Capacitor Allocation Study Considering Integration of Distributed Photovoltaic (PV) Systems in Power Distribution Networks using Enhanced PSO

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Abstract. Current advances in renewable energy, along with the infrastructure and government regulations changes, have greatly improved the penetration of distributed generation of photovoltaic (DG PV) in the electricity distribution systems. This integration plays a crucial role in supplying contemporary electrical systems. The absence of reactive power compensation sources such as capacitors while the PVs integrate may increase total system losses and voltage-instability threats. Therefore, capacitor planning is highly required due to the intensive use of DG PV. This paper proposes an optimization of the capacitor and DG PV allocation and sizing by considering the uncertainty condition resulting from the fluctuating DG PV output. The appearance of uncertainty parameters in the problem formulation makes the load flow analysis have to be performed using the probabilistic approach. Then the losses arising from the probabilistic load flow are considered as the objective function to formulate the allocation of capacitors and DG PV problem. The installed location and sizing of the capacitor and DG PV are optimally determined using Particle Swarm Optimization (PSO). the output of this optimization includes the loss minimization, voltage profile enhancement, the best location and size for installation of capacitors, and DG PV. The developed optimization is verified in the IEEE 34 radial bus system. The findings results show that the losses are decreased by up to 53.18 %, specifically from 220 kW to 103 kW. Furthermore, this optimization scheme also identifies suitable bus candidates for the installation of capacitors, including buses 8, 9, 20, 25, 30, and 31, and PV DG in buses 12,24,25,26, 27, and 24.

Keywords: Allocation of capacitors, photovoltaic, distributed generation, solar irradiance uncertainty, probabilistic load flow, Monte Carlo, losses minimzation.

1 Introduction

In general, a power system comprises generating units, transmission lines, and distribution networks connected to loads. Due to the rising power demand and loads, power companies need to develop and enhance the power networks. Usually, the actions are commonly done in

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the distribution network and may generate some problems e.g increasing power losses and resulting in poor voltage values. The distribution network systems that have high resistance and reactance (R/X) characteristics will create high losses [1]. Developing the system means producing more R and X values that can produce more power losses. It has been reported distribution networks account for 13% of the overall power losses in power systems. The power losses will result in an inadequate voltage profile. This condition is unacceptable as it can affect the reliability and stability of the system [2]. Therefore, power companies need to find solutions in minimizing the power losses and maintain a stable system voltage.

Recently, these issues can be solved by installing power compensators such as the capacitor bank. Adding the distributed generations (DG) in the distribution system has also been considered as a solution because it can prevent the new power network's establishment to supply power, resulting in economic savings as well as improving system reliability [3].

The allocation of capacitors and distributed generation (DG) has emerged as a promising solution for minimizing power loss and enhancing voltage. However, if not positioned and sized appropriately, they might lead to poor performance and unnecessary expenses [4]. Previous scholars have devised numerous strategies for this issue, including both conventional and meta-heuristic approaches [5][6][7][8][9][10][11]–[18]. Nevertheless, several approaches have not addressed the impact of characteristics and fluctuating output of DG units, particularly those based on renewable energy sources integrated into the system. Therefore, this paper proposes a method, enhanced Particle Swarm Optimization as a need to overcome the previous challenges by addressing the capacitor and distributed PV units allocation optimally in the distribution power systems subjected to distributed PV generation uncertainty to enhance the overall performance of distribution systems.

2 Problem Formulation

The goal of this research is to define the optimal placement and size of capacitors and DG PV in distribution systems, considering the PV output uncertainty. The primary objectives are the active power losses minimization and enhancement of voltage stability. In this research, the problem's objective function mathematically is described in Equation (1).

$$min\,F(x)=min(P_{Tloss}) \qquad (1)$$

where, P_{Tloss} is the total of active power loss in the system.

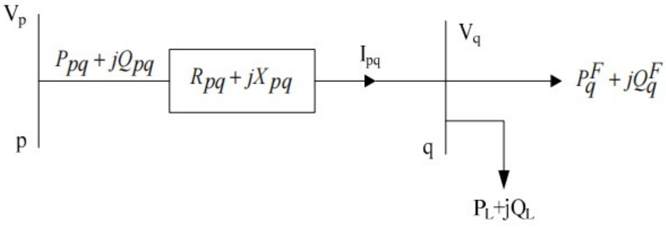

Fig. 1. Power flow in distribution feeder from bus p to q

The Figure 1 illustrates a distribution line between two buses p and q, where the resistance and reactance are denoted as Rpq and Xpq, respectively. The load on the line is PL+jQL. The active power loss between the two buses is determined using Equation (2)[2].

$$P_{loss}=R_{pq}\times\frac{\left(P_{pq}^{2}+Q_{pq}^{2}\right)}{\left|V_{p}^{2}\right|}(2)$$

3 Distributed generationg Photovoltaic (DG PV) modelling with Uncertainty Solar Irradiance

The output DG PV system is normally influenced by both the global solar radiation and the ambient temperature [19]. According to [20], the ambient temperature has minimal impact and can be disregarded. In this study, The PV output uncertainty is estimated by applying the solar irradiance probability density function (PDF). The normal distribution function, as defined in Equation (3), is the one of the suitable method for representing solar irradiance uncertainty[20].

$$\mu=\frac{\sum_{1}^{No}O_{bs}}{N_{o}},\ \sigma=\sqrt{\frac{\sum_{1}^{No}\left(O_{bs}-\mu\right)^{2}}{\left(N_{o}-1\right)}} \quad (3)$$

Where,μ is the mean value,σ is standard deviation,N_{o} is the observation in hours.

The following equation (4) is used to calculate the estimation of the uncertain output of a solar PV array, which is dependent on a random solar irradiation.

$$PV_{output}=solar_{irr}\times\frac{PV_{R.O}}{STC_{S.I}}\times no\,of\,modules \quad (4)$$

The concept of statistical linear transformation postulates that if Y is a function of a random variable X, then the statistical moments of this function are determined by the expressions indicated in Equations (5) to (7).

$$Y=a+b*X \quad (5)$$

$$Mean:\mu_{Y}=a+\left(b*\mu_{X}\right) \quad (6)$$

$$Standard\,deviation:\sigma_{Y}=\left|b\right|*\sigma_{X} \quad (7)$$

Given that solar PV arrays consist of several modules, the following formulation is employed to estimate the uncertain output of a solar PV array. This output is determined by a random solar irradiation, as shown in Equations (8) and (9).

$$\mu\, PV_{output} = \mu\, solar_{irr} \times \frac{PV_{R.O}}{STC_{S.I}} \times no\, of\ modules \qquad (8)$$

$$\sigma\, PV_{output} = \sigma\, solar_{irr} \times \frac{PV_{R.O}}{STC_{S.I}} \times no\, of\ modules \qquad (9)$$

Where:

$STC_{S.I}$: The value of solar irradiance utilized in standard testing conditions (STC) with solar irradiance magnitude that arrive on earth is 1 kW/m$^{2.}$

$PV_{R.O}$: Photovoltaic panel rated output under standard testing condition calculated using equation (9)

$$PV_{R.O} = STC_{S.I} \times area \times eff \qquad (9)$$

$solar_{irr}$: Solar irradiation data

The solar constant is approximately 1.36 kW/m^2, thereby defining the maximum solar irradiance penetrating the earth's atmosphere. However, the highest solar irradiance that reaches the earth surface is around 1 kW/m^2. Solar data is frequently displayed at monthly intervals, indicated by the average or mean value of a month or year, along with its standard deviation if available.

Solar irradiance data is retrived from the NASA Surface Meteorology and Solar Energy data bank [21] with the location used is the city of Medan, North Sumatra, Indonesia at 3.57° S (latitude), 98.6° E (longitude). Table 1 shows the monthly average values of solar irradiance in this location.

Table 1. Average solar irradiance value (kWh/m^2)

January	February	March	April	May	June	Average value (annual)
0.36	0.42	0.45	0.49	0.48	0.48	0.43
July	**August**	**September**	**October**	**November**	**December**	
0.47	0.47	0.45	0.39	0.37	0.35	

4 Monte Carlo Probabilistic Load Flow

Consider a data set *x* of size *n*, where *f(x)* denotes the power flow function and *y(x)* denotes the outputs of the power flow solution. An optimal power flow solution is obtained for every data set in the interval *x* up to *x(n)*. Following the storage of all the solution sets from the power flow runs. Definitions of the mean, variance, and standard deviation are provided in Equations (11) and (12).

For the mean:

$$Mean\left(Y\left(x\right)\right)=\frac{1}{n}\sum_{i=1}^{n}Y\left(x\left(i\right)\right) \qquad (11)$$

For the standard deviation:

$$\delta\left(Y\left(x\right)\right)=\sqrt{\frac{1}{n}\sum_{i=1}^{n}\text{¿¿¿}} \qquad (12)$$

Through the application of an iterative procedure on a large dataset, the probabilistic outcomes are estimated. Figure 2 outlines the prescribed procedures for implementing the Monte Carlo probabilistic power flow.

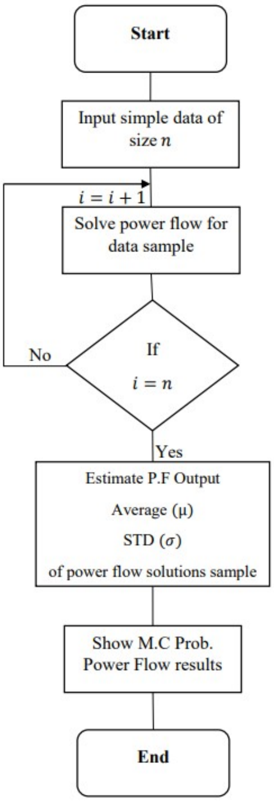

Fig. 2. Probabilistic flowchart using Monte Carlo Method

The optimization problems regarding the placement and sizing of capacitors include many potential solutions, which can make it difficult to discern the best possibilities, particularly when uncertainty is taken into account. Thus, this method is utilized to include the uncertainty parameters when formulating the load flow analysis to define the losess in the system. The optimal location and sizing problem is then addressed independently, considering the PV output uncertaity.

5 The Proposed Particle Swarm Optimization for Allocation of Capacitor and DG PV

The PSO was invented by Eberhart and Kennedy in 1995. This method is population based optimization and uses a population of individuals called particles. Each individual particle within the swarm represents a prospective solution to the problem under consideration. Every each particle searches for the optimal solution inside the search space of dimensions *d* at a stochastic velocity. Particles continuously update their velocity and position as stated in Equation (13) and (14).

$$V_{id}^{k+1}=W*V_{id}^{k}+C_1*rand_1*\left(Pbest_{id}^{k}-X_{id}^{k}\right)+C_2*rand_2*\left(Gbest_{d}^{k}-X_{id}^{k}\right) \quad (13)$$

$$X_{id}^{k+1}=X_{id}^{k}+V_{id}^{k+1} \quad (14)$$

The swarm particles' position and velocity are dynamically adjusted based on the experiences of the particles in collective and individual. Every particle adjusts its position and velocity based on its own previous flying experience as well as the collective flights of the entire swarm. When a particle, denoted as particle *i*, is randomly positioned in the search space *d* at point (x_{id}), it moves through the problem search space with a random velocity (V_{id}). Each particle retains the best position it has acquired thus far and stores it as (p_{best_id}). It then compares its best position with the positions achieved by other particles. The optimal location attained by each particle in the entire swarm is stored as g_{bestd}.

In this research, the PSO is enhanced for not only define one solution but also provides multi-solutions since the optimization problem integrate several problems involving location and size of DG PV and capacitors.

$$min\,F(x)=\left|f_1(X),\ldots,f_N(X)\right| \quad (15)$$

$$X=\left|x_1,\ldots x_n\right| \quad (16)$$

The variable sizes of the capacitors and DG PV are continous and their placement buses are positive integers.

The size of capacitors is generated randomly using the Equation below.

$$Q_{cap}=\left[0,Q_{cap}^{max}\right] \quad (17)$$

Meanwhile the PV DG optimized variables is PDG as described in Equation below.

$$P_{DG}=\left[0,P_{DG}^{max}\right] \quad (18)$$

As a result, the initial population from each particles can be generated as illustrated in Equation (19).

$$X_i = ¿ \quad (19)$$

Overall, the procedure of PSO for determining the location and size of capacitor and PV DG in loss minimization is exlained as follow.

Step 1.

Input all required system data for running probablisitic load flow such as bus data, load profile, PV DG generating units,line data.

Step 2.

Calculate the losses in network using probablistic Monte Carlo load flow analysis as described in Figure 1. Store the losses.

Step 3.

Specify the parameter settings for the PSO.

Step 4.

Generate an initial population where each particle has random position and velocitie in the search dimension *k.*

Step 5.

Set the iteration *k.*

Step 6.

Calculate the objective function

Step 7.

Compare the objective value with the individual best value *(Pbest)*for each particle, , if the objective value is lower than *Pbest* then set this value as the latest particle value for the next iteration and calculate the value of the particle's latest position.

Step 8.

Choose the best *Pbest* value among all particles and set that value as *Gbest* value.

Step 9.

Update the velocity and position values

Step 10.

If the iteration has reached the specified maximum iteration limit, return to step 7. If not, set *k+1* iterations and return to step 4.

Step 11.

Display the optimal solution obtained. The best position includes the optimal location and size of the capacitor and PV DG. Meanwhile, the objective function represents the minimum power losses.

6 Results and Discussion

To verify the suggested approach, the performance, effectiveness, and efficiency of the method in discovering solutions are observed using the IEEE 34 radial distribution system depicted in Figure 3. The algorithm is developed using Matlab.

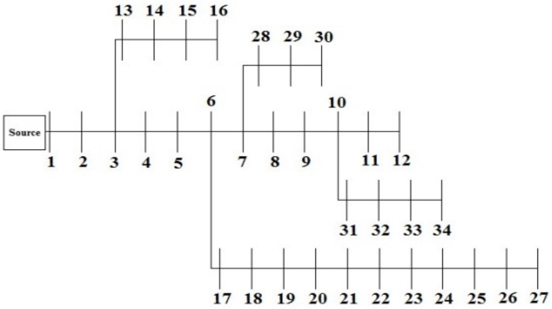

Fig. 3. The test system of IEEE 34 bus

The load profile for this system is based on the peak load condition with the total is 4.64 MW and 2.87 MVar. Meanwhile the PV DG output is derived from the equation (7) and (8) based on historical solar irradiance as shown in Table 1. Based on the uncertainty of solar irradiance in Medan, North Sumatra, Indonesia at 3.57° S *(latitude)*, 98.6° E *(longitude*), the solar periode probablisitic case data can be derived as shown in Table 2.

Table 2. Solar Irradiance Period Case Data

Solar period (MW)		**Solar period (MVar)**	
Mean	3.49	Mean	2.16
Sandard deviation	1.03	Sandard deviation	0.85

For the simulation, there are 6 (six) capacitors ranging from 0 kVar to 1 MVar which will be installed. Meanwhile, six DG PVis also considered in this case. Under the solar uncertainty that corresponds to the system location, the average output each PV DG is 270 kW.

The capacitor and DG PV allocation using the PSO algorithm yields several byproducts, including the otpimal location and size of installed these equipments in the system, the power losses resulted from before and after capacitor and DG PV installation, as presented in Table 3 and 4. Furthermore, the voltage profile of each bus in the system is illustrated in Figure 4.

Table 3. The optimal allocation and sizing for installing capacitors and DG PV in the system

Capacitor		**DG PV**	
Bus location	**Size (kVar)**	**Bus location**	**Size (kW)**
8	75	12	270
9	75	24	270
20	675	25	270
25	675	26	270
30	75	27	270
31	450	34	270

Table 4. The losses reduction before and after optimization

Condition	**Result**
Before optimization	220 kW
After optimization	103 kW
The total loss reduction	53,18%
The total of reactive power compensation	2025 kVar
The total of active power compensation	1620 kW

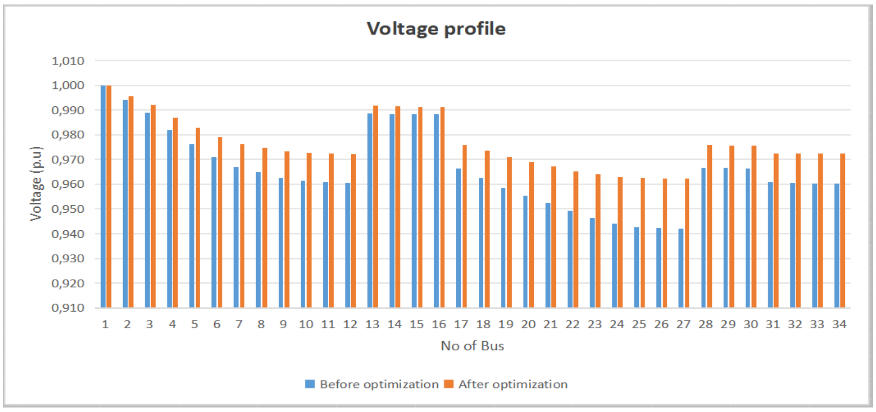

Fig. 4. The voltage profile comparison between the system condition before and after allocation of capacitor and DG PV

Figure 5 shows that the developed method can enhance the voltage in the system and maintain them in the acceptable operational voltage values.

7 Conclusion

An optimization approach for the capacitor allocation problem under the influence of DG PV integration in electrical distribution systems is presented in this paper. The objectives of this optimization is to reduce the active power losses and enhance the voltage profile. During the problem formulation, the uncertainty output condition of DG PV is considered. Due to the appearance of uncertainty parameters in the system, the load flow analysis has to be conducted using probabilistic estimation using the Monte Carlo model. The losses resulting from probabilistics are taken as an objective function for optimal allocation of capacitor and DG PV. In this research, an enhanced PSO is chosen to find the best location and optimal size of the installed capacitor and DG PV in the system. This method is implemented on a radial distribution system of the IEEE 34. The by-products of this optimization is losses minimization, voltage enhancement, the bus location for installing capacitors and DG PV, and the size/rating of the capacitor and DG PV. The experimental findings demonstrated that by strategically installing capacitors and DG PV in systems, it is possible to decrease power losses in the system by up to 53.18 %, specifically from 200 kW to 103 kW. Furthermore, this optimization scheme also identifies suitable bus candidates for the installation of capacitors, including buses 8, 9, 20, 25, 30, and 31, and DG PVin buses 12,24,25,26, 27, and 24.

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References

[1] E. Astrid, M. D. Solihin, R. Siregar, and B. D. Waluyo, “The Optimal Capacitors Allocation and Sizing in Radial Distribution System for Power Losses Reduces,” *JTEIN J. Tek. Elektro Indones.*, vol. 4, no. 2, pp. 1081–1088, 2023, doi: 10.24036/jtein.v4i2.580.

[2] H. N. Hickok, “Electrical Energy Losses in Power Systems,” *IEEE Trans. Ind. Appl.*, vol. IA-14, no. 5, pp. 373–387, 1978, doi: 10.1109/TIA.1978.4503557.

[3] R. Elazab, M. Ser-Alkhatm, M. A. Abu Adma, and K. M. Abdel-Latif, “Allocation and sizing of reactive power compensators considering PV power and load demand uncertainty using beetle-antenna grey wolf optimization,” *Clean Energy*, vol. 7, no. 2, pp. 350–362, 2023, doi: 10.1093/ce/zkac078.

[4] R. Gholami, M. Shahabi, and M. R. Haghifam, “An efficient optimal capacitor allocation in DG embedded distribution networks with islanding operation capability of micro-grid using a new genetic based algorithm,” *Int. J. Electr. Power Energy Syst.*, vol. 71, pp. 335–343, 2015, doi: 10.1016/j.ijepes.2015.03.005.

[5] E. S. Ali, S. M. Abd Elazim, and A. Y. Abdelaziz, “Improved Harmony Algorithm and Power Loss Index for optimal locations and sizing of capacitors in radial distribution systems,” *Int. J. Electr. Power Energy Syst.*, vol. 80, pp. 252–263, 2016, doi: 10.1016/j.ijepes.2015.11.085.

[6] E. A. Almabsout, R. A. El-Sehiemy, O. N. U. An, and O. Bayat, “A Hybrid Local Search-Genetic Algorithm for Simultaneous Placement of DG Units and Shunt Capacitors in Radial Distribution Systems,” *IEEE Access*, vol. 8, pp. 54465–54481, 2020, doi: 10.1109/ACCESS.2020.2981406.

[7] M. M. Aman, G. B. Jasmon, K. H. Solangi, A. H. A. Bakar, and H. Mokhlis, “Optimum Simultaneous DG and Capacitor Placement on the Basis of Minimization of Power Losses,” *Int. J. Comput. Electr. Eng.*, vol. 5, no. 5, pp. 516–522, 2013, doi: 10.7763/ijcee.2013.v5.764.

[8] D. Cetkovic and V. Komen, “Optimal Distributed Generation and Capacitor Bank Allocation and Sizing at Two Voltage Levels,” *IEEE Syst. J.*, vol. 17, no. 4, pp. 5831–5841, 2023, doi:

10.1109/JSYST.2023.3280673.

[9] A. A. A. El-Ela, R. A. El-Sehiemy, and A. S. Abbas, “Optimal Placement and Sizing of Distributed Generation and Capacitor Banks in Distribution Systems Using Water Cycle Algorithm,” *IEEE Syst. J.*, vol. 12, no. 4, pp. 3629–3636, 2018, doi: 10.1109/JSYST.2018.2796847.

[10] K. Fettah, T. Guia, A. Salhi, S. Mouassa, A. Bosisio, and R. Shirvani, “Optimal Allocation of Capacitor Banks and Distributed Generation: A Comparison of Recently Developed Metaheuristic Optimization Techniques on the Real Distribution Networks of ALG-AB-Hassi Sida, Algeria,” *Sustain.* , vol. 16, no. 11, 2024, doi: 10.3390/su16114419.

[11] N. Kanwar, N. Gupta, K. R. Niazi, and A. Swarnkar, “Improved meta-heuristic techniques for simultaneous capacitor and DG allocation in radial distribution networks,” *Int. J. Electr. Power Energy Syst.*, vol. 73, pp. 653–664, 2015, doi: 10.1016/j.ijepes.2015.05.049.

[12] N. Karmakar and B. Bhattacharyya, “Hybrid intelligence approach for multi-load level reactive power planning using VAR compensator in power transmission network,” *Prot. Control Mod. Power Syst.*, vol. 6, no. 1, pp. 1–17, 2021, doi: 10.1186/s41601-021-00202-1.

[13] R. Mena, Y. Li, E. Zio, M. Hennebel, and C. Ruiz, “Optimal sizing and allocation of distributed generation for reliable energy distribution accounting for uncertainty,” *Safety, Reliab. Risk Anal. Beyond Horiz. - Proc. Eur. Saf. Reliab. Conf. ESREL 2013*, pp. 2899–2907, 2014.

[14] A. Naderipour *et al.*, “Spotted hyena optimizer algorithm for capacitor allocation in radial distribution system with distributed generation and microgrid operation considering different load types,” *Sci. Rep.*, vol. 11, no. 1, pp. 1–15, 2021, doi: 10.1038/s41598-021-82440-9.

[15] L. D. L. Pereira *et al.*, “Optimal allocation of distributed generation and capacitor banks using probabilistic generation models with correlations,” *Appl. Energy*, vol. 307, pp. 1–40, 2022, doi: 10.1016/j.apenergy.2021.118097.

[16] T. D. Pham, T. T. Nguyen, and B. H. Dinh, “Find optimal capacity and location of distributed generation units in radial distribution networks by using enhanced coyote optimization algorithm,” *Neural Comput. Appl.*, vol. 33, no. 9, pp. 4343–4371, 2021, doi: 10.1007/s00521-020-05239-1.

[17] Y. I. Song, “ribution network reconfiguration for loss reduction using fuzzy controlled evolutionary programming,” no. 1, pp. 345–350.

[18] A. Zeinalzadeh, Y. Mohammadi, and M. H. Moradi, “Optimal multi objective placement and sizing of multiple DGs and shunt capacitor banks simultaneously considering load uncertainty via MOPSO approach,” *Int. J. Electr. Power Energy Syst.*, vol. 67, pp. 336–349, 2015, doi: 10.1016/j.ijepes.2014.12.010.

[19] H. M. K. Al-Masri, S. K. Magableh, and A. Abuelrub, “Output power computation and sizing of a photovoltaic array by advanced modeling,” *Sustain. Energy Technol. Assessments*, vol. 47, no. August, p. 101519, 2021, doi: 10.1016/j.seta.2021.101519.

[20] M. K. El-Aser, R. El-Azab, and A. A. El-Samahy, “Probabilistic Model of Utility Scale PV Plants,” *2019 21st Int. Middle East Power Syst. Conf. MEPCON 2019 - Proc.*, pp. 189–194, 2019, doi: 10.1109/MEPCON47431.2019.9008019.

[21] NASA, Surface meteorology and Solar Energy, at Site: eosweb.larc.nasa.gov/sse, retrieved: 20/07/2024.