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Impact of Renewable Sources on Electrical Power System

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Abstract— *In this paper, Renewable energy sources (RES) are incorporated into the electricity grid. A real-time Andhra Pradesh 14 bus system is considered in which, windy and sunny locations are identified for this study. A new algorithm called Persistence - Extreme Learning Machine (P-ELM) is suggested. The suggested methodology is used to predict wind speed and solar insolation in the selected regions across the short-term and long-term time period horizons. The load flow problem is handled in 12 distinct by penetrating the wind and solar power into the system. The research findings are examined in terms of voltage variation and active power loss. The results obtained observed as, with wind and solar integration, the voltage variation is higher in both the short and long-term time frames, but the active power losses are lower than in the other cases.*

Keywords— Forecasting, Persistent-extreme learning machine algorithm, Power flow solution, Renewable energy sources, Renewable penetration.

1. Introduction

The electrical system is such a very large interconnected complex network to understand and also to analyze. The load flow solution, which is a steady state behavior of a power system is an integral part of most of the studies involving its planning and operation [1]. The load flow solution involves obtaining the bus voltage magnitudes and their angles along with the active and reactive power flows into the transmission lines [2]. With the integration of Renewable Energy Sources (RES), the load flow problem has become even more difficult to analyze, because of their intermittent nature of generation [3].

Various authors have contributed a lot to yield best solution with RES penetration. The authors of [4] proposed Lagrangian based algorithm involving Supervisory Control and Data Acquisition system (SCADA) for modelling of load flow solution with the RES penetration by considering the minimization of loss and cost as objectives. A Cumulant based probability power flow method to handle the uncertainties raised by different RES is proposed in [5]. The authors have used probability distribution of wind power for the analysis. There are certain cases where an unbalance will arises in the power system with the incorporation of RES in to the grid. By penetrating the solar power into the grid, the authors of [6] have proposed methodology for load flow solution for variable load conditions. Now a days the RES penetration is also observed to be in distribution system. The authors of [7] contributed and proposed novel methodology towards the solving of load flow solution with RES incorporation in a radial distribution system. They have heighted the concept of forward and backward sweep algorithm and also to address the intermittent generation of RES, time series analysis is used.

Handling of RES in electric grid demands sophisticated algorithms. In [8], the authors have proposed Imperialist competitive algorithm (ICA) to solve probabilistic load flow problem by integrating the RES into the weakly meshed distributed network. The authors of [9] emphasizes on the feasibility of replacing all the conventional plants to RES. They elaborately discussed on importance of migration to RES, advantages and the scope of further improvements.

A real time project was carried out on Tafilah of Jordan in [10]. The authors proposed LCA method to carry out study on environmental impacts of incorporation of wind power. The analysis was held by considering the design from scratch of the work to the ultimate development of the complete system. In [11], the authors have developed generalized approach and put the efforts to enhance payback period with the integration of solar power.

Recently, an US research body has developed HOMER software for building cost effective distributed generation system with variety of combinations [12].

With the advancements in machine learning algorithms for handling intermittent nature of RES [13], Antlion optimization algorithm was used to address the scheduling problem. The authors of [14] has extended their work to suggest a proper solution to schedule as well as secure operation of power system containing combined heat and power plants. With the evolvement of hybrid prediction models the authors of [15] proposed a hybrid and novel forecasting methodologies which perfectly suits for short term time period horizons.

The literature covered so far is either addressed the forecasting of RES or solving of load flow problem with only one RES. To have complete analysis and for the secure operation of electrical system it is very much essential for accurate forecasting, integrating RES to grid and evaluating the power flow.

The novelty of the proposed work is, a mathematical approach is developed to handle the load flow problem using RES by considering the uncertain nature of wind and solar generations. The present study is carried out for the time frames of short-term and long-term durations in various seasons. The entire work is

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divided into two modules. The first module is to forecast the amount of wind as well as solar energy that is accessible in the identified locations using the proposed hybrid machine learning algorithm. The second module involves executing the solution for the load flow by the integration of estimated RES into the grid over different intervals.

2. P-ELM ALGORITHM

It is crucial to anticipate renewable energy output with great accuracy and precision, in order to incorporate it into the central electric system. It cannot be denied that the usage of advanced forecasting tools is very much required for efficient system planning, operation, and security. In [16, 17] wind speed and wind power forecasting across different time horizons, a massive literature search has been conducted. And also, solar power forecasting also has been reviewed in [18, 19].

The methods of persistence, physical, statistical, artificial neural network and hybrid models are presented in the state of the art of forecasting. Persistence is a basic and straightforward approach to forecasting that is best used for short-term time horizons Physical atmospheric characteristics such as wind speed, pressure, temperature, and others are used in physical forecasting systems. Time series and regressive techniques are employed in statistical procedures. The artificial neural network requires historical data, and hybrid techniques are produced by integrating any of the two methodologies stated above.

In the present study, the wind speed and sun insolations were predicted using P-ELM method, which is a hybrid of Persistence and Extreme Learning Machine (ELM) techniques [20]. The persistence technique is most efficient for shorter time horizons, which implies the predicted value in the (t+1)th instant is the same as that in the tth instant. The ELM method is a feed forward neural network with a single hidden layer.

The following section describes the P-ELM mathematical modeling:

The patterns of the P-ELM structure are $(s_i, s_{i+1})_{i=1}^{N-1}$,$s_i \in R^N$, in which$s_i = [s_{i1}, s_{i2}, s_{i3}, \ \ldots, \ s_{ip}]$, are considered as inputs for the samples and $s_{i+1} = [s_{(i+1)1}, s_{(i+1)2}, s_{(i+1)3}, \ \ldots, \ s_{(i+1)p}]$ are the corresponding output sample. The objective function of P-ELM, which is to be optimized is stated as

$$F(s_j) = \sum_{i=1}^{M} c_i f(a_i * s_j + b_i), j = 1, 2, 3, \ \ldots, \ N \tag{1}$$

M: The total number of nodes in the hidden layer, the vectors of weights between hidden and output layer is c, also the weight vector between input to hidden layers is given by a and the threshold given to each neuron in the hidden layer is b. The general layout of proposed P-ELM is presented in Fig. 1.

In matrix notation,

$$f * c = S \tag{2}$$

The matrix of targets is S which is:

$$S = [s_2, s_3, s_4, \ \ldots, \ s_N]$$

The cost function can be characterized as

$$f = \begin{bmatrix} f(a_1.s_1 + b_1) & f(a_2.s_1 + b_2) & \ldots & f(a_M.s_1 + b_M) \\ \vdots & & & \vdots \\ f(a_1.s_{N-1} + b_1) & f(a_2.s_{N-1} + b_2) & \ldots & f(a_M.s_{N-1} + b_M) \end{bmatrix}_{N-1*M} \tag{3}$$

The parameters $a$and b are initialized randomly at first. The objective of back propagation algorithm is to minimize:

$$F_{BP} = \sum_{j=1}^{N-1} \left[\sum_{i=1}^{M} c_i f(a_i.s_j + b_i) - s_{j+1} \right]^2 \tag{4}$$

3. CALCULATION OF WIND POWER

Wind turbines or windmills will be used to generate the wind power. The spinning of wind turbine blades converts the kinetic energy in the flowing air to mechanical energy, which is then transformed to electrical energy by the electric generator.

Kinetic energy available in the air particles which are travelling at ν velocity may be written as

$$Kinetic\, Energy\, (KE_W) = \frac{1}{2}\, m\, \nu^2 \tag{5}$$

The power that can be extracted from the wind is represented as the rate of change of kinetic energy.

$$P_{Wind} = \frac{\mathrm{d}\,(KE_W)}{\mathrm{d}t} = 0.5 \times \nu^2 \times \frac{\mathrm{d}\,m}{\mathrm{d}t} \tag{6}$$

$$\text{and } \frac{\mathrm{d}\,m}{\mathrm{d}t} \text{ is given as } \frac{\mathrm{d}\,m}{\mathrm{d}t} = \frac{\mathrm{d}\,(\rho \times Volume)}{\mathrm{d}t} \tag{7}$$

$$= \rho \times A \times \frac{\mathrm{d}\,l}{\mathrm{d}t} \tag{8}$$

Where,

'ρ' - air density

'A' - Area swept by the blade

'l' - wind turbine blade length

The swept area of wind turbine blades is depicted properly in Fig. 2. Substitute Eqn (8) in Eqn (6),

$$P_{Wind} = 0.5 \times \nu^2 \times \rho \times A \times \frac{d\,l}{dt} \tag{9}$$

$$P_{Wind} = 0.5 \times \rho \times A \times \nu^3 \tag{10}$$

'C_P' is known as Betz constant or power coefficient, and hence

$$P_{Wind} = 0.5 \times \rho \times A \times \nu^3 \times C_P \tag{11}$$

The wind power varies with the cube power of wind speed, as described by Eqn (11). Fig. 3 depicts a typical wind turbine power curve derived which shows the relationship between wind speed in m/s and active power generated in p.u [21]. The wind power characteristics can be discuss in to four zones.

- As the wind speed in Zone A is less than cut-in speed ($V_{Cut\ in}$), the power generated in Zone A is 0.
- The region between Cut-in speed and rated speeds (V_{rated}) is represented as Zone B, in which the power generated will rapidly rise. The power generated will achieve the rated output power capacity at V_{rated}.
- In Zone C the continuous output power is achieved which is in between Vrated and Cut-out speed ($V_{Cut-Off}$ or $V_{Cut-out}$). The maximum speed for power generation is called $V_{Cut-Off}$.
- The turbine will stall if the wind speed exceeds $V_{Cut-Off}$, which is in Zone D, to prevent damage to the structure from heavy winds. From the above-detailed discussion the wind power generation equation can be expressed as

$$\begin{aligned} P_{Wind} &= 0; \quad v < V_{Cut\, in} \\ &= 0.5 \times \rho \times A \times v^3; \quad V_{Cut\, in} < v < V_{Cut\, out} \\ &= P_r\,; \quad v > V_{Cut\, out} \end{aligned} \tag{12}$$

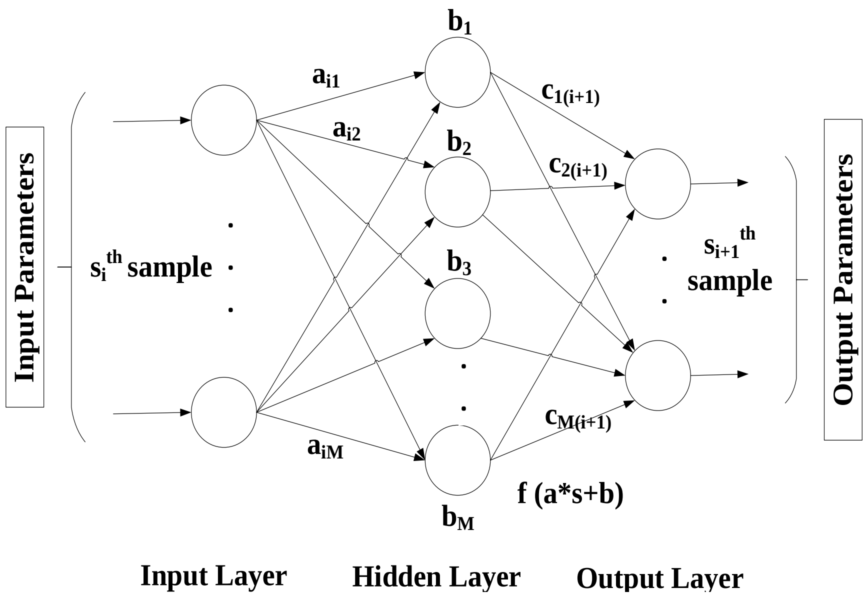


Fig. 1. Pictorial representation of P-ELM algorithm

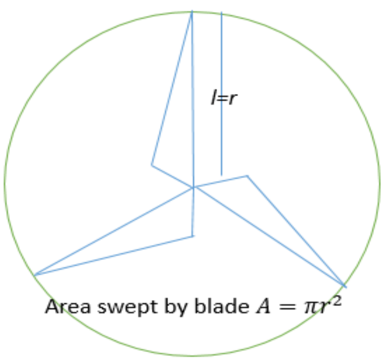


Fig. 2. Wind turbine blade

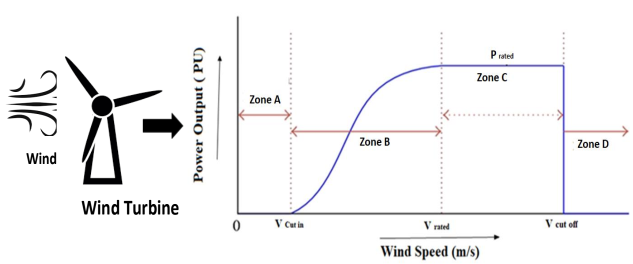


Fig. 3. Wind power output variation

4. Solar Power Generation

Solar energy is a renewable resource that is abundantly available in nature. Solar energy offers a numerous advantages, including the fact that it is pollution-free, low-maintenance with a long lifespan. Solar energy is created as a result of the sun's radiation. A solar panel is a device that transforms sunlight into electricity. A solar cell, also known as a PV cell, is the basic component that is used to build solar panels and solar arrays by joining them in series and parallel configurations based on the voltage, current, and power requirements.

A conventional solar cell is made up of a PN junction and a semiconductor-N junction diode [22]. It functions on the basis of the photovoltaic effect. When sunlight strikes the diode, the junction absorbs the light and generates electricity. The equivalent circuit of a single diode model of solar cell [23] consists of a current source connected to a diode which is in forward bias is shown in Fig. 4. Where,

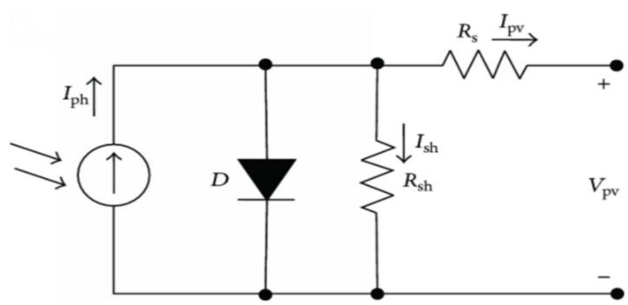


Fig. 4. Circuit of a diode model of PV cell

'I_{ph}' is photocurrent
'I_{sh}' is the current through shunt branch
'I_{pv}' is the output current of a solar panel in Amps and is expressed as

$$I_{pv} = I_{ph} - I_0 e^{\left(\frac{qV_D}{KT}\right)} - \frac{V_D}{R_{sh}} \tag{13}$$

Where,
'I_0' = Reverse saturation current.
'q' = Electron charge in Coulombs.
'V_D' = Diode voltage.
'K' = Boltzman Constant.
'T' = Cell temperature.
'R_{sh}' = Shunt resistance.

The output power equation of a solar cell is given as

$$P_{PV} = V_{PV} \times I_{PV} \tag{14}$$

The output power of a solar plant (P_S) is given as

$$Ps = \textit{Performance ratio} \times \textit{solar insolation} \times \textit{panel area} \times \textit{solar panel efficiency} \tag{15}$$

The performance ratio value ranges between 0.5 and 0.9, the default value is 0.75. The efficiency of a solar panel is approximately 0.15.

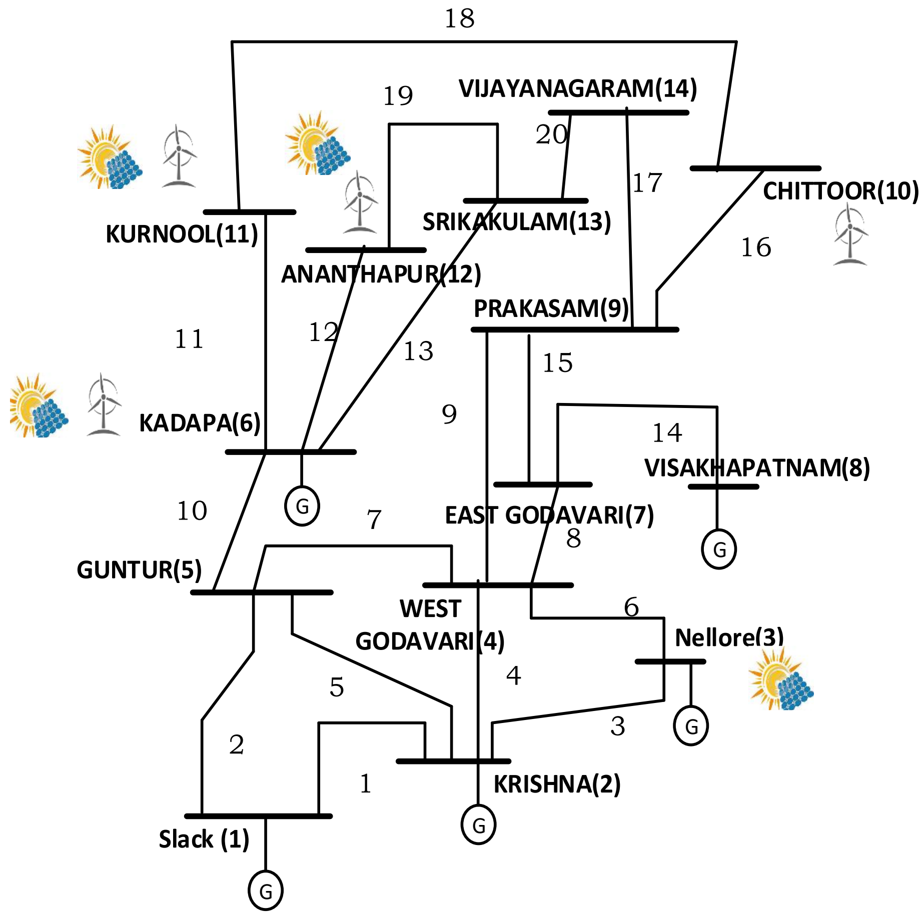


Fig. 5. AP 14 bus system with RES

5. Optimal placement of RES installation

In the present work, AP 14 bus system is considered [24]. In the state of AP, Kurnool, Ananthapur, Kadapa, and Chittoor are rich in wind as per the data given by the New & Renewable Energy Development Corporation of Andhra Pradesh (NREDCAP). Ananthapur, Kadapa, Kurnool and Nellore are observed to be rich in sun insolation by using Clearness index approach [25]. The considered AP 14 bus system along with RES integration is depicted in Fig. 5.

The proposed P-ELM network is trained with the help of data provided by the Indian solar resource data website and wind/ solar power is forecasted in the considered locations. Later the load flow problem of AP 14 bus system along with RES is solved.

6. Load flow solution by incorporating RES

The power flow solution involves determination of voltages, real and reactive powers in the entire system. The mathematical formulation with the integration of RES for Newton-Raphson method is presented as follows. The injected active and reactive powers (P_i & Q_i) at ith bus are calculated as

$$P_i = \sum_{i=1}^{Nbus} |V_i|\,|V_j|\,|Y_{ij}|\,Cos(\delta_i - \delta_j - \theta_{ij}) \tag{16}$$

$$Q_i = \sum_{i=1}^{Nbus} |V_i|\,|V_j|\,|Y_{ij}|\,Sin(\delta_i - \delta_j - \theta_{ij}) \tag{17}$$

Let either wind power (P_{Wind}) or solar power (P_S) are connected at bus k, the Eqn (16) is modified as

$$P_i = \left[\sum_{i=1}^{Nbus} |V_i|\,|V_j|\,|Y_{ij}|\,Cos(\delta_i - \delta_j - \theta_{ij})\right] - P_{RES(at\, i=k)} \tag{18}$$

Where,
'$|V_i|$' is the magnitudes of bus voltages at bus i.
'$|V_j|$' is the magnitudes of voltage at bus j.
'δ_i' is the phase of the voltage at bus i
'δ_j' is the phase of the voltage at bus j.
'$|Y_{ij}|$'is the Y-Bus magnitude.
'θ_{ij}' is phase angles of the Y-Bus.
'P_{RES}' is renewable power generation i.e P_{Wind} or P_S.

The governing equation of NR method is as follows.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{19}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = [J] \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \tag{20}$$

Matrix '$[J]$' is known as Jacobian matrix.

To get an effect of RES incorporation, the real power and mismatch at kth bus can be modified as

$$\Delta P_k = (P_k^{Sch} - P_k{}^{Cal}) = (P_k^{Gen} + P_{RES} - P_k^{Load} - P_k{}^{Cal}) \tag{21}$$

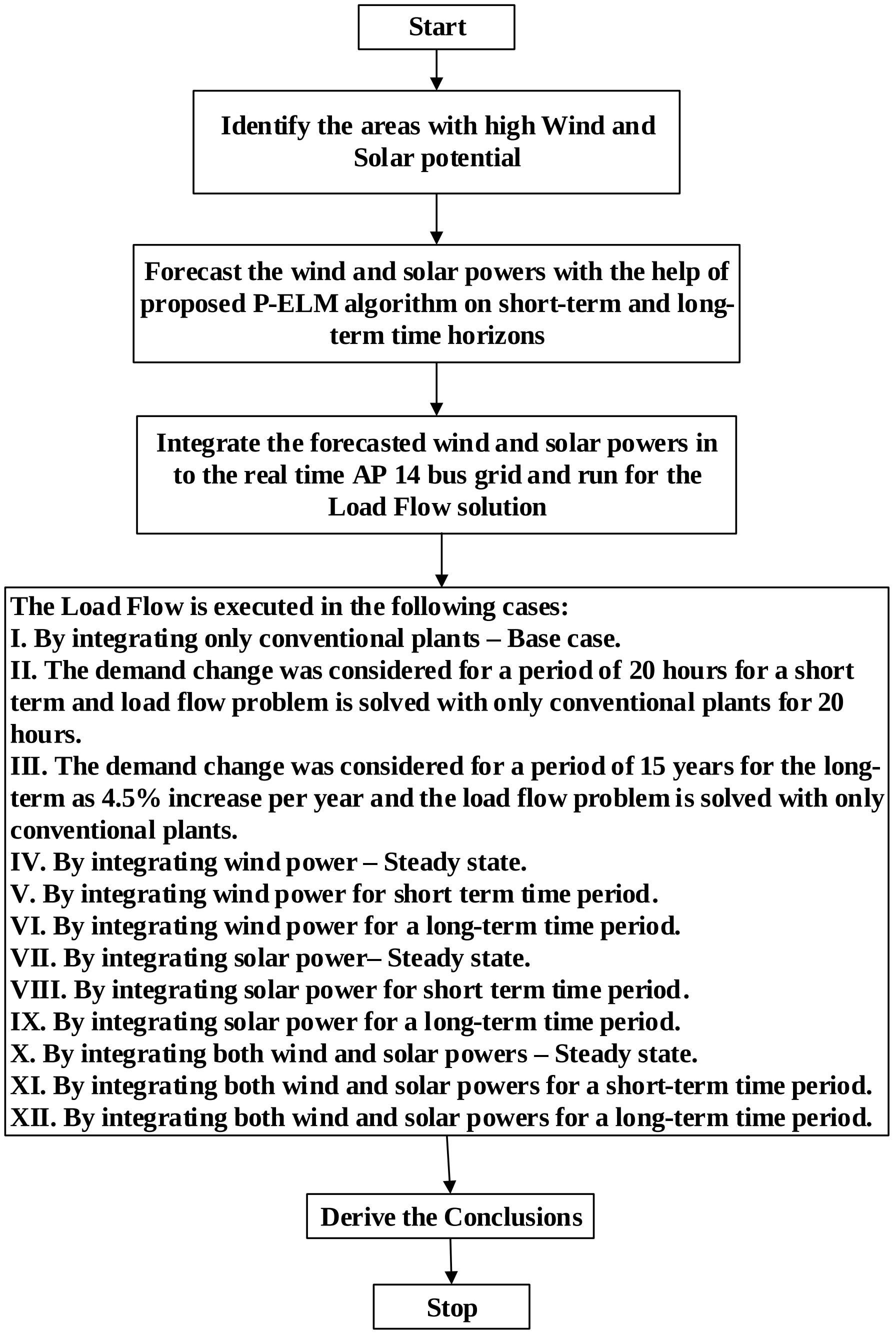


Fig. 6. Flowchart describing the objectives

The remaining procedure holds the same as in the basic NR load flow approach.

The deviation in voltage (V_{Dev}) is the deviation of actual voltage from the reference voltage. Mathematically, it can be expressed as

$$V_{Dev}=\sum_{i=1}^{LB}\left|\left(V^{reference}-V_i^{Actual}\right)\right| \tag{22}$$

Where, LB is the number of load buses

Transmission loss calculation can be obtained using Eqn (19).

$$P_L=\sum_{i=1}^{nl} g_i\left[V_i^2+V_j^2-2V_iV_j cos(\delta_i-\delta_j)\right] \quad MW \tag{23}$$

Where,

'g_i' represents conductance of ith line (mho).

'V_i' and 'V_j' are magnitudes of voltages (p.u),

'δ represents the phases of voltages at the respective buses (radians),

'nl' is the total lines,

Fuel cost function 'C(P_i)' is represented as in Eqn (24)

$$C(P_i)=a_iP_i^2+b_iP_i+c_i \;\; \$/hr \tag{24}$$

Where, a, b and c are the respective generator cost coefficients.

7. Solution Methodology

The step-by-step procedure for solving load flow problem by integrating the identified renewable sources are described below

Step 1: Choose the wind rich locations which are feasible to install wind power.

Step 2: Predict the wind speed in the selected locations for the considered periods by making use of proposed P-ELM algorithm.
Step 3: Using Eqn (11) obtain the wind power that can be extractable.
Step 4: At the same time, using CI methodology [24] identify sunny areas.
Step 5: Forecast the 'GHI' available in the considered areas for short-term time period and long-term using proposed P-ELM approach.
Step 6: Using Eqn (15), obtain solar power.
Step 7: Execute the power flow without integrating RES, which is a standard case and perform the same for different time horizons.
Step 8: During the long-term time horizons, consider the demand increment in step of 4.5% per year.
Step 9: Integrate wind power, Solar power and both wind and solar powers combination in three different cases and execute load flow in the considered areas for the defined seasons.

8. Results and Analysis

In the present work, the load flow problem is addressed by utilizing RES as described below.

I. Only conventional plants – Base case.
II. The demand change was considered for a period of 20 hours for a short term and load flow problem is solved with only conventional plants for 20 hours.
III. The demand change was considered for a period of 15 years for the long-term as 4.5% per year and the load flow problem is solved with only conventional plants.
IV. With the involvement of wind power.
V. With the involvement of wind power for a period of 20 hours.
VI. With the involvement of wind power for a period of 15 years.
VII. With the involvement of solar power.
VIII. With the involvement of solar power for a period of 20 hours.
IX. With the involvement of wind power for a period of 15 years.
X. With the involvement of both wind and solar powers.
XI. With the involvement of both wind and solar powers for a short-term time period of 20 hours. The entire process is described in flow chart shown in Figure 6.

To validate the accuracy of the proposed P-ELM approach, wind speed is forecasted using P-ELM and the obtained results are compared with that of the methods which are reported in the literature.

From the Table 1, It is evident that, the proposed P-ELM yields better forecasting results with less errors in terms of MAE as 0.0485 and RMSE as 0.0490 compared to that of other published methods. It is observed that, the MAE with proposed P-ELM method is reduced by 67.6% and RMSE as 71.1% on comparing with ANFIS method. In comparison with SARIMA the MAE and RMSE errors are reduced by a percentage of 65.35% and 72.7% respectively. However, in comparison with the novel method claimed by the authors in ref. [15], the proposed P-ELM method results to better forecasting with less MAE and RMSE errors by 3% and 18.3% respectively. Therefore, from the obtained results it can be decided that, the proposed method can be utilized for the real time forecasting also.

The proposed methodology is implemented on a real time AP 14 system and the obtained results are presented and discussed with supporting numerical and graphical analysis. The figures from Fig. 7(a) to Fig. 7(c) shows the voltage variations for different cases.

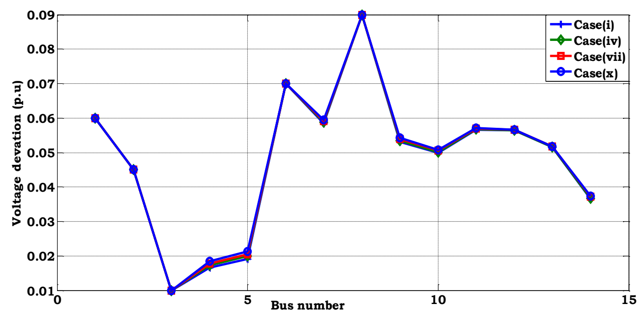
The Fig. 8(a) to Fig. 8(c) shows the active power loss in different scenarios.

From Figures 7 and 8 the conclusions that can be derived are:

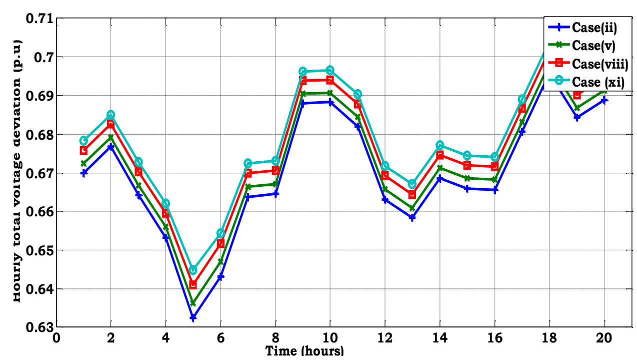
- Under base case condition, the voltage deviation is more or less same for all the cases. But, the average active power loss is comparatively less in case of wind and solar combined.

Table 1. Comparison of statistical metrics with existing and proposed method for wind speed forecasting

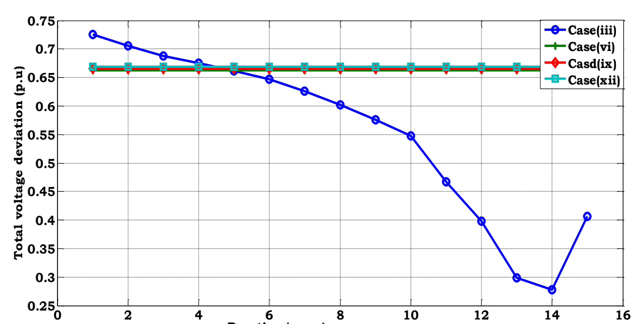
	Algorithms	MAE	RMSE
Existing	ANFIS [15]	0.15	0.17
	SARIMA [15]	0.14	0.18
	In [15]	0.05	0.06
	Persistent	0.0498	0.0496
	ELM	0.0491	0.0524
	Proposed Method	0.0485	0.0490



(a) Total voltage deviation for base case

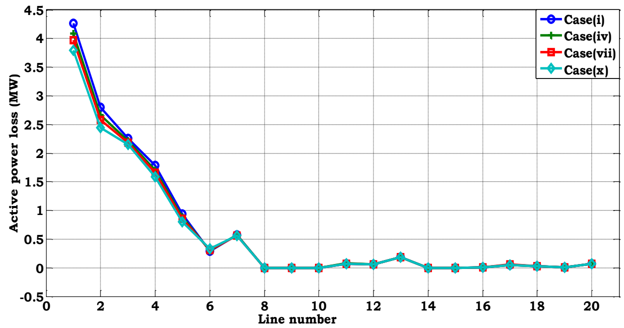


(b) Total voltage deviation for short term time period

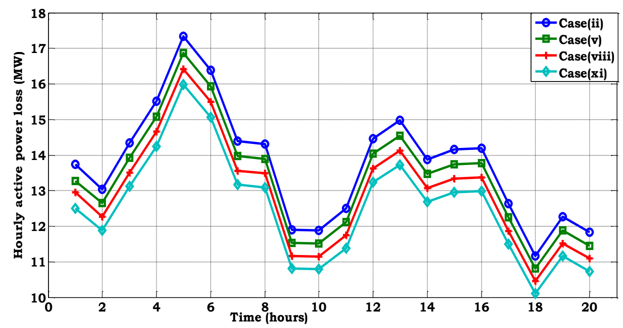


(c) Total voltage deviation for long term time period

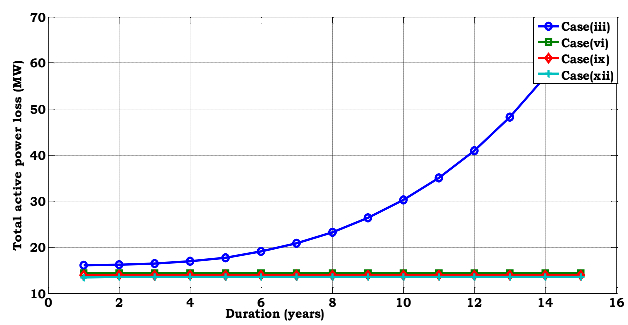
Fig. 7. Total voltage deviations for (a). Base Case (b). Short term time period (c). Long term time period



(a) Total active power loss for base case



(b) Total active power loss for a short term time period



(c) Total active power loss for long term time period

Fig. 8. Total active power loss (a). Base case (b). Short term time period (c). Long term time period

- Under shorter time periods, i.e. over a period of 20 hours, the voltage deviation is more with wind and solar combination, while in this case only, the active power loss is much less compared to other cases.
- Over a long term time period horizons, i.e. for a period of 15 years, the voltage deviation is more for wind and solar combined, but, the yearly active power loss and average active power losses are less in wind and solar combined connected to the grid.

9. Conclusion

In this paper, the optimal locations to install wind and solar power generations have been identified by comparing them with the other locations. The proposed P-ELM, forecasts wind speed and solar insolation with less error in the range of around 3% to 67% less as compared with that of conventional methods. After validating the accuracy of P-ELM only it is used to forecast wind speed and solar insolation values for short-term and long-term periods. Then, the load flow problem has been solved with these renewable integrations. The effect of wind or/and solar energy sources on system performance has been analyzed with supporting numerical and graphical results.

The following observations are made with the obtained results. The total voltage drop is minimum which is 0.048094 pu under the base case and it is maximum with the incorporation of both wind and solar powers. However, the total power loss observed to be in the reverse scenario. In the base case, it is 0.66937 pu which is the maximum and a minimum of 0.6066 pu is observed with the integration of both wind and solar. During the considered short-term time period, the total voltage drop is observed to be minimum during 5^{th} hour and maximum during 18^{th} hour in the four cases. During the considered long-term time period, the total voltage drop is observed to be improved a lot.

The total power loss is observed to be minimum during the 18^{th} hour in all the considered cases and is maximum during the 5^{th} hour in short-term time horizon. During the long-term time horizons, the total power loss is reduced in case of both wind and solar integration which is 13.504 pu. At the end, it can be concluded that, with the integration of both wind and solar in the considered electrical system the maximum techno benefits can be obtained.

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