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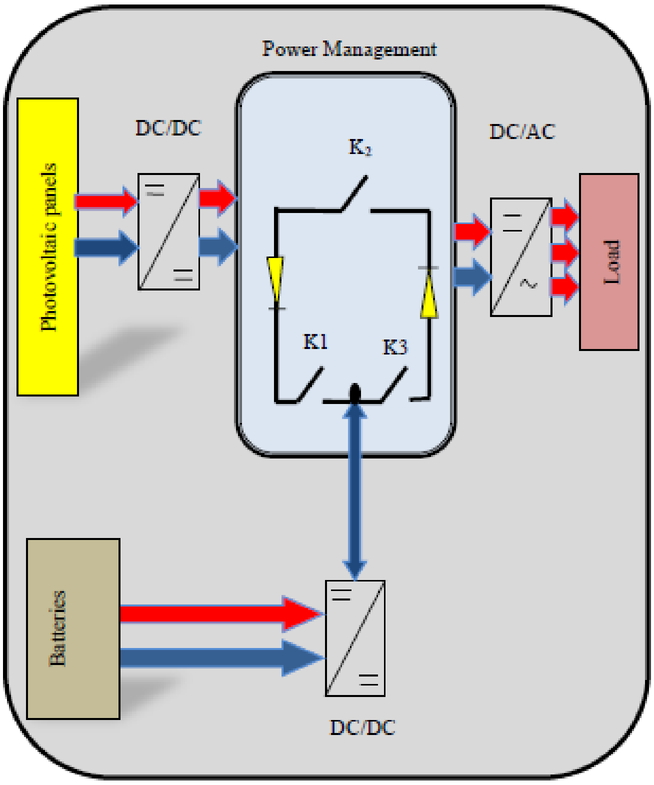

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Editorial

"Refreshing Turkish Journal of Electromechanics & Energy in its Fourth Year"

We are delighted to present fourth volume of Turkish Journal of Electromechanics & Energy (TJEE). Each volume and issue bring new joy and excitement to us as the journal is in its crawling stage. We appreciate our authors, reviewers and editorial board members for their contribution in bringing this issue to you.

The current issue of the TJEE (Vol 4. No:1 January-June 2019) consists of two articles. The first study by Hassan Ali et al. addresses a methodology to evaluate the lifetime of photovoltaic generators by extracting parameters from a Weibull distribution and using the Akaike criterion test. The second study by Rekioua et al. presents a modeling and fuzzy logic control of a stand-alone photovoltaic system with battery storage.

As we go through our fourth year, we aim TJEE to be indexed in respected databases. A good news which encourages us is that the journal has been included in SOBIAD and PUBLONS databases. As the TJEE aims to provide a common platform for interdisciplinary studies and researchers, our editorial board has been expanded with 4 new members. The following is their brief biographies.

***Dr. Dina Šimunić** was born in Zagreb in 1963. She received B.Sc. and M.Sc. degrees in electrical engineering from the University of Zagreb, Faculty of Electrical Engineering and Computing (FER), Zagreb, Croatia, in 1985, and 1992, respectively. She was awarded with Dr.Sc. degree from Graz University of Technology, Austria, in 1995. Since 1991, she is with the Department for Wireless Communications at University of Zagreb, Faculty of Electrical Engineering. She was a guest professor in research laboratories "Wandel & Goltermann" in Germany and "Motorola Inc.", USA during 1996. Professor Šimunić served as editor-in-chief of the Journal of Green Engineering and currently editorial board member of international scientific journal JOSE and a reviewer for various international scientific journals.*

***Dr. Francesco Iannuzzo** (M'04-SM'12) received the M.Sc. degree in Electronic Engineering and the Ph.D. degree in Electronic and Information Engineering from the University of Naples, Italy, in 1997 and 2002, respectively. He is currently a professor in reliable power electronics at the Aalborg University, Denmark, where he is also part of CORPE, the Center of Reliable Power Electronics. His research interests are in the field of reliability of power devices, including mission-profile based life estimation, condition monitoring, failure* *modelling and testing up to MW-scale modules under extreme conditions. He is author or co-author of more than 210 publications on journals and international conferences, three book chapters and four patents. Besides publication activity, over the past years he has been contributing 17 technical seminars about reliability at first conferences as ISPSD, EPE, ECCE, PCIM and APEC. Prof. Iannuzzo is a senior member of the IEEE (Industry Application Society, Reliability Society, Power Electronic Society, and Industrial Electronic Society). He currently serves as Associate Editor for Transactions on Industry Applications, and is secretary elect of IAS Power Electronic Devices and Components Committee. In 2018 he was the general chair of the 29th ESREF, the first European conference on reliability of electronics.*

Dr. Zhe Zhang *received the B.Sc. and M.Sc. degrees in power electronics from Yanshan University, Qinhuangdao, China, in 2002 and 2005, respectively, and the Ph.D. degree from the Technical University of Denmark (DTU), Kgs. Lyngby, Denmark, in 2010. He is currently an Associate Professor in the Department of Electrical Engineering, and Head of Studies in charge of Electrical Engineering M.Sc. Programme at DTU. From 2005 to 2007, he was an Assistant Professor at Yanshan University. He was an Assistant Professor at the Technical University of Denmark during 2011 and 2014. In 2010, he was with the University of California, Irvine, CA, USA, as a visiting scholar. Dr. Zhang's current research interests include applications of wide bandgap devices, high frequency dc-dc converters, multiple-input dc-dc converters, soft-switching power converters and multi-level dc-ac inverters for renewable energy systems (RES), hybrid electric vehicles (HEV) and uninterruptable power supplies (UPS); piezoelectric-actuator and piezoelectric-transformer based power conversion systems. He is also a guest associate editor in IEEE Transactions on Industrial Electronics and guest editor in IEEE Journal of Emerging and Selected Topics in Power Electronics.*

Dr. Younes Noorollahi *received his Ph.D. from Kyushu University-Japan in 2008, and carried out postdoctoral studies in Kyushu University School of Earth Resources Engineering. Presently, he is head of Renewable Energies and Environmental Engineering Department at University of Tehran, Iran. His expertise includes energy resources assessment and evaluation, geothermal energy exploration and resource assessment and its application in different industrial fields. He has published more than 25 papers in reputed international journals and more than 100 papers in national and international conferences and has been serving as an editorial board member of more than 10 international journals.*

Hope to see you in next issue in December 2019.

Editors-in-Chief

Mustafa Ergin ŞAHİN, Ph.D. & Ömer Necati CORA, Ph.D.

Research Article| Submit Manuscript

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Lifetime Estimation Method for Photovoltaic Generators

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ABSTRACT This article addresses a methodology to evaluate the lifetime of photovoltaic generators (*PVGs*) by extracting parameters from a Weibull distribution and using the Akaike criterion test. A degradation index is developed for outdoor photovoltaic generators affected by operating conditions. Degradation index quantification, through weather monitoring $(\boldsymbol{T_i}\,;\ \boldsymbol{G_i})$ and instantaneous continuous output power, is proposed. For this purpose, statistical data series are extracted that correspond to the instantaneous number of contributing *PVGs*, which allows a reliability study. Akaike Criterion Test (*AIC*) shows that these data series tend towards a Weibull distribution. Efforts are made to be able to quantify the parameters of the distribution model and thereby obtain the lifetime of the *PVG*. The approach is validated by using data from several *PVGs*.

Keywords: Modelling, Prognosis, Akaike Criterion Test, Parameters Estimation, Weibull Distribution

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1. INTRODUCTION

Nowadays, the future of renewable energy is undisputed. Among these sources of renewable energy, solar energy harnessed through Photovoltaic (*PV*) modules is increasingly performant. However, until today, the electrical production of many *PV* installations is not monitored with tools and functions of prognosis and diagnosis to obtain the best possible efficiency. It is well known that without a control function, the presence of faults can cause power losses, but they could also lead to safety risks that could significantly reduce the performance of the *PV* system.

The evolution of degradation with respect to operating conditions impacts the behavior of the system. Numerous studies on photovoltaic generator (*PVGs*) in outdoor environments have confirmed performance degradation [1]. Prognosis approaches discussed by Byington et al. [2] can be categorized into three levels: experience-based methods, data-based, and model-based. As shown in Figure 1, applicability and cost & accuracy change respectively per used prognostic methods.

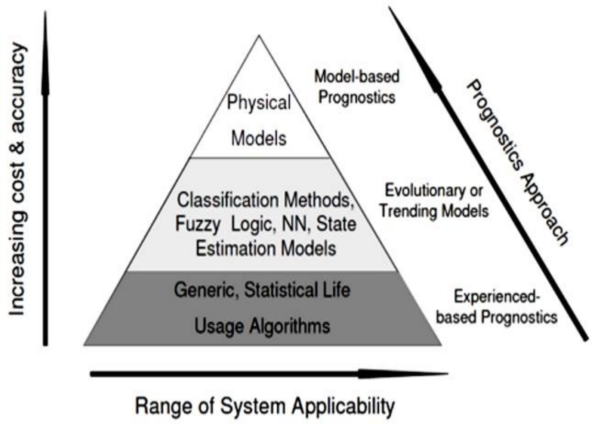


Fig. 1. Classification of prognosis approaches

The direct or indirect measurement of the state of degradation represents an important knowledge for the prognosis evaluation [3]. The selection of a prognosis approach depends mainly on available information about the considered system [4]. Formally, the prognosis is defined as the ability to predict the lifespan of a system. This lifespan indicates the remaining time before the system cannot perform its main functions. In the considered system, this lifespan figure will be estimated under specific operational conditions and random environmental conditions that can cause faults and aging. Indeed, a system can be affected by abnormal events which accelerate or not it's aging process, and by such means reduce its lifetime [1]. Osterwald and McMahon [5] used population data to obtain a distribution model to estimate the degradation rate of the PV modules. Vazquez and Rey-Stolle also proposed to model the power probability density of a *PVG* with an exponential distribution [6]. These authors demonstrated the possibility of modeling the data acquired from *PVGs* by means of statistical distributions. In this way, we propose an approach to calculate the *PVG* lifetime by using a distribution model developed using actual *PVGs* data series [7]. The proposed approach follows the well-known approaches by Pan and Crispin [8], Monroe and Pan [9] and Wohlgemuth et al. [10], but it uses real data series rather than the extracted model from Accelerated Life Test (*ALT*) tests. The following sections relate to time series extraction used to calculate *PVG* lifespan.

Our study uses monitoring data from two photovoltaic plants and their MATLAB/Simulink models. For this purpose, we extract meteorological data from the *PV* plants to evaluate the maximum power signal by simulation. Then, we propose a reliability model to calculate the photovoltaic power plants lifespan. This approach is useful for reducing maintenance, and allowing optimization of operating conditions.

2. PROPOSED APPROACH

2.1. Extraction of Time Series

A statistical analysis method is proposed to use the data series extracted by monitoring the *PV* power stations and to confirm the impact of environmental conditions. This is a transposition of the data from the monitoring to obtain usable statistical series for lifetime determination.

The statistical series are aimed to be obtained by transposing the actually recorded data from the *PV* system into a total that represents surviving or failing modules (i.e. statistical series). The model used, proposed by Notton et al. [11], provides ideal performance in terms of maximal output power without considering environmental effects or faults. It follows the polynomial form as stated in Equation (1) below [11]:

$$P = \eta_{ref} \times A \times G \times \begin{bmatrix} 1 - \beta_{ref} \times (T_i - T_{ref}) + \\ \gamma_{ref} \times \log G_i \end{bmatrix} \quad (1)$$

The output power of the *PV* system is obtained using an approach based on the model defined through Equation (1) in which faults or aging effects are not considered. Obtained outputs with the MATLAB/Simulink model are shown in Figure 2 (b) and acquired actual weather condition in Figure 2 (a).

The produced maximal power by each *PVG* for the weather condition $(T_i\ ;\ G_i)$ is done by:

$$P_{i_{maximal\_PV\_Syst}} = f(T_i\ ;\ G_i) \quad (2)$$

$$P_{i_{maximalperunit}} = \frac{P_{i_{maximal\_PV\_Syst}}}{Number_{installedmodules}} \quad (3)$$

Considering that the actual power provided by *PV* systems has been obtained from the system's monitoring ($P_{i_{measured\_PV\_Syst}}$) and by Equations (2) and (3), then the number of instantaneous contributing *PVGs* ($N_{I\_C\_PVG}$) can be determined for each of meteorological conditions $(T_i\ ;\ G_i)$ using:

$$N_{I\_C\_PVG} = \frac{P_{i_{measured\_PV\_Syst}}}{P_{i_{maximalperunit}}} \quad (4)$$

Measured real power divided by maximal estimated power per unit, gives the number of instantaneous contributing *PV* modules. Thus, the number of the surviving modules (i.e. contributing modules) can be found by Equation (4). Compared to the total number of installed modules, we can deduct the number of failing modules. This method is based on the reliability analysis of population under the same operating conditions and stress [12]. Indeed, we have a population of identical modules affected by the same operating environment from the *PVG* level to the entire photovoltaic plant level. With this constraint and by using exactly the same *PVGs*, we can obtain statistical data series in Equation (4). Under these two assumptions, a reliability analysis to predict *PVG* lifespan becomes possible.

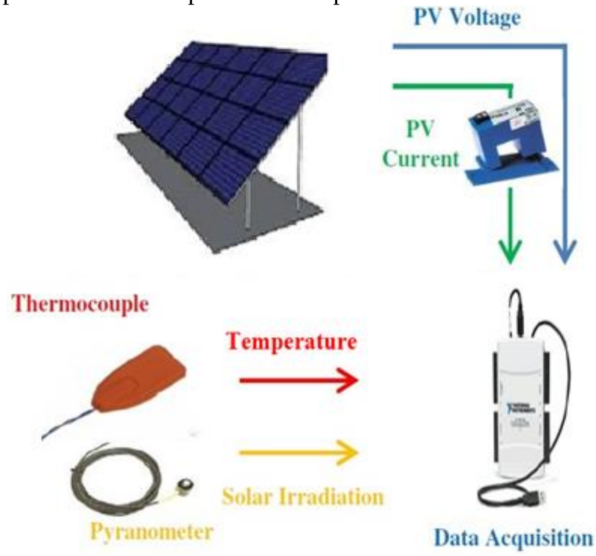


Fig. 2 (a). Real-time data acquisition for each *PV* plant

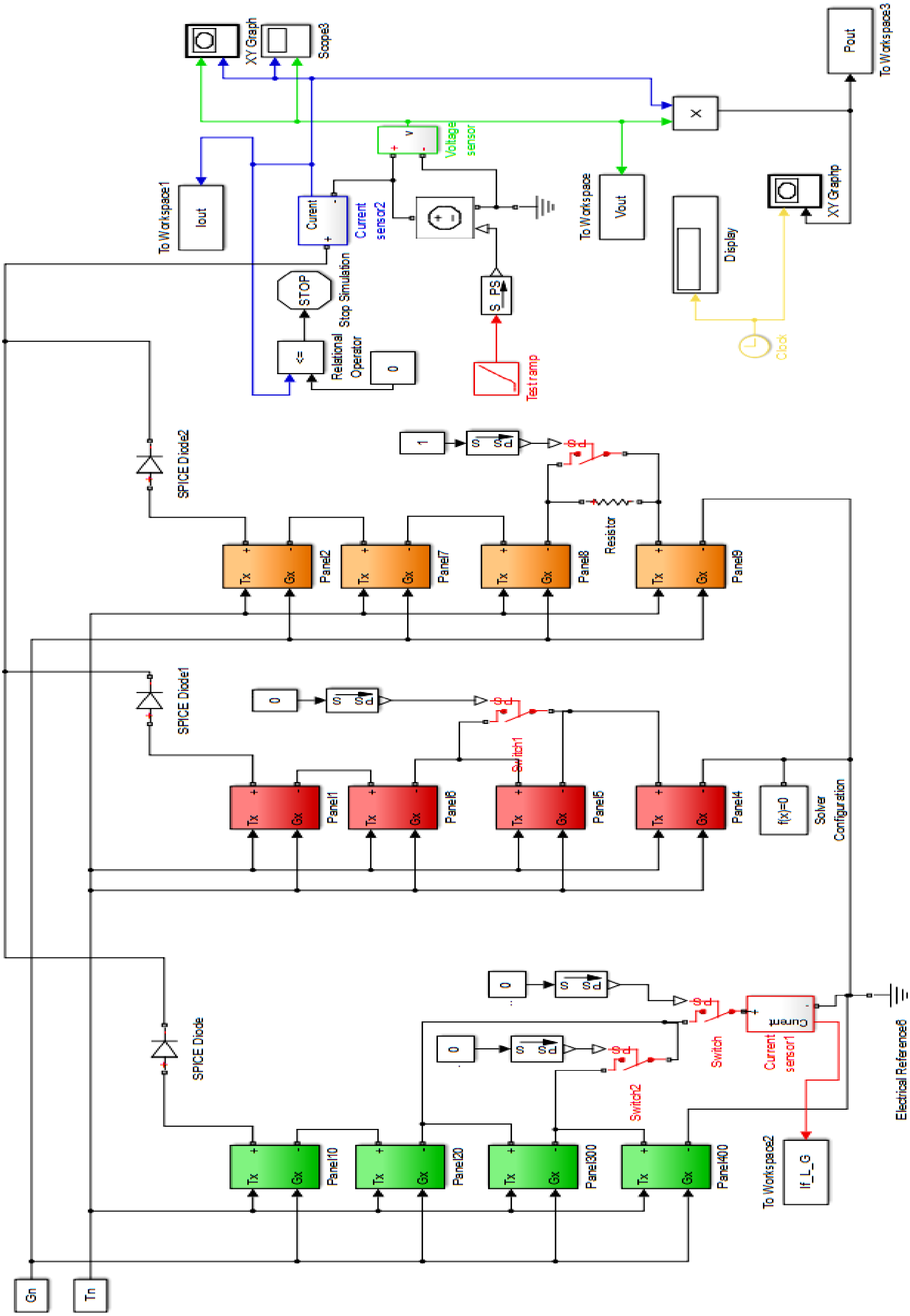


Fig. 2 (b). MATLAB/Simulink model adapted for each *PV* plant

2.2. Akaike Information Criterion and Candidate Distribution Set

Akaike information criterion (*AIC*) is a quality measure of statistical models proposed by Akaike [13]. This information criterion is based on a trade-off between precision and model complexity. It penalizes the model according to the number of parameters to satisfy the parsimony criterion. This test represents a compromise between the bias, which decreases with the number of parameters, and the parsimony, that describes data with fewest parameters. The interval between data and tested model is approximated using Kullback-Leibler divergence [13]. This criterion is noted as *AIC* and defined by the following relation:

$$AIC = -2 \times log(L) + 2 \times k \tag{5}$$

where: L is the maximized likelihood of data and k the number of model parameters.

From the set of candidate models, the chosen model is the one that will have the lowest *AIC* value. In our case, it compares the selected data from Equation (4) with four classical distributions (i.e., χ^2, Exponential, Beta, Weibull) which have known properties [12]:

- χ^2 Distribution :

$$f(x;k) = \frac{\left(\frac{1}{2}\right)^{\frac{k}{2}}}{\Gamma\left(\frac{k}{2}\right)} \times x^{\frac{k}{2}-1} \times e^{-\frac{x}{2}} \tag{6}$$

Where: k is degrees of freedom, x is for independent random variables and $\Gamma(n) = \int_0^\infty e^{-x} \times x^{n-1} dx$

- Exponential Distribution :

$$f(x;\lambda) = \begin{cases} 0, & x < 0 \\ \lambda \times e^{-\lambda x}, & x \geq 0 \end{cases} \tag{7}$$

With: > 0 : intensity parameter.

- Beta Distribution :

$$f(x;\alpha,\beta) = \begin{cases} 0, & else \\ \dfrac{x^{\alpha-1} \times (1-x)^{\beta-1}}{\int_0^1 u^{\alpha-1} \times (1-u)^{\beta-1} du}, & if\ x \in [0,1] \end{cases} \tag{8}$$

Where(α,β) are two positive shape parameters.

- Weibull Distribution:

$$f(x;\beta,\eta) = \frac{\beta}{\eta} \times \left(\frac{x}{\eta}\right)^{\beta-1} \times e^{-\left(\frac{x}{\eta}\right)^{\beta}} \tag{9}$$

Where $(\eta,\beta)$are shape and scale parameters.

The Akaike criterion makes it possible to test the calculated statistical data series against monitored data, to identify the most suitable distribution model. Selection will be made among four candidate distribution models described by Equations (6), (7), (8), and (9). Subsequently, we can extract the parameters of the selected model to estimate the lifespan of a *PV* system [12].

2.3. Estimation of Distribution Parameters by Maximum Likelihood Method

In this approach, we estimate the parameters of the selected distribution model by using the maximum likelihood method. It consists of looking for a theoretical model that maximizes the probability density of the observed data. For example in the case of Weibull law, the parametric values that maximize the product:$\prod_{i=1}^{n} f(x_i)$ for the n operating times obtained from previous series. This method gives us:

$$L(\beta,\eta) = \prod_{i=1}^{n} \frac{\beta}{\eta} \times \left(\frac{x_i}{\eta}\right)^{\beta-1} \times e^{-\left(\frac{x_i}{\eta}\right)^{\beta}} = \left(\frac{\beta}{\eta}\right)^{n} e^{\left(-\sum_{i=1}^{n}\left(\frac{x_i}{\eta}\right)^{\beta}\right)} \prod_{i=1}^{n} \left(\frac{x_i}{\eta}\right)^{\beta-1} \tag{10}$$

We can maximize this function by maximizing its logarithm:

$$\ln[L(\beta,\eta)] = \ln\left[\left(\frac{\beta}{\eta}\right)^{n} e^{\left(-\sum_{i=1}^{n}\left(\frac{x_i}{\eta}\right)^{\beta}\right)} \prod_{i=1}^{n} \left(\frac{x_i}{\eta}\right)^{\beta-1}\right] \tag{11}$$

$$\ln[L(\beta,\eta)] = n \times ln\left(\frac{\beta}{\eta}\right) - \eta^{-\beta} \sum_{i=1}^{n} x_i^{\beta} + (\beta - 1) \sum_{i=1}^{n} ln\left(\frac{x_i}{\eta}\right) \tag{12}$$

The estimation of parameters ($\eta; \beta$) are finally obtained mathematically as follows:

$$\begin{cases} \dfrac{\partial \ln[L(\beta,\eta)]}{\partial \beta} = 0 \\ \dfrac{\partial \ln[L(\beta,\eta)]}{\partial \beta} = 0 \end{cases} \tag{13}$$

We obtain the two following equations whose resolution permits to estimate parameters ($\eta; \beta$):

$$\begin{cases} n \times \frac{1}{\beta} - \frac{1}{\eta^{\beta}} \times \sum_{i=1}^{n} x_i^{\beta} \times \ln\left(\frac{x_i}{\eta}\right) + \sum_{i=1}^{n} \ln\left(\frac{x_i}{\eta}\right) = 0 \\ -n \times \frac{1}{\eta} - \frac{\beta}{\eta^{\beta+1}} \times \sum_{i=1}^{n} x_i^{\beta} + (1-\beta) \times n \times \frac{1}{\eta} = 0 \end{cases} \tag{14}$$

This method allows us to obtain the parameters of distribution selected in Equation (9) Weibull law section and will be used for lifetime determination.

2.4. Lifetime Determination

The relevance of modeling was established with Akaike criterion test which allows selection of the most suitable classical law among the available four following candidates: $\chi 2$, Exponential, β, Weibull [13]. Then, we can obtain the lifespan of the *PV* system according to [12] with the following relation:

$$MTTF(t) = \eta \times \Gamma\left(\frac{1}{\beta} + 1\right)$$

$$\text{With : } \Gamma(n) = \int_0^\infty e^{-x} \times x^{n-1} dx \tag{15}$$

3. RESULTS AND DISCUSSION

The proposed methodology, described in Figure 3, is applied to determine the lifespan of the *PV* system using monitoring data provided by the International Energy Agency report [14]. We have focused on Localnet as shown in Figure 4 and Liestal as shown in Figure 5 *PV* plants for the validation of the proposed method. These two *PV* plants were developed using polycrystalline technology, whose performances have been monitored for 163 months and 155 months respectively as shown in Figure 6 and Figure 7. By using polynomial *DC* power model (elaborated through equation (1)) and information from the structure of these *PV* plants in Table 1, we have developed a MATLAB/Simulink model without faults and aging, which provides the instantaneous maximal power for recorded meteorological condition $(T_i; G_i)$[15].

In both presented cases, models slightly overestimate experimental data with low mean bias error (*MBE*) and a high degree of approximation, low root mean square error *(RMSE*), as shown in Table 2. The accuracy of the models shown in Figure 6 and Figure 7 is crucial for the determination of the time series. The evolution of blue curves (Figures 6 and 7) shows electrical production in two different environments. We can see both seasonality of solar radiation and the effects of major breakdowns that appear during signal monitoring. Our approach allows to consider all unfavorable factors together for electrical production and calculate *PV* plant lifetime.

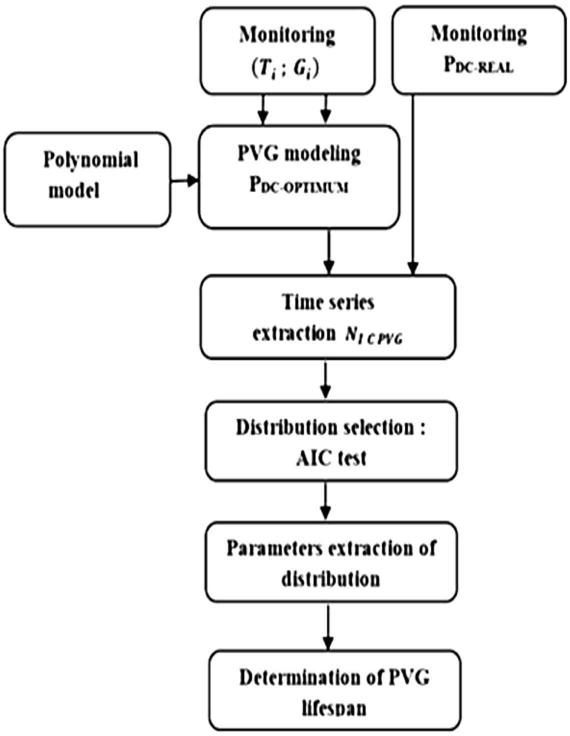


Fig. 3. Flowchart of the evaluation method for *PVG* lifetime

Using the MATLAB/Simulink model shown in Figure 2(b) and the recorded actual data for each case of the considered *PV* systems, the number of instantaneous maximal contributing modules, $N_{I\_C\_PVG}$ is extracted through Equation 4.

Table 1. Data and locations of the two PV plants

PV plant	*Localnet*	*Listal*
Types and technologies	Solarex MSX 120 Poly-Si	Kyocera LA361H51 Poly-Si
Latitude	47.06	47.29
Longitude	7.61	7.44
Height (meter)	530	327
The angle of inclination (degree Celsius)	30	30
Efficiency (%)	10.8	11.67
Module area (m^2)	1.112	0.437
Number of modules	136	363

By using Equation 5, the Akaike criterion test permits selection among four candidate statistical distributions, presented in section II, and then classifies them [16]. Table 3 presents calculated values for the four distributions. The weakest *AIC* values are obtained with Weibull models.

Indeed, these two statistical data series for two power stations respectively, exhibit similar behavior to Weibull distributions, as depicted in Figures 8 and 9.

Table 2. Determination of MBE and RMSE errors.

Errors	*MBE*	*RMSE*
PV plant in Liestal	0.0016214	0.3773
PV plant in Localnet	0.0054489	0.2763

Once the model has been chosen, the parameters of the two Weibull distributions are extracted for each case. Calculated results are presented in Table 4. Finally, the life span of PV plants is estimated in real time depending on the effects of the environment (aging effects and faults). This method depends mainly on data provided by the monitoring sensors. As acquisition progresses, it becomes more precise. Indeed, the knowledge of the remaining lifespan becomes important in the second part of the life cycle of PVG, i.e. after 20-25 years. Our method with acquired data allows a better knowledge of the performance and real-time estimation of PVGs lifetime.

Table 3. *AIC* values for four candidate distributions on both sites.

Weibull distribution parameters	*Shape* β	*Scale* λ	*MTTF (months)*
PV plant Localnet	32.62	120.04	118.02
PV plant Liestal	11.89	250.33	239.81

Table 4. Extraction of Weibull parameters and *MTTF* determination.

Candidates distributions	*AIC values (Localnet case)*	*AIC values (Liestalcase)*
β	0.545	3.88
χ^2	614.801	595.95
Weibull	-185.146	-180.582
Exponential	59.646	100.656

(a) (b)

Fig. 4. (a) *PV* plant Localnet, Burgdorf (Switzerland) (b) *PV* plant EBL Liestal (Switzerland) [14].

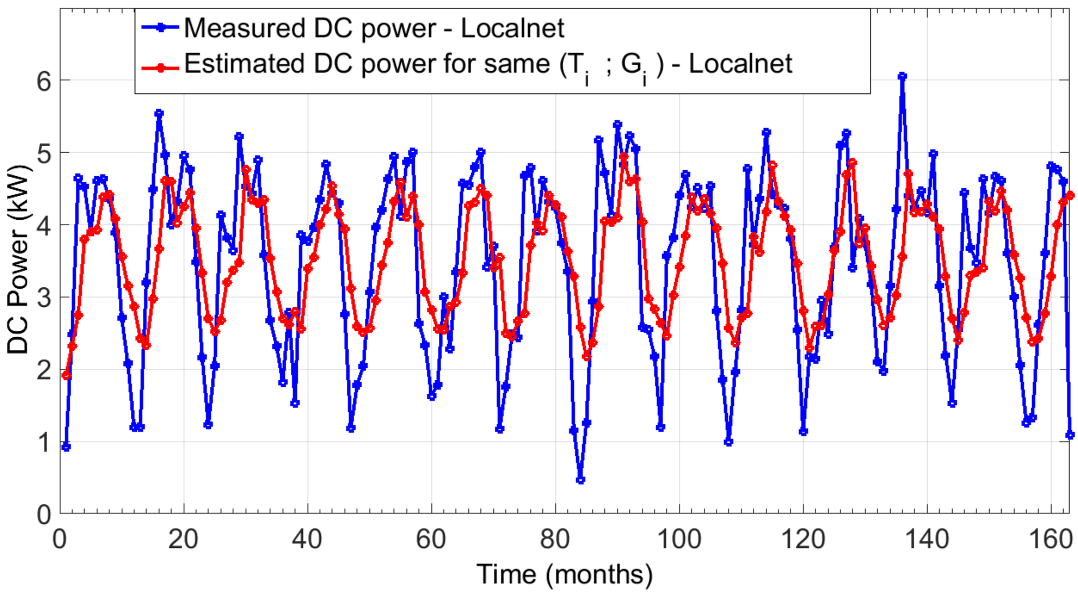


Fig. 5. Comparison between measured and estimated power for Localnet *PV* plant.

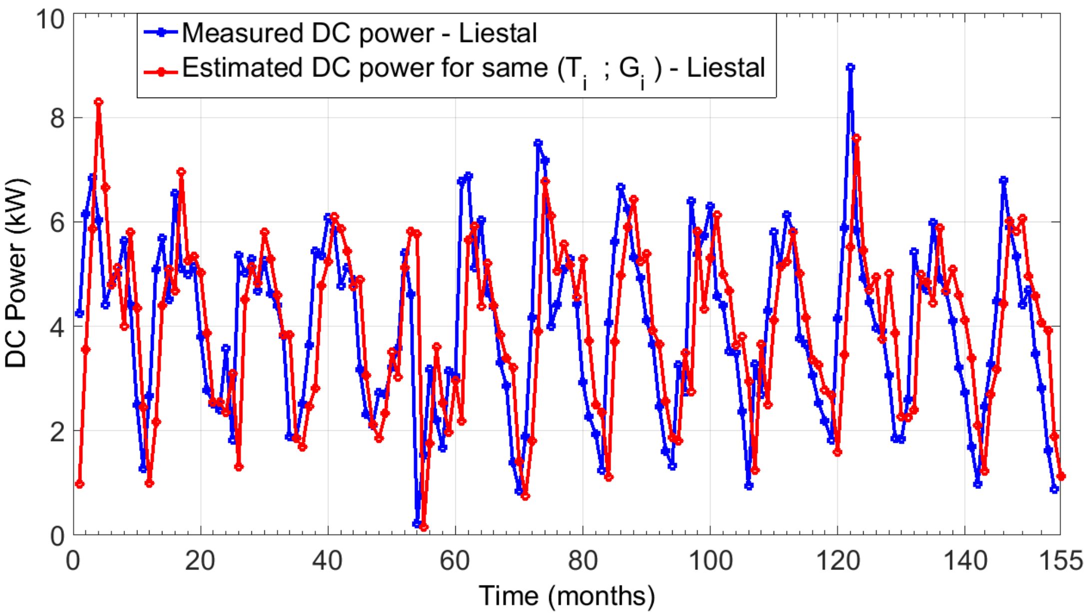
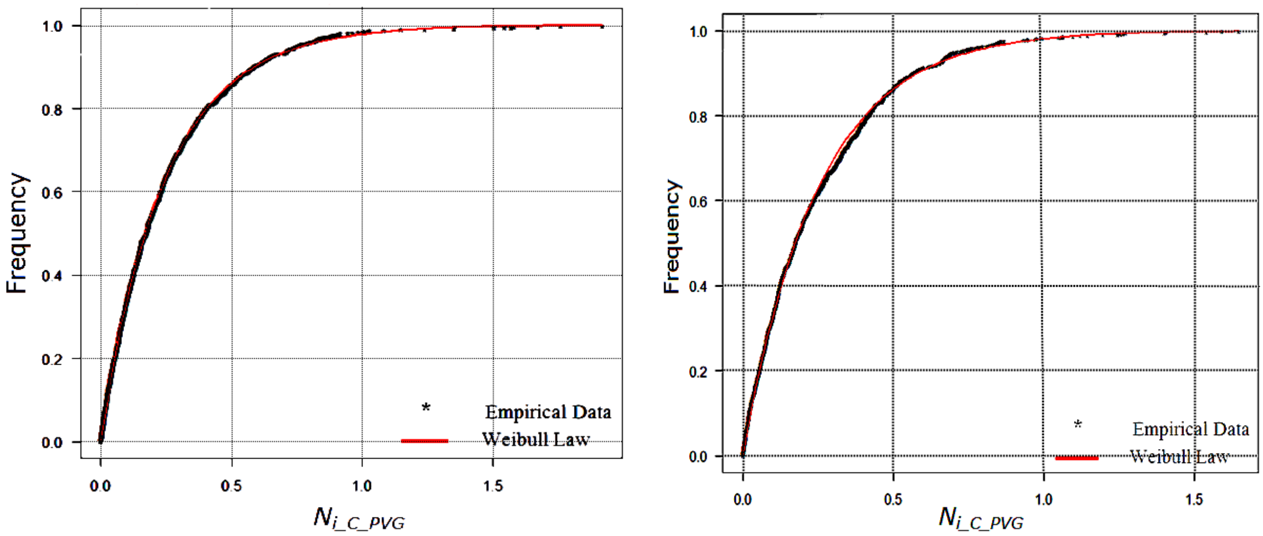


Fig. 6. Comparison between measured and estimated power for Liestal *PV* plant.



(a) (b)

Fig. 7. Comparison between empirical distribution of $N_{I\_C\_PVG}$ and it's Weibull law for: (a) Localnet / (b) Liestal.

4. CONCLUSION

In this article, we present an approach to estimate the lifespan of a *PV* system in real time. It is a method based on reliability analysis models. First, with the MATLAB/Simulink model, we obtained maximal power of each considered *PVG* without considering the effects of environmental degradation. Then, by correlating it with measured power, we can extract time series corresponding to the number of maximal contributing *PVGs*. A Weibull law, validated by Akaike criterion test, allows modeling such time series. This criterion is known to have a predictive tendency and it allows to our approach to anticipating the trend based on current data. Subsequently, the parameters are extracted using obtained Weibull distributions in each considered case.

Finally, with these extracted parameters, *MTTF* can be calculated, that would lead to the estimation of considered *PV* system lifetime. Obtained values correspond to 118.02 months (9.83 years) for Localnet site and to 239.81 months (19.9 years) for Liestal site. They correspond to the assertion of manufacturers who foresee a maximum lifetime of 264 months. Lifetime results come from truncated data, limited to data already acquired. This can limit the method accuracy. Furthermore, occurrences of serious faults can reduce this expected lifetime, as for Localnet, to less than half duration. However, this approach makes it possible to evaluate in real time impacts of environmental conditions and degradations from operating conditions on a *PV* system lifetime.

Appendix

AIC	Akaike criterion test
PV	Photovoltaic
PVG	Photovoltaic generator
DOF	Degrees of freedom
MBE	Mean bias error
MTTF	Mean time to failure
RMSE	Root mean square error
η_{ref}	Efficiency of the module at reference temperature T_{ref}
T_{ref}	Reference temperature (25 °C).
β_{ref}	Temperature coefficient at reference temperature T_{ref} (°C^{-1})
γ_{ref}	Absorption coefficient at reference temperature T_{ref}
A	Module Area (m^2).
T_i	Measured instantaneous temperature (°C).
G_i	Measured instantaneous irradiance (W.m^{-2}).

REFERENCES

[1] E. D. Dunlop, D. Halton, The performance of crystalline silicon photovoltaic solar modules after 22 years of continuous outdoor exposure, Progress in photovoltaics, 14(1), 53-64, (2006).

[2] C.S. Byington, M. J. Roemer, T. Galie, Prognostic enhancements to diagnostic systems for improved condition-based maintenance, Proceedings IEEE aerospace conference, vol.6(6), (2002).

[3] D. Jordan, S. Kurtz, Photovoltaic degradation rates-an analytical review, Progress in photovoltaics, 21(1), 12-29, (2013).

[4] P. Ribot, Y. Pencolé, M. Combacau, Functional prognostic architecture for the maintenance of complex systems, IFAC Proceedings Volumes, 42(8), 1450-1455, (2009).

[5] C.R. Osterwald, T. J. McMahon, History of accelerated and qualification testing of terrestrial photovoltaic modules: A literature review, Progress in photovoltaics, 17(1), 11-33, (2009).

[6] M. Vázquez, I. Rey-Stolle, Photovoltaic module reliability model based on field degradation studies, Progress in photovoltaics, 16(5), 419-433, (2008).

[7] R. F. Stapelberg, Handbook of reliability, availability, maintainability and safety in engineering design, Springer Science & Business Media, 99-105, (2009).

[8] R. Pan, T. Crispin, A hierarchical modeling approach to accelerated degradation testing data analysis: A case study, Quality and reliability engineering international, 27(2), 229-237, (2010).

[9] E. Monroe, R. Pan, Knowledge-based reliability assessments for time-varying climates, Quality and reliability engineering international, 25(1), 111-124, (2009).

[10] J. H. Wohlgemuth, D.W. Cunningham, P. Monus, J. Miller, A. Nguyen, Long term reliability of photovoltaic modules, IEEE 4th World Conference on Photovoltaic Energy Conference, vol. 2, 2050-2053, (2006)

[11] C. Notton, C. Cristofari, M. Mattei, P. Poggi, Modeling of a double-glass photovoltaic module using finite differences, Applied thermal engineering, 25(17-18), 2854-2877, (2005).

[12] A. Grous, Eléments d'analyse de la fiabilité et du contrôle de qualité : Statistiques appliquées par l'exemple, 113-199, Lavoisier, (2013).

[13] H. Akaike, A new look at statistical mode identification, IEEE Transactions on Automatic Control, 19(6), 716-723, (1974).

[14] International Energy Agency (IEA) Photovoltaic Power Systems Programme Task 13 Database, http://www.iea-pvps.org/, International Energy Agency, (2018).

[15] M. E. Şahin, H. İ. Okumuş, Physical Structure, Electrical Design, Mathematical Modeling and Simulation of Solar Cell Modules, Turkish Journal of Electromechanics & Energy 1(1), 5-12, (2016).

[16] X. Chen, Using the Akaike Information Criterion for selecting the field distribution in a reverberation chamber, IEEE Transactions Electromagnetic Compatibility, 55(4), 664-670, (2013).

Biographies

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Modeling and Fuzzy Logic Control of a Stand-Alone Photovoltaic System with Battery Storage

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ABSTRACT This work aimed to study and control of a photovoltaic installation with batteries. The system is composed of a photovoltaic generator and a bank of batteries that are used to supply a load. The maximization of power is obtained using perturb and observes (P&O) algorithm and fuzzy logic controller (FLC). It is proposed to add a supervisor to manage the different powers, protect the batteries against overcharge and deep discharge and of course to satisfy the load. MATLAB/Simulink is used in simulations. Obtained results showed that the proposed power management control run the global systems with a good agreement under variable solar irradiance and temperature conditions.

Keywords: Photovoltaic, Battery, Power Management, Fuzzy Logic Controller, Perturb & Observe, Power Maximization

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1. INTRODUCTION

In photovoltaic systems, it is important to use efficient maximization strategies to maximize power under all environmental conditions [1-3]. Concerning optimization, many MPPT algorithms exist including direct and indirect methods. Each of them has advantages and disadvantages and depends on the analog digital applications intended, the number of variables, the number of sensors used, the precision and of course the degree of complexity and therefore the cost. Moreover, other factors may come into play in order to choose the right method for the system under study, such as the dependence on photovoltaic generator or search speed of the maximum power point.

Traditional methods such as; perturb & observe, incremental conductance yield good results, and are very useful if the application does not require high requirements such as intelligent methods. Other more sophisticated methods such as; FLC, Fuzzy Logic Sliding Mode Controller (FLSMC) are also interesting because of their performance [4]. In recent years, metaheuristic methods such as; ant colony optimization, swarm optimization particle, and the others have been developed with very high performances.

Concerning the good management of different sources in a system, several studies were carried out on this problem and several solutions have been proposed [5-22]. All are based on the power balance and allow the load to be satisfied under different climatic conditions. Some methods are very simple, and offer flexibility for different sources of a hybrid system [23]. Others are more intelligent, and of course give more accurate and efficient results. While a general overview on the management of hybrid systems is available in the literature, it must be concluded that all the works focused on intelligent energy management and for different applications such as; electrification, water pumping, where the authors demonstrated the effectiveness of the system regardless of variations in climate conditions and load.

In this context, intelligent energy management applied to photovoltaic systems with batteries is presented in current study. Our contribution is an application with power management control (PMC) designed to manage any random variation in climatic conditions and load variations. It consists of a photovoltaic (PV) generator and a battery bank, both of which supply a load.

For maximization, we preferred to choose a classic and simple method (P&O) as well as the FLC.

Simulation results were obtained under MATLAB/Simulink for both configurations to monitor the power flow and verify the effectiveness of the proposed energy management.

2. MODELING

The studied system is illustrated in Figure1. It comprises of a PV generator, two DC/DC converters, a battery bank and an inverter supplying an AC load. The power management depends on the three switches state (K_1, K_2 and K_3), where K_2 for photovoltaic panels, K_3 for batteries and K_1 for the compensation.

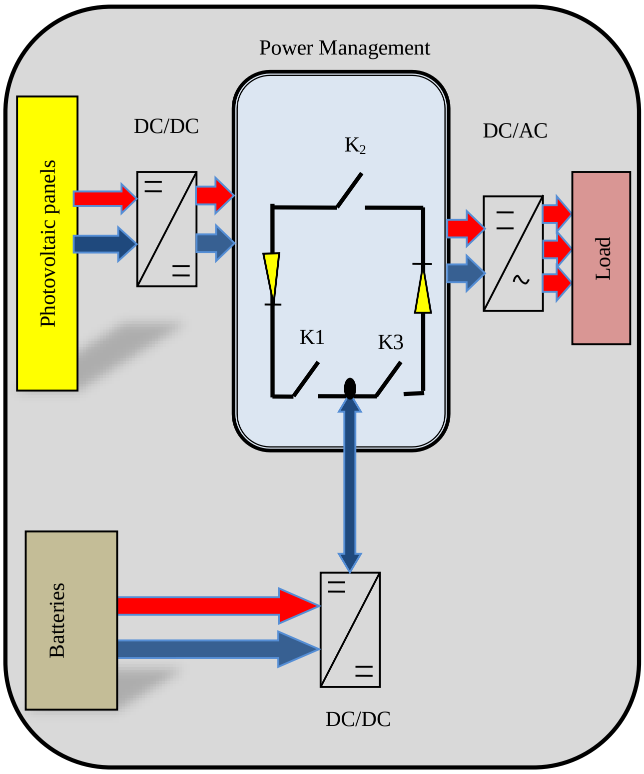


Fig.1. Studied configuration with variable load

2.1. Photovoltaic panel model

The model considered in current study is obtained from [6-8] and is given in Figure 2.

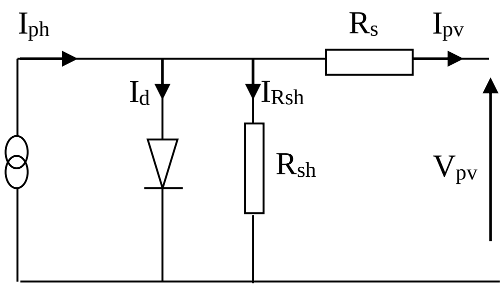


Fig. 2. Equivalent circuit of photovoltaic cell used in the study

Where: I_{ph} is the photo generated current, I_d is the diode-current, I_{Rsh} is the shunt-leakage current, R_{sh} is the shunt resistance, I_{pv} is PV current, R_s is the series resistance, and G is the solar radiation [6, 25].

The electrical equations of photovoltaic module are:

$$I_{pv} = I_{ph} - I_d - I_{Rsh} \tag{1}$$

$$I_{pv} = I_{ph} - I_0 \times \left[\exp\left(\frac{q \times (V_{pv} + R_s \times I_{pv})}{A \times N_s \times K \times T_j} \right) - 1 \right] - \frac{V_{pv} + R_s \times I_{pv}}{R_{sh}} \tag{2}$$

A test bench, seen in Figure 3, has been constructed to obtain the different electrical characteristics. The utilized PV module parameters are listed in Table 1.

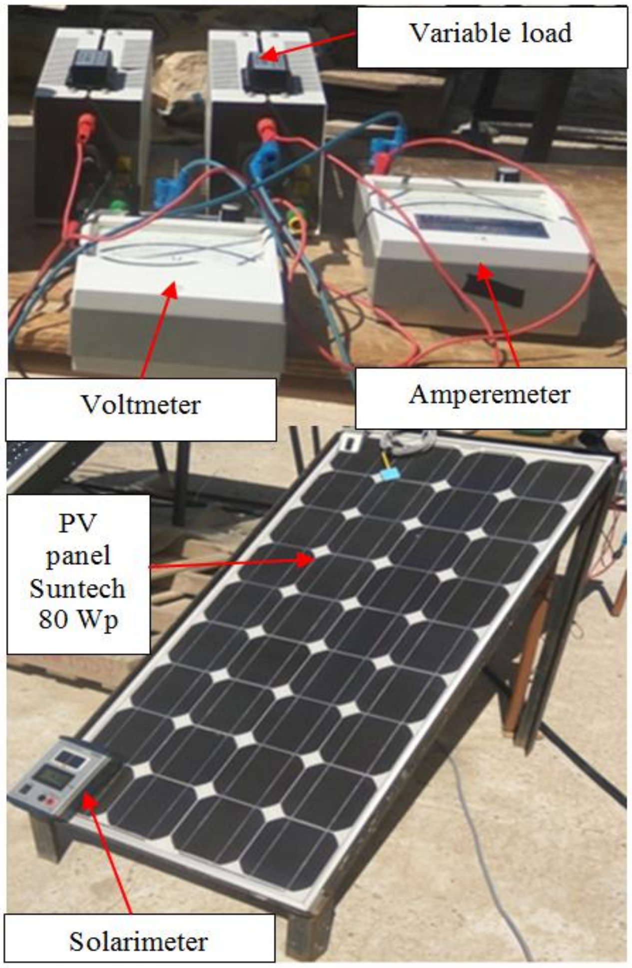


Fig.3. Experimental PV bench

Table 1. Parameters of the SuntechTPO80S-12/BB PV panel

Symbols	*Parameters*	*Values*
P_{pv}	Peak power	80 Wp
I_{mpp}	Maximum currentat MPP	4.65 A
V_{mpp}	Maximum voltage at MPP	17.5 V
I_{sc}	Short circuit current	4.95 A
V_{oc}	Open circuit voltage	21.9 V
α_{sc}	Temperature coefficient of short-current	3 mA/°C
B_{oc}	Voltage temperature coefficient of short-current	-150 mA/°C

Figure 4 shows the obtained results of the current-voltage characteristics under employed conditions. As it can be observed from Figure 4 that the nonlinear nature of the PV array is apparent. Thus, the MPPT algorithm was applied to increase the systems performance by keeping it always operating around a maximum power point.

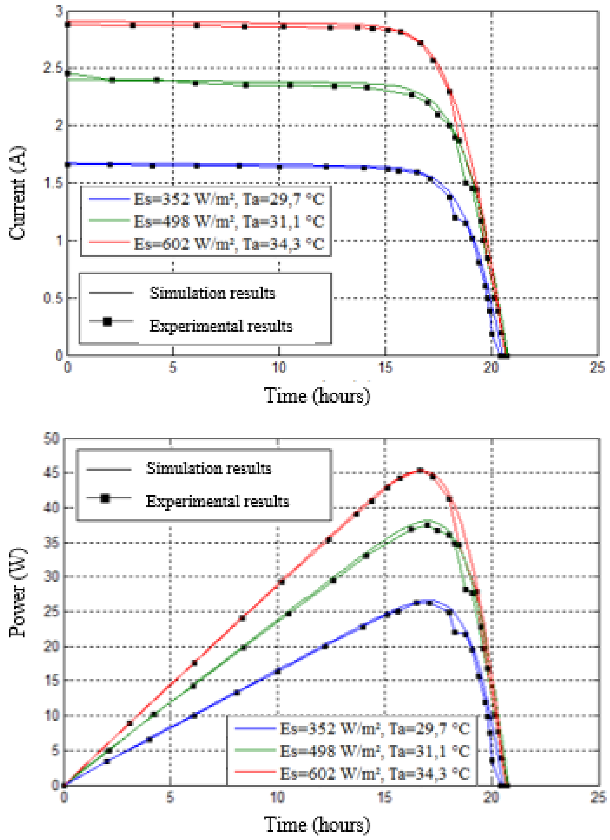


Fig. 4. Obtained I-V, P-V curve simulations and experimental results

2.2. Battery model

The battery used in current study with test setup based on lead acid technology is shown in Figure5.

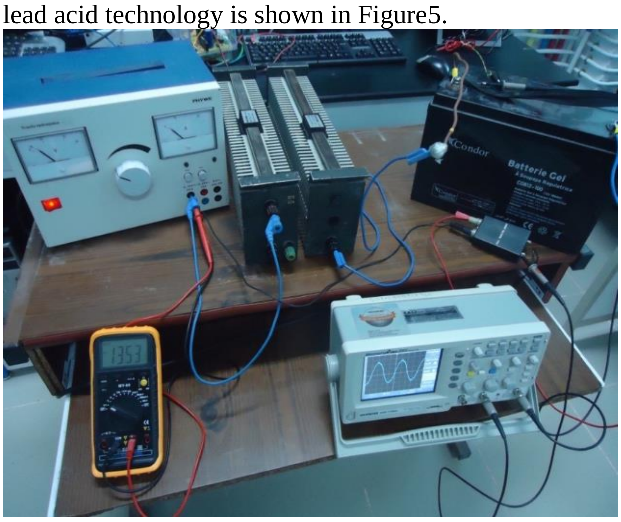


Fig.5.Used lead acid battery and test setup

The mathematical model of the battery is as follow [9-10].

$$V_{batt} = E_b \pm R_b \cdot I_{batt} \tag{3}$$

where E_b: voltage source and R_b: internal resistance.
The battery capacity C_{batt} can be written as [1]:

$$C_{batt} = C_{10} \times \frac{1.76 \times (1 + 0.005 \times \Delta T)}{1 + 0.67 \times \left(\frac{I_{batt}}{I_{10}}\right)} R_b \cdot I_{batt} \tag{4}$$

where ΔT is the accumulator's heat and C_{10} is the rated capacity at I_{10} current.

The battery state of charge is represented with Equations 5 and 6.

$$SOC(\%) = 100.(1 - \frac{Q}{C_{batt}}) \tag{5}$$

$$Q = I_{batt} \times t \tag{6}$$

where t is current discharging time.

The model can be implemented in MATLAB/Simulink as shown in Figure. 6.

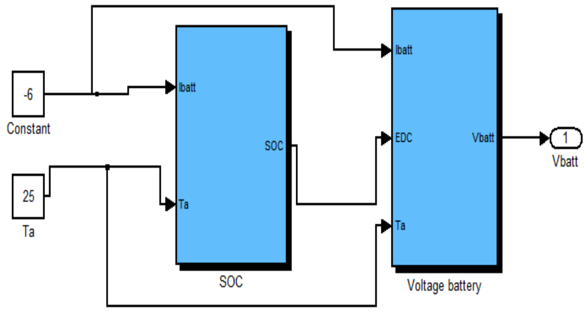


Fig. 6. Battery model used in MATLAB/Simulink

3. FUZZY LOGIC CONTROL

The FLC is mainly composed of three steps which are: fuzzification, inference engine and defuzzification. The MPPT fuzzy logic controller is composed of two inputs as shown in Figure 7 [24, 26-29].

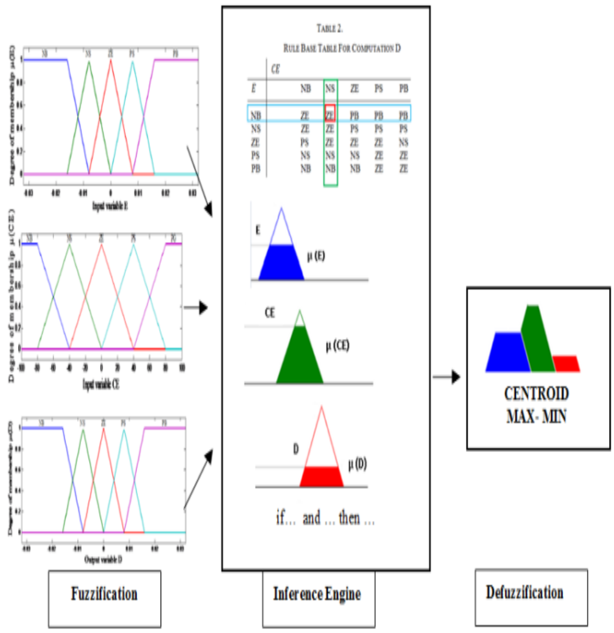


Fig.7. Fuzzy system structure

The error and the change in error are calculated as:

$$E(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)} \tag{10}$$

$$CE(k) = E(k) - E(k-1) \tag{11}$$

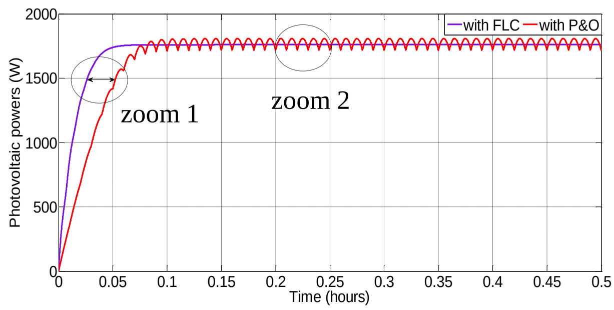
The inference matrix for the adaptation mechanism is given in Table 2.

Table 2. Inference matrix

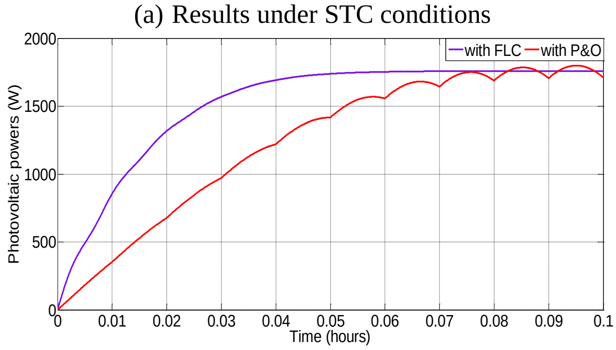
E \ CE	NB	NS	ZE	PS	PG
NB	ZE	ZE	PB	PB	PB
NS	ZE	ZE	PS	PS	PS
ZE	PS	ZE	ZE	ZE	NS
PS	NS	NS	NS	ZE	ZE
PB	NB	NB	NB	ZE	ZE

The fuzzification process makes possible to introduce fuzzy sets relative to the desired values to a degree of membership. According to the Figure 8, the defined classes are denoted as: *NB*: Negative Big, *NS*: Negative Small, *ZE*: Zero Environment, *PB*: Positive Big, and *PS*: Positive Small. The duty cycle (*D*) is the system's output variable that can be found with the relations of center of area (COD). Defuzzification is the last stage of the FLC [24].

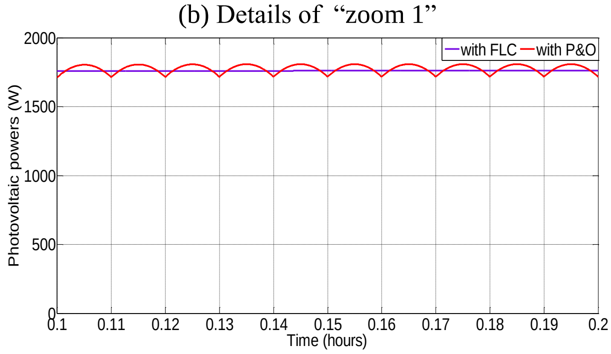
The choice of MPPT technique is important due to different parameters. In this work, two techniques (P&O and FLC) were applied. Simulation results under STC conditions are represented in Figure 8. It appears that the FLC gives a fast and precise response compared to the P&O which contains oscillations in its steady state.



(a) Results under STC conditions



(b) Details of "zoom 1"



(c) Details of "zoom 2"

Fig. 8. Photovoltaic power waveform

4.POWER MANAGEMENT OF THE STUDIED SYSTEM

Power management is a very important step before studying a system. It permits to manage the different sources and of course supplying the load based on the power balance. In this work, the PV power and the state of charge (SOC) of the batteries are the two important factors to control [14-24]. Under different variables climate conditions, different cases can be tested.

Case 1 (M1): The power available at the PV generator is sufficient to supply the load and charge the batteries.

Case 2 (M2): The power supplied by PV is insufficient, and in this case the compensation of batteries power is necessary to satisfy the power demand.

Case 3 (M3): There is no power from the PV generator, so the batteries supply the load.

Case 4 (M4): The PV power is sufficient and batteries are completely charging. In this case, the batteries are disconnected to protect them.

Case 5 (M5): There is no production from the PV generator and the batteries are discharged. In this case, the load is disconnected.

The management flow chart is presented in Figure 9.

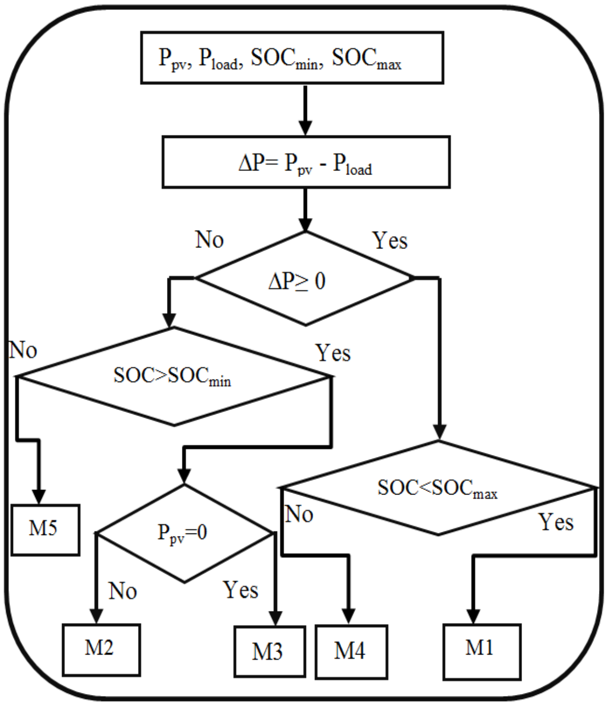


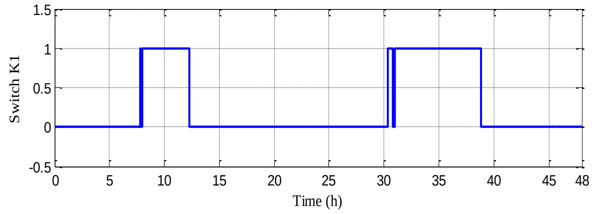
Fig. 9. Power management algorithm

The different cases based on three switches can be summarized in Table 3.

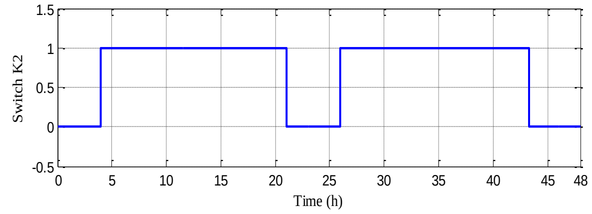
Table 3. Different cases based on three switches

Modes	***Switch States***		
	K_1	K_2	K_3
M1	1	1	0
M2	0	1	1
M3	0	0	1
M4	0	1	0
M5	0	0	0

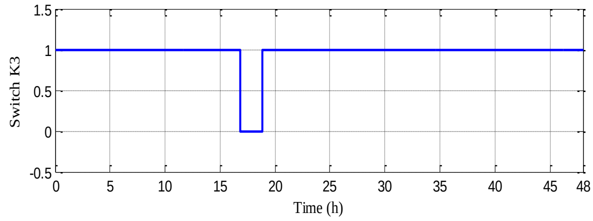
The obtained switching signals, on the other hand, are shown in Figure 10.



a



b



c

Fig.10. Switch signals K_1, K_2, and K_3

A load profile has been chosen as in Figure 11.

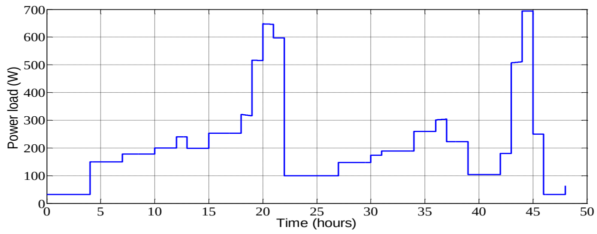
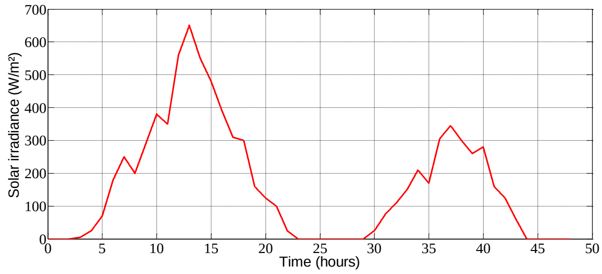
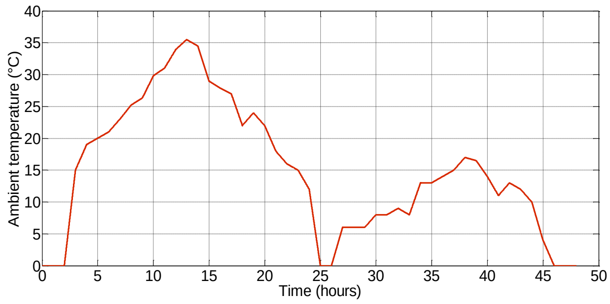


Fig.11. Profile load

The application is made under two different days as shown in Figure 12.



a)



b)

Fig.12. a) Solar irradiation and, b) temperature profiles

The sizing of the studied system has been performed. It uses a PV system of 11 panels of 80 W and 12 lead acid batteries of 12 V-100 Ah. The different powers are as follows as shown Figure 13.

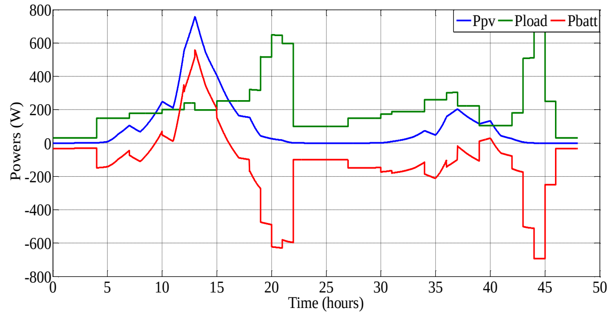


Fig.13. Photovoltaic, battery, and load power

Battery state of charge is represented to show its variations between its minimum and maximum value in Figure 14. It is noticed that the use of the management allows protecting the batteries against overcharge and deep discharge.

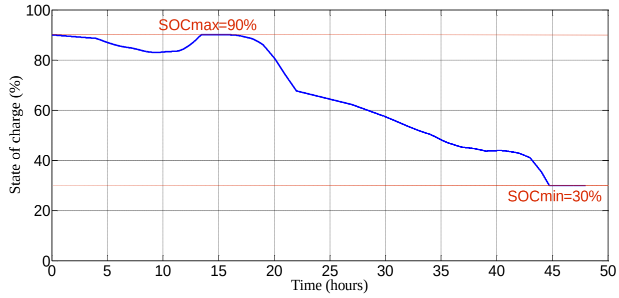


Fig.14. Batteries state of charge

It is noticed that the system operates continuously supplying the load and protects the batteries (between 30 and 90%) which show the effectiveness of the proposed management system under the various climate conditions.

6. CONCLUSION

A modeling and fuzzy logic control of a stand-alone photovoltaic system with battery storage has been presented. A power management of PV/battery system has been proposed. An application to supply power for a residential house has been tested both experimentally and numerically. The obtained results under MATLAB/Simulink, show the effectiveness of proposed method. Implementation of proposed method in real time and for applications such as pumping water systems would be beneficial.

References

[1] M. A. Vitorino, M. B. Rossiter Corrêa, An Effective Induction Motor Control for Photovoltaic Pumping, IEEE Trans. Industrial Electronics, 58(4), 1162-1170, (2011).

[2] S. Abouda, F. Nolet, A. Chaari, N. Essoumbouli, Y. Koubaa, Direct Torque Control DTC of Induction Motor Used for Piloting a Centrifugal Pump Supplied by Photovoltaic Generator, International Journal of Electrical, Computer and Communication Engineering, 7(8), 1110-1115, (2013).

[3] Z. Mokrani , D. Rekioua , T. Rekioua , Modeling, control and power management of hybrid

photovoltaic fuel cells with battery bank supplying electric vehicle, International Journal of Hydrogen Energy, 39(27), 15178-15187, (2014).

[4] B. Bendib, H. Belmili and F. Krim, A survey of the most use MPPT methods: Conventional and advanced algorithms applied for photovoltaic systems, Renewable and Sustainable Energy Reviews, 45, 637- 648, (2015).

[5] P. K. Behera, M. K. Behera, A. K. Sahoo, Comparative Analysis of Scalar & Vector Control of Induction Motor Through Modeling & Simulation, International Journal of Innovative Research, Electronics, Instrumentation and Control Engineering, 2(4), 1340-1344, (2014).

[6] D. Rekioua, E. Matagne, Optimization of Photovoltaic Power Systems, Modelization, Simulation and Control, Edition Springer, Green Energy and Technology, 102, (2012).

[7] D. Rekioua, S. Bensmail, N. Bettar, Development of Hybrid Photovoltaic-Fuel Cell System Stand-Alone Application, International Journal of Hydrogen Energy, 39(3), 1604-1615, (2014).

[8] F. Chekired, C. Larbes, D. Rekioua, F. Haddad, Implementation of a MPPT Fuzzy Controller for Photovoltaic System on FPGA Circuit, Energy Procedia, 6, 541-550, (2011).

[9] S. Bensmail, D. Rekioua, H. Azzi, Study of hybrid photovoltaic/fuel cell system for stand-alone applications, International Journal of Hydrogen Energy, 40(39), 13820-13826, (2015).

[10] N. Achaibou, M. Haddadi, A. Malek, Modeling of Lead Acid Battery in PV System, Energy procedia, 18, 538-544, (2012).

[11] H. Fakhal, D. Lu, B. François, Power Control Deing of Battery Charge in a Hybrid Active PV Generator for Load-Following Applications, IEEE Trans on. Industrial Electronics, 58(1), 85-94, (2011).

[12] A. Khiareddine, C. Ben Salah, D. Rekioua, M.F Mimouni., Sizing methodology for hybrid photovoltaic /wind/ hydrogen/battery integrated to energy management strategy for pumping system Energy, 153, 743-762, (2018).

[13] A. Mohammedi, D. Rekioua, N. Mezzai, Experimental study of a PV water pumping system, Journal of Electrical Systems, 9(2), 212-222, (2013).

[14] N. A. Sam Koohi-Kamali, H. Rahim, Mokhlis, Smart power management algorithm in microgrid consisting of photovoltaic, diesel, and battery storage plants considering variations in sunlight, temperature, and load, Energy Conversion and Management, 84, 562-582, (2014)

[15] G. M. Tina, C. Ventura, Simulation tool for energy management of photovoltaic systems in electric vehicles, Energy Conversion and Management, 78, 851-861, (2014).

[16] M. Sarvi, I. N. Avanaki, An optimized Fuzzy Logic Controller by Water Cycle Algorithm for power management of Stand-alone Hybrid Green Power generation, Energy Conversion and Management, 106, 118-126, (2015).

[17] A. Rabhi, J. Bosch, A. Elhajjaji, Energy Management for an Autonomous Renewable Energy System, Energy Procedia, 83, 299-309, (2015).

[18] S. N. Singh and Snehlata, Intelligent home energy management by fuzzy adaptive control model for solar (PV)-grid/DG power system in India, International Journal of Power Control Signal and Computation (IJPCSC) 2(2), 61-66. 2011.

[19] A. Hajizadeh, and M. A. Golkar, Intelligent power management strategy of hybrid distributed generation system,Electrical Power and Energy Systems, 29, 783-795, (2007).

[20] M. Hatti, A. Meharrar, M. Tioursi, Power management strategy in the alternative EPV/PEM fuel cell hybrid system, Renewable and Sustainable Energy Reviews, 15, 5104-5110, (2011).

[21] Z. Roumila, D. Rekioua, T. Rekioua, Energy management based fuzzy logic controller of hybrid system wind/photovoltaic/diesel with storage battery, International Journal of Hydrogen Energy, 42 (30) , 19525-19535, (2017).

[22] S. N. Singh, A. K. Singh, Rural Home Energy Management by Fuzzy Control Model for Solar (PV)-Grid/ DG Power System in India Journal of Electrical and Control Engineering (JECE), 2(1), 29-33, (2012).

[23] C. Serir, D. Rekioua, N. Mezzai, S. Bacha, Supervisor control and optimization of multi-sources pumping system with battery storage International Journal of Hydrogen Energy, 41 (45), 20974-20986, (2016).

[24] H. Hassani, D. Rekioua, S. Aissou, S. Bacha, Hybrid stand-alone photovoltaic/batteries/fuel cells system for green cities, Proceedings of 2018 6th International Renewable and Sustainable Energy Conference, IRSEC 2018.

[25] M. S. Ebrahim, A. M. Sharaf, A. M. Atallah, A. S. Emarah, Modified P&O Technique for Hybrid PV-Battery-Smart Grid Integrated Scheme, Turkish Journal of Electromechanics and Energy, 3(2), (2018).

[26] K. Rahrah, D. Rekioua, T. Rekioua, S. Bacha, Photovoltaic pumping system in Bejaia climate with battery storage, International Journal of Hydrogen Energy, 40 (39), 13665-13675, (2015).

[27] H. A Attia., F. Del Ama Gonzalo, Stand-alone PV system with MPPT function based on fuzzy logic control for remote building applications, International Journal of Power Electronics and Drive Systems, 10(2), 842-851, (2019)

[28] M. R. Douiri, Particle swarm optimized neuro-fuzzy system for photovoltaic power forecasting model, Solar Energy, 91-104, (2019).

[29] S. Al-Sakkaf, M. Kassas, M. Khalid., M. A. Abido, An energy management system for residential autonomous DC microgrid using optimized fuzzy logic controller considering economic dispatch, Energies, 12(8), (2019).

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