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Impact Study of Solar Energy on Power System State Estimation Utilizing Weighted Least Square Technique

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ABSTRACT

Duo to the importance of studying the stability of electrical power networks, the most important of which is estimating the state of the electrical network SE in the control centers of power systems. This study aims to improve voltage levels and reduce electrical power losses in the network, in addition to studying the integration of photovoltaic (PV) energy systems into the network. Then using simulated annealing algorithm (SA) to determine the optimum location to integrate photovoltaic energy systems in an IEEE 14 bus electrical network using the weighted least square (WLS) technique. The photovoltaic energy was injected into the specified location based on the minimum value of power and reactive power losses. The study achieved an enhancement in electrical power , reactive losses and voltage profile, comparing that before and after integrating the photovoltaic system into the network. The electrical network state estimation (SE) technique was used to filter the readings from errors resulting from measuring devices using MATLAB/PSAT tool box program to simulate this study.

KEYWORDS: Weighted least square WLS; State estimation SE; Simulated annealing algorithm SA; Energy management system EMS; Photovoltaic PV.

دراسة تأثير الطاقة الشمسية على تقدير حالة الشبكة الكهربية با ستخدام تقنية المربعات الصغرى المرجحه

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الملخص

نظرا لأهمية دراسة إستقرار شبكات القوى الكهربية والتي من أهمها تقدير حالة الشبكة الكهربية (SE) في مراكز التحكم الخاصة بأنظمة الطاقة. تهدف هذه الدراسة إلى تحسين مستويات الجهدالكهربى وتقليل فقد الطاقة الكهربية في الشبكة، بالإضافة الى دمج أنظمة الطاقة الفوتوفولتية (PV) في الشبكة. ثم باستخدام خوارزمية ال (SA) Simulated annealing algorithm لتحديد أفضل مكان لدمج أنظمة الطاقة الفوتوفولتية وذلك على شبكة كهربية IEEE 14 bus حيث تم حقن الطاقة الفوتوفولتية فى المكان المحدد بناءا على أقل قيمة فقد فى الطاقه الكهربيه. توصلت الدراسة إلى تحسين قيم الطاقة الكهربية المفقودة وقيم الجهد الكهربى مع مقارنة ذلك قبل وبعد دمج الطاقة الفوتوفولتية للشبكة. وتم استخدام تقنية تقدير حالة الشبكه الكهربيه (SE) عن طريق استخدام

طريقة المربعات الصغرى المرجحه (WLS) لتصفية القراءات من القراءات الغير الدقيقة الناجمه عن أجهزة القياس وذلك بإستخدم برنامج MATLAB/PSAT tool box لمحاكاة تلك الدراسه.

الكلمات المفتاحية : المربع الأصغر المرجح، خوارزمية ال SA، نظام ادارة الطاقه، الطاقة الكهروضوئية .

1-INTRODUCTION

1.1.Global Energy Requirements.

The use of renewable energy systems has recently increased, especially solar energy systems, which have become an important alternative energy source for oil, gas, and coal. The electricity from solar power can be produced and used in the same place, saving many transportation costs. Additionally, it is clean, environmentally friendly, and inexhaustible energy and is used in many practical applications, including increasing voltage profile enhancement and decreasing electrical power losses within the electrical network. Moreover, energy source consideration, strategy formulation, global energy requirement assessment, and solar energy prioritization due to economic incentives were all influenced by economic motivations. The cleanliness of the system is unaccompanied by substantial maintenance and operational expenses [1].

The first real global energy crisis, brought on by Russia's incursion into Ukraine, has given renewables unparalleled impetus. Disruptions in fossil fuel supply have highlighted the energy security benefits of domestically generated renewable electricity, prompting many countries to enhance renewables legislation. Meanwhile, increased global fossil fuel costs have boosted the competitiveness of solar PV and wind generation against other fuels. The renewable capacity expansion over the following five years will happen far faster than predicted even a year ago. Renewables are predicted to rise by nearly 2400 gigawatts (GW) between 2022 and 2027, equaling the total installed electricity capacity of China today. This represents an 85% increase over the preceding five years and a nearly 30% increase over the forecast in the report of last year, making it our highest-ever upward adjustment. Over the projected period, renewables are expected to account for more than 90% of worldwide energy capacity increase. China and the European Union are mostly responsible for the upward revision. In response to the energy crisis, the United States and India are adopting current policies and regulatory and market changes besides introducing new ones more swiftly than projected. The key drivers of the updated projections include the 14th five-year initiative and market changes in China, the REPower EU initiative, and the US Inflation Reduction Act [2].

The anticipated global renewable power capacity increase will rise by a third in the current year, which can be attributed to the increasing momentum of policies promoting renewable energy, increasing fossil fuel costs, and mounting worries over energy security. Consequently, solar PV and wind power technologies have been widely deployed. Solar PV amplitude, encompassing large-scale program installations and small distributed programs, constitutes around two-thirds of the anticipated growth in renewable global capacity for the current year. The IEA anticipated continuing development in the upcoming year, resulting in a global renewable electricity capacity of 4500 GW. This capacity is equivalent to the combined electrical output of China and the US. Figs. 1–2 show the net additions in renewable electricity capacity across several technologies from 2017 to 2024 and the proportion of renewable energy production of global electricity by 2025, respectively [3].

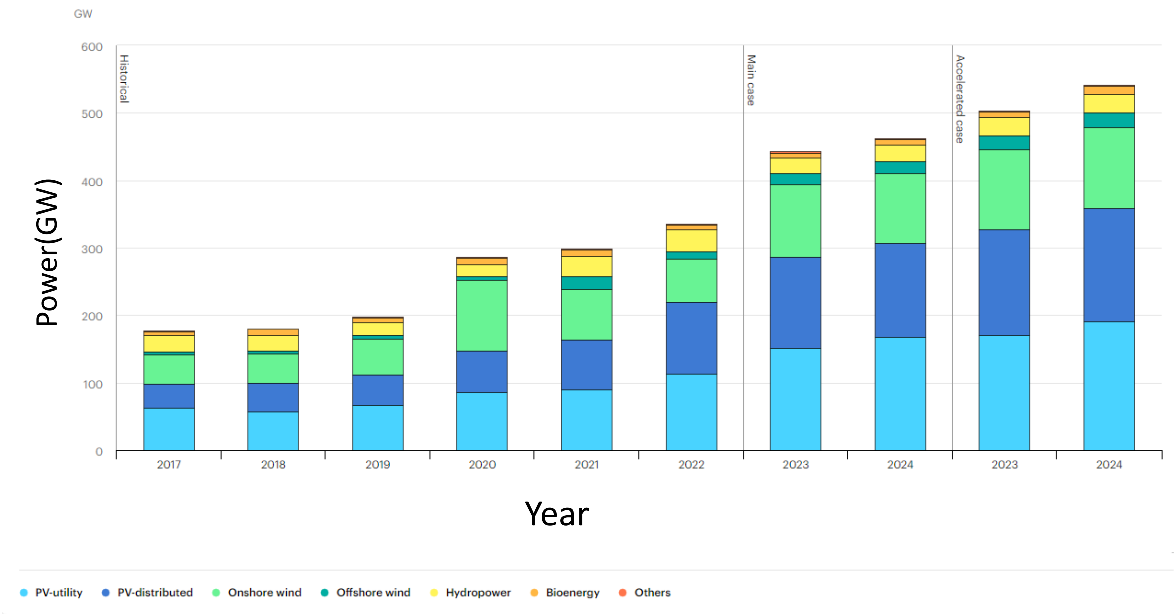

Fig. 1. The net additions of renewable electricity capacity by technology from 2017 to 2024 [3].

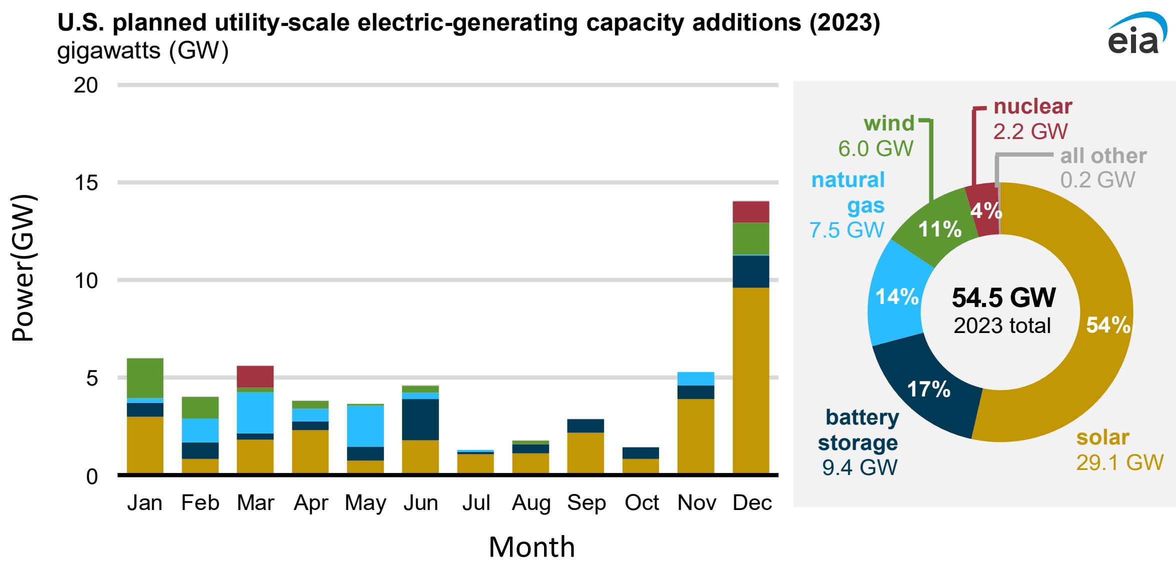

Fig. 2. The percentage of renewable energy production of global electricity by 2025 [4].

There has been a growing interest in transitioning from nonrenewable to renewable energy sources (RESs), particularly in light of recent energy strategies and updates to electric utilities energy policy. These developments aim to prioritize urban energy strategies and increase the proportion of RESs, consequently decreasing CO2 emissions and holding fossil fuel removal [5].

1.2.State Estimation Technique.

The state estimation (SE) approach is employed to investigate the operating conditions of a power system. As a result, the SE technique is critical in real-time power system monitoring, control, and dynamic tracking. Generally, estimate methods are divided into static and dynamic approaches. Since the static method assumes the power system is running properly, it collapses to study its dynamics, encountering stochastic variations such as load fluctuations. Accordingly, dynamic state estimation (DSE) is necessary for understanding the real-time stochastic behavior of power systems. Unlike the static technique, which focuses on existing measurement, dynamic techniques consider prior predicted states in addition to data obtained from a measuring unit, such as the phasor measurement unit (PMU). Using Kalman filters, the forecasting aided state estimation (FASE), a dynamic technique, has evolved [6].

The detrimental consequences are attributed to the unfavorable impact of overloading. The resulting reduction in equipment lifetime necessitates preserving network electrical equipment to prevent its eventual loss. The occurrence of frequent journeys prompted through beneficial relays as a consequence of overload, under frequency, and voltage protection [7].

The static SE algorithm transforms measurements affected by noise and uncertainty into a dependable system state evaluation. The SEs rely on establishing mathematical relations between the measurements obtained and the variables representing the system state [8].

1.3.Enhacement of Voltage Profile in Power Systems.

One of the primary needs in power systems involves voltage augmentation and regulation, ensuring its adherence to the intended magnitude. Enhancement of voltage profile of the Delta Egypt network was illustrated to guarantee voltage stability. To achieve this objective, utilizing optimal reactive power compensators, specifically capacitor banks was shown. The capacitor bank distribution was conducted utilizing the genetic algorithm (GA) method. The outcomes were obtained by the system voltage profile comparison in four conditions. The initial scenario involved the absence of each reactive power compensation or voltage enhancement device. A transformer automatic tap changer (ATC) was involved in the second scenario. In contrast, the third scenario entailed implementing ATC alongside a reactive power compensation device (capacitor bank) installation employing a trial approach informed by the expertise of operators. The fourth scenario involved using GA to identify the optimum placement and reactive power compensator device sizing. The optimal outcomes were attained by deploying the final scenario based on GA optimization techniques. The contrast was conducted based on enhancing power losses, voltage profile, and active power reserve, facilitating the system operation with elevated dependability, stability, and effectiveness [9].

1.4.State Estimation Methods.

Within the context of the power system, various methodologies were employed across SE including, normal equation technique, orthogonal transformation, hybrid method, weighted least square SE (WLS), normal equation method with constraints, Hachtel's augmented matrix method, observability analysis, bad data detection, and variables. The mathematical analysis of distribution system state estimation (DSSE) has been presented. The WLS method was more efficient than other methods regarding various factors such as robustness, accuracy, and computation time [10].

An overview of SE methods was studies, including the WLS method for the IEEE 14-bus employing the MATLAP/PSAT toolbox to conduct the power flow analysis. The suggested technique was tested on the IEEE 14-bus network with varying solar energy penetrations [11].

A simulated annealing (SA) technique is employed to optimize parameters, specifically the optimal placement of PV systems within the network, to minimize active and reactive energy losses. The SE method has primary challenges such as modeling complications (nonlinear, nonconvex power-flow equations, and restricted accessibility of sensor estimations) and PV production, which can lead to over-voltage issues and perhaps cover the load from the protective apparatus. Moreover, cloud cover variations can cause excessive functioning of load tap changers and result in voltage flicker. The issues above can be effectively mitigated by implementing advanced control techniques, which can yield significant advantages when distribution system operators possess enhanced observability of the power system status [12].

1.5.Power Factor correction in Power Systems.

Several potential measures was proposed to enhance voltage stability within the Cairo, Delta, and Canal regions. Initially, enhancing the 500 kV transmission network is important. Innovative overhead transmission lines have been applied in these three regions to mitigate the discontinuation of conventional power plants. Furthermore, there was an increase in the quantity of connector transformers operating at the voltage levels of 500/220 kV. Implementing this upgrade has significantly enhanced voltage stability and reduced network loss by 443 MW (–6%). However, several Cairo, Delta, and Canal regions experienced inadequate voltage stability. The load power factor was corrected/ in specific areas, specifically from 0.85 to 0.92. This improvement was achieved by introducing a shunt capacitor bank to the weak-bus voltage, which are buses experiencing voltage drops between two adjacent buses. This intervention reduced losses by 11.6%. Another approach involved updating and repurposing conventional power plants that were previously inactive, such as those in Shopra, that yielded favorable outcomes obtained through GA optimization procedures. The contrast was conducted based on enhancing voltage profile, power losses, and active power reserve, which facilitate the system operation with heightened dependability, stability, and effectiveness [13].

1.6.Fequency Deviation in Power Systems.

The Egyptian Electricity Holding Company (EEHC) strategy was to replace the thermal station with RESs to improve the RES ratio to 20% by 2022; the total replacement capacity was 4271 MW. The method was tested in three circumstances: these scenarios raise RES by 10%, 15%, and 20% in 2019, 2020, and 2022. A comparison was made between the frequency of the Egyptian network basic case in 2015 and frequency deviations below 0.009 pu, specifically focusing on the load levels of generators, transmission lines, and transformers. Therefore, the network was improved to minimize loading and enhance frequency deviation. After network upgrading, the frequency deviation for the first and second situations dropped to 0.003 and 0.006 pu, respectively, but the third scenario remains unchanged. Accordingly, the principal control reduced speed droop gain from 1 to 0.9 to improve frequency deviation. The frequency deviation of the third scenario decreased from 0.009 to 0.002. The RES can be enhanced to 20% by improving the Egyptian network to keep frequency variation and loading safe [14].

Ultramodern control centers frequently estimate the power system state.The system status was described as a phasor, encompassing the voltage magnitudes and angles at different buses. The SE is the fundamental energy management systems (EMS) component that monitors and controls power systems [15].

However, power system management and strategies have garnered considerable attention due to the widening disparity between power generation and demand. The variation between production and demand might potentially give rise to several challenges, including outages, inadequate power quality, and even blackouts. Nevertheless, addressing the gap through centralized power plants necessitates augmentating transmission system capacity and implementing several system-wide reinforcements. From an economic perspective, this would incur significant costs and lack efficiency. Implementing decentralized power generation units near the load center, sometimes called distributed generation (DG), can enhance efficiency and cost-effectiveness in meeting the growing power demand. In addition, this technology offers numerous technological advantages, including reducing power losses, enhancing voltage stability, and improving power quality [16].

1.7.Optimal Location of PV in Power Systems.

A GA is employed to select the most appropriate DG technology for the best functioning of the power system. Additionally, it is used to establish the optimum DG position and size to reduce energy loss throughout the power system [17]. The absence of proper location and sizing in integrating a PV system into a grid might adversely affect system variables, leading to voltage instability within the grid. Consequently, several optimization techniques, including the self-correction algorithm and the multi-objective artificial bee colony, have been studied [18].

The PV systems with electrical distribution networks can cause several challenges, including power fluctuations and voltage flickers. Extensive research and advancements in this field have played a significant role in identifying and devising effective solutions for these issues [19]. The interline power flow controller (IPFC) discussed the modeling and design of a conventional system of IEEE 14-bus. The IPFC is a recommended solution for functional load sharing between transmission lines; it transfers demand power from the higher-loaded line to the less-loaded transmission line. The suggested IPFC was connected to two, three, and four buses of the conventional system of the IEEE 14-bus. Two inverter-based five-level IPFCs was shown related to the Chief IEEE system. The investigation of an IPFC with two parallel lines system proved the active/reactive power flexibility regulation to aid the FACTS device transmission system. The system behavior under transient and load fluctuations at the receiving end of the transmission system was displayed and studied. An IEEE 14-bus system was shown with and without IPFC. At each level, the voltage angel, voltage, reactive, and real powers of 14 buses were compared and tabulated. The IPFC series compensation, the power system handling voltage profile, and capability were improved across all busses [20].

The appropriate DG sizing and location was investigated using the particle swarm optimization (PSO) method to improve voltage profile and reduce power loss in distribution networks. The analysis of IEEE 69/33-bus radial distribution systems was considered. Each system was evaluated for two separate scenarios, and the obtained comparative findings indicated the usefulness of the suggested technique concerning size, location, and power loss mitigation. A PSO-based multi-DG placement technique was described for voltage profile enhancement and loss reduction. Suitable DG location and size in the system will significantly minimize power loss. Type-2 DGs injecting reactive and real power will minimize power loss more than Type-1 DGs with identical DG locations. The suggested approach was useful for increasing voltage, reducing loss, and raising the tail-end node voltage [21].

1.8.The Advantages of Real-Time Energy Estimation

The insufficiency of infrastructure, particularly in terms of poor electric energy monitoring, poses a significant challenge for numerous developing nations. The ability to measure in real-time and establish connectivity to a central data gathering station. Accordingly, further exploration and implementation of contemporary approaches are crucial for sensing and distributing electrical energy. Acost-effective real-time load monitoring and control system utilizing Long Range (LoRa) technology was disscused. Electrical variables involving voltage, current, power factor, and harmonics can be measured by implementing a data acquisition system based on a microcontroller. Additionally, the system can collect and present the acquired data and offer remote power cut and restore functionality by accessing an Internet-of-Things Supervisory Control and Data Acquisition (SCADA) server. The advantages of real-time energy estimation and its potential in addressing the energy crisis in Asia was illustraited. The system uses power derived from the power line, supplemented by a battery backup system, to mitigate the risk of data loss during a power outage or failure. The system was evaluated using software simulations before its hardware implementation. The obtained results was described from both evaluations. The system demonstrated energy efficiency due to utilizing LoRa wireless technology and low-power components, resulting in a power draw of only 680 mA. Furthermore, it exhibited high accuracy in real-time analysis of load power consumption characteristics. This accuracy was verified through comparison with standard laboratory equipment, revealing an error rate of approximately 0.9%, 2.91%, and 1.6% for voltage, current, and frequency measurements, respectively [22].

1.9.The Advantages and disadvantages of Incorporating Solar PV Systems into a Power Grid

Incorporating solar PV systems into a power grid has several benefits, including an increased proportion of renewable energy sources. However, it is important to acknowledge the potential drawbacks of this integration, such as system stability concerns, dependability challenges, and frequency disturbances [23]. Power system operators and researchers work together to tackle distribution system issues such as energy and power losses, as well as voltage stability and profile via optimum DG allocation. Additionally, optimal DG allocation protects the distribution system from undesired occurrences and enables the system to operate in islanding mode. Detailed research was conducted to determine the best DG placement while minimizing losses in power and energy, improving voltage stability and profile. A synopsis of current approaches has been attempted, which offers a thorough debate that might help energy planners choose which targets and planning aspects require greater consideration to optimize the region of DG allocation. The current optimum allocation trend of DG (OADG) with numerous goals was discussed, such as voltage stability improvement, power loss reduction, voltage profile enhancement, and their multiple-objective method. Researchers postulated specific planning restrictions (e.g., bus voltage limitations, highest possible DG capacity, current limits, and limits of DG reactive power loss, among others) and arranging components (e.g., DG size, placement, type and quantity, and load level), each with its distinguishing characteristics. Nonetheless, one area of research that academics have yet to address is the systematic approach to addressing distribution system planning issues [24].

1.9.Energy Management in Power Systems.

One of the definitions of energy management pertains to the systematic observation, regulation, and preservation of energy inside a structure, institution, or network [25]. The present investigation examined the effects of higher PV integration within distribution systems, revealing the impact of scattered PV systems on the overall voltage profile. An increase in the level of PV integration results in a corresponding increase in voltage fluctuations within the system. The fluctuation in voltage levels can pose a significant challenge for distribution networks, as it can decrease the operational lifespan of equipment or even damage the linked devices. To ensure the proper functioning of the electrical apparatus, it is important to maintain the system voltage at acceptable thresholds. By selecting the dispersion level appropriately, the voltage profile of the distribution system can be improved. [26]. Optimum dispatch of optimal power flow is a subset of optimal reactive power dispatch (ORPD), traditionally considered an objective function that is minimized, representing the overall losses in active power in electrical networks. The limitations included tap-regulating transformer ratios, generator voltages, and reactive shunt compensators.

The optimized control variable vectors was discovered to reduce power loss. An updated metaheuristic approach energized by humpback whale bubble-net pursuit (WOA), tackled the ORPD issue. The WOA approach has been tested and validated on the IEEE 30/14-buses and Algeria's extensive 114-bus electric test systems. The results were compared to two previously developed approaches, PSO and particle swarm optimization with time-changing acceleration coefficients (PSO-TVAC). Following that, the one-way ANOVA test was performed to validate the efficacy of our suggested method in addressing the ORPD issue. The comparative research illustrated the possibilities of this novel optimization strategy and demonstrated its resilience and efficacy while resolving the ORPD issue [27].

The DSSE has only been deployed by a few utility providers, and to overcome the barriers to the widespread use of DSSE, new approaches and a dependable source of data are necessary [28]. Accordingly, a massive power system monitoring system with few measurements was offered. The stability margin was defined as the load ability limit. Assuming the power system has many areas, the overall security was evaluated by measuring among the regions, stating that the interior area. The loading margin was estimated using adaptively trained artificial neural networks (ANNs). The network reduction procedure merges information about external measures into internal measurements. The precision of the estimation ANNs is increased with this extra embedded knowledge of the operating state of the exterior domains. The utilization of a restricted quantity of measurements obtained from the inside while voltage stability measuring of the overall power system maintains a lower computational cost. A Z-score-driven technique was used to identify and handle any faulty data in the ANN collection of training data. The suggested approaches have been examined satisfactorily on IEEE 118/14-bus test systems [29]. When a fault occurs, the system requires additional reactive power to fix the fault and bring the system back to a stable condition. Therefore, FACTS have been reviewed in the power system. The FACTS family has various benefits, such as increased system stability, transmission system loading capabilities, and power quality [30]. A power engineer worries about voltage breakdowns causing power system instability; voltage fluctuations are a major customer issue. Stability analysis is crucial for network voltage enhancement; load demand daily affects the network voltage profile. To solve this challenge, load flow analysis is essential. Advanced technologies like FACTS are useful in improving system voltage profiles [31].

From all previous data , This study aims to improve voltage levels and reduce electrical power losses in the network, in addition to studying the integration of photovoltaic (PV) energy systems into the network.

2-THE WEIGHTED LEAST SQUARE (WLS) APPROACH

This section overviews the standard WLS SE equation, introducing fundamental concepts and notations. The nonlinear equations establish the relationship between the estimations and the state vector [15], as presented in Eq. (1),

$$z = h\ (xt) + w \tag{1}$$

Z refers to measured values in voltage, real/ reactive power injection, and real/reactive power flow measurements that were inserted from the load flow result of the IEEE 14-bus system using the Newton-Raphson method.

where z is the (m x 1) measurement vector from the power flow report extracted by the MATLAB/PSAT toolbox, and h (x) is the (m x 1) vector of nonlinear functions

```
%Measurement Function, h

h1 = V (fbus(nvi),1);

h2 = zeros (npi,1);

h3 = zeros (nqi,1);

h4 = zeros (npf,1);
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h5 = zeros (nqf,1);

where,
    nvi = length (vi);   %Number of voltage measurements.
    npi = length (pi); %Number of real power injection measurements.
    nqi = length (qi)  ; %Number of reactive power injection measurements
    npf = length (pf);  %Number of real power flow measurements.
    nqf = length (qf);  %Number of reactive power flow measurements.
    h = [h1; h2; h3; h4; h5]; % h matrix
  % Residue.
```

$$r = z - h \tag{2}$$

x is the (n x 1) true state vector of voltage and phase angle at buses, w is (m x 1) measurement error vector, and the number of measurements denoted as the "m" and number of state variables of voltage and phase angle is denoted as the "n." The estimation of the unknown state vector xt (v&Θ) is denoted by $\hat{x}$ and is determined by minimizing the least square's function, as in Eq. (3):

$$J(x) = [z - h(x)]T\ W\ [z - h(x)] \tag{3}$$

```
Ri = diag (z data (:,6)); % Measurement Error.
%Objective Function.
J = sum (inv (Ri)*r.^2);
```
(4)

where W is a diagonal matrix whose elements are the inverses of the measurement variances, as in Eq. (5):

$$W = [Cov(w)] -1 \tag{5}$$

The condition for optimality is that the gradient of J vanishes at the optimal solution $\hat{x}$, as in Eq. (5):

$$H^T(\hat{x})W[z - h(x)] \tag{6}$$

where, the Jacobian matrix H(x) is,

$$H(x) = \partial H/\partial x.\ (x) \tag{7}$$

The estimate x ̂ is acquired through the resolution of the nonlinear system ∂j/∂x = 0 by the iteration process where x refers to measurements:

$$G(x^k)\Delta x^k = HT\ (x^k)W(z - h(x^k)) \quad (8)$$

% Gain Matrix, Gm.

Gm = H'*inv (Ri)*H; (9)

$$x^{k+1}=x^k + \Delta x^k \quad (10)$$

For k = 0, 1, 2.... until suitable convergence is achieved.

Here, the gain matrix G is,

$$G = H^T\ (x^k)WH\ (x^k) \quad (11)$$

H matrix is the derivative of the measurements with both state variables (voltage and phase angle at some buses)

CvE = diag(inv(H'*inv(Ri)*H)); % Covariance matrix. (12)

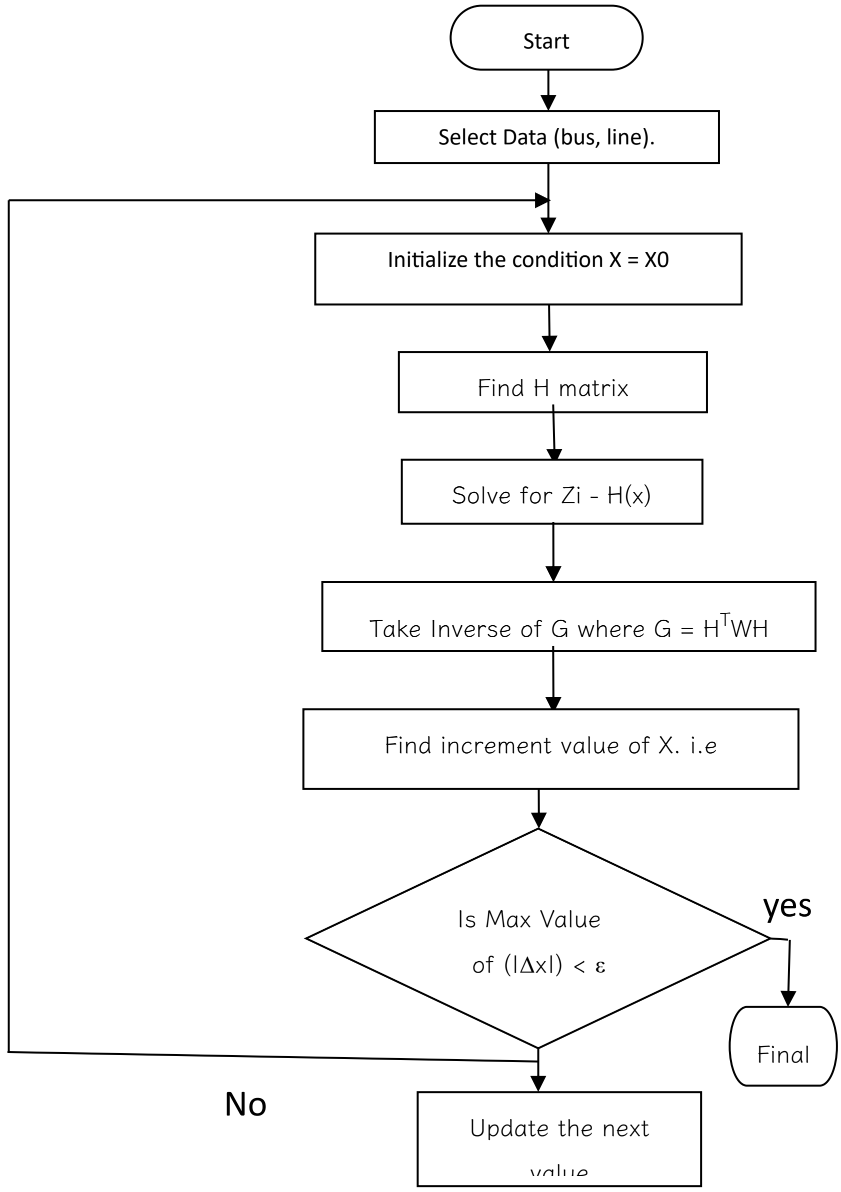

Fig. 3. Flow chart of WLS method.

3-SYSTEM MODELING

Herein, we employed MATLAB simulation software to model the IEEE 14-Bus distribution system; it is a medium voltage balanced three-phase system with three levels of voltage 69, 13.8 and 18kV, as well as 60 HZ frequency. It consists of one slack bus at bus1, 100 MVA base, another power source at bus 2 with a total production of 272.58 MW and 108.89 MVAR active and reactive power respectively, and a total load with 259MW and 81.4 MVAR active and reactive power respectively. The load was modeled as a constant PQ load and independent of voltage magnitude. The study was performed in steady-state conditions after adding the PV to the system; the transient condition was not a concern in this study. The PV generators utilized in this research represent the unity power factor, representing PV generation. These generators were modeled as static generators that inject active power. **Table 1** shows the loads at buses as PQ buses and generation at PV buses.

Table 1. The loads at buses as PQ buses and generation at PV buses.

Bus no.	**P gen pu**	**Q gen pu**	**P load pu**	**Q load pu**
1	2.3258	0.14978	0	0
2	0.4	0.48824	0.217	0.127
3	0	0.27373	0.942	0.19
4	0	0	0.478	0.04
5	0	0	0.076	0.016
6	0	0.2251	0.112	0.075
7	0	0	0	0
8	0	0.25163	0	0
9	0	0	0.295	0.166
10	0	0	0.09	0.058
11	0	0	0.035	0.018
12	0	0	0.061	0.016
13	0	0	0.135	0.058
14	0	0	0.149	0.05

4-METHODOLOGY

The effect of injecting PV power on the allocation network losses and bus voltages has been examined at various levels of PV penetration using the MATLAB/PSAT toolbox. The study encompasses three primary and baseline scenarios, as outlined below.

1-First scenario: connecting PV with 10% of peak load.
2-Second scenario: connecting PV with 20% of peak load.
3-Third scenario: connecting PV with 30% of peak load.
4-Base case scenario: no PV connected.

A power flow analysis must be conducted for each scenario to assess the voltage profile and quantify the total active and reactive power losses. This analysis utilized the load flow study feature within the PSAT toolbox after considering the selection of the most suitable locations and sizes of the PV system to be interconnected in each scenario. To fulfill the primary objective, our study evaluated and contrasted various case situations at varied penetration levels. However, combining and thoroughly analyzing certain variables is necessary to obtain an in-depth knowledge of the job technique. The present study aims to investigate many factors that influence the performance of PV solar systems, including penetration level and ideal positioning, through the SA technique as a computational tool. The concept of penetration level refers to the proportion of solar power generation to the overall load demand [11].

$$\% \text{ solar penetration} = (P \text{ solar} / P \text{ Load}) * 100 \quad (13)$$

where: % solar penetration is the penetration level. The situations above were examined at four distinct penetration levels, ranging from 0% to 30%, with a step of 10%. **Fig. 4** shows the single-line diagram of the IEEE 14-bus distribution system.

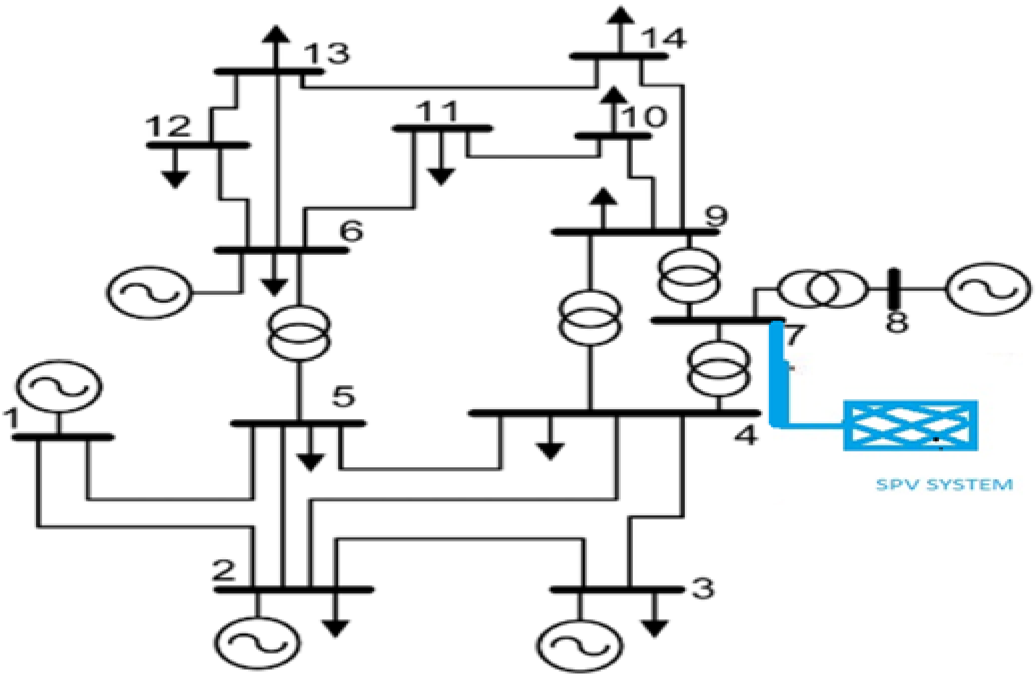

Fig. 4. Single line diagram of the IEEE 14-bus system with the solar system.

5-SIMULATION RESULTS AND DISCUSSION

Our study revealed that integrating the solar system into the electrical grids can reduce transmission and distribution system electrical power losses consistent with [1] results. Moreover, we refer to the need for renewable energy worldwide, as mentioned [2, 3] and mentioned in [5]. The traditional SE method was not optimally suited for power systems with FACTS devices; accordingly, a novel approach to SE with interphase power controllers was used. The simulation results of the IEEE 14-bus system illustrated the performance and accuracy of the novel approach compared to the results in [6] to reduce CO_2 emissions. In [6], the authors used DSE by Kalman filter to monitor IEEE 14/33/57 bus systems, and a novel minimum error entropy unscented Kalman filter was developed to estimate the power system and achieve minimum errors. However, we utilized a static SE to monitor the system voltage and phase angles to improve the performance of the power system, such as voltage profile enhancement, reducing the electrical power losses, and increasing voltage stability, which aligns with [8]. **Table 2** illustrates the comparison between this work and that mentioned in the literature review.

Table 2. The comparison between this work and that mentioned in the literature review

Year [Ref.]	Planning objectives and results	Methods
This Work	Minimize total power losses and enhance the voltage profile and SE in the power system	SE&SA
2019 [9]	Improving voltage profile to ensure voltage stability and reducing total power losses	GA
2023 [10]	Review and comparison of DSSE methods	SE
2020 [11]	Study the effect of PVDGs on power losses, optimal location of PVDG, maximum improvement of voltage profile	LSF&VSI
2019 [12]	Study the SE in power systems in the presence of high solar penetration	WLS
2018 [13]	Study of increasing RES on voltage stability and power losses	Power flow analysis
2019 [14]	Improve the frequency deviation during increasing RES in the power system	Primary Control
2015 [15]	Study the SE in power system	WLS
2016 [16]	Voltage stability improvement and power loss reduction	Z-test
2015 [17]	Minimizing power loss	GA
2021 [18]	Study the voltage stability with high PV penetration	Novel method
2016 [20]	Enhancement of voltage profile	IPFC
2016 [21]	Power loss reduction	PSO algorithm
2016 [24]	Minimize total power losses and improve voltage stability and voltage profile	OADG
2016 [26]	Improve the voltage profile, reducing electrical power losses	Forward/Back word sweep
2017 [31]	Voltage stability monitoring	ANNs
2019 [29]	Power quality improvement	STATCOM device
2018 [30]	Voltage profile enhancement	UPFC/TCSC/SSSC

According to the preceding section, the primary objective of the current investigation was to reduce the overall active and reactive power losses while enhancing the voltage profile across all buses between 0.95 and 1.05pu through the WLS SE technique to acquire error-free readings of phase angle and voltage at all busses as well as through SA algorithm to optimize the best location of PV system, trial, and error approach to give fewer power losses and keep the voltage profile between the acceptable ranges of the nominal voltage. This was performed in every scenario of connecting PV with (10%, 20%, and 30%) of the peak load to find the optimum location of the PV power station at bus 7, achieving the minimum power losses and the optimum voltage profile. **Fig. 5** shows the total active power generated in MW at buses 1/2/7. Bus 1 was the slack bus that balanced active and reactive power in the network, bus 2 was the PV bus, and bus 7 was the optimal bus chosen by a SA algorithm with minimum power and reactive power losses to inject the solar power into the distribution network. Fig. 6 show the Reactive power generated in the four scenarios (MVAR).

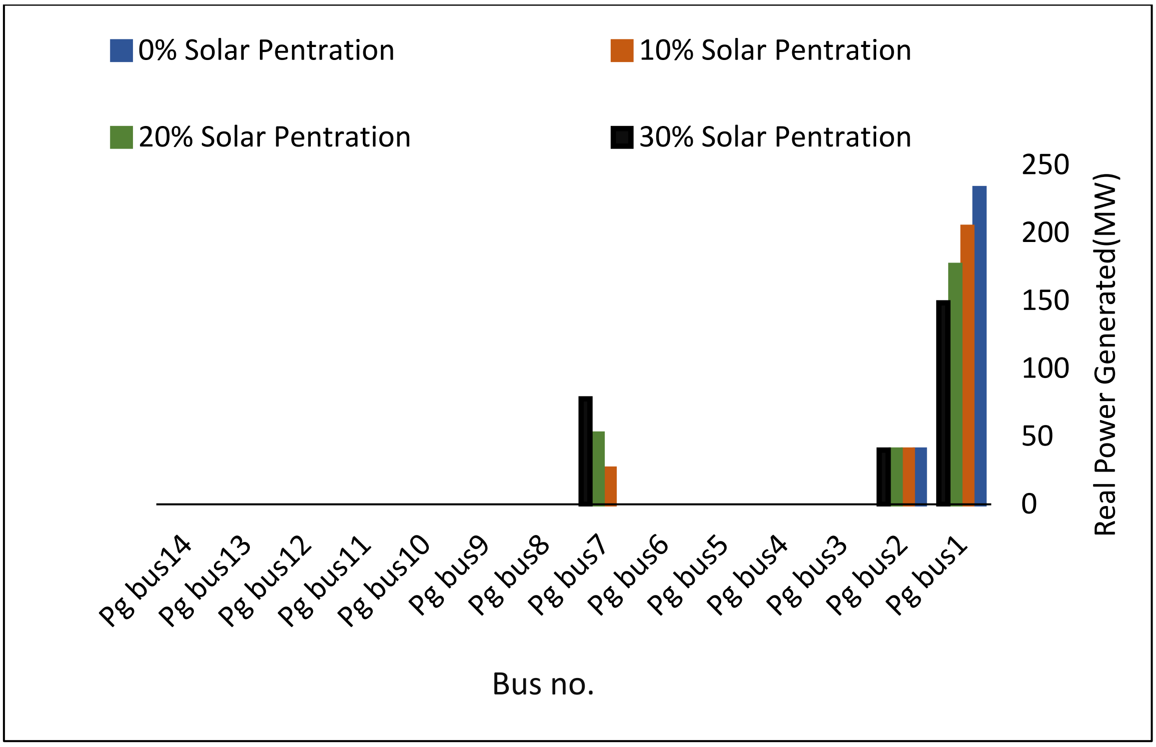

Fig. 5. Active power generated in the four scenarios (MW).

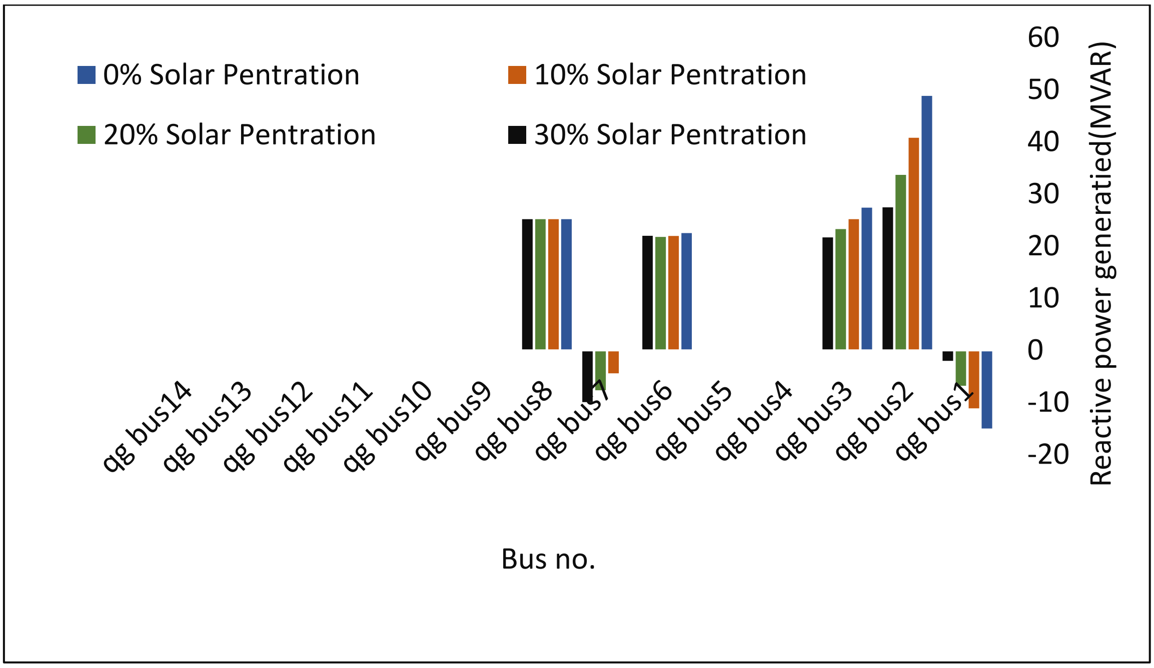

Fig. 6. Reactive power generated in the four scenarios (MVAR).

Fig. 7 indicates that a reduction in total active power losses occurred by 20%, 35%, and 48% between 10%, 20%, and 30% of the peak load as solar penetration scenarios, respectively, compared to base case active power losses.

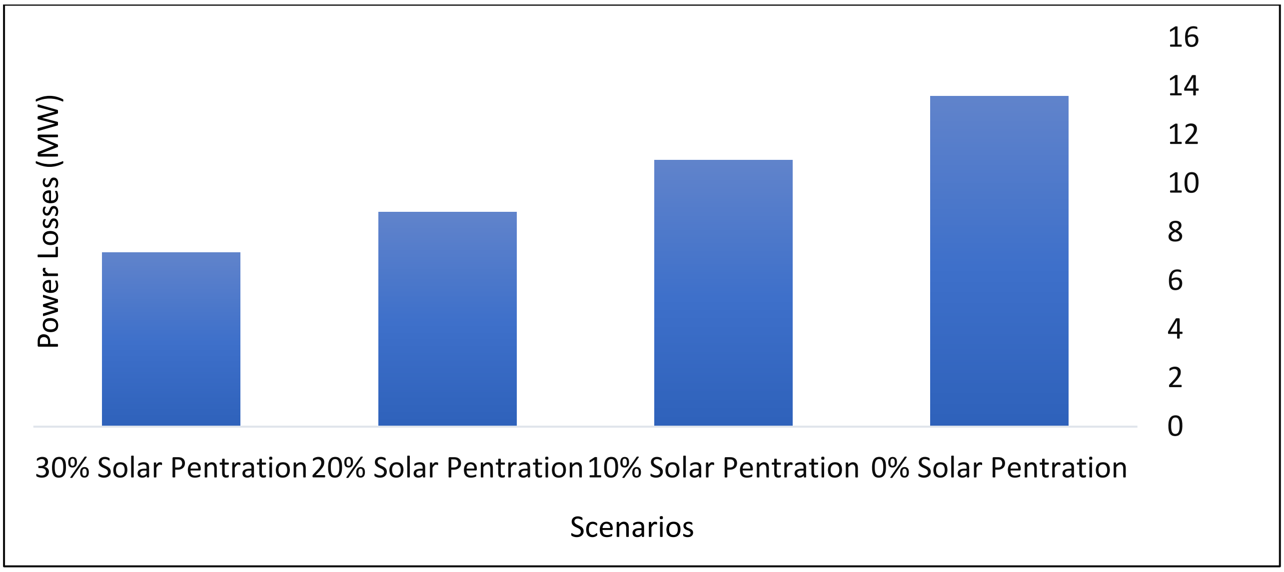

Fig. 7. Power losses in the four scenarios (MW).

As expected from the comparison between voltage profiles at all buses, the voltage has improved after connecting the PV system. However, the voltage profile slightly increased at bus 4 by 0.9867, 0.9901, and 0.9911 pu at the base cases, 10%, and 20% penetration cases, respectively. Then, it slightly decreased to 0.9909 pu at 30% penetration case. At bus 5, the voltage was slightly elevated by 0.9905, 0.9935, and 0.9938 pu at base case, 10%, and 20% penetration cases, respectively. However, the voltage slightly decreased at the remaining busses but was still within the range of 0.95–1.05 pu (**Fig. 9**). Reactive power losses dropped by 20%, 35%, and 48% at 10%, 20%, and 30% scenarios, respectively, compared to the base case active power losses. The reactive power losses dropped by 41%, 71%, and 90% at the 10%, 20%, and 30% scenarios, respectively, compared with the base case **(Fig.8.)**. In Fig.7 and Fig.8 the values of Active and reactive power losses are obtained by using PSAT toolbox under MATLAB program, then power flow report has been exported, in addition by using SA (simulated annealing algorithm results) for verification, both results are the same.

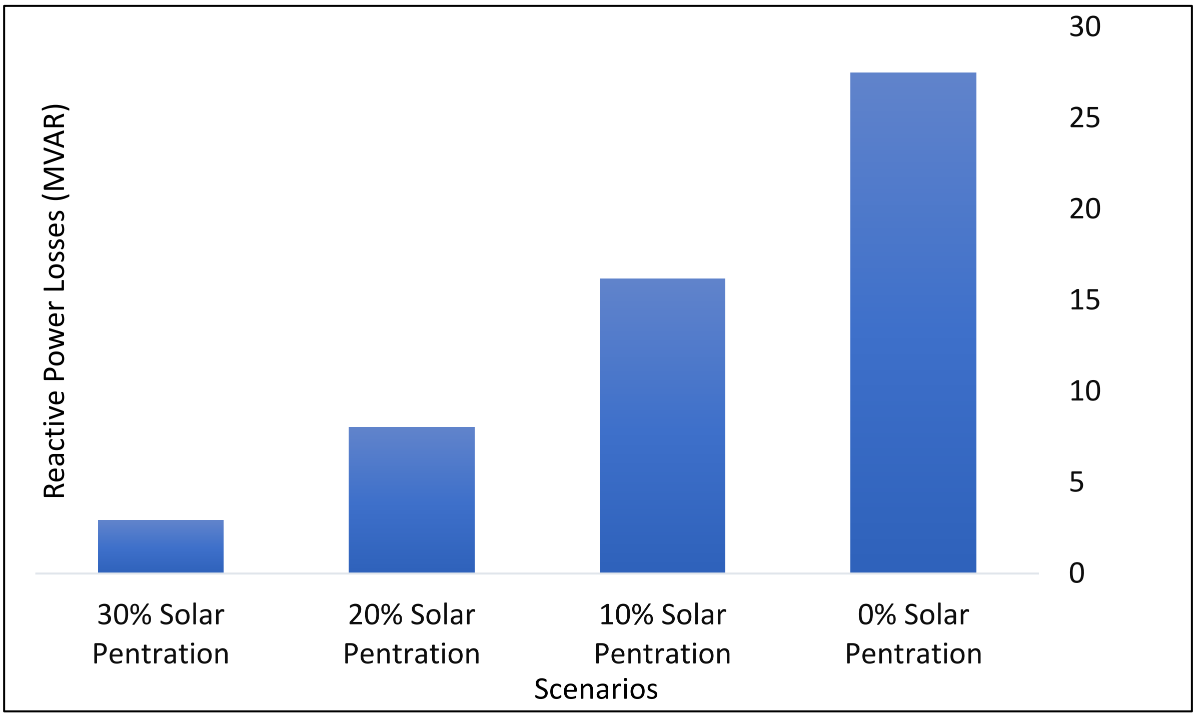

Fig. 8. Reactive power losses in the four scenarios (MVAR).

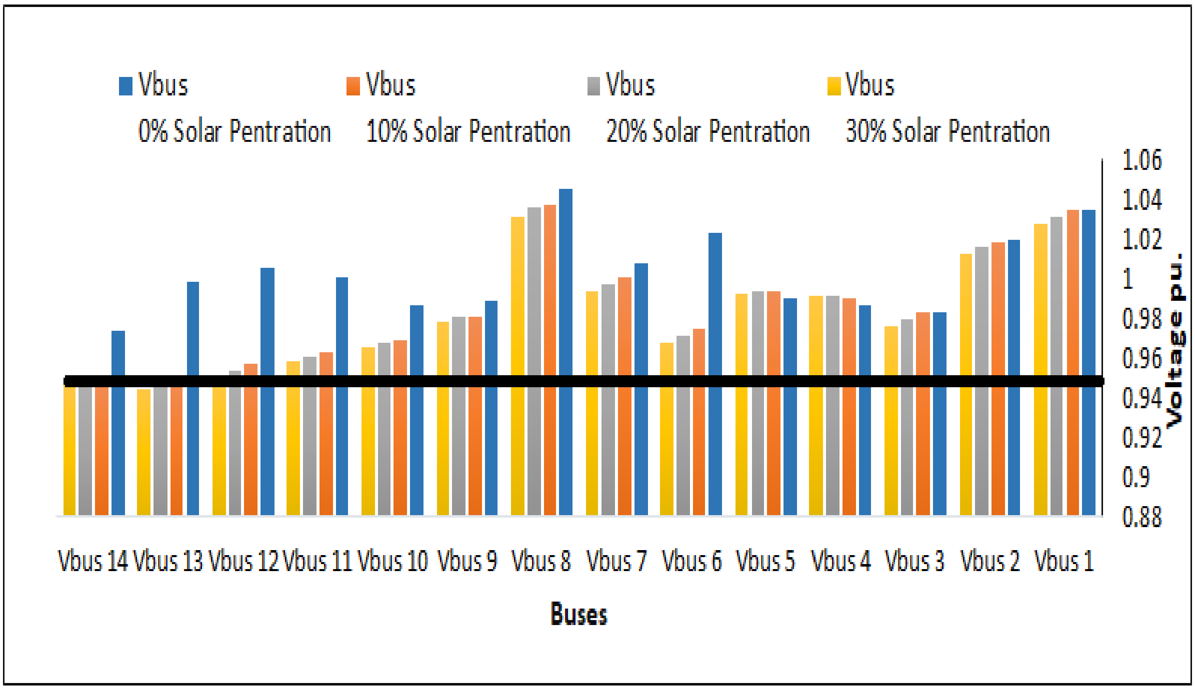

Fig. 9. Voltage at all buses in the four scenarios.

Herein, we have discussed our results, conducted the simulation in MATLAB, and represented the simulated WLS test data for 14 bus power systems. **Figs. 10–13** demonstrate the results obtained from the Newton-Raphson load flow and WLS method, which are represented by true values of voltage at buses and estimated values (measured values) of voltage at buses, respectively. The comparison between the true and estimated values of voltages is represented when the PV power was injected into the IEEE 14-bus network by 0%, 10%, 20%, and 30%, respectively.The voltage profile at certain buses show no notable changes in voltage magnitude at some buses (changes are very small to be mentiond) after the addition of PV to the network, while others demonstrate significant changes because the main objective function used by SA algorithm is minimum power and reactive power losses, in addition to these buses are far from the generation buses 1,2,7 at the proposed network

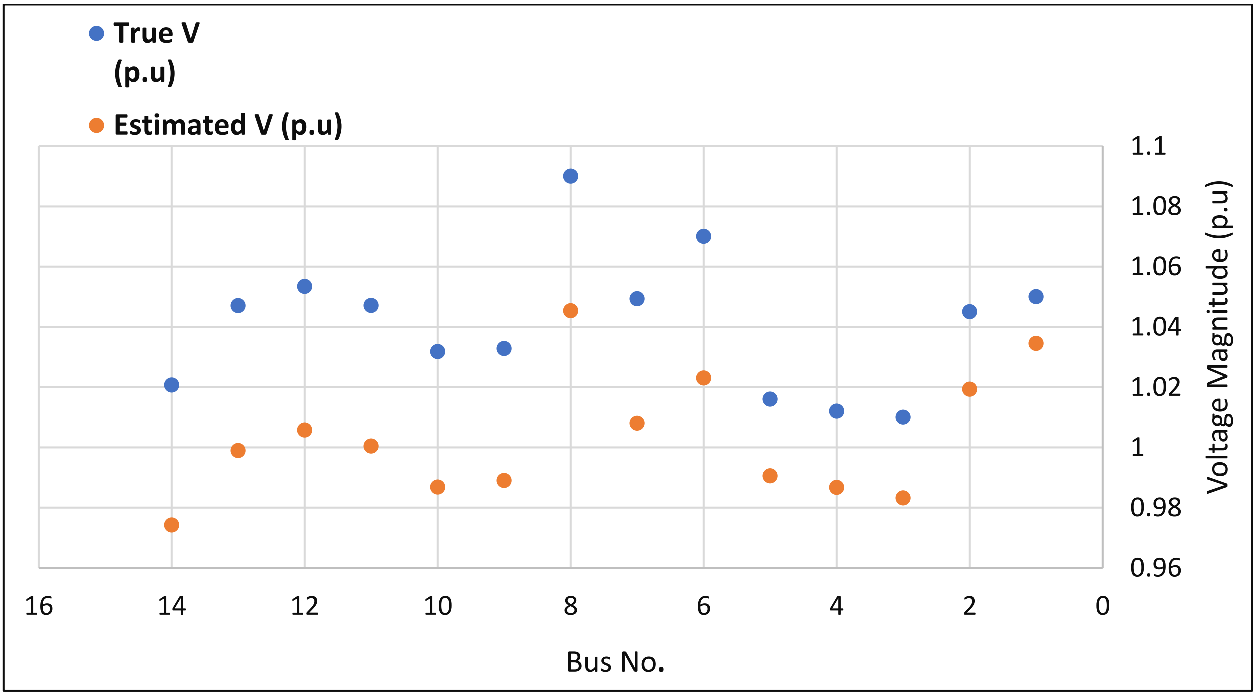

Fig. 10. Comparison of the true and estimated values of bus voltages in the IEEE 14-bus system at 0% solar penetration.

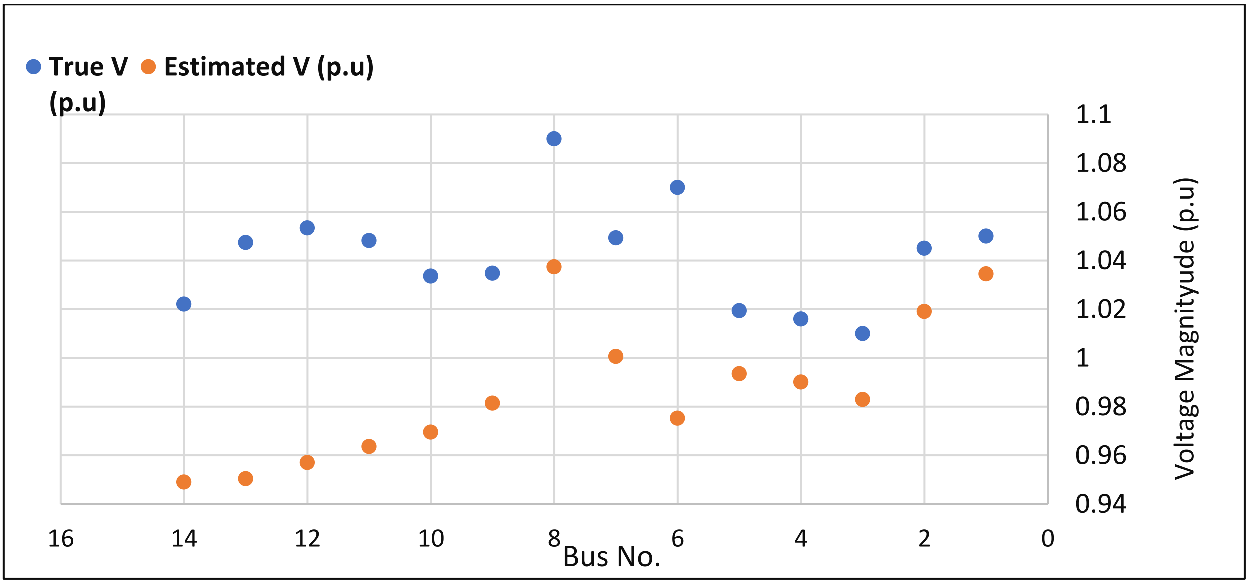

Fig. 11. Comparison of the true and estimated values of bus voltages in the IEEE 14-bus system at 10% solar penetration.

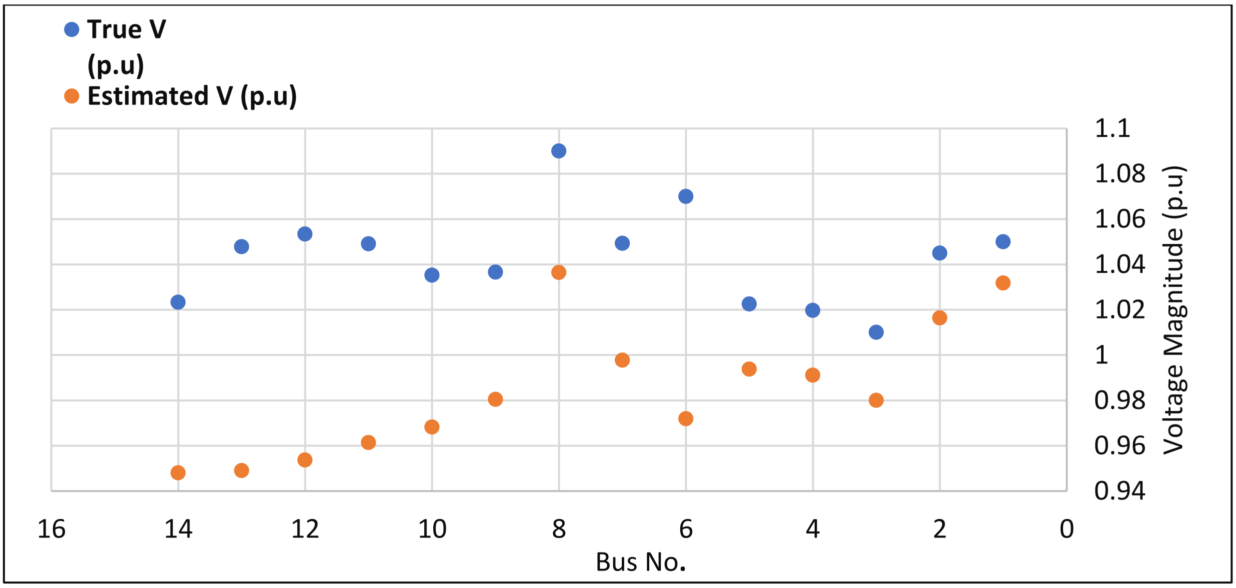

Fig. 12. Comparison of the true and estimated values of bus voltages in the IEEE 14-bus system at 20% solar penetration.

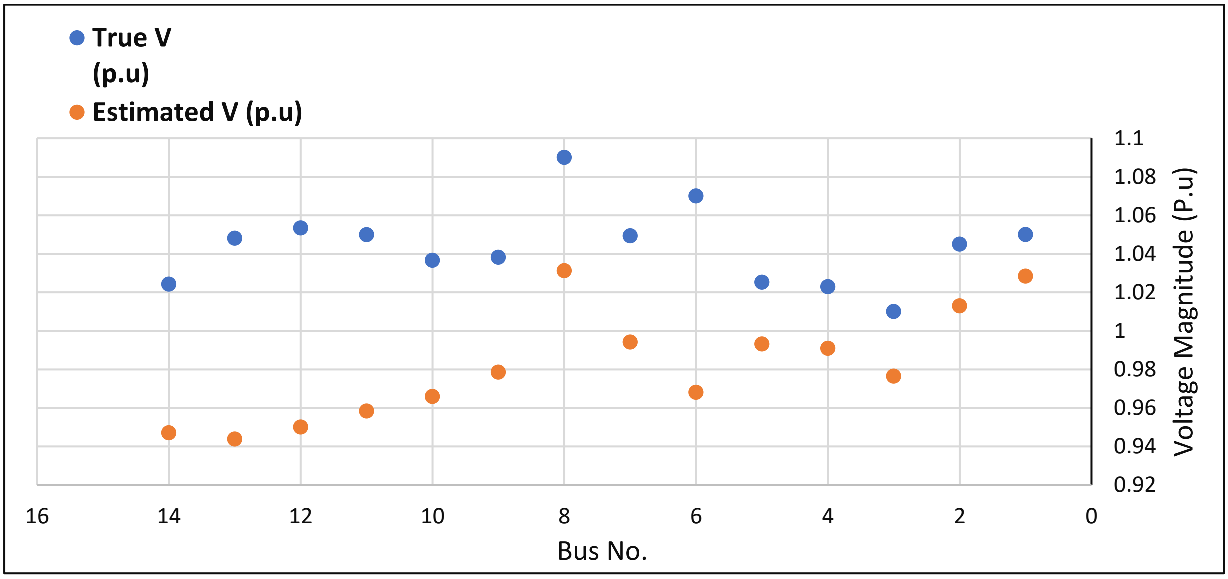

Fig. 13. Comparison of true and estimated values of bus voltages in the IEEE 14-bus system at 30% solar penetration.

SUMMARY AND CONCLUSIONS

The WLS technique has been examined on the IEEE 14-bus network, showing that the estimated values are very close to the actual values with slight errors can not be neglected . The errors can potentially cover the load on protection devices and cause an excessive functioning of the load tap regulators, which can cause system instability. The WLS SE technique can provide a reliable estimate of state variables. The best estimation technique of the system and accuracy were obtained by the WLS SE method. Moreover, WLS was a more efficient SE method compared to other SE methods. This investigation aims to study the impact of PV by 10%, 20%, and 30% of the peak load injected into the IEEE 14-bus network on power losses (active and reactive) and voltage profile. The voltage profile was enhanced by connecting PV with a large percentage of the peak load at bus7, the bus location obtained by Artificial Intelligent technique which is simulated annealing algorithm to find the best location of PV injection with minimum power and reactive power losses. The power loss reduction has been reinforced by injecting more PV power into the distribution network. The injection of solar power into the grids can reduce transmission and distribution lines losses.

CONFLICT OF INTEREST

The authors have no financial interest to declare in relation to the content of this article.

LIST OF ABBREVIATIONS

SYMBOL	Abbreviations
ANNS	Artificial neural networks
ANOVA	Analysis of variance
ATC	Automatic tap changer
CO_2	Carbon dioxide
DG	Distributed generators
DSE	Dynamic state estimation
DSSE	Distributed system state estimation
EEHC	Egyptian Electricity Holding company
EMS	Energy management system
EU	European Union
FACTS	Flexible AC transition systems
FASE	Forecasting aided state estimation
GA	Genetic algorithm
IEA	International energy association
IPFC	Interline power flow controller
LORA	Long-range
LSF	Loss sensitivity factor
OADG	Optimal allocation of distributed generators
ORPD	Optimal reactive power dispatch
PMU	Phasor measurement unit
PSO	Practical swarm optimization
PV	Photovoltaic
PVDGS	Photovoltaic distributed generators
RES	Renewable energy resources
SA	Simulated annealing algorithm
SCADA	Supervisory control and data accusation
SE	State estimation
SSSC	Static synchronous series capacitor
TCSC	Thyristor-controlled series capacitor
TVAC	Time-varying acceleration coefficient
UPFC	Unified power flow controller
US	United States
VSI	Voltage stability index
WLS	Weighted least square
WOA	Whole optimization algorithm

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