due to long-term degradation

5. PV STRING POWER REDUCTION DUE TO LONG-TERM DEGRADATION - STUDY CASE

Determination of PV string power losses due to degradation is a complex task, because of the mismatch condition occurrence. The term “mismatch condition” refers to differences in current-voltage (*I-V*) curves of individual PV modules in PV string due to different degradation rates. In the field conditions, during long exploitation periods, it is very common that PV modules degrade differently. In order to investigate PV string’s degradation and degradation mismatch power losses, the special study case, consisting of adopted PV module’s degradation modelling cases, is defined in Table 2.

Table 2 PV string under long-term degradation study case

Period of PV string exploitation	10 years			15 years			20 years			25 years		
Type of long-term degradation	Del.	Disc.	Corr.	Del.	Disc.	Corr.	Del.	Disc.	Corr.	Del.	Disc.	Corr.
PV_1	del 0	dis 1	cor 1	del 1	dis 2	cor 2	del 2	dis 2	cor 2	del 2	dis 2	cor 3
PV_2	del 0	dis 0	cor 1	del 1	dis 0	cor 2	del 1	dis 1	cor 2	del 2	dis 1	cor 3
PV_3	del 0	dis 1	cor 0	del 0	dis 3	cor 1	del 1	dis 3	cor 2	del 2	dis 3	cor 2
PV_4	del 0	dis 0	cor 0	del 0	dis 1	cor 1	del 1	dis 2	cor 2	del 1	dis 2	cor 2
PV_5	del 0	dis 0	cor 0	del 0	dis 1	cor 1	del 0	dis 2	cor 2	del 1	dis 2	cor 2
PV_6	del 0	dis 0	cor 0	del 0	dis 0	cor 1	del 0	dis 1	cor 2	del 1	dis 2	cor 2
PV_7	del 0	dis 0	cor 0	del 0	dis 1	cor 0	del 0	dis 3	cor 1	del 1	dis 3	cor 2
PV_8	del 0	dis 0	cor 0	del 0	dis 1	cor 0	del 0	dis 3	cor 1	del 1	dis 3	cor 2
PV_9	del 0	dis 0	cor 0	del 0	dis 0	cor 0	del 0	dis 1	cor 1	del 0	dis 3	cor 2
PV_{10}	del 0	dis 0	cor 0	del 0	dis 0	cor 0	del 0	dis 1	cor 1	del 0	dis 1	cor 2
PV_{11}	del 0	dis 0	cor 0	del 0	dis 0	cor 0	del 0	dis 1	cor 0	del 0	dis 1	cor 1
PV_{12}	del 0	dis 0	cor 0	del 0	dis 0	cor 0	del 0	dis 0	cor 0	del 0	dis 1	cor 1

According to data in Table 2 it can be observed that several key time points are defined during 25 years long exploitation period of PV string. Long-term degradation modelling cases are assumed to take place after 10, 15, 20 and 25 years of exploitation period. The highest combined degradation rate is set for PV modules with starting indexes (1, 2, 3 …). It is assumed that degradation rate is negligible in the first 10 years of exploitation.

In order to determine PV string degradation losses and mismatch losses separately, it is necessary to identify total maximum power of individual PV modules (12 PV modules operate separately), beside the maximum power of the entire PV string (12 PV modules operate in series connection). For defined study case (Table 2), under constant ambient temperature T = 20°C and irradiation I = 600 W/m^2 conditions, maximum power points of individual PV modules P_{MPP-IM} and PV string $P_{MPP-String}$ have been determined and presented in Table 3.

Table 3 Maximum power points of individual PV modules and PV string for study case defined in Tab.5.1 under constant ambient temperature and irradiation values (T = 20°C and I = 600 W/m^2)

Maximum power point PV modules / string (P_{MPP-IM} / $P_{MPP-String}$)	Period of PV string exploitation 10 years	15 years	20 years	25 years
$P_{PV1-MPP}$ [W]	126.773	115.478	111.637	109.500
$P_{PV2-MPP}$ [W]	133.563	126.533	119.793	113.653
$P_{PV3-MPP}$ [W]	127.631	121.935	114.847	111.005
$P_{PV4-MPP}$ [W]	134.518	126.918	115.478	115.478
$P_{PV5-MPP}$ [W]	134.518	126.918	121.895	115.478
$P_{PV6-MPP}$ [W]	134.518	133.702	126.189	115.478
$P_{PV7-MPP}$ [W]	134.518	127.773	121.935	114.847
$P_{PV8-MPP}$ [W]	134.518	127.773	121.935	114.847
$P_{PV9-MPP}$ [W]	134.518	134.518	126.914	121.268
$P_{PV10-MPP}$ [W]	134.518	134.518	126.914	126.189
$P_{PV11-MPP}$ [W]	134.518	134.518	127.773	126.194
$P_{PV12-MPP}$ [W]	134.518	134.518	134.518	126.194
$P_{MPP-IM} = \Sigma P_{PVi-MPP}$ (i=1…12)	1598.6 W	1561.1 W	1475.2 W	1418.5 W
$P_{MPP-String}$	1591.7 W	1511 W	1440.4 W	1392.7 W
Power losses due to long-term degradation	22.52 W	103.2 W	173.82 W	221.52 W
$P_{MPP-New\ string}$* - $P_{MPP-String}$	1.4 %	6.4 %	10.8 %	13.7 %
Mismatch losses due to long-term degradation	6.9 W	50.1 W	34.8 W	25.8 W
P_{MPP-IM} - $P_{MPP-String}$	0.43 %	3.1 %	2.16 %	1.6 %

*New PV string maximum power - 1614.22 W

According to results presented in Table 3 it can be concluded that power losses due to long-term degradation are increasing from 1.4% to 13.7% over the 25 years exploitation period. On the other hand, mismatch losses have the highest value after just 15 years of exploitation (3.1%), because the degradation rates of individual PV modules differ the most in that time period. It is important to notice that mismatch losses are very difficult to predict and they certainly depend on particular study cases. Their values could reach up to 50% of power losses due to long-term degradation itself.

6. PV String Annual Energy Production

Statistical prediction of energy production from PV string is based on horizontal irradiation and ambient temperature measurements. Acquisition system provided measurements of horizontal irradiation and ambient temperature for every 10 minutes between July 15th, 2013 and July 15th, 2014, at location of Belgrade, Serbia, with WGS coordinates: 44.8^0; 20.47^0; 120 m. The obtained irradiation and ambient temperature values have been averaged for every three hours and in the next step monthly-averaged.

Based on the procedure given in [24], horizontal irradiation can be divided into direct and diffuse component. In addition, reflected component can be determined by using corresponding reflection coefficient.

In order to determine irradiation components on PV string surface, position angles need to be defined. Corresponding assumed tilt and azimuth angles are Σ=30^0 and ϕ_S=0^0, respectively. In the process of determining ambient reflection coefficient, it is assumed that household with PV string on its roof is located on a grassy surface. The adopted reflection coefficient value is ρ=0.15. Total irradiation on the surface of PV string has been calculated by usage of following relation:

$$I_{PV} = I_{Dir} + I_{Dif} + I_{Ref}\,, \tag{1}$$

where: I_{Dir}, I_{Dif} and I_{Ref} are direct, diffused and reflected irradiation components, respectively.

By using calculated irradiation and measured ambient temperature data, it is possible to determine operating temperature of PV string, according to following relation:

$$T_{PV} = T_{amb} + (\frac{NOCT - 20}{0.8}) \cdot I_{PV}\,, \tag{2}$$

where: T_{PV} is operating temperature of PV string; T_{amb} is ambient temperature; $NOCT$ is nominal operating temperature of PV cell (47 °C for considered PV cells); I_{PV} is irradiation value on the surface of PV string.

Based on the calculated and averaged I_{PV} and T_{PV} values, PV string DC power values are obtained (P_{DC}). Conventional relation for calculation of PV systems' DC power in the field conditions, expanded with insertion of degradation factor, is defined as follows:

$$P_{DC(\mathrm{field})} = P_{DC}(I_{PV}, T_{PV}) \cdot (1 - \mu_N) \cdot (1 - \mu_Z) \cdot (1 - \mu_D), \tag{3}$$

where: μ_N is efficiency reduction factor due to resulting unequal I-V curves in the manufacturing process of PV modules; μ_Z is efficiency reduction factor resulting from soiling of PV modules in the field; μ_D (DF) is newly defined efficiency reduction factor as a consequence of long-term degradation (degradation factor).

Assumed values of efficiency reduction factors in the analysed study case are μ_N = 0.03 (3%) and μ_Z = 0.04 (4%). Degradation factor has been calculated on the hour basis according to relation (4) and initially averaged for every three hours, and in the next step also monthly-averaged.

$$\mu_D = DF = \frac{P_{new\_string} - P_{long-term\_d\_\mathrm{string}}}{P_{new\_string}}. \tag{4}$$

Monthly averaged PV string maximum power and degradation factor have been presented in Fig.4 for analysed exploitation period of one year and considered study case. Daily time intervals with irradiation values below 30 W/m^2 have been neglected in the analysis.

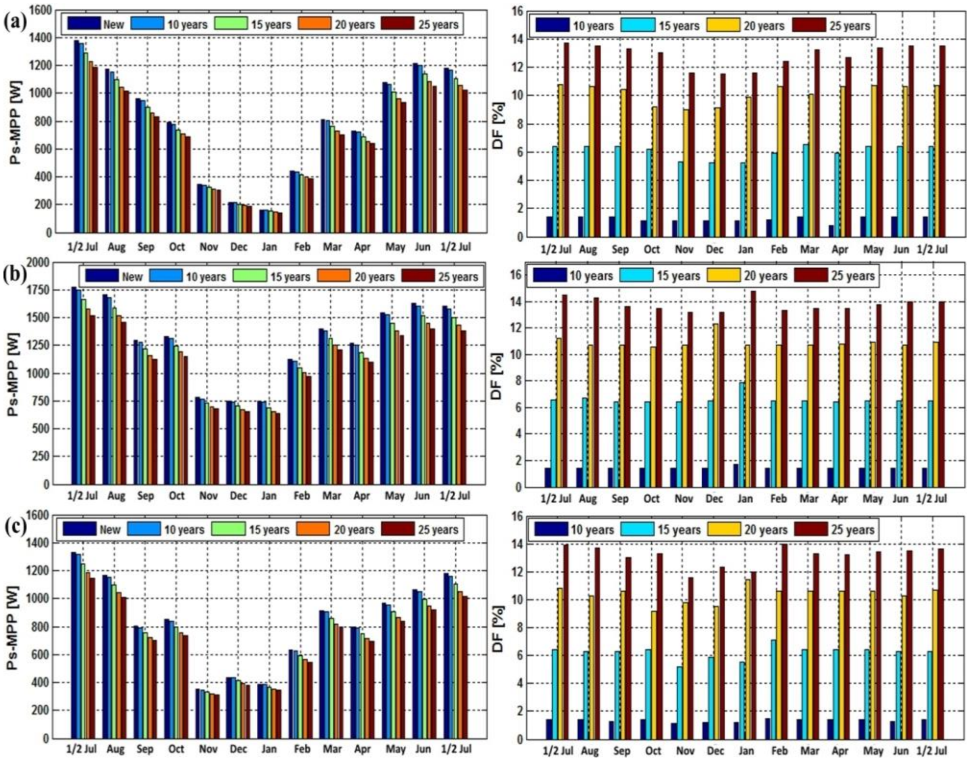

Fig. 4 Monthly averaged PV string maximum power and degradation factor during the considered year of exploitation in different hourly-based time intervals: (a) 8:30h - 11:30h; (b) 11:30h - 14:30h; (c) 14:30h - 17:30h

According to results from Fig.4, the following observations can be obtained:

- Degradation factor has higher values in the summer time (up to 14%), with the exception of January in time interval 11:30h - 14:30h.
- The highest values of degradation factor are present in the period with maximum irradiation (11:30h - 14:30h).
- Degradation factor monthly-based differences are most expressed after 25 years of PV string exploitation.

Prediction of annual energy production exhibits PV string AC power calculation by using the following relation:

$$P_{AC(\text{field})} = P_{DC(\text{field})}\mu_I\,, \quad (5)$$

where μ_I is inverter efficiency.

After determination of $P_{AC\text{-}(field)}$ values, annual energy production can be easily calculated. Purchase price of electricity produced from small capacity PV systems, installed on the households in Serbia, can be calculated by using relation (6).

$$0.01\cdot(20.941\ -\ 9.383\cdot P)\left[EUR/kWh\right], \quad (6)$$

where P is installed power of PV system in MW units.

With assumed inverter efficiency of μ_I = 97%, PV string annual energy production has been predicted, together with annual money income and losses due to long-term degradation. Corresponding results are presented in Table 4.

Table 4 PV string annual energy production, money income and losses due to long-term degradation

PV string annual energy production and income	Period of PV string exploitation				
	New string	10 years	15 years	20 years	25 years
Annual energy production [kWh]	3422	3374	3204	3058	2962
Annual money income [EUR]	715.6	705.6	670.1	639.5	619.4
Loss of money due to degradation [EUR]	0	10	45.5	76.1	96.2

With assumption that loss of money due to long-term degradation is approximately equal in consecutive time periods of 5 years (e.g. loss of money in time period 7.5 - 12.5 years is equal to 5 × loss of money in the 10th year of exploitation) it is possible to roughly estimate total loss of money in time period 0 - 27.5 years (very close to lifetime of PV string): 5 × (10 + 45.5 + 76.1 + 96.2) = 1139 EUR. It can be concluded that predicted amount of money loss due to long-term degradation is enough to buy several new PV modules during considered exploitation period. Even rough estimation of degradation factor could be of significant interest for economic predictions, especially for larger installed PV capacities (> 20 kW) where money income could be reduced for more than 10 000 EUR in lifetime exploitation period due to long-term degradation.

7. Conclusions

Modelling of PV system degradation in terms of statistical prediction of annual energy production proved to be a very complex task, mainly because of many uncertainties related to long exploitation period and field conditions. Several useful guidelines and study case results have been presented in this article. The most common long-term degradation types have been modelled by using approximate relations, adopted on the basis of experimental observations. It has been shown that power losses of individual PV modules due to delamination and discoloration remain approximately constant under wide range of irradiation and ambient temperature values, while power losses due to corrosion proved to be temperature-dependent. Mismatch power losses, caused by different degradation rates of individual PV modules in PV string, have been identified as potentially significant part of total degradation losses. Methodology for prediction of annual energy production from PV string, based on horizontal irradiation and ambient temperature field measurements, has been modified in order to include long-term degradation effects. Degradation factor has been introduced as useful tool for validating power losses due to long-term degradation. Analysis of PV string consisting of 12 PV modules, located in Belgrade, study case, showed that money losses during lifetime exploitation period, caused by long-term degradation could overcome price of several new PV modules.

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