Determining Nodal Prices for Radial Distribution System with Wind and Solar Power Integration using Probabilistic load

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Abstract -*This paper depicts a theoretical approach for nodal pricing mechanism to estimate active and reactive nodal prices with penetration of wind power and solar energy. Nodal price refers to the price paid for electricity calculated at various transmission nodes. The mean and standard deviation for each hour of 24 hrs a day are calculated from historical wind speed data and solar irradiance data. This study uses Weibull modeling to examine wind velocities and consider different types of time varying load models to estimate the photovoltaic penetration in DG. MLCs are calculated to show the deviation in net power loss attained from Jacobian Matrix that results a loss derivative from AC load flow. An IMO based analytical approach is used to describe PV impacts using active power loss, reactive power loss, and voltage deviation. The result is carried out on a 69-bus RDS and was run in MATLAB 2021.*

Key Words: **Jacobian Matrix, Marginal loss Coefficients, Nodal price, Photovoltaic Penetration, Probabilistic load, Radial Distribution System, Weibull Modeling**

1. INTRODUCTION

Prior to the degradation of fossil fuels, renewable energy resources have been formulated as the exception to fossil fuel-based power plant such as biomass, solar and wind. Many large power stations are forbidden due to the environmental issues for which government agreed to promote the energy industry. The DG penetration may affect the distribution system operation in both economic and environmental ways. The beneficial impacts include power loss reduction, reliability, voltage profile improvement and dynamic stability. Renewable energy is endorsed with various DG's due to its low cost and environmental viability.

MLC technique had been employed to calculate locational marginal prices in the transmission network [1]. It is noticed that this technique can be even adopted in distribution network [2]. A multi-objective performance index is used with distributed generation that considers various technical issues [3]. The integration of renewable energy into dispatchable DG minimizes energy losses compared to non-dispatchable DG units at optimal power factor [4]. We make use ofAmp-mile tariff and nodal pricing with the impact of wind power for the distribution network [5]. The penetration of wind and solar power is assumed to be dominated over conventional resources [6]. The determination of nodal prices with realistic ZIP loads is carried out using MLC's [7]. The renewable energy sources are considered as an alternative for generation of power which are eco-friendly and economically efficient [8]. The US2PM method is used for handling the uncertainties caused by the proliferation of wind turbines and solar panels [9]. A PPF Algorithm is applied to estimate the uncertainties PV generation by considering correlation among input random variable [10]. CSI's are capable of providing only active power can be generated by VSI [11]. To minimize the energy losses, time varying loads are considered in which 3 analytical expressions are represented to identify the best location [12].

This paper is précised into 6 different segments. 2nd one depicts the nodal pricing mechanism using MLC's whereas 3rd segment tells the probabilistic load and wind power source modeling. 4th segment narrates the load and solar PV modeling, where the 5th one gives the results and discussion on nodal prices comparison with wind energy and solar PV penetration. 6th segment represents the paper conclusion. In this paper, IEEE 69 bus Radial Distribution System is considered as system for testing and was run in MATLAB 2021.

2. NODAL PRICING METHODOLOGY

Similar to the transmission network, nodal prices can be obtained in the distribution network. Firstly, MLC's are determined to find the nodal prices on each bus of distribution network. MLC's are marginal cost coefficients that reflect the portion of change in cost that is due to a change in system line losses.

$$\rho_{Pi}=\frac{\partial L}{\partial P_i} \qquad (1)$$

$$\rho_{Qi}=\frac{\partial L}{\partial Q_i} \qquad (2)$$

Here, L = total power loss,ρ_{Pi}=MLC of active power and ρ_{Qi}= MLC of reactive power at junction$i$.

The link between the transmission and distribution networks is called as power supply point. λ is termed as active power electricity price (USD/MWh) at power supply point, so the real and reactive power nodal prices at different nodes are:

$$C_{Pi} = \lambda + \lambda.\rho_{Pi}$$

$$C_{Pi} = \lambda(1+\rho_{Pi}) \quad (3)$$

$$C_{Qi} = \lambda.\rho_{Qi} \quad (4)$$

Where C_{Pi} and C_{Qi} are the active, and reactive power nodal prices at junction$i$. The reactive power nodal price is regarded as zero at power supply point.

2.1 Reconciliated Marginal Loss Coefficients:

From MLCs, the system losses can be obtained as follows:

$$L_{approx} = \sum_{i=1}^{n}[\rho_{Pi}.P_i + \rho_{Qi}.Q_i] \quad (5)$$

WhereP_i and Q_i are the active and reactive power injections at node i. Compared to the actual losses, the losses obtained using MLCs are almost twice. Therefore, to evaluate the exact cost of losses, MLCs have to be adjusted using the factor of reconciliation(Rf).

$$Rf = \frac{L}{L_{approx}} \quad (6)$$

By reconciliation factor, the new active and reactive nodal prices are expressed as below:

$$N_{Pi} = \lambda + \lambda.Rf.\rho_{Pi} = \lambda(1+Rf.\rho_{Pi}) \quad (7)$$

$$N_{Qi} = \lambda.Rf.\rho_{Qi} \quad (8)$$

2.2 Determination of Marginal Loss Coefficients:

Jacobian matrix method is chosen to find out the MLC's.

$$\begin{bmatrix}\rho_{Pi}\\ \rho_{Qi}\end{bmatrix} = \begin{bmatrix} \frac{\partial P_1 \partial P_2}{\partial\theta_1\partial\theta_1} & \cdots & \frac{\partial P_n}{\partial\theta_1} & \frac{\partial Q_1 \partial Q_2}{\partial\theta_1\partial\theta_1} & \cdots & \frac{\partial Q_n}{\partial\theta_1} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_1 \partial P_2}{\partial\theta_n\partial\theta_n} & \cdots & \frac{\partial P_n}{\partial\theta_n} & \frac{\partial Q_1 \partial Q_2}{\partial\theta_n\partial\theta_n} & \cdots & \frac{\partial Q_n}{\partial\theta_n} \\ \frac{\partial P_1 \partial P_2}{\partial V_1\partial V_1} & \cdots & \frac{\partial P_n}{\partial V_1} & \frac{\partial Q_1 \partial Q_2}{\partial V_1\partial V_1} & \cdots & \frac{\partial Q_n}{\partial V_1} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_1 \partial P_2}{\partial V_n\partial V_n} & \cdots & \frac{\partial P_n}{\partial V_n} & \frac{\partial Q_1 \partial Q_2}{\partial V_n\partial V_n} & \cdots & \frac{\partial Q_n}{\partial V_n} \end{bmatrix}^{-1} \begin{bmatrix} \frac{\partial L}{\partial\theta_1} \\ \vdots \\ \frac{\partial L}{\partial\theta_n} \\ \frac{\partial L}{\partial V_1} \\ \vdots \\ \frac{\partial L}{\partial V_n} \end{bmatrix} \quad (9)$$

$$\frac{\partial P_i}{\partial\theta_j} = V_iV_j[G_{ij}\sin(\theta_i-\theta_j) - B_{ij}\cos(\theta_i-\theta_j)] \quad (10)$$

$$\frac{\partial P_i}{\partial\theta_i} = -B_{ii}V_i^2 - \sum_{j=1}^{n}V_iV_j[G_{ij}\sin(\theta_i-\theta_j) - B_{ij}\cos(\theta_i-\theta_j)] \quad (11)$$

$$\frac{\partial P_i}{\partial V_j} = V_i[G_{ij}\cos(\theta_i-\theta_j) + B_{ij}\sin(\theta_i-\theta_j)] \quad (12)$$

$$\frac{\partial P_i}{\partial V_i} = G_{ii}V_i + \sum_{j=1}^{n}V_j[G_{ij}\cos(\theta_i-\theta_j) + B_{ij}\sin(\theta_i-\theta_j)] \quad (13)$$

$$\frac{\partial Q_i}{\partial\theta_j} = -V_iV_j[G_{ij}\cos(\theta_i-\theta_j) + B_{ij}\sin(\theta_i-\theta_j)] \quad (14)$$

$$\frac{\partial Q_i}{\partial\theta_i} = -G_{ii}V_i^2 + \sum_{j=1}^{n}V_iV_j[G_{ij}\cos(\theta_i-\theta_j) + B_{ij}\sin(\theta_i-\theta_j)] \quad (15)$$

$$\frac{\partial Q_i}{\partial V_j} = V_i[G_{ij}\sin(\theta_i-\theta_j) - B_{ij}\cos(\theta_i-\theta_j)] \quad (16)$$

$$\frac{\partial Q_i}{\partial V_i} = -B_{ii}V_i + \sum_{j=1}^{n}V_j[G_{ij}\sin(\theta_i-\theta_j) - B_{ij}\cos(\theta_i-\theta_j)] \quad (17)$$

The equation that expresses the distribution system's total loss is as follows

$$L = \frac{1}{2}\sum_{i=1}^{n}\sum_{j=1}^{n}G_{ij}[V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i-\theta_j)] \quad (18)$$

By considering the above equation, the loss derivative can be obtained with respect to bus voltage and bus angle as follows:

$$\frac{\partial L}{\partial\theta_i} = 2\sum_{j=1}^{n}V_iV_jG_{ij}\sin(\theta_i-\theta_j) \quad (19)$$

$$\frac{\partial L}{\partial V_i} = 2\sum_{j=1}^{n}G_{ij}[V_i - V_j\cos(\theta_i-\theta_j)] \quad (20)$$

where V_i and V_j are voltage magnitudes and θ_i and θ_j are voltage angles of sending and, receiving end respectively. G_{ij} , B_{ii} express the conductance and susceptance and n is the total nodes.

3. PROBABILISTIC LOAD AND WIND POWER SOURCE MODELING

3.1 Probabilistic Load Modelling:

In distribution system, the requirements of load can't be determined. Hence this fluctuation is examined with probability distribution function. The load are simulated as random variables with a variance and a mean value about a mean value. The load demand on each bus with random variables involves Gaussian distribution.

$$f(P_L, i) = \left(\frac{1}{\sigma_{PL,i}\sqrt{2\pi}}\right) exp - \frac{(P_{L,i}-\mu_{PL,i})^2}{2\sigma_{PL,i}^2} \quad (21)$$

$$f(Q_L, i) = \left(\frac{1}{\sigma_{QL,i}\sqrt{2\pi}}\right) exp - \frac{(Q_{L,i}-\mu_{QL,i})^2}{2\sigma_{QL,i}^2} \quad (22)$$

where $P_{L,i}$ is the active and $Q_{L,i}$ is the reactive load demands at i^{th} bus. The terms $\sigma_{PL,i}$; $\sigma_{QL,i}$ and $\mu_{PL,i}$; $\mu_{QL,i}$ are standard and mean deviations of active and reactive power respectively.

3.2 Wind Power Source Modelling:

Since wind speed is not constant everywhere, it is taken as a random variable. Weibull distribution function is used to describe the speed of wind as follows:

$$f(v) = \frac{k}{s}\left(\frac{v}{c}\right)^{k-1} exp\left(\frac{-v}{c}\right)^{k}, 0 \leq v \leq \infty \qquad (23)$$

Where c is the scale parameter, k is the shape of parameter and $\boldsymbol{v}$ is the wind speed in m/s.

The power output from a wind turbine is given:

$$P_w = \begin{cases} 0, v \leq v_{ci} \\ k_1 v + k_2, \ v_{ci} < v < v_r \\ P_r, \ v_{ci} < v < v_{co} \\ 0, \ v > v_{co} \end{cases} \qquad (24)$$

where V_{ci}, V_{co}, V_r are cut in speed, cut out speed and rated wind turbine speed in m/s and P_w is the output power (MW). $k_1 = \frac{P_r}{V_r - V_{ci}}$ and $k_2 = -k_1 * V_{ci}$, where P_r is rated wind turbine power output in MW.

4. SOLAR PV MODELING

4.1 Solar Irradiance Modeling:

The solar irradiance for each hour of 24 hrs a day is characterized by the Beta Probability function (PDF) is derived from pervious historical data collected over 3 years. To attain this Probability Distribution Function, a day is divided into 24 hrs, of which every hour has its own solar insolation function. From the previous data, the mean and standard deviation of solar irradiance is calculated hourly. Approximately, there are 20 states generated for each hour from the calculated mean and standard deviation and the probability of each state for solar irradiance is obtained.

The PDF for solar irradiance s can be described as follows:

$$f_b(s) = \begin{cases} \frac{s^{\alpha-1}(1-s)^{\beta-1}}{\Gamma(\alpha).\Gamma(\beta)}\Gamma(\alpha+\beta), \ 0 \leq s \leq 1, \ \alpha, \ \beta \geq 0 \\ 0 \end{cases}$$
(25)

in which $f_b(s)$ is the Beta distribution function of s, s is the random variable of solar irradiance (kW/m^2), α and β are parameters of $f_b(s)$, which are obtained using the mean (μ) and standard deviation (σ) of solar irradiance s as follows:

$$\beta = (1-\mu)\left(\frac{(1+\mu)\mu}{\sigma^2} - 1\right) \qquad (26)$$

$$\alpha = \frac{\mu \times \beta}{1-\mu} \qquad (27)$$

For any particular hour the probability of solar irradiance state $\boldsymbol{s}$ can be derived from the above equation (25) as follows:

$$\rho(s) = \int_{s1}^{s2} f_b(s)ds \qquad (28)$$

where $s1$ and $s2$ are limits of solar irradiance state $\boldsymbol{s}$.

The power output at solar irradiance state $\boldsymbol{s}$, P_{Pv_o}(s) from the PV module can be expressed as:

$$P_{Pv_o}(s) = N * FF * V_y * I_y \qquad (29)$$

where,

$$FF = \frac{V_{MPP} * I_{MPP}}{V_{oc} * I_{sc}}$$

$$V_y = V_{oc} - K_v T_{cy}$$

$$I_y = s[I_{sc} + K_i(T_{cy} - 25)]$$

$$T_{cy} = T_A + s\left(\frac{N_{OT} - 20}{0.8}\right)$$

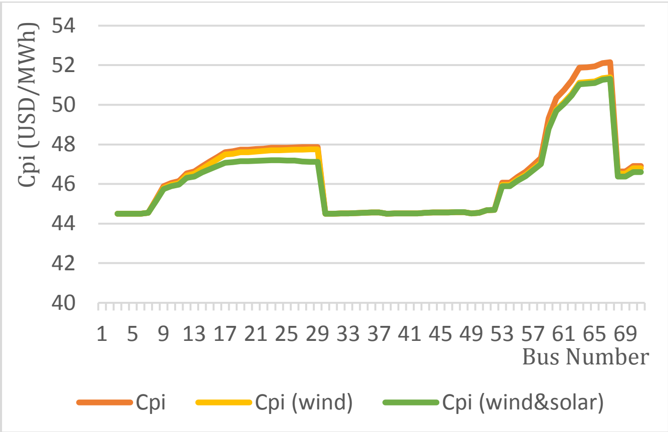
where, N =no. of modules, $T_{cy}$is cell temp. and $T_A$is ambient temp.; $K_i$is current temperature coefficient (A/°C);$K_v$isvoltagetemperature coefficient(V/°C),N_{OT} is nominal operating temperature of cell in °C, FF is fill factor, $V_{oc}$is open-circuit voltage (V);$I_{sc}$is short-circuit current (A), $V_{MPP}$and $I_{MPP}$and are the voltage and current at maximum power point respectively.

The expected power output of a PV module over in specific period t, can be acquired from (28) and (29) as belows:

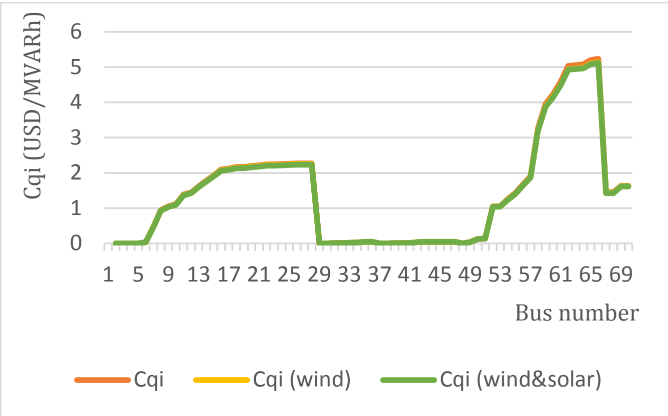
$$P_{PV}(t) = \int_0^1 P_{PV_o}(s)\rho(s)ds \qquad (30)$$

5. RESULTS AND DISCUSSIONS

The IEEE 69 bus Radial Distribution System is simulated in MATLAB 2021. The active and reactive power nodal prices using probabilistic load has been determined. The effect of wind and solar power penetration on active and reactive power nodal prices are studied. The wind and solar power are integrated into distribution system at 61^{th} bus since it is observed as the optimal location which is found from GAMS 23.4 CONOPT MINLP solver calculations. The mean and standard deviation for each hour of 24 hrs a day is derived from pervious wind and solar data.



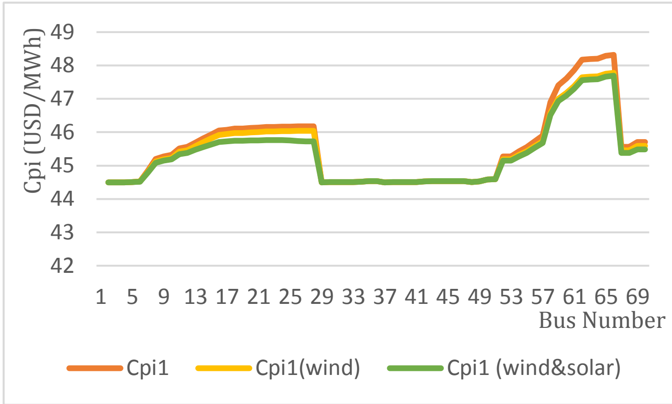
(a)



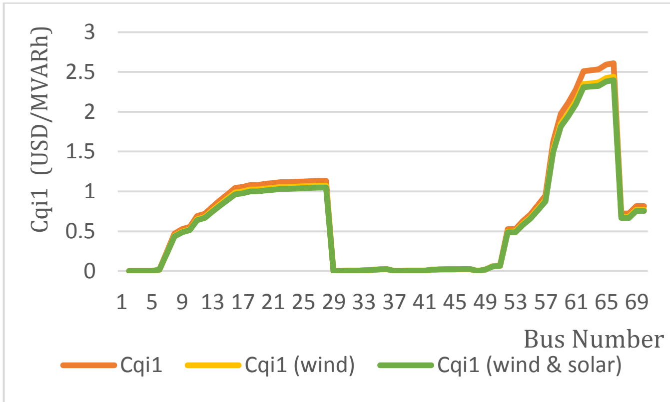
(b)

Fig.1 (a) Real and (b) Reactive power nodal price comparison without and with wind and solar

Fig.1(a) and Fig. 1(b) represents the comparison of real and reactive power nodal prices for probabilistic load with and without wind and with combination of wind and solar power integration. It is seen that nodal prices have been reduced with the integration of wind power and it is also seen that nodal prices have been significantly reduced with wind and solar power integration compared to integration with only wind. Fig.2(a) and Fig.2(b) shows the real and reactive power nodal price comparison without and with wind and solar power considering reconciliation factor. It is observed that prices are further reduced with the consideration of reconciliation factor.



(a)



(b)

Fig.2(a) Real and (b) Reactive power nodal price comparison without and with wind and solar considering reconciliation factor

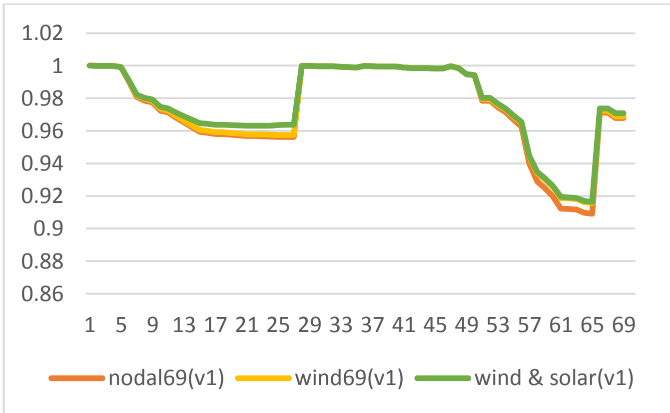


Fig.3 Voltage comparison without and with wind and solar

6. CONCLUSIONS

This paper illustrates the methodology for achieving nodal pricing mechanism in 69 bus RDS considering wind and solar power integration. Comparison of nodal prices with and without wind and solar power is calculated for probabilistic load. The obtained nodal prices are reduced with the penetration of wind power. The combined wind and solar power penetration into RDS results reduced nodal prices drastically contrast with wind. Voltage profile has been increased since the losses are decreased. It can be seen that there is noticeable difference in nodal prices by increasing renewable energy resources.

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