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Altamimi, Abdullah; Jayaweera, Dilan

DOI:
10.1049/cp.2017.0336

Reliability Performances of Grid-Integrated PV Systems with Varying Climatic Conditions

Abdullah Altamimi, ***Student Member, IEEE*[*]**, **Dilan Jayaweera,** ***Senior Member, IEEE*[†]**

*,†Dept. of Electronic, Electrical and system engineering,
University of Birmingham, UK
[*]Email :axa1127@bham.ac.uk

Keywords: Ageing, Climate change, Monte Carlo simulation (MCS), Photovoltaic (PV) system, Reliability

Abstract

Photovoltaics (PV) power generation is vulnerable to climate changes because operating voltages of PV cells can be affected by the operating temperature, power outputs can be affected by the levels of irradiances, and level of cell current can be affected by shading resulting from various causes. This paper explores variations in climatic conditions, operating temperature, irradiance, and shading on a PV system that sits on an ageing spectrum. Such PV systems are integrated to a power grid and the reliability performances of the grid were assessed using Monet Carlo simulation under varying demand conditions. The study incorporates probabilistic climate change projections from UKCP09 under different emission scenarios low, medium and high, for three time frames 2020s (2010-2039) , 2050s (2040-2069) and 2080s (2070-2099) based on observation of 30 years historical weather data.

Case study results suggest that the PV systems are vulnerable to climatic conditions considerably in the long run. The reliability performance of a power system can be affected by high penetration of PV power generation that is susceptible to varying climatic conditions. The impacts resulting from climatic conditions are inconstant with the ageing conditions of PV systems. A quantitative assessment is required for tracing PV system influences on a power system that is susceptible to varying climatic conditions.

1 Introduction

The global energy consumption of fossil fuels usage produces the Green House Gases (GHGs), which can severely damage the environment based on the predictions. The critical need of mitigating GHGs emissions and global warming have promoted the adoption of renewable power generation such as wind, hydropower, waves, and photovoltaics (PV). PV systems are being developed significantly around the world as an alternative source of energy as it is clean, involves zero CO_2 emission, and no fossil fuel consumption is needed in the operation [1]. PV power generation is vulnerable to climate changes and global warming while the higher uncertainties and variabilities in weather directly affects PV power system components, their performances, and grid reliability if they are integrated in a power system.

In the framework of a PV system reliability and impact of a climate change assessment, it is also vital to investigate the impact of future climate changes that can potentially influence the operability of PV systems. Therefore, it is pivotal to study the long-term reliability performance of PV systems for planning, operation, and maintenance of modern power systems [1]. Long-term reliability assessment helps predicting the system performance and behaviour over a PV system life.

The output power of photovoltaics is affected by environmental variables and components failures. Those make PV power generation with high uncertainties, variabilities, completely random and different than power generation from conventional units [2, 3]. In the case of environmental factors, high penetration of PV power generation affects the power system by impacting the power distribution, while a major reverse power flow can produce serious effects of voltage rise on the grid [4]. Overvoltage could shut down PV power generation systems and may affect the PV inverter protection, that can lead to a change in the power flow with unacceptable voltage fluctuations [2, 5]. On the other hand, grid connected PV systems are composed of a large number of vulnerable components such as solar panels and power electronic circuits. Their reliability is highly depending on the operation, power loss, temperature and ambient conditions that may reduce the overall reliability [6]. Although the PV systems have been available for more than thirty years, relatively little attention has been paid for assessing the reliability of grid connected PV systems and generation adequacy in detail [7]. Most of the presented papers to assess the PV system reliability have focused on the reliability of PV inverter components such as capacitors and IGBTs whereas very little work has been done to assess the reliability of an entire PV system. None of the researches have investigated the reliability of an entire PV system considering climate changes in very detail using comprehensive models.

In [8], the reliability assessment of both string inverter and central inverter for grid connected solar PV systems has been studied. In addition, the impacts of uncertainties of ambient conditions and variations on PV system failure rates have been considered for a reliability assessment. Reference [9] used hourly mean solar radiation of one year as an input to simulate the reliability analyses of an isolated power system using solar Photovoltaics on a Monte Carlo simulation (MCS) platform. Authors of [10] implemented sequential MCS to generate capacity adequacy evaluation of a small stand-alone power system using solar Photovoltaics operating in parallel with battery storage. MCS was used in [11] to assess the reliability of PV and wind hybrid system. The reliability of PV-Wind hybrid systems connected to micro storage systems have been explored in [12]. Roy Billinton (et al) evaluated the reliability assessment of small power systems, containing PV and Wind energy [13]. In [14], a new mathematical model was developed for reliability assessment of an active distribution network with PV power generation in order to capture detailed effects of a PV system.

In this paper, the climatic effects are studied in detail by taking into the account different ageing spectrums of PV systems. A major contribution of this study is that climate ambient conditions are applied on a grid intergraded PV system and their influences on a power system are quantified using MCS in order to investigate PV integrated impacts in the futuristic operating conditions of the power grid.

The paper is organised as follows. Section 2 presents the climate change by generating and simulating hourly weather data of air temperature and solar insulation that are obtained from the UK Climate Projection 2009 (UKCP09). The integrated PV system is modelled using Simulink in section 3. Section 4 delineates the PV system reliability assessment with ageing and the case study is presented in section 5. Finally, conclusions are given in section 6.

2 Weather Simulation

In this study, the UK Climate Projection 2009 (UKCP09) is used in order to generate synthetic hourly time series of future weather variables. In general, UKCP09 is a climate projection which provides future climate analyses that can be simulated using Weather Generator (WG). WG is generating synthetic time series by using a stochastic model based on absorbed historical weather data and the climate change data that is delivered by UK meteorological Office Hadley Centre [15]. Furthermore, it provides hourly and daily probability distribution for a number of climate variables within the UK and for different scenarios emission including low (B1), medium (A1B) and high (A1F1) emission. In addition, the output of WG comes in a terms of 30 years periods for seven overlap periods during the 21^{st} century. This study incorporated three non-overlap periods of 2020s (2010-2039), 2050s (2040-2069) and 2080s (2070-2099) based on observation of 30 years historical weather data. Moreover, the worst case (high level scenario) was considered because of CO2 emission increase as climate change occurs [15].

The output of the UKCP09 is a cumulative Distribution Function (CDF) for different climate change possible outcomes. Figure 1 shows the probability of the change in climate for air temperature at 2080 for the assumption of high emission with different probability outcomes. However, the air temperature is very unlikely to be less than the probability level of 10% (Blue colour curve) and on the other hand, it is very unlikely to be greater than the probability level of 90% (Red colour curve). The green colour curve represents the central estimation of the air temperature at the probability level of 50% [15].

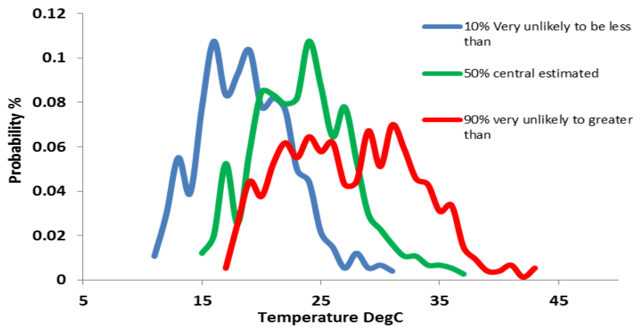

Figure 1: July air temperature for 2080 at high emission scenario at Birmingham area at probability levels of 10%, 50% and 90%

The change in air temperature is linearly dependant on the emissions such that low emission scenario has a little impact on air temperature whereas, high emission scenario prominently influences the air temperature. For example, July's mean temperature at high emission level during 2080 will rise between $2.5^{o}C$ and $10.6^{o}C$ than 2010 July mean temperature $15.7^{o}C$ (very unlikely to be less than $18.2^{o}C$ and greater than $26.3^{o}C$) as shown in Figure 1.

Figure 2 shows the probability distribution function (PDF) of different ambient temperatures for some selected periods at the high emission scenario. It can be seen from Figure 2A that the probability curve for the period of from 2040 to 2069 (30 years) nearly follows normal (Gaussian) distribution, but Figure 2B is one year from the period of 2050s and does not exactly follow the normal distribution. In addition, the PDF in Figure 2D almost follows a normal distribution, but in Figure 2C there are high uncertainties especially during the summer season.

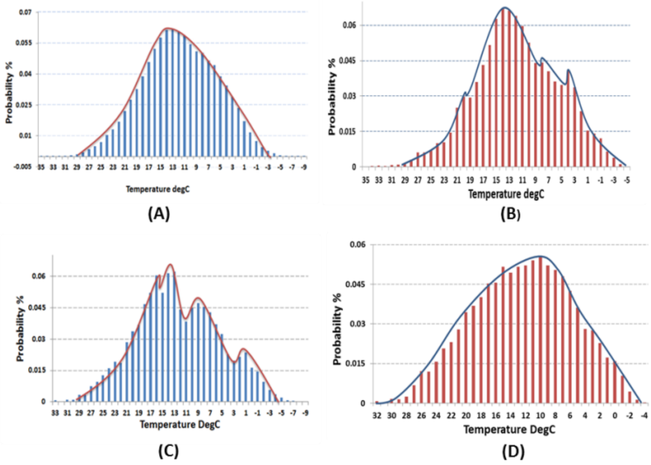

Figure 2: The probability of having different temperature during 30 years between 2040-2069 (2050s) (A), for the year 2040 (B), for the year 2072 (C) and for the year 2080 (D)

However, due to the effects of climate change, the probability of having a higher temperature increases as the time increases. For instance, average temperature in 2090 is greater than the average temperature in 2030 in the same emission scenarios.

Figure 3 shows an average of hourly solar irradiation, which is generated using the UKCP09 WG for different selected years 2041 (A), 2048 (B), 2072 (C) and 2093 (D). The uncertainty variation on solar irradiation throughout the day depends on some factors including cloud cover. For instance, in Figure 3D in summer time on July, 2093, the solar irradiation is low at almost 700 (W/m^2) due to cloud cover, whereas in Figure 3C on July, 2072 the solar irradiation is the maximum in the year is almost above 900 (W/m^2) because of the clear sky. However, generally, the effect of climate change on solar irradiation is small and less than air temperature.

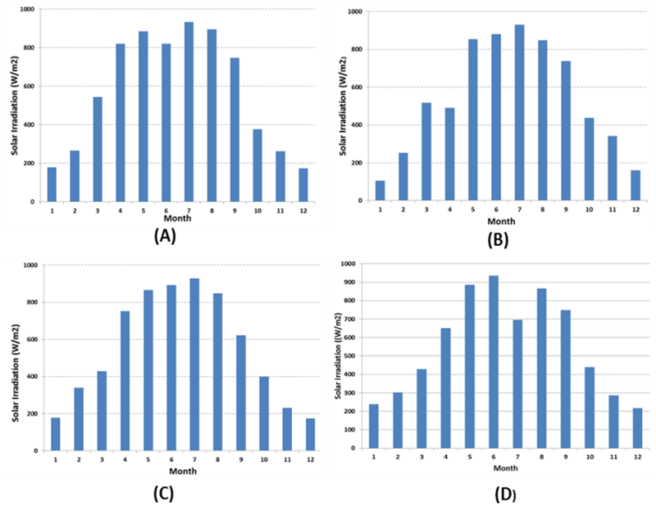

Figure 3: The probability of Solar Irradiation (W/m^2) for selected years 2041 (A), 2048(B), 2072 (C) and 2093 (D)

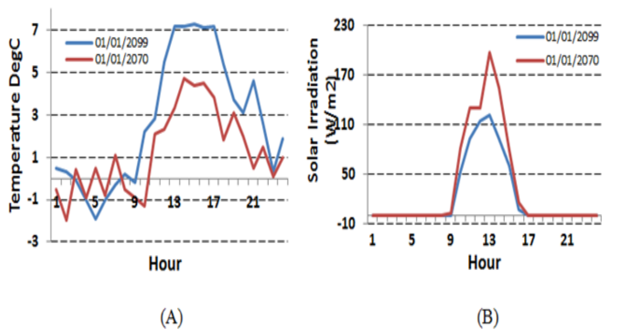

Figure 4: An example of Ambient temperature (degC) (A) and Solar Irradiation (W/m^2) (B) and for one day at 1st of January for 2070(red) and 2099(blue)

Figure 4 gives comparison of an example of simulated hourly air temperature (A) and solar irradiation (B) for a high emission scenario over two different days at 2070 and 2099. The variation in temperature is due to rainfall and cloud cover. Finally, it can be seen Figures 2, 3 and 4 that the summer period air temperature is warmer than winter period. In addition, the sunshine hours in Figure 4 are the same but with different amount of solar irradiation.

3 PV Generator system modelling

The PV generation system consists of subsystems as illustrated in Figure 5. The key subsystem in the PV generation system is the PV array which represents the power conversion unit. PV array consists of string connected either in a series or parallel depends on a specific design in order to connect to the grid. Each string has PV modules, and each module contains a number of PV cells. The mathematical model for the PV system is investigated briefly in the following section[16, 17].

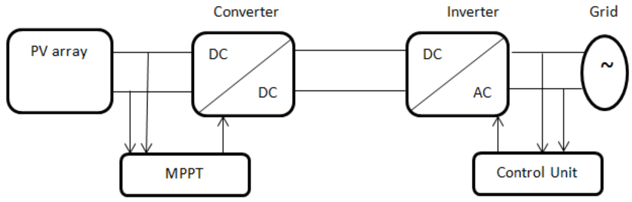

Figure 5: Structure of Grid connected PV system

Figure 6 shows the equivalent circuit for a practical solar cell and the output current of the PV cell I_{PV} can be computed by using Kirchhoff law:

$$I_{PV} = I_{ph} - I_d - I_{sh} \quad (1)$$

I_{ph} is the photocurrent (A), I_d is the diode current (A) , I_{sh} is the current (A) leak in shunt resistor and normally very small, which can be neglected. The photocurrent depends on both of insolation and temperature and can be computed using (2)

$$I_{ph} = \frac{G}{G_{ref}}\left(I_{ph.ref} + K_t(T - T_{ref})\right) \quad (2)$$

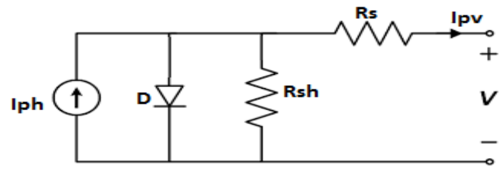

Figure 6: Practical Solar cell equivalent circuit

G and T are incident insolation (W/m^2) and temperature in (degrees Celsius) respectively, G_{ref} and T_{ref} is reference insolation and temperature under Standard Test Condition (STC) and normally (1000 W/m^2 and $25\,C^o$). K_i is coefficient temperature of a short circuit current that it comes with PV module manual provided by the manufacture. $I_{ph.ref}$ is the reference photocurrent (A) at STC and can be assumed to be $I_{ph.ref} \approx I_{sc}$.

However, the diode current I_d is proportional to saturation current I_o, so diode current can be computed as stated in (3) [16, 17].

$$I_d = I_0 \left[\exp\left(\frac{V_{PV} + I_{PV}\,.\,R_s}{a\,.\,Ns\,.\,V_{Th}}\right) - 1\right] \quad (3)$$

Rs is the series resistance, it is very small but it is considered in this study, a is the ideality factor. And Ns is the number of cells connected in series. V_{Th} is the thermal voltage and can be computed by using (4).

$$V_{Th,} = \frac{K.T}{q} \quad (4)$$

K is the Boltzmann constant $(1.38\,x\,10^{-23}\,J/K)$ and q is the electron charge $(1.6\,x\,10^{-19}\,C)$. The saturation current, I_0, with temperature dependence is given in (5) [16].

$$I_0(T) = \frac{I_{sc}\,K_i(T-T_{ref})}{\exp\left(\frac{V_{oc}+K_v(T-T_{ref})}{a\,.\,Ns\,.\,V_{Th}}\right)-1} \quad (5)$$

K_i is the temperature coefficient for short circuit current (A/C^O) whereas K_v is the open circuit voltage temperature coefficient(V/C^O).
I_{sh} can be computed by using (6).

$$I_{sh} = \frac{V_{PV}+I_{PV}\,.\,R_S}{R_{sh}} \quad (6)$$

Then, by substituting (2), (3) and (6) into (1) gives the mathematical model for a PV module. Therefore, the PV array and subsystems are designed and implemented in Simulink as shown in Figure 7. However, there are several methods that can be applied to the PV module in order to extract the Maximum Power Point (MPP) from the PV module. In this study the Perturb& Observe (P&O) method has been applied using Simulink. The output of the MPPT is a duty cycle, it controls the MOSFET switch of DC-DC boost converter, which is designed and implemented to obtain the desired voltage and DC maximum power. Then, the maximum power from the converter is connected to DC-AC inverter in order to integrate the PV system to the power grid.

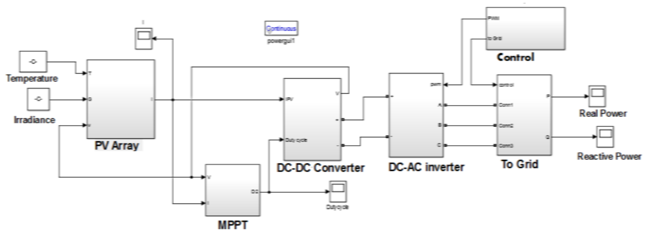

Figure 7: Grid connected PV system

4 PV system Reliability and Ageing

A large grid-connected PV system can fail due to random disturbances and during extreme events such as extreme flooding, temperature and wind. The reliability of PV system components has been investigated in [18], where, the reliability performance of a large grid connected PV system is investigated in detail. In addition, the climate change and their impacts have a significant negative affect on a large scale PV system due to the change in ambient condition for a longer period. The change in reliability can be seen clearly at a large scale PV system however, one of the most needed reliability index in this study is the Expected Energy Not Supplied (EENS). EENS is energy which could not be supplied to the system (MWh/y) due to failure rate of the components or due to change in temperature and solar irradiation.

This study excludes the impact on PV system components from events other than the climate change effects. Thus, any variation in reliability performance (EENS) of the power system against the base case is due to the effects of climate change. It is also reported that the temperature has a negative influence on the PV system reliability which can impact PV system output energy [18]. On the other hand, insolation is the input power to the PV system; the output power increases as input increases, but it also has a negative influence in the power electronic devices [18].

However, the PV module is expected to be the most reliable subsystem in a PV system. The PV module reliability decreases due to PV ageing as a result of the reduction in the output power over years. Generally, PV modules have different age level of life cycle, despite the fact that PV module commission product have life cycle as high as 25 years [19]. In addition, manufactures normally provide a warranty for the PV module output power. This usually guaranties that after 10-12 years of operation, the output power will be at least 90% and after 20-25 years, the output power will be at least 80%. The common tolerance on the PV module is 5% [19].The output power of the PV system is degrading linearly and the output power can be computed as in (7) and (8) [8].

$$P_{total=}\,P_{initial}\;[1-(K-L)d] \text{ where } K=1,2,\ldots L \quad (7)$$

$$P_{PV,K=-}\,P_{total} + 2\,P_{initial} \quad (8)$$

Where $P_{initial}$ is the initial power capacity of the PV module, K is the specified year, L represents the life cycle power of the PV module and d is the constant slop [8].

5 Case Studies

A large PV system has been designed with a capacity of 40 MW on Simulink for the purpose of grid connected operation. This PV system was used for the assessment of the reliability of a power system under different climatic conditions. Due to the unavailability of a real power system data corresponding to Birmingham area of the U.K., this study incorporated IEEE 24-Bus test system [20] as the power system that is under investigation of climatic effects. The designed PV system was integrated to the power system through the resource locations identified in the following sections. DigSILENT Power Factory software was used as the software platform for the reliability assessment while Mat Lab provided the necessary inputs to the power system model simulated on DigSILENT.
There are four scenarios in this study. The first scenario is the base case without integrating any PV system. The second scenario represents the power system with a PV system integrated at Bus 24. The third scenario represents the power

system with two PV systems integrated at Buses 24 and 9. The fourth scenario represents the power system with three PV systems integrated at Buses 24, 10, and 9. The second to fourth scenarios carries the climate change models of the PV systems when they are integrated with the power system.

In the first scenario, EENS was resulted as 5197 MWh/y. This result was used as the reference result for the comparison of other scenarios where the climate change conditions were applied.

Figure 8 shows the expected energy not supplied for the second to fourth scenarios under the high emission conditions in 2020, 2050, and 2080. In case of the second scenario, in comparison with the reference scenario, significant improvements can be seen in 2020 which proportionally degrade with the time. Although, in years 2050 and 2080 the EENS improvement decreases, however there is substantial improvement as compared to the reference case. Adding more PV generators with same capacity in the third and fourth scenarios improves the reliability compared to the reference and first scenarios. However, third and fourth scenarios also suffer from the problem of decrease in the EENS improvement with time i.e. a reduction respectively from 2020 to 2050 and 2080. From Figure 8, it can be observed that with more generating capacity, the improvement in reliability index of EENS would be more.

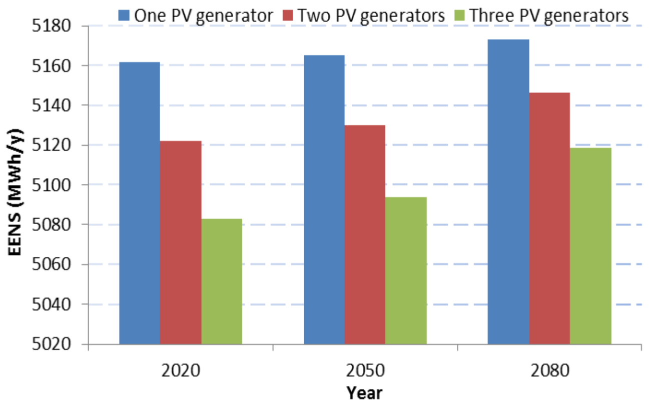

Figure 8: EENS for the grid power system with one, two and three PV generators unit.

However, this is without considering PV ageing. The reduction in the EENS improvement over the time is due to the fact that output of the PV system is affected by the change in both temperature and solar irradiation that is a climate change. Thus, due to climate change over the years, it does not deliver consistent outputs as per design of the PV system. Therefore, the results depicts that the PV system is vulnerable to climate change conditions in the long run. This situation is very real when the penetration level of PV power generation increases in the long run. Furthermore, although the EENS improvement increases with adding extra capacity, the collective effect of EENS improvement degradation due to climate change also increases manifold with higher PV capacity integration.

The power grid performances can also be affected by PV ageing beside climate change conditions. The results in the PV system in the case A in Figure 9 were in a situation where the new installation would have been taken place in 2020 and it ends the life in 2045 (PV1).Then, case B in Figure PV2 installation will be taken place in 2045 and it ends the life in 2075 to simulate and extended lifetime due to the technological advances applied in PV system materials, fabrications, and others. Similarly, in 2075 a new installation will be taken place and it ends the life in 3005 adding a 30 years of life-span. In the three cases, the PVs output power decreased with constant slop with considering maintenance and PV clean. The PV efficiency degradation due to ageing for three cases is shown in D Figure 9.

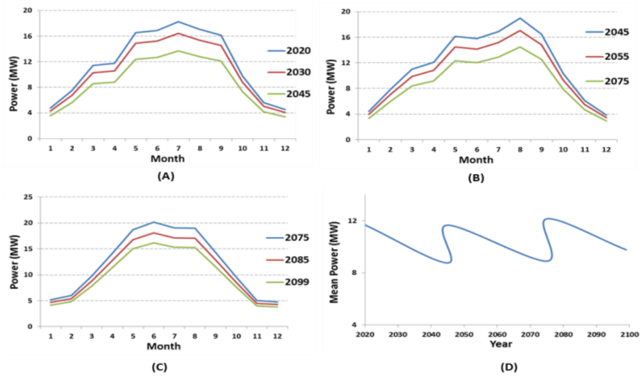

Figure 9: Change in power produced by PV system with PV ageing, PV1 from2020-2045 (A), PV2 from2045-2075 (B), PV3 from2075-2099 (C) change in power for long term with PVs replacement (D)

Figure 10 shows the effect of both PV ageing and climate change conditions to the power grid reliability performance. Results suggest that the impacts are inconsistent against the years ahead. Thus, it is apparent that the impacts on a power system due to climate change and ageing effects should be assessed quantitatively and the impacts do not necessarily increase with the times ahead, however, in the very long run the PV system integrated power systems could be faced some significant challenges in maintaining the reliability of power supply than present.

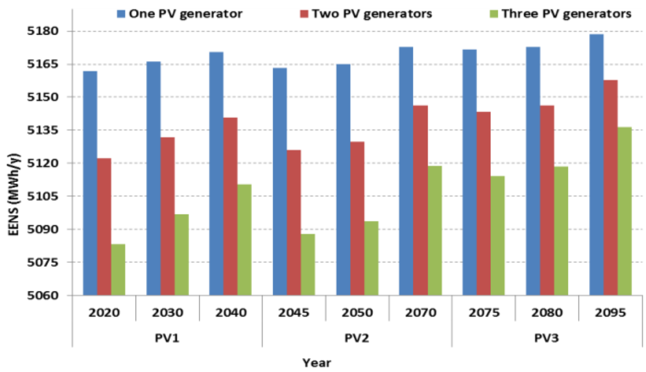

Figure 10: EENS for the power system with one, two and three PV power generating, considering PV ageing

6 Conclusion

The paper presents specific studies undertaken to investigate the impacts of climate change and PV system ageing on the reliability performances of a power system. The study incorporated a probabilistic climate change projection from UKCP09 for different periods 2020s, 2050 and 2080.

The results suggest that the reliability performance of a power system can be affected by the climate change influences on a PV system and its' ageing conditions. The impacts on a power system is not necessary increases with the times ahead, however, in the very long run, the reliability of PV system integrated power systems can be challenging and a quantitative assessment is required for the estimation of impacts for a specific power system .

Acknowledgement

The author Abdullah Altamimi scholarship is supported by Majmaah University, Saudi Arabia

Reference

1. Ahadi, A., N. Ghadimi, and D. Mirabbasi, *Reliability assessment for components of large scale photovoltaic systems.* Journal of Power Sources, 2014. **264**: p. 211-219.
2. Zhang, P., et al., *Reliability assessment of photovoltaic power systems: Review of current status and future perspectives.* Applied Energy, 2013. **104**: p. 822-833.
3. Jayaweera, D. and S. Islam, *Security of energy supply with change in weather conditions and dynamic thermal limits.* IEEE Transactions on Smart Grid, 2014. **5**(5): p. 2246-2254.
4. Jayaweera, D. and S. Islam, *Risk of supply insecurity with weather condition-based operation of plug in hybrid electric vehicles.* IET Generation, Transmission & Distribution, 2014. **8**(12): p. 2153-2162.
5. Ghaedi, A., et al., *Incorporating large photovoltaic farms in power generation system adequacy assessment.* Scientia Iranica. Transaction D, Computer Science & Engineering, Electrical, 2014. **21**(3): p. 924.
6. Sulaeman, S., M. Benidris, and J. Mitra. *Modeling and assessment of PV solar plants for composite system reliability considering radiation variability and component availability*. in *Power Systems Computation Conference (PSCC), 2016*. 2016. IEEE.
7. Stember, L., W. Huss, and M. Bridgman, *A methodology for photovoltaic system reliability & economic analysis.* IEEE Transactions on Reliability, 1982. **31**(3): p. 296-303.
8. Wang, Y., et al. *Comparative analysis of the reliability of grid-connected photovoltaic power systems*. in *Power and Energy Society General Meeting, 2012 IEEE*. 2012. IEEE.
9. Moharil, R.M. and P.S. Kulkarni, *Reliability analysis of solar photovoltaic system using hourly mean solar radiation data.* Solar Energy, 2010. **84**(4): p. 691-702.
10. Billinton, R., *Generating capacity adequacy evaluation of small stand-alone power systems containing solar energy.* Reliability Engineering & System Safety, 2006. **91**(4): p. 438-443.
11. Kishore, L.N. and E. Fernandez. *Reliability well-being assessment of PV-wind hybrid system using Monte Carlo simulation*. in *Emerging Trends in Electrical and Computer Technology (ICETECT), 2011 International Conference on*. 2011. IEEE.
12. Burgio, A., et al. *Reliability studies of a PV-WG hybrid system in presence of multi-micro storage systems*. in *PowerTech, 2009 IEEE Bucharest*. 2009. IEEE.
13. Billinton, R. and R. Karki, *Capacity expansion of small isolated power systems using PV and wind energy.* IEEE Transactions on Power Systems, 2001. **16**(4): p. 892-897.
14. Esau, Z. and D. Jayaweera, *Reliability assessment in active distribution networks with detailed effects of PV systems.* Journal of Modern Power Systems and Clean Energy, 2014. **2**(1): p. 59.
15. Jones, P., et al., *UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator.* 2009.
16. Shannan, N.M.A.A., N.Z. Yahaya, and B. Singh. *Single-diode model and two-diode model of PV modules: A comparison*. in *Control System, Computing and Engineering (ICCSCE), 2013 IEEE International Conference on*. 2013. IEEE.
17. Gallegos, C.D.R. and M.S.A. Alvarado, *Analysis of the Stationary and Transient Behavior of a Photovoltaic Solar Array: Modeling and Simulation.* Analysis, 2015. **127**(4).
18. Zhang, P., et al., *Reliability evaluation of grid-connected photovoltaic power systems.* IEEE transactions on sustainable energy, 2012. **3**(3): p. 379-389.
19. Vázquez, M. and I. Rey-Stolle, *Photovoltaic module reliability model based on field degradation studies.* Progress in photovoltaics: Research and Applications, 2008. **16**(5): p. 419-433.
20. *Reliability test system task force, The IEEE reliability test system-1996.* IEEE Trans. Power Syst, 1999. **14**(3): p. 1010-1020.