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An Innovative Methodology for Load and Generation Modelling in a Reliability Assessment with PV and Smart Meter Readings

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***Abstract*—With a paradigm shift from centralized to decentralized integration of distributed generation, particularly the photovoltaic (PV) systems made significant impacts on the reliability of power systems. The intermittency of PV and the stochastic nature of load results in a complex interaction of PV and load profiles, in a reliability assessment. In order to reduce the complexities of intermittent power generation interaction with smart meter customer consumptions, this paper presents an innovative methodology for the modeling of intermittent PV generation and smart meter readings in a reliability assessment in a power system. A case study was performed incorporating different scenarios of PV integrations with real-world smart meter load data, and climate projections weather in a UK environment. The results validate robustness of the proposed modeling framework for the reliability assessment in a power system with an accuracy of more than 99.5% and 97.5%, compared with actual generation and load profiles respectively.**

***Index Terms*— Expected energy not supplied, Load modelling, PV modelling, Reliability assessment**

I. Introduction

Transformation of conventional grids into smart grids has been orchestrated by the integration of renewable energy sources and in particular photovoltaics (PV). This journey towards a smarter grid has become more challenging with the increase in penetration of PV. Intermittency of PV generation is not the only challenge faced by the future grids, smart loads and energy consumption behavior of consumers is another aspect which enhances uncertainties in the power system. On one side the probabilistic performance of PV system along with uncertainties of solar irradiation and ambient temperature, make the output power completely random [1] and at the same time the technological advancement has enhanced the uncertainties on the demand side. However, on the demand side, big data of smart meters although provides a detailed information of consumer's load consumption pattern, however, processing this data is a daunting task particularly for the purpose of reliability assessment.

To ascertain the impacts of challenges faced by the future grids on reliability of the system, a different approach needs to be adopted which should incorporate load demand at consumer level and the intricacy of interaction of load and generation profiles needs to be reduced. To address these challenges, this paper proposes a novel approach for reliability assessment of power system using a novel PV modelling scheme in conjunction with a similar load modelling scheme using smart meter data.

This paper proposes an innovative approach to assess the reliability of power system. A novel PV generation modelling approach is proposed. The approach reduces the complexity of interaction of generation and load profiles with other uncertainties by minimizing the non-linearity while maintaining the energy balance close to the original profiles. The approach is validated by incorporating the profiles generated by the novel generation model and smart meter load data considering different scenarios of PV penetration and different network topologies.

II. Methodology

Reliability assessment of a system has always been very important but with the increased penetration of distributed generation in the power system, the complexity has enhanced manifold. Some of the key elements required for reliability assessment by the system operator are the generation levels and load demands. In this paper, for PV generation data, the hourly weather data including air temperature and total solar radiation were simulated using the UKCP09 (UK Climate Projections 2009) weather generator [1] for Belfast city. In the weather simulation, a stochastic model was used based on the historical observations of weather data provided by the U.K. Meteorological Office [1]. For load demand, the 'ISSDA CER' Smart metering dataset [2] was used which consisted of half hourly energy consumption records of almost 6000 consumers.

To reduce the data of smart meters, extended k-means clustering algorithm [3, 4] was applied on energy consumption data of duration of one year after data pre-processing. This resulted in 38 clusters for profiles extraction and each profile consisted of 17520 records of energy consumption. The hourly solar generation was interpolated into half hourly generation data using linear interpolation to

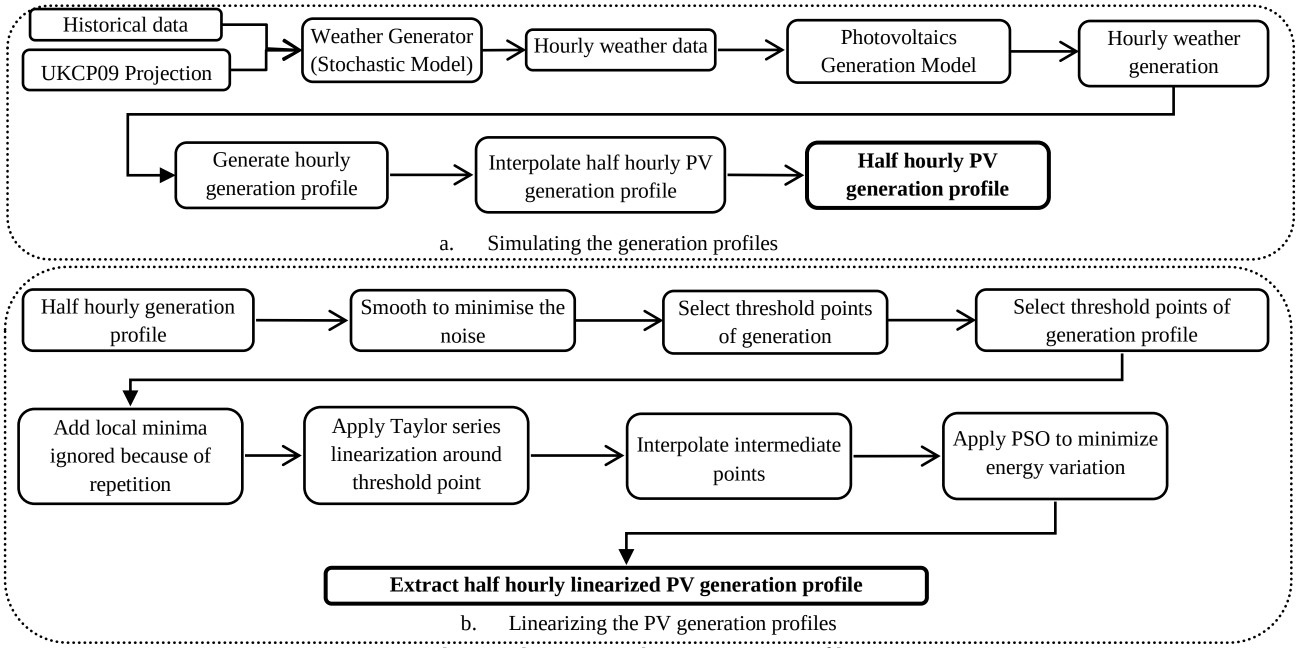


Fig. 1 Simulating and Linearizing the PV generation profile

match the details of load data. To reduce the intricacy of the generation and load profiles, the profiles were linearized to maximize the energy capture and minimize the difference in energy of original and linear profiles. For load profiles, the linearized profiles were available from our previous work [3]. The approach adopted for simulating, linearization and optimization of the PV generation profiles is given in Fig. 1.

The proposed model uses smart meter data to generate clusters of consumers to extract representative profiles of each consumer classes. The linearization process is carried out by linearizing the generation and load profiles around incremental selection of two threshold points at a time, which are either local minima or maxima. The linearization is performed using Taylor series expansion up to first degree only as effects of high order terms are negligible. As the linearization is executed using just two threshold/operating points, the missing data points between the linearized points are interpolated. Finally each linear pattern is optimized using particle swarm optimization [5] to match the energy of original profile. Linearization of generation profiles involves additional step as compared to the load profiles. Mainly this additional step is due to intermittent nature of PV generation which results in constant zero generation for long time creating single local minima over long period of time. Therefore, in case of the generation profiles the algorithm requires to consider the long zero generation duration as having two local minima by adding an additional threshold point at the end for linearization. The incremental optimization of each linear pattern is performed using particle swarm optimization to minimize the energy variation.

Mathematically the PV generation profile is complex function which can be represented by set of functions such that for the *'m'* dimensional profile *'P'*, can be represented by system of differential equations of n^{th} order such (1) that

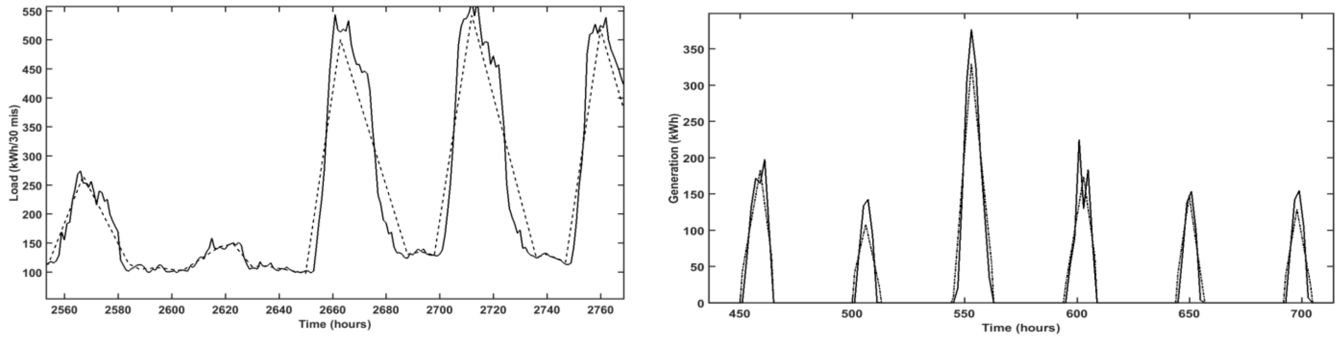
$$\begin{aligned} p_0 &= a_1 x_0 + a_2 {x_0}^2 + \ldots + a_n {x_0}^n \\ p_1 &= a_1 x_1^{'} + a_2 {x_1}^{2'} + \ldots + a_n {x_1}^{n'} \\ &\vdots \\ p_m &= a_1 {x_m}^{m'} + a_2 {x_m}^{2^{m'}} \ldots + a_n {x_m}^{n^{m'}} \end{aligned} \tag{1}$$

Where *'x_m'* is the m^{th} time step and *'a_m'* is the m^{th} coefficient. However, the complexity involved in calculating this function is quite high. Thus, the linearized generation profiles significantly reduce this complexity by converting the complex non-linear function into concatenation of linear functions and can be represented by (2)

$$P = \sum_{i=0}^{n} w_i \left(f(a_i) + f'(a_i)(x - a_i) \right) \tag{2}$$

Where *'a_i'* is the operating point and $f'(a_i)$ gives the derivative of the a_i. *'w_i'* represents the weightage factor determined by the particle swarm optimization to minimize the energy variation. Once the linear PV generation and load profiles are extracted, they are used for reliability evaluation of power system.

The reliability of power system ensures that the electricity demand of the consumer is met within the system capacity limits while considering economic feasibility, quality of service and power continuity degree [6]. To cope with these vital factors holistically is demanding, not only because of distinctive behavior of the system, but also proposed system data accuracy with compatibility on power system reliability assessments. Within the transition from traditional power system to smart powered grids, integration of available large volume of detailed data on evaluation algorithms is becoming challenging task and increasing computational effort [7]. To reduce computational cost, time and effort, proposed linearization method is used to evaluate the power system reliability utilizing linearized generation and load profiles.



a. Original (solid line) and linearized (dotted line) load profile   b. Original (solid line) and linearized (dotted line) PV generation profile

Fig. 3 Original and linearized PV and load profiles

Following the creation of linearized profiles, the case study for reliability assessment is divided into three main scenarios based on the PV-load capacity limits while considering centralized-decentralized integration of PV. The case study 1 compares reliability index when proposed linearized load and real load is applied with different scaling factors into 13 different load buses. Case study 2 analyses impacts on reliability in case of centralized and distributed PV integration by using proposed linearized PV profiles and real ones. Case study 3 is further classified into two scenarios, which are evaluated at minimum and maximum load limits using linearized and real PV profiles with centralized-decentralized PV integration. In light of the resultant PV data provided by the proposed linearization methodology with case study scenarios, the approach adopted for reliability assessment of power system is given in Fig. 2. The EENS of a system can be calculated using (3) where C_i and p_i denote load curtailment and the system state probability [6]:

$$EENS\,(MWh\,/\,y) = \sum_{i=0}^{n} C_i \times p_i \times 8760 \qquad (3)$$

III. Numerical Application and Results

To validate the applicability of the approach, as described earlier the smart meter energy consumption data from ISSDA CER' Smart Metering dataset [8] was used and for PV generation, the hourly weather data including air temperature and total solar radiation were simulated using the UKCP09 (UK Climate Projections 2009) weather generator [1, 9] for Belfast city.

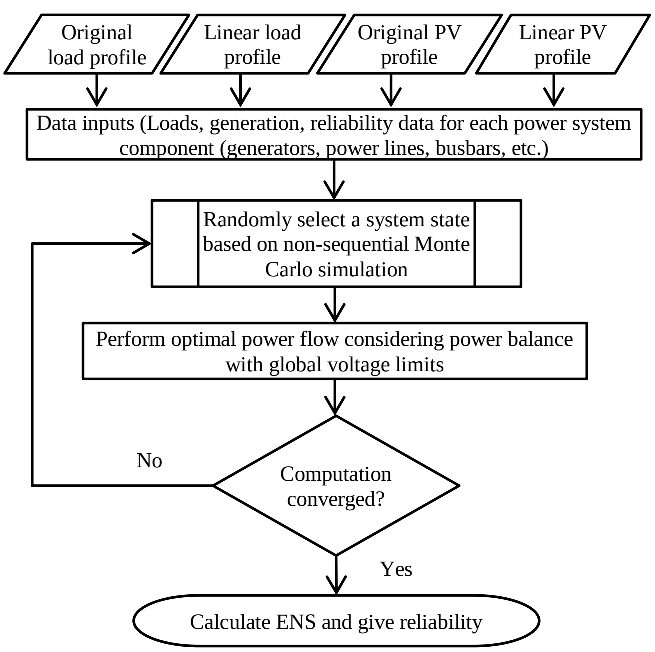


Fig. 2 Proposed approach for power system reliability assessment study

Dimension of the profiles used for this study (both load and PV generation), with a half hourly temporal resolution, was *D = (60×24×365)/30 i.e. 17520.* The highly non-linear load and PV generation profiles were successfully linearized. Fig. 3 shows random sections of the load and PV generation profiles with both original and linearized profiles. From these profiles, it can be clearly seen how the non-linearity of the generation and load is reduced by linearizing leaving only eminent variations. Modelling the variations in the solid lines i.e. original profiles is a complex task and on the other hand, the simplistic profiles which are linear, however, are highly accurate representative of the original profiles are much easier to model.

To validate the applicability of the proposed generation model and for reliability assessment study, IEEE RTS79 bus system is selected as a topology of the power system. The system consists of 24 buses, 32 conventional generators. Details of the system topology and data are given in [10]. For each scenario, the bus system is modified slightly, and these modifications are given in case study results.

A. Case Study 1:Comparison of Linearizied and Real Load

The aim of this case study 1 is to observe the effects on the reliability of power grid when linearized load data is used for reliability assessment of system as compared to the real load data. To simulate this scenario, 13 load buses of the test system are chosen for load clusters. Previously connected loads from each load bus are removed and proposed 38 load clusters are connected for every load bus. After connection of load cluster in each load bus, connected load capacity is increased 2 times higher load capacity for each simulation compared to previous simulation. This approach is implemented until maximum loading capacity of the test system. EENS changes in proposed linearization applied load profiles and original load profiles are compared using load scaling factor as shown in Fig. 4. It is apparent from Fig. 4 that EENS gradually increases in both scenarios from base case to maximum scaling factor, which is the point that describes maximum loading capacity of the system. The

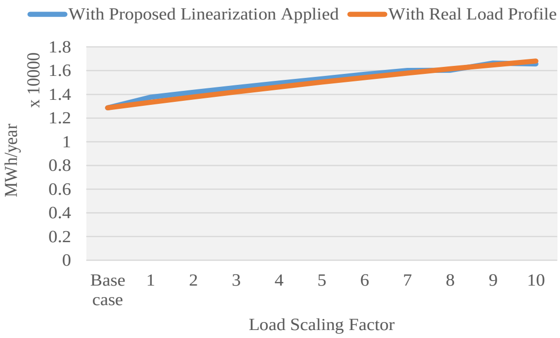
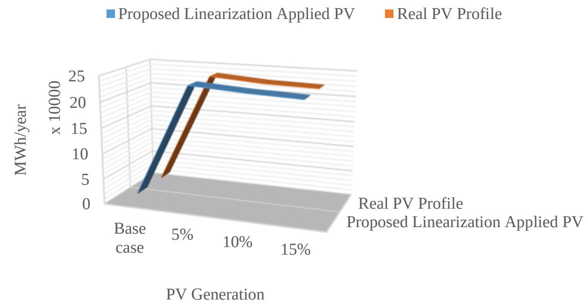


Fig. 4 Line graph of EENS considering Load scale

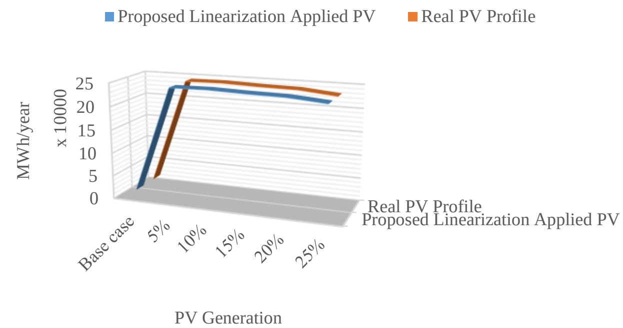
overall reliability index of proposed linearized load has slightly higher value as compared to real load which totals up to 1.33% of the original. After scaling factor of 7, EENS index fluctuates until reaching maximum scaling factor. In summary, these results show that linearization of the loads given in [3] is a good representative of the original load profiles with very little error of 1.33%.

B. Case Study 2:Centralised-Decentralised PV Integration

To assess impact of proposed linearized PV profiles versus real PV profile data on the power system, centralized and de-centralized PV generation integration approaches are implemented. For reliability evaluation of the centralized PV integration, busbar 7 is selected. On the other hand, busbar 4, 5, 6, 7, and 8 are chosen for de-centralized PV integration analysis. Nominal capacity of a PV system is set as 5 % of maximum load of the reliability test system, which is almost 140 MW. For case study 2 only the original load profiles are used. The load capacity of IEEE RTS79 is implemented as 2850 MW. In both approaches of case study 2, PV system capacity is projected to rise steadily with 5% of total load steps until reaching global voltage stress limits. In perspective of original PV data and proposed linearized PV data, Fig. 5a and 5b provide EENS index of centralized and distributed PV system integrations into the reliability test system respectively. As shown in Fig. 5a and 5b, there is abrupt increase on reliability indicator of the system from base case to 5% of PV generation in both PV integration scenarios. It can be clearly seen in Fig. 5a that centralized PV generation system in both real data and proposed linearization approach reaches capacity limits, which are almost 15 % generation of



a. Centralized PV System Integration



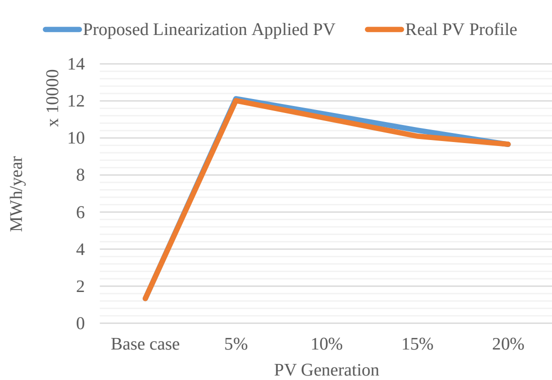
b. De-centralized PV System Integration

Fig. 5 Line diagrams of EENS changes considering PV integration method

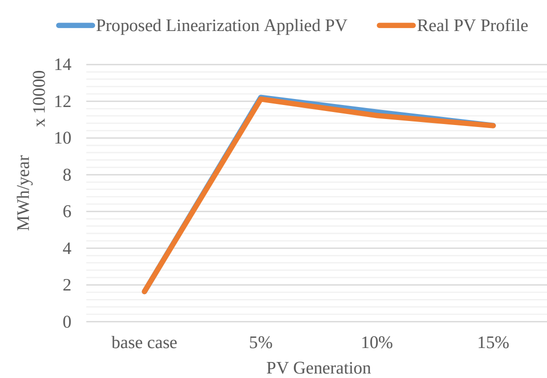
total load capacity. For distributed PV generation in Fig. 5b, the reliability index for centralized PV integration in both cases turns out to be almost same i.e. negligible error of 0.009%. Moreover, de-centralized PV system integration can reach up to 25% of total capacity without any voltage limit problem. Although high increment on PV capacity limits, the EENS of the system is decreased slightly.

C. Case Study 3:Comparison of Minimum and Maximum Load Scaling Impact on PV Integration Capacity

The target of this case study 3 is to demonstrate proposed linearization applied load and PV profiles impact on EENS. To achieve this, same load scenarios of case study 1 is implemented considering maximum (10 times of the minimum load) and minimum load. Fig. 6a and 6b represent EENS changes with centralized PV integration versus minimum and maximum load capacity respectively while



a. With Minimum Load Capacity



b. With Maximum Load Capacity

Fig. 6 Line diagram of EENS changes versus with centralized PV integration

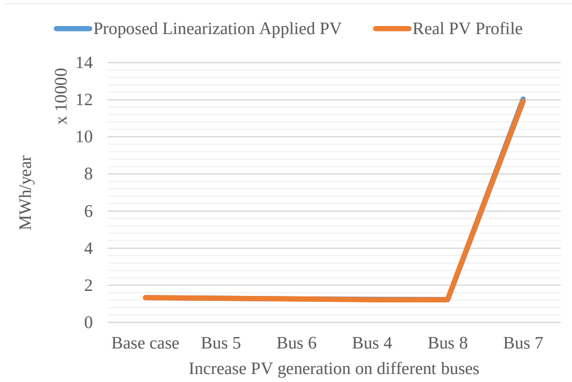


Fig. 7 De-centralized PV integration with Maximum Load Capacity

considering PV generation only in substation 7. Theoretically, in both parts of Fig. 6 should follow same reliability pathway. Nevertheless, it can be noticed that there is a slight difference in EENS index between proposed linearization implemented PV and original PV generation data. Besides, de-centralized PV integration with proposed linearization applied load as maximum level is evaluated. The buses given in Fig. 7 are connected to PV system, where the total PV generation is 25% of the total load. PV generation on each bus consists 5% of total load capacity level. To conduct the reliability study, a step-wise incremental approach has been adopted by adding PV generation at each bus. Interestingly, EENS was levelled until busbar 8. After this, it sharply rises when busbar 7 is connected to the system. It is worth to mention that substation 7 is a critical busbar for this reliability test system.

The proposed innovative generation model of PV profiles is highly accurate representative of original PV profiles as is evident from Fig. 3. Application of reliability assessment with linearized data as compared to original data revealed that the reliability index accuracy for centralized and decentralized PV generation turned out to be more than 99.5%. This level of accuracy benchmarks the applicability, robustness and precision of the approach. However, as compared the linearization process of PV profiles, the load profile linearization lagged behind in terms of accuracy but still achieving a very good level of accuracy i.e. 97.5 % compared to original load data. This can be clearly seen in Fig. 4 for load and for PV system in Fig. 5. The disparity between the accuracy of the confidence level of load and PV linearization process is due to the additive effect of the errors in conjunction with number of consumers in the load clusters. Table I shows the proposed model deficit of all simulated case study scenarios. Despite of the disparity rate of different case studies, the proposed PV and load linearization model provides a very high confidence level of more than 97%.

IV. Conclusion

An innovative approach has been proposed for the study of power system reliability by incorporating a novel PV generation model. A case study validates the robustness of the approach with accuracy level of more than 99.5% compared with realistic generation and 97.5% for load profiles. The proposed generation model is an alternative

Table I. Comparison linearized PV profile and original PV profile

Case Study 2			
Centralized PV Integration	***EENS (MWh/year)***	***PV Capacity Limit (%)***	***Disparity Rate (%)***
Proposed Linearization PV Profile	225266.398	13.25	1.35
Original PV Profile	225063.441	11.9	
Case Study 3 with Minimum Load Capacity			
Centralized PV Integration	***EENS (MWh/year)***	***PV Capacity Limit (%)***	***Disparity Rate (%)***
Proposed Linearization PV Profile	96570.22	19.75	2.25
Original PV Profile	96608.266	17.5	
Case Study 3 with Maximum Load Capacity			
Centralized PV Integration	***EENS (MWh/year)***	***PV Capacity Limit (%)***	***Disparity Rate (%)***
Proposed Linearization PV Profile	106832.619	14.75	1.6
Original PV Profile	106725.494	13.15	

generation model that can be used for reliability assessment. It reduces complexity of data management by reducing the data by clustering, minimizing the variations, reduces computational time and complexity in interaction of the PV generation profiles with other underlying systems.

The application of the proposed model is not limited to the reliability assessment and it can be used for power system security assessment, risk modelling and many others.

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