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José Alexandre Gonçalves
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Preface

Going to a conference is always an opportunity to establish contacts with other researchers and to grow culturally. Often, from informal conversations fostered by the conference's social programme, synergies are generated, leading to new ideas and partnerships. Indeed, networking is the fundamental reason for being present at any conference. Moreover, every time we visit a new country, distinct realities are observed and a kind of mild acculturation happens. Experiences gathered from travelling shape our vision of the world and promote cultural enrichment. The CONTROLO 2020 Conference was intended not only to be a scientific event, but also to give the opportunity for the control community to know Bragança, the Polytechnic Institute of Bragança, and to network face-to-face in friendly, safe, stimulating and international environment. The city was prepared to receive this scientific community, with a welcome reception at the Castle of Bragança and a gala dinner at the gardens of the Abade de Baçal Museum, providing all the participants to get in touch with some of the most important landmarks of the Bragança cultural heritage. The ideal situation would be to communicate in person but, due to the current pandemic situation, the CONTROLO 2020 Conference was forced to change to an online event. In spite of all these difficulties, the decision to maintain the date of this event has demonstrated the resilience of APCA in adapting to extreme conditions. In addition, it was also important in this decision-making, to ensure that the dissemination of the research and development works, submitted and accepted for publication, would be made public in due time.

A total of 93 papers, originating from 39 different countries, were submitted for publication, from which 76 were accepted, after an evaluation process that totalled more than 300 reviews. Besides its six special sessions and a MATLAB course, the CONTROLO 2020 Conference had the honour of having five of the most relevant personalities in automatic control community in its five plenary sessions, namely professors André Preumont, Eduardo Camacho, Karl Johansson, Kevin Passino and Sebástian Dormido. We hope that all interested readers can benefit scientifically from this conference proceedings.

Best Regards,
CONTROLO 2020 Local Organizing Committee

Soiling Monitoring Modelling for Photovoltaic System

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Abstract. Soiling on photovoltaic panels is a factor that has a significant impact on the photovoltaic production. The monitoring of the soiling index appears as a relevant alternative for the maintenance of solar systems. This work proposes a soiling index modelling for photovoltaic systems based on two input variables, namely the solar radiation and the generated current, providing a simple, programmable and reliable way to check the efficiency and be able to establish the parameters for cleaning the system. The study was based on the adaptation of an existing mathematical modelling, that besides to estimate the soiling index also allows to establish an optimal point for cleaning. The proposed model is compared with the results provided by the PVSyst software aiming its validation. The achieved results show that, despite the developed system only consider two input variables, it presents a low relative error, i.e. 2.07%, when compared to the PVSyst software, allowing to conclude that the proposed modelling system is valid and presents excellent reliability, having a vast applicability in the monitoring of solar producers of any model or size.

Keywords: Soiling · Photovoltaic systems · Solar panels · Modeling · Maintenance management.

1 Introduction

The growing global energy demand has been a significant challenge for authorities today. Environmental commitments to reduce greenhouse gases are being made, leading many countries to invest in other energy alternatives [1], mainly from sources that aim to reduce and prevent the impacts caused by conventional energy sources, e.g., coal, natural gas and fossil co-generation, as reported by the International Energy Agency (IEA) [2]. In this scenario, the implementation of

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photovoltaic (PV) systems appears as a promising alternative that aims to meet this growing need, since it derives a renewable source and its form of adaptation, with the implementation of a solar tracker, increases the generation of energy. According to the International Renewable Energy Agency (IRENA) [3], the PV power in the world was 22,816.0 MW in 2009, rising to 480,619.0 MW in 2018. According to the Portuguese Renewable Energy Association (APREN), Portugal data for these periods were 110 MW in 2009, rising to 673 MW in 2018.

However, similarly to other energy sources, PV has its limitations and problems, even with the implementation of a solar tracker, which significantly increases the system energy generation [4]. The accumulation of dust on the surface of the panels shows a decrease in the power generation of the modules, and this problem may vary in different regions [5]. The determination of a module soiling is a very relevant problem to this source of energy. According to [6], the current can suffer a reduction of 2.78% per day due to the dust accumulation, where it represents the impact caused by the accumulation of debris in the generation of PV energy [7].

A simplified single-axis solar tracker prototype was developed, which has a soiling monitoring system that only considers the solar irradiation and the output current as data source, which may contribute to the increase of the power generation by PV modules. This paper describes the development of a soiling index modelling that also only uses the solar irradiation and the output current as input data, but take into account the cost/benefit ratio. From the application of a soiling index calculation model, it is possible to improve the cleaning cycles, avoiding the late cleaning and the loss of electricity production, since in different regions the dirt indices vary, which makes difficult to stabilise a cleaning schedule. The application of the soiling index modelling was based on the meteorological data from Bragança, Portugal, where the study was conducted.

The rest of this paper is organised as follows: Sect. 2 presents the related work and Sect. 3 presents the modelling methodology for the soiling index. Section 4 discusses the obtained results, and finally, Sect. 5 rounds up the work with conclusions, contributions and limitations, and points out the future work.

2 Related Work

This section analyses the different solar tracker models, as well as the reasons for selecting the target model used in this work. Additionally, it also addresses the impact of dirt on the electrical generation of the PV system.

2.1 Solar Tracker

The solar tracker is a technology that allows to monitor the path of the sun during the period of exposure of the PV plates to the solar irradiation, in order to increase the absorption of light irradiation, consequently increasing the electrical generation. The cost of implementing this technology provides an increase of approximately 20% in the total cost of the project and may generate an increase in energy production of 40% [4].

Solar trackers can be classified into two broad groups, those with one axis and two axes. The trackers with double axes represent 42.57% and single-axis 41.58% of searches [8], showing a profound difference in the interest between the two models. Among the two large groups, the literature still divides the models according to the form of screening, namely azimuth/elevation for the double axis, and azimuth, horizontal and polar for the single-axis. The differences regarding the presented models are related to the number of actuators that move their structure and the shape of the structure.

For the single-axis trackers, the azimuth model presents the pile structure. In contrast, the polar and horizontal models present a roll-tilt structure, differentiating with each other due to the existence of an inclination of the axis in the polar model, which makes it more efficient in the generation in places with more considerable latitude. The determining factors in choosing the tracker model are the geographic location, the cost of implementation and the increase in the generation. Comparing the different types of solar tracking, the North-South inclined single-axis tracker had an absorption of 93.2% in relation to the dual-axis tracker [9]. A study carried out in Changdu / China, that is located at approximately 31° of latitude, demonstrated a close performance, with a more simplified structure and with less investment, justifying the decision for this model, i.e. a single polar axis, as the target of the application of this study.

2.2 Soiling Impact

Among the external factors that impact the generation of the PV energy, the accumulation of debris is one of the most important to be considered [5,10], as shown in Fig. 1. The impact caused by the accumulation of debris can be observed as a progressive loss of power, due to the shading caused by the dirt [5], presenting values of loss by soiling between 40–70% for an exposure of the system for 6 months, in environments with a very dry climate and with low incidence of rain. However, in contrast, it was observed that more humid climates could end up increasing the adhesion of dirt on the surface of the modules, which must be taken into account when cleaning the modules, in order to clean more carefully and not end up damaging the system [11].

The difference between the types of debris that affect the plates surface is another relevant factor analysed in the literature. The influence of the sizes and composition of the dirt can cause different impacts on the modules [11]. Among the impacts treated in this paper is the loss of light transmittance to the cells depending on the size of the debris, as the slope of the system can help to reduce the dirt, making possible to escape the dirt without the cleaning intervention.

Modelling the impact of the dirt is a way to identify this drop in the PV generation and to improve the system's operating conditions. According to the analysed literature, the models where the level of dirt was modelled based on climatic factors [13,14] presented the best results [5], but other models use the behaviour of the system as the base [15].

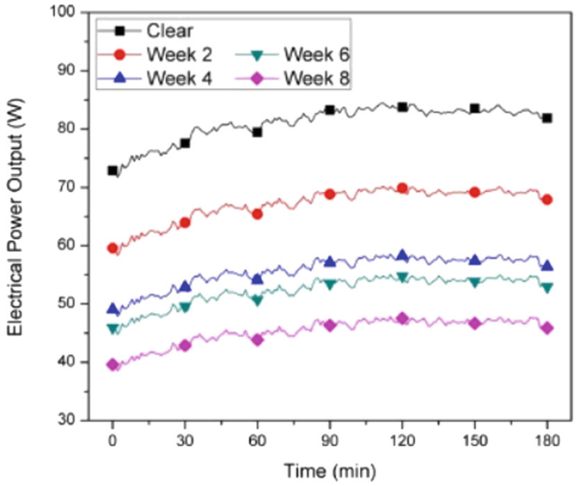

Fig. 1. Soiling impact on energy generation [12].

The analysed models have very complex monitoring forms, which may end up making them challenging to implement, possibly because they have a high implementation cost. Moreover, the number of sensors required and the need for big data processing are other factors, as they require to use artificial neural networks (ANN) and very complex calculations, making these methods economically unviable [5].

The objective of this paper is to develop a low-cost monitoring system for the soiling index on the PV system, avoiding the use of sophisticated analysis tools, such as neural networks, and avoiding the use of many input variables as presented in [13–15]. In this way, allowing the application of the system with fewer sensors, using a microcontroller system with less processing power, therefore with a less cost, and presenting output current values close to the simulated database, with a low error level. Such solution is useful, reliable and low-cost, making this technology easier to be introduced in the market.

3 Methodology

The experimentation model is based on the values obtained from the modelling presented in [16,17] and applied to the PVSyst software. In order to calculate the generated current (I_{out}) and to estimate the level of soiling existing on the PV system, the methodology follows the diagram shown in Fig. 2.

3.1 Model Calibration

The soiling monitoring uses as input parameters in the system modelling, the specifications provided by the manufacturer of the modules, to obtain the best result for each specific case.

The necessary constants for the system calibration are: V_{oc} - module open circuit voltage (V), V_{mp} - maximum module power voltage (V), I_{sc} - Module

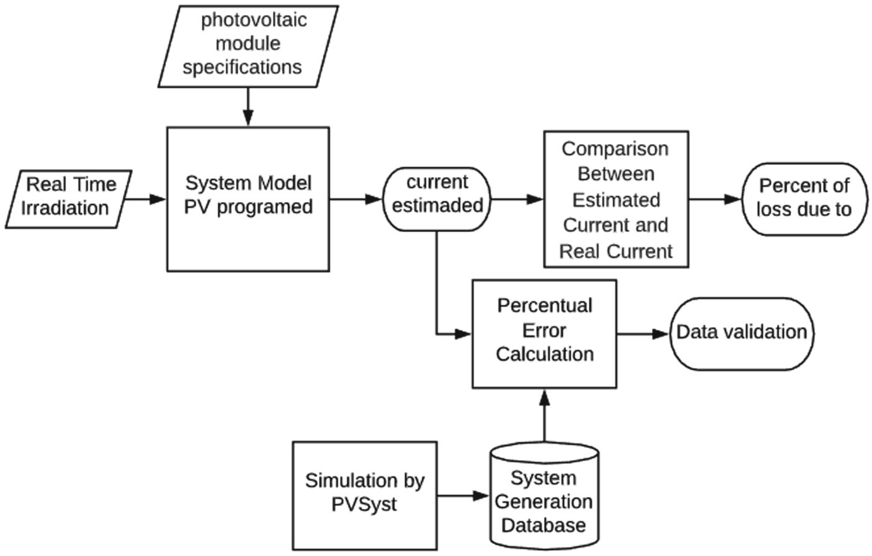

Fig. 2. Methodology flowchart of modelling's system.

short-circuit current (A), I_{mp} - maximum module power current (A), α - temperature coefficient of the current change in the insolation reference (A/°C), β - temperature coefficient of voltage change in the insolation reference (V/°C), R_s - module series resistance (Ω), S_{ref} - insolation reference (1000 W/m2) and T_{ref} - reference temperature (25 °C).

These data are provided by the tests carried out by the manufacturers and are available in the datasheet of the photovoltaic plates and must be updated for each case of application of the study according to the module used.

3.2 Real-Time Data Acquisition

Considering the system modelling developed by [16], it was found that the following equations can define the behaviour of the PVS:

$$I_{out} = I_{sc} * \left[1 - C1 * (e^{\frac{V_{out} - \Delta V}{C2 * V_{oc}}} - 1)\right] + \Delta I \qquad (1)$$

$$C2 = \frac{(\frac{V_{mp}}{V_{oc}}) - 1}{ln(1 - \frac{I_{mp}}{I_{sc}})} \qquad (2)$$

$$C1 = (1 - \frac{I_{mp}}{I_{sc}}) * e^{\frac{-V_{mp}}{C2 * V_{oc}}} \qquad (3)$$

The Eqs. 1, 2 and 3 show the behaviour of the generated current (I_{out}) before the circuit modelling system. This behaviour is related to the specific constants of the module model, other three system variables, namely temperature (T), irradiation (S) and output voltage (V_{out}), and also with ΔI and ΔV explained in Eqs. 4 and 5.

$$\Delta I = \alpha * \frac{S}{S_{ref}} * \Delta T + [\frac{S}{S_{ref}} - 1] * I_{sc} \quad (4)$$

By ΔI, we observe the influence suffered by the I_{out} caused by the variation of the temperature and the solar irradiation, and if the α value is minimal, the temperature has a reduced impact in the variation of the current.

In addition, the variation of the voltage in relation to the temperature and ΔI is observed by the Eq. 5. However, contrary to the current behaviour, the V_{out} suffers a small decrease with temperature.

$$\Delta V = -\beta * \Delta T - R_s * \Delta I \quad (5)$$

However, this system focuses on a simplified and less costly implementation, being decided to decrease the number of necessary sensors. After analyzing the effect of dirt on some systems, demonstrated in their results that the most significant impact of the accumulation of debris is on the generated current, as the debris limits the amount of irradiation absorbed by photocells [18,19]. Based on these studies and our goal of reducing the price and complexity, it was decided to decrease the number of input variables, considering the output voltage (V_{out}) at Eq. 1 constant and equal to the V_{mp} value provided by the manufacturer.

To simplify the analysis, the impact of the photovoltaic cell temperature on the output current was observed by the ratio of coefficients presented by the manufacturer, where α presents the effect of temperature on the current and β the impact of temperature on the voltage, in the model of the module chosen for this study: $\alpha = 5.0$ mA/C and $\beta = -163$ mV/C.

Observing the low proportional impact of the temperature in I_{out}, it was decided to work only with the irradiation relation with the current to determine the soiling index present in the system. Hence, discarding the need for a thermal sensor in the application, it was decided that T in Eq. 6 is equal to T_{ref}.

$$\Delta T = T - T_{ref} \rightarrow T = T_{ref} \rightarrow \Delta T = 0 \quad (6)$$

3.3 Calculus of the Soiling Index

After the validation, made by comparing the I_{out} determined by the Eq. 1 applied to the programming, with the current from the PVSyst software [20], it was possible to calculate the soiling index of the module. For such, the I_{out} was used for modelling the relation to the radiation measured by the sensor, and the current generated by the system (I_{act}), measured by an ammeter sensor. From a direct relation expressed in Eq. 7, it is possible to check the value of the soiling index present in the system by comparing the current value that should be generated if the system is clean (I_{out}), with the current value measured in the actual state (I_{act}).

$$Soiling\% = \frac{I_{out} - I_{act}}{I_{out}} * 100 \quad (7)$$

The value obtained when implemented in the real system, can be used to monitor the level of accumulated soiling index of the modules.

4 Analysis of Results

The proposed methodology was applied to a case study, and the achieved results compared with the ones generated by the PVSyst software [20], which served as a database for validating the methodology.

4.1 Soiling Index Modelling Application

The designed PV system considers the existing models in the literature [13–15] and the mathematical formulations for the electronic model of a PV module [16,17], allowing to obtain the real values of PV modules to be used in the methodology.

The PV case study contains six PV modules with a total generation capacity of 1.5kW. After collecting the data from the PV system, it was simulated, obtaining the values that made up the database. The entire data collected was used to apply the proposed methodology. According to the proposed model, the data obtained from the simulation allowed to perform a comparison with the generated values, as shown in Fig. 3, noticing a similarity between the database and the modelled values.

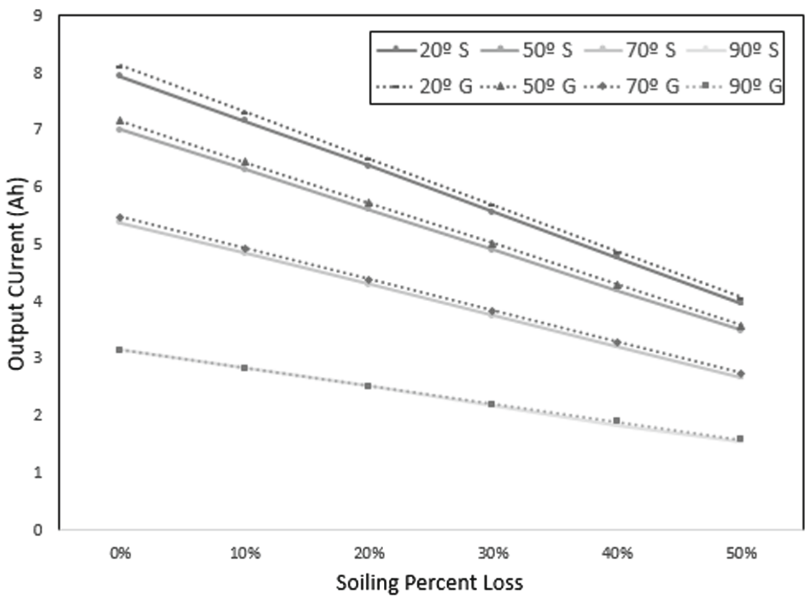

Fig. 3. Comparison between some simulated and modelled values

Figure 4 represents the relative error between the database values and the data generated by the modelling approach.

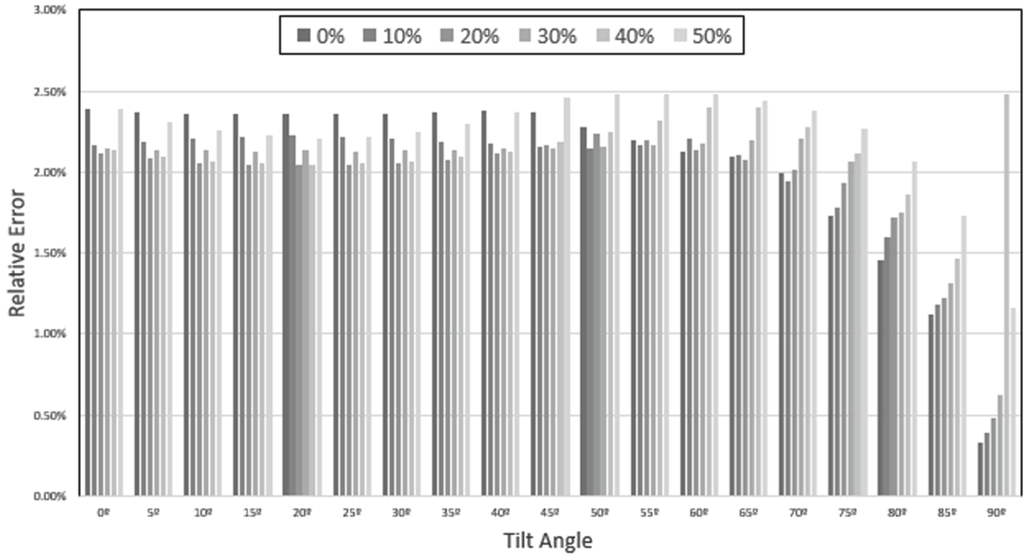

Fig. 4. Relative error between simulated and modeled values

From the behaviour observed in Fig. 3, it was possible to identify the current decay related to the increased impact of dirt on the PV modules, demonstrating a direct relationship between the current and the soiling index, due to the drop absorption of solar radiation. The decay analysed earlier shows a pattern in the current drop, which can also be analysed in the graph presented in Fig. 4, showing how this pattern is maintained for the most usual tilt angle.

According to a comparative analysis between the achieved results, it is possible to identify that the error remained constant for the most of analysis, presenting a variation only in the values of greater inclination, and due to this variation the errors range between 0.33% to 2.48%. These values have a consistency to be taken into account when compared to existing studies used as a basis for carrying out this research [13–15].

With all the obtained results, it is possible to add the weather information and create a database, which may come to build a new model in order to predict the dirtiness index for the studied region. From the changes of the climate with the variation of the soiling index, it is possible to discover the pattern of the incidence of dirt on the modules, making the creation of cleaning cycles even easier.

As can be seen in Fig. 4, for an angle of 90° inclination and with a soiling index of 40%, it was possible to notice an unusual variation compared with the others, an error that may come from the analysis at very low values, where a small difference can raise this error unexpectedly as seen, but remaining within the values presented by the others.

5 Conclusions

This paper proposes a soiling index modelling for photovoltaic systems, that only consider two input variables, the solar radiation and the generated current. The

PVsyst software was used to generate the database, and these data were used to test the model, obtaining an average relative error of 2.04%, a good result when compared with the other empirical studies found in the existing literature. As it was a modelling based on simulated data, an actual application was not performed, being the most significant limitation of the work. Another limitation is that the results and what was observed from them was all obtained from computational simulation. Thus, not being from a real application, it limits the data and the interpretations.

For future work, the practical application of this modelling to a real system is desirable in order to make a comparison between the values obtained in theory and to be able to validate them in practice. Additionally, along with the experimental validation, it is recommended to study the system's behaviour in comparison with the climate in which the system is exposed. This will allow a database to be provided so that the system is only a real-time index model, and can perform the soiling index forecast according to the climate changes around it.

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