New Ex-ante Indices of Market Power Considering The Impact of Renewable Energy Resources in Oligopoly Power Markets

Ehsan Halakou, Asghar Akbari Foroud

***Abstract*— Market power is a result of anti-competitive behaviors in oligopoly power markets. Ex-ante indices evaluate the potential of market power through the capacity analysis of participants. In this study, structural indices are modified, and new indices are proposed to overcome the shortcoming of market power assessment in electricity markets. In the proposed indices, two types of assessment are considered as deterministic and probabilistic terms. These indices evaluate the incentive of each participant (supplier) to exercise market power. The probabilistic term of these indices considers the stochastic and uncertain nature of renewable energy resources. The Monte Carlo method (MCM) is used for modeling the uncertainty of renewable resources. The impact of each participant's transmission constraints, size, generation cost, and geographical differences in market power assessment are considered. Examination of the results taken from an IEEE 30-bus test system confirms the proposed indices' effectiveness in assessing market power potential.**

***Keywords*— Electricity market, Market power, Ex-ante indices, Renewable energy resources, Monte Carlo method.**

Nomenclature

Indices:

n	Index of participants (generators)
i	Index of buses

Variables:

$C(P_{Gn})$	Cost function of conventional thermal units
P_{Gn}	Generation of thermal unit n
P_{Li}	Load at node i
θ_i	Angle at node i
PI_i	Total power inflow into the node i
PL_{ji}	Power inflow from node j to i
P_{Gi}	Generation at node i
M	Distribution matrix
PI	Vector of nodal power inflow
P_G	Vector of nodal generations
$P_{G_{n,DCOPF}}$	Delivered power by unit n through DCOPF problem
$P_{G_{n,i,DCOPF}}$	Contribution OF unit n in node i to supply load at node i through the DCOPF problem

Parameters:

$a_n,\ b_n, c_n$	Coefficients of the generation cost function of the n-th generator
X_{ij}	Reactance of line connecting nodes i and j
$P_{ij\max}$	Capacity of the line connecting nodes i and j
$P_{Gn\min}$	Lower limits on generation
$P_{Gn\max}$	Upper limits on generation
p_d	Total demand
N	Number of independent observations
C_n	capacity of unit (participant) n

Abbreviations / acronyms

MRS_n^*	Modified most run share of participant n in deterministic term
$MMRS_n$	Modified most run share of participant n in probabilistic term
$NMRS_{n,i}^*$	Modified nodal must run share of participant n at bus i in deterministic term
$MNMRS_{n,i}$	Modified nodal must run share of participant n at bus i in probabilistic term
$IDSI_n$	Integrated dominant supplier index of participant n
$Probabilistic\_IDSI_n$	Probabilistic term of integrated dominant supplier index
$NIDSI_{n,i}$	Nodal integrated dominant supplier index of participant n at bus i
$Probabilistic\_NIDSI_{n,i}$	Probabilistic term of nodal integrated dominant supplier index

I. INTRODUCTION

One of the major objectives of deregulation in the electric power industry and the creation of electricity markets is to increase competition and facilitate and expand the effective participation of generation companies in the market. Therefore,

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the issue of competitiveness is very important. While market power reduces the level of competition in the market, indeed, it is an anti-competitive problem. As a definition, market power is the ability of a supplier or a firm to raise the price above the competitive level for a significant period [1]. Before deregulation, the electric utilities were often vertically integrated so that the electrical energy was generated, transmitted, and distributed by them to individual consumers. At this type, the consumers had the least choices to choose utilities to buy the energy. These utilities had held a monopoly for supplying the electricity demand of consumers. So, they could control the energy price at the monopoly level and make it higher than usual [2]. By deregulation in the power industry, the electric utilities' monopoly status was removed and changed into a competitive and oligopoly status that caused efficient operation in the power industry and encouraged unnecessary investments. Electricity markets created and often of vertically integrated utilities displaced by horizontally integrated utilities and market power became an essential issue in the power industry [2]. The main focus is on horizontal market power, where a supplier merges or colludes with other suppliers in the market to act like a monopolist. Like transmission constraints and non-competitive behaviors of suppliers like capacity withholding and financial withholding, many factors can lead to market power. Nowadays, market power potential is a growing concern in the design, planning, and operation of the electricity market, which results in inefficient short term dispatch outcome and long term generation investment decisions, the pressure to over-build generation and transmission capacity, and most importantly, substantial wealth transfer from electricity customers to generators [3]. Market power assessment is necessary to have a market with a higher level of competition. Therefore, indicators with a precise function for measuring market power are needed. According to the studies of market power in the electricity market, there is a difference between the potential of market power and exercised market power. In this regard, the market power assessment monitoring indices can be classified into two categories called ex-ante and ex-post, which ex-ante indices of market power assessment are used to estimate the future market power, and ex-post indices are used to detect the exercised market power in the electricity markets [4].

The first step to assess market competitiveness among the suppliers is evaluating the market structure in terms of suppliers' shares and concentrations. The HHI is the most common and simplest ex-ante (structural) index of market concentration that is defined as the sum of squares of market shares of all the suppliers in a market [5]. Numerical intervals have been set to assess the market concentration level by this index; if the value of HHI is between 0 and 1000, it represents that market is non-concentrated and between 1000 and 1800 is moderately concentrated, and the value more than 1800 is highly concentrated. This index has a static nature and also ignores the demand-side effect. The pivotal supplier index (PSI) with considering the demand side, represents whether a supplier's generation is pivotal for supplying the load or not. Indeed, this index examines whether the capacity of a generator is greater than the surplus in the wholesale market or not. This assessment outcome is 0 or 1, where one means the supplier's output is necessary to serve the load, and hence the supplier or generator is pivotal. On the other side, if the PSI is 0, the supplier or generator is not pivotal. A pivotal supplier has complete control over the market-clearing price, and it can set the price much higher than the competitive market price. However, PSI is only a binary evaluation of market power assessment and does not reveal the potentiality of having market power [6], [7]. The residual supplier index (RSI) is similar to PSI, but it assesses the supplier's likelihood of having market power in percentage, but not in binary form. RSI less than 100% represents that the supplier is pivotal. The overall RSI score of a market for a period is the sum of all supplier's RSI in a market. According to the California independent system operator (CAISO), an overall RSI score of 120%-150% is an indicator of a reasonably competitive market [8]. The indices mentioned above have a static nature and ignore demand-side effect, transmission constraints, and generation uncertainties.

Another ex-ante assessment of the market power monitoring index is the must run share (MRS) index; it also reflects the generation and transmission constraints in electricity markets. The MRS is defined as the minimum required market share of participants in a power market to supply a given demand. Meanwhile, if the amount of MRS is larger than zero, it means that the participant can exercise market power [5], [9]. Furthermore, it ignores the impact of the cost function of participants. The nodal must run share (NMRS) index is proposed in [9] to assess locational market power. NMRS is a developed Type of MRS, Which the MRS is applied to each load bus to assess nodal market power by considering geographical difference and load variation effects. Lerner index (LI) is another market power monitoring index related to price and marginal cost and load elasticity, which measures the price's proportional deviation at the firm's profit-maximizing output from the firm's marginal cost [10]. In [11], the Herfindahl concentration index (HCI), an amended and mixed concept of aggregate Lerner index and HHI, is used to detect market power. In [12], must run ratio (MRR) and system-wide locational market power index (SWI) are represented by a zonal approach and a nodal approach, respectively, that both consider transmission constraints. MRR provides necessary information about the capacity generated by a generating company to supply a given load through a congestion zone. SWI examines what percentage of a power system total capacity under the control of generator(s) with locational market power. They depend on market share owned by generators to supply load at congestion zone and cannot satisfy the effect of generators on an increase of market price in situations that generators in different congestion zones due to having different market shares may have the same MRRs and they do not consider renewable energy resources effects. In [13], two indices named price offset index (%ΔL) and wealth transfer yield rate (ΔN) were proposed to evaluate market power in power markets. This paper’s approach contributes to clarifying market power by classification. Market power is classified in four-level as none, weak, medium, and strong. The indices mentioned above have static nature and ignore the impact of participants' cost function and generation uncertainties of renewable energy resources.

In [14], market power in an oligopoly power market was analyzed by the capacity withholding index, capacity distortion index, price distortion index, and distortion-withheld index (DWI). These indices ignore transmission constraints and evaluate the potential of generating companies' market power by modeling their bidding behavior through the supply function equilibrium (SFE). In [15], some indices were proposed to investigate capacity withholding in an anti-competitive electricity market by considering the impacts of congestion and transmission constraints. Also, the bidding behavior of participants is modeled through the Cournot-Nash equilibrium function. A game-theoretic characterization of market power in power markets is represented in [16]. Also, analysis of the supply function game holds static nature. In [17], the strategic behavior of market participants is analyzed, and the power market structure is optimized supporting capacity constraint, transmission congestion, and DC load flow. A game-theoretic model utilized in the Indonesian power market. Residual Supply Index (RSI) employed for evaluating market power. In [18], the theoretical and quantitative analysis of the profitable consequence of demand shifting in mitigating market power by participants represented by the generation side. In [19], a market power mitigation clearing mechanism (MPMCM) is recommended that leads to restricting the successful exercise of potential market power. Market power modeling executed by Nash equilibrium method. Also, impacts of transmission constraints and expansion on the market power potential of participants were investigated in this research.

In [20], some indices named as transmission-constrained financial withholding index (TCFWI), transmission-constrained physical withholding index (TCPWI), and transmission-constrained block acceptability index (TCBAI) are proposed that assess the real market power and represent the way of exercising them by investigating the submitted biddings of participants. In [21], two new behavioral indices are introduced to assess market power in transmission-constrained electricity markets effectively. The proposed indices determine the actual level of market power by examining the bidding behavior of participants.

In recent years, employing wind power generation in power systems has increased due to its environmental benefits and fuel prices. Various countries are planning to invest in expanding renewable energy resources such as wind power in power systems. Whereas wind generation has stochastic and uncertain nature, its produced power varies as a function of wind speed, and the uncontrollable nature of the wind is undeniable [22]. It can be seen that in the mentioned indices, the impact of renewable generation and the generation cost of generators are ignored. In the following, we will continue to review some of the other studies attempting to consider the impact of renewable energy resources on market power potential in the electricity markets.

Studies of wind in the South Australian electricity market in [23] represent that market power exercise results in a preference for conventional generators' investment rather than in wind generators. Therefore, the profitability of investments in conventional generators is highly sensitive to the exercise of market power. In South Australia, extreme price periods result from very high temperatures that reduce wind speed to lower than average. Thus, wind generators in these areas receive lower average prices in the spot market than conventional generators. This paper has concluded that renewable generation benefits less from market power than conventional generation. In [24], market power in wholesale electricity markets has been analyzed by considering variations of wind farms' capacities and power systems dynamics. The proposed transmission constrained pivotal supplier indicator (TC-PSI) using MCM, and two-point estimation methods have been examined market power in a probabilistic term. It is used to detect pivotal suppliers in the electricity markets. It does not consider generators' generation cost and cannot represent direct information about the amount of supplied load by each generator. Besides, it is not used to detect locational market power due to geographical differences of suppliers.

In this study, to consider the impact of the stochastic nature of renewable generation and the generation cost of generators, ex-ante indexes are modified. New ones are proposed to market power assessment in locational and system points of view in power markets. The new proposed indices try to evaluate the incentive of each participant to exercise market power. In the proposed indices, two types of assessment are considered as deterministic and probabilistic terms. The probabilistic term of these indices considers the stochastic and uncertain nature of renewable energy resources. As known, renewable energy resources such as wind power have stochastic nature and need to analyze more than one scenario to detect the impact of their

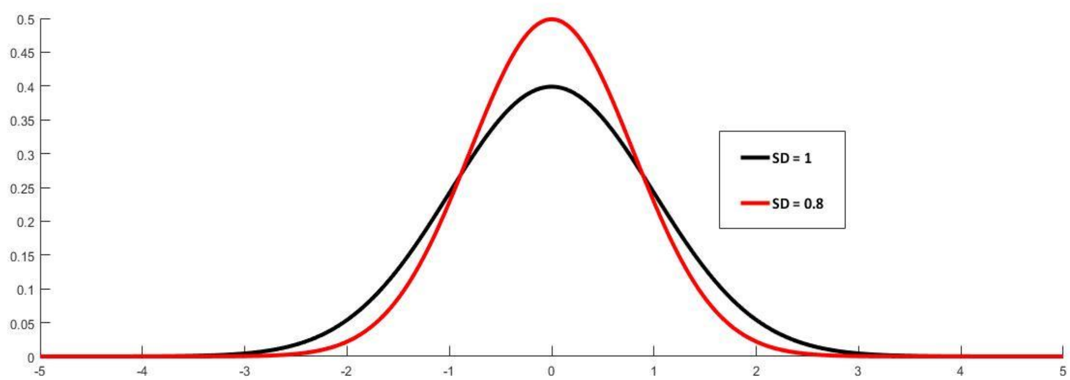

Fig. 1. Typical normal distribution curve

uncertainty. In this study, the MCM is used to model uncertain renewable generation and performs each index's calculation process. It is a probabilistic method used to model wind generators' stochastic behavior by implementing simple sampling of a normally distributed function of random input variables. Participants' cost function to detect how a unit is efficient compared to the other units is included in calculating each index. Also, the cumulative distribution function (CDF) is implemented to discuss the results.

The main contributions of this paper are summarized as follows:

- Modifying existing market power assessment indices for considering the uncertainty of renewable generations.
- Proposing new indices to evaluate the incentive of each participant to exercise market power. The probabilistic term of these indices considers the stochastic and uncertain nature of renewable energy resources.

The rest of this paper is organized as: Section 2 represents a brief review of the Monte Carlo method. In section 3, the modified ex-ante indices and new proposed indices are described. Section 4 represents the numerical results. Section 5 concludes the paper.

II. A BRIEF REVIEW OF MONTE CARLO METHOD (MCM)

The Monte Carlo simulation method is an iterative process for stochastic simulation using random numbers as inputs. On the other hand, Monte Carlo calculation is a numerical stochastic process. The MCM computes the results by simulating the system's actual process and random behavior and is computationally effective than the deterministic method. The main advantages of this method as a stochastic simulation method in power system are as follow [25]:

- It includes the actual system processes (without approximation).
- It is suitable for large-scale system evaluation.
- Its ability to simulate probability distributions associated with component failure and maintenance.
- Its ability to simulating nonelectrical factors in power system.

The MCM is different from one study to another but by tending to follow a particular pattern that can be summarized as the following steps:

1. Set the domain for possible inputs.
2. Take inputs randomly from a probability distribution over the domain.
3. Consider a deterministic computation on the inputs.
4. Aggregate the results.

The above steps are used for calculating the probabilistic market power indices supposing that there are 'n' independent observations. Then, the mean of these observations is calculated from the following equation:

$$\frac{1}{n}\sum_{i=1}^{n} x_i \quad (1)$$

In this paper, renewable generations as uncertainty resources are modeled by normal distribution function (bell curve) that is defined by a mean value and standard deviation (SD) (as a percentage of the mean value). A higher value of SD means more dispersion of the normal distribution curve that illustrates more uncertainties (Fig.1).

III. MODIFIED EX-ANTE INDICES AND NEW PROPOSED INDICES

A. *Modeling of renewable energy resources*

Nowadays, in modern power systems, wind power is known as one of the renewable energy resources. In addition to the benefits, they have some disadvantages; due to increasing wind power generation integration, uncertainties have been grown significantly since wind generation is strongly related to weather conditions. The generation of wind power producers can vary from zero to the installed capacity of the farms. Thus, wind power has stochastic behavior and generation. So, the generation of wind power is considered as a random input variable for this study. The mean value of wind power capacity is considered 50% of the respective wind generators installed capacity. The standard deviation is considered as 0.05% of the mean capacity for all wind power producers in the system.

B. *Modifying the ex-ante market power indices*

In this study, conventional ex-ante indices like RSI, MRS, NMRS, and ENMRS are modified to be used in a probabilistic term. All of these indices are deterministic and cannot detect uncertainties of the power system. This paper evaluates the impacts of renewable generations on market power using the modified ex-ante indices. The effects of the other stochastic parameters, like load, can be studied by the modified indices similarly. So, the impact of renewable generations as uncertainty resources is performed by the MCM on these indices, and the cumulative distribution function (CDF) of each index is obtained. The cost function to detect the efficiency of participants compared to others is included in calculating the indices. This helps in considering the efficiency and real situation of each unit in market power. Therefore, this criterion is calculated through DC optimal power flow (DCOPF) problem. These indices are extended to detect stochastic scenarios of the power system and add prefix M (modified) named MRSI, MMRS, MNMRS. This modifying process is performed, as shown by the flowchart in Fig. 2.

1) *DC optimal power flow (DCOPF)*

The cost function of conventional thermal units is considered as Eq. 2.

$$C(P_{Gn}) = \frac{1}{2}aP_{Gn}^{\ 2} + bP_{Gn} + c_n \quad (2)$$

Where a, b, c are cost parameters of thermal units and P_G is the generation of thermal unit.

DC optimal power flow's goal is to determine the generation dispatch that minimizes the cost to supply a given load, taking operational constraints such as line limits and generation capacities. DCOPF includes the power flow limits of the lines and extends the economic dispatch. Its formulation is described as following:

$$\min_{P_G} \sum_{n\in\Omega_G}\left(\frac{1}{2}a_n P_{Gn}^{\,2} + b_n P_{Gn} + c_n\right) \quad (3)$$

Subject to

$$\sum_{n\in\Omega_{Gi}} (P_{Gn} - P_{Li}) = \sum_{i\in\Omega_i} \frac{\theta_i-\theta_j}{X_{ij}} \quad (4)$$

$$P_{Gn_{\min}} \le P_{Gn} \le P_{Gn_{\max}} \quad (5)$$

$$-P_{ij\max} \le \frac{\theta_i-\theta_j}{X_{ij}} \le P_{ij\max} \quad (6)$$

Where P_{Li} is the load at node i, P_{Gn} is the output of generator n, θ_i the angle at node i, a_n, b_n, c_n are cost parameters of generator n, X_{ij} the reactance of line connecting nodes i and j, $P_{Gn\min}$, $P_{Gn\max}$ are lower and upper limits on generation, $P_{ij\max}$ the capacity of the line connecting nodes i and j [26]. The goal of considering the impact of generation cost of units on market power is implemented by determining power generation in the power market through the DCOPF problem

Modified most run share (MRS) index reflects the generation and transmission constraints in electricity markets. The MRS is defined as the minimum required market share of a supplier (generator) in a market to supply a given market load, as follows:

$$MRS_K = \frac{Pg_n^{must}}{p_d} \quad (7)$$

Where P_d is total demand, and Pg_k^{must} is the minimum capacity of generator k (must run generation (MRG) of generator n) to supply the load. MRG for generator k is obtained from a linear optimization problem as follows:

$$\min Pg_n \quad (8)$$

Subject to

$$e^T(P_g - P_d) = 0 \quad (9)$$

$$0 \le P_g \le P_{g\max} \quad (10)$$

$$-PL_{\min} \le F(P_g - P_d) \le PL_{\max} \quad (11)$$

To considering the impacts of the stochastic nature of renewable resources and the cost function of participants, MRS is modified by performing the MCM, as shown in the flowchart of Fig.2. The DCOPF problem is included in the calculation of the MRS, and it is named as MRS^*. The formulation of MMRS that represents probabilistic term is described as follow:

$$MRS_n^* = \frac{P_{G_{n,DCOPF}}}{P_d} \quad (12)$$

The expected value of MMRS is calculated as:

$$MMRS_n = \frac{1}{N}\sum_{t=1}^{N} MRS_{n_t}^* \quad (13)$$

Where $P_{G_{i,DCOPF}}$ is delivered power by unit i through the DCOPF problem, P_d is total load, and N is the number of independent observations. Also, the index is analyzed by CDF.

2) Modified nodal must run share (NMRS) index

The NMRS, which is used to the nodal ex-ante assessment of market power, is modified to recognize the impact of renewable generations and participants' cost function. MNMRS with the probabilistic approach is formulated as below:

$$NMRS_{n,i}^* = \frac{P_{G_{n,i,DCOPF}}}{P_{d_i}} \quad (14)$$

The expected value of MRSI is calculated as:

$$MNMRS_{n,i} = \frac{1}{N}\sum_{t=1}^{N} NMRS_{n_t,i}^* \quad (15)$$

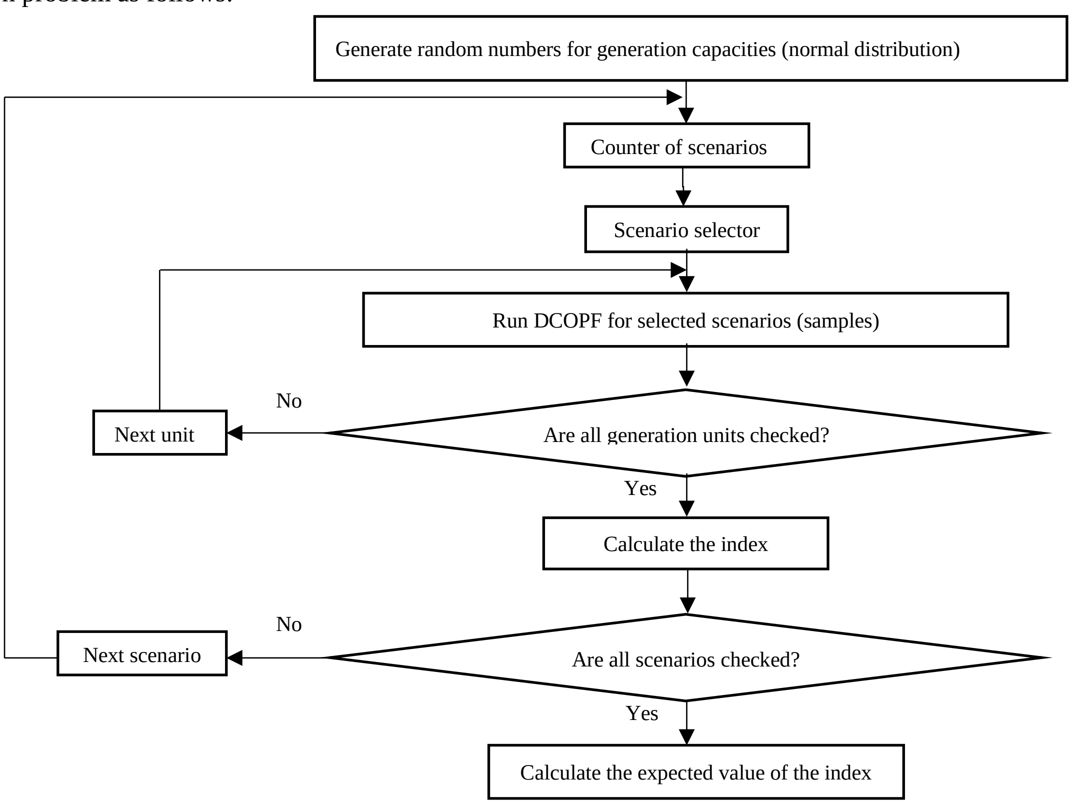

Fig. 2. Flowchart of modifying ex-ante indices of market power

Where P_{d_i} is the load at node i, $P_{G_{n,i,DCOPF}}$ is the unit nth contribution in node i to supply P_{d_i} through the DCOPF problem, and N is the number of independent observations. The $P_{G_{n,i,DCOPF}}$ is calculated from equation (16) to (23):

The generation vector of the unit (P_G) is obtained through the DCOPF problem from (3) to (6) equations, and the delivered power of each unit at each node is calculated from the below equations as a trend of [9]:

The total power inflow PI_i into the node i is obtained from:

$$PI_i = \sum_{j \in N_S} PL_{ji} + P_{Gi} \tag{16}$$

Where N_s is the number of inflows at node i, PL_{ji} is inflow from node j to i, and P_{Gi} is generation at node i. (16) can be expressed as equation (17) or in (18), which is its matrix form.

$$PI_i - \sum_{j \in N_S} \left(\frac{PL_{ji}}{PL_j} PI_i \right) = P_{Gi} \tag{17}$$

$$M.PI = P_G \tag{18}$$

Where PI is the vector of nodal power inflow, P_G is a vector of nodal generations and M is the distribution matrix and its elements (M_{ij}) is examined from equation (19), and if M^{-1} exist we can have equation (20) as:

$$M_{ij} = \begin{cases} 1 & j = i \\ \frac{PL_{ji}}{PI_j} & j \in N_s \\ 0 & otherwise \end{cases} \tag{19}$$

$$PI = \left[M^{-1} \right] P_G \tag{20}$$

The PI of each node is expressed as:

$$PI_i = \sum_{j \in N} \left[M^{-1} \right]_{ij} P_{Gi} \tag{21}$$

By considering equation (21), the load at node i (P_{d_i}) can be expressed as below:

$$\begin{aligned} P_{d_i} &= \frac{P_{d_i}}{PI_i} PI_i = \frac{P_{d_i}}{PI_i} \sum_{j \in N} \left[M^{-1} \right]_{ij} P_{Gj} = \sum_{j \in N} \frac{P_{d_i}}{PI_i} \left[M^{-1} \right]_{ij} P_{Gj} \\ &= \frac{P_{d_i}}{PI_i} \left(\left[M^{-1} \right]_{i1} P_{G1} + \ldots + \left[M^{-1} \right]_{ik} P_{Gk} + \ldots \right) \end{aligned} \tag{22}$$

The above equation explains the contribution of each unit in power inflow to supplying load at node i, now the $P_{G_{k,i,DCOPF}}$ which is the kth unit contribution in node i to supply P_{d_i} through DCOPF problem can be expressed as:

$$P_{G_{k,i,DCOPF}} = \frac{P_{d_i}}{PI_i} [M^{-1}]_{ik} P_{G\,k} \tag{23}$$

C. New proposed indices

The new proposed indices try to evaluate the incentive of each participant to exercise market power. In the proposed indices, two types of assessment are considered as deterministic and probabilistic terms. The probabilistic term of these indices considers the stochastic and uncertain nature of renewable energy resources. These proposed indices are named integrated dominant supplier index (IDSI) and nodal integrated dominant supplier index (NIDSI).

1) Integrated dominant supplier index

Integrated dominant supplier index (IDSI) is proposed to assess the participant's market power potential effectively. It is defined as the proportion of each generator's contribution in power supply to its own total capacity multiplied by the proportion of the contribution of each generator in power supply to total demand. It means that each generator with what percent of its total capacity supplies what percent of total load while participating in its power with minimum generation cost. It can be said that the proposed index is completed and amended form of the MRS index. It considers transmission constraints and the generation cost of the units. The proposed index is represented in deterministic and probabilistic terms. The probabilistic term considers the impact of the uncertain nature of renewable resources on market power potential, and it is obtained through performing the MCM on IDSI. The proposed index has the ability to recognize the potential of market power for participants with different sizes (total available capacity) and the same delivered power (generation). The formulation of the IDSI in a deterministic term is defined as follows:

$$IDSI_n = \frac{P_{G_{n,DCOPF}}}{C_n} \times \frac{P_{G_{n,DCOPF}}}{P_d} = \frac{P_{G_{n,DCOPF}}}{C_n} \times MRS_n^* \tag{24}$$

Where $IDSI_n$ is Integrated dominant supplier index of participant n, C_n is the capacity of unit n, $P_{G_{n,DCOPF}}$ is generated power by unit i through DCOPF, and P_d is the total load.

Moreover, the probabilistic term of integrated dominant supplier index is defined as:

$$Probabilistic\_IDSI_n = \frac{1}{N} \sum_{t=1}^{N} IDSI_{n_t} \tag{25}$$

Where N is the number of independent observations, and then it is analyzed by CDF and provides wider information to assess the potential of market power. Also, the larger percentage of the IDSI means the greater incentive on the unit to exercise market power.

2) Nodal integrated dominant supplier index

The concept of IDSI is performed to each node of the system with the goal of considering geographical differences on market power to define nodal IDISI (NIDISI). It can be said that this index is completed and modified form of NMRS. This nodal index is proposed in deterministic and probabilistic terms. Its probabilistic term considers the impact of renewable generations on market power. The MCM performs it as shown process indicated in Fig.2. The formulation of this index in the deterministic term is as below:

$$NIDSI_{n,i} = \frac{P_{G_{n,DCOPF}}}{C_n} \times \frac{P_{G_{n,i,DCOPF}}}{P_{d_i}} = \frac{P_{G_{n,DCOPF}}}{C_n} \times NMRS_{n,i}^* \tag{26}$$

Where $NIDSI_{n,i}$ is nodal integrated dominant supplier index of participant n at bus i, C_n is the capacity of unit n, P_{d_i} is the load at node i, $P_{G_{i,DCOPF}}$ is delivered power by unit n through DCOPF problem from equations (3) to (6), $P_{G_{k,i,DCOPF}}$ is the kth unit contribution in node i to supply P_{d_i} through DCOPF problem

(3) to (6). The probabilistic term of nodal integrated dominant supplier index is defined as:

$$Probabilistic\_NIDSI_{n,i} = \frac{1}{N}\sum_{t=1}^{N} NIDSI_{n_t,i} \qquad (27)$$

Where N is the number of independent observations, furthermore, the result of the index is analyzed through CDF to assess the local market power.

IV. NUMERICAL STUDIES

This section illustrates the effective performance of the proposed indices and the modified ex-ante indices, they are applied to the modified IEEE 30-bus system. The system data is derived from [27]. The results are examined and compared with the previous indices. In this paper, in a probabilistic term, units 1 and 3, located at nodes 1 and 22, are modeled as wind generators. The other units are conventional thermal units, and this study does not consider the uncertainties of thermal units and transmission lines. Furthermore, in this study, the coding and simulations were performed in MATLAB R2018 software.

A. Results of the modified indices

1) MRS and MMRS*

According to Fig.3, in a deterministic term, MRS* for each unit is calculated, which varies from %5.28 to %32.79; thus, all of them have market power potential. The maximum MRS* is determined for unit 1, about %32.79, and units 5 and 6 possess the least market power. In probabilistic terms, MMRS is calculated too, which is over zero for all units, so units possess market power potential. The largest MMRS is for unit 2, which is expected to be about %31.09, and units 5 and 6 with about %8.55 possess the same and lowest potential of market power than others. Fig.4 illustrates the CDF of unit 1 that with a probability of about %99, its MMRS is equal or over % 16.18, and with a probability of about under %0.08, it is larger than %23.85. The CDF of unit 2 in Fig.5 illustrates that for about %96 of scenarios and situations, MMRS is expected to be over %30.19, but the deterministic term, MRS* is calculated %26.42. MMRS and MRS* are compared in Fig.3, and for units 1 and 3 that are modeled as wind power producers, the MMRS is decreased, and for conventional thermal units, it has larger amounts than MRS*. The MMRS effectively analyzes units' market power by considering wind generation uncertainty and generation cost of units. Furthermore, by using CDF, the expected probability of MMRS for each unit is examined, which assesses market power more possible and effective than the deterministic term.

2) NMRS and MNMRS*

The NMRS* and MNMRS of unit 3 at each node are represented in Fig.6, which expresses that by considering the cited conditions as generation uncertainty, the potential of market power for unit 3 has been dramatically decreased at all nodes. In probabilistic terms, it is expected that unit 3 only at nodes 10, 17, 19, 20, 21, 22 possesses the market power potential. NMRS* varies from zero to %100 as shown in the results, this unit at nodes 21 and 22 has its maximum rate. The MNMRS varies from zero to %91.5 and has lower amounts than a deterministic term at different nodes. Fig.7 represents the expected rates of market power at node 2 through the probabilistic approach, and it can be concluded that only units 1 and 2 have the potential of market power, and unit 2 is the dominant supplier at this node. The MNMRS of unit 1 is %25.42 and has a lower amount than NMRS* with a rate of %41.81. The MNMRS of unit 2 is %70.58 and has a higher amount than it's NMRS*, which is %58.16. So, it can be concluded that generation variations significantly affect the rate of market power. CDF of each rate of an index for each unit at each node can be obtained that for example, CDF of unit 3 at node 10 is shown by Fig.8, which represents that with a probability of about %84, the rate of MMRS* is expected to be equal to %30.2 or larger and it may be over %50 with probability about under %0.08.

B. Employing the proposed indices

1) Results of the IDSI

The proposed IDSI index is calculated in deterministic and probabilistic terms, and the results are indicated in Fig.9. According to Fig.9, in a deterministic term, IDSI for all of the units is reached over zero, and they possess the incentive to exercise market power, or it can be said that they possess the potential of market power. Unit 1 has a maximum amount of IDSI, which is equal to %25.423, and it is more incentive to exercise market power than others, and unit 6 with IDIS equal to %1.32 possesses the lowest potential of market power. In probabilistic terms, the probabilistic IDSI is calculated by performing the MCM and determined over zero for all of the units that means all of them are possessing the market power, and expected amounts for this index vary from %3.46 for unit 6 to %22.86 for unit 2.

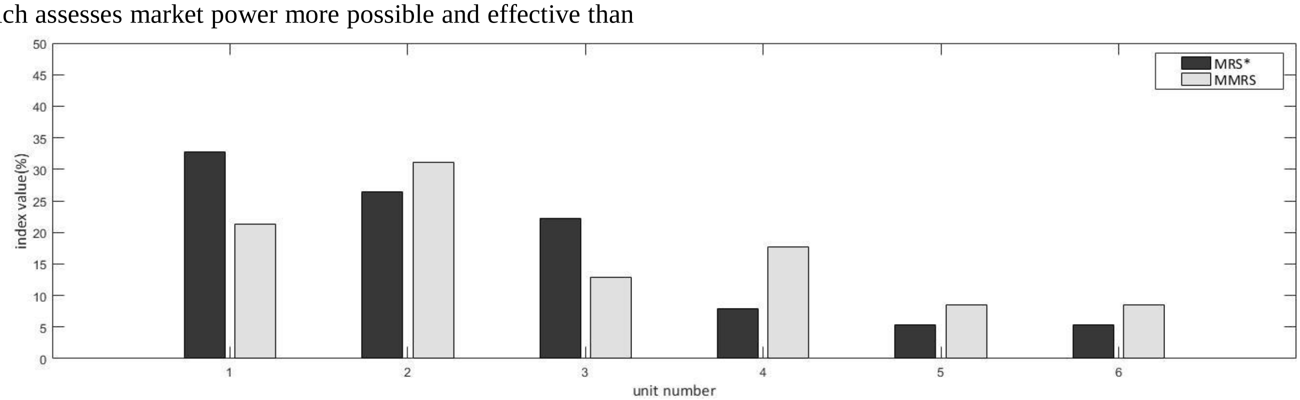

Fig. 3. Comparison of MRS* and MMRS

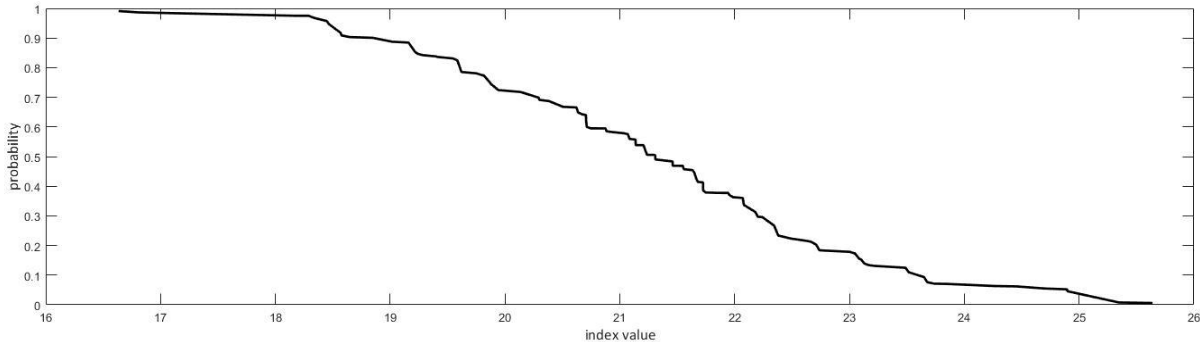

Fig. 4. Cumulative distribution factor curve for MMRS of unit 1

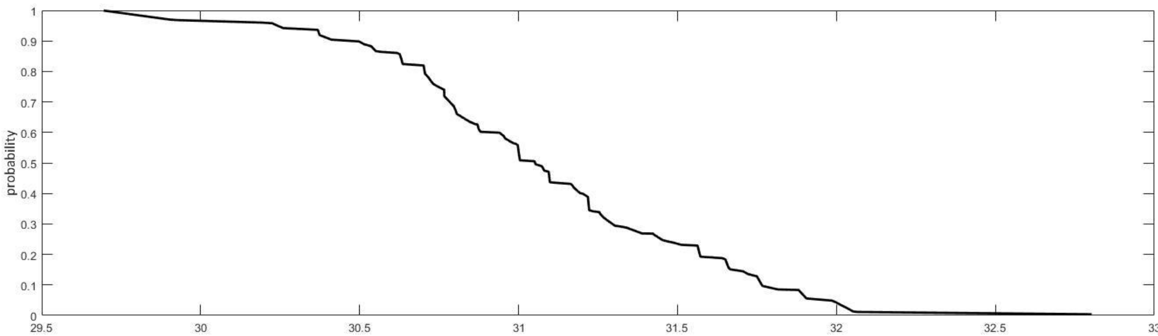

Fig. 5. Cumulative distribution factor curve for MMRS of unit 2

The CDF of each unit to probable analyze its expected rate of market power can be obtained; for example, unit 1's CDF is indicated in Fig. 10, which represents that with a probability of about %90, its rate is expected to be over or equal to %8.4 and with a probability of about %13 is over %12.82. In probabilistic term amounts of this index for unit 1 and 3 has dramatically decreased compared to the deterministic term; thus, other units' potential of market power has been increased. Furthermore, by considering the mentioned impacts, it can be concluded that the market is analyzed more effectively to detect actual market power.

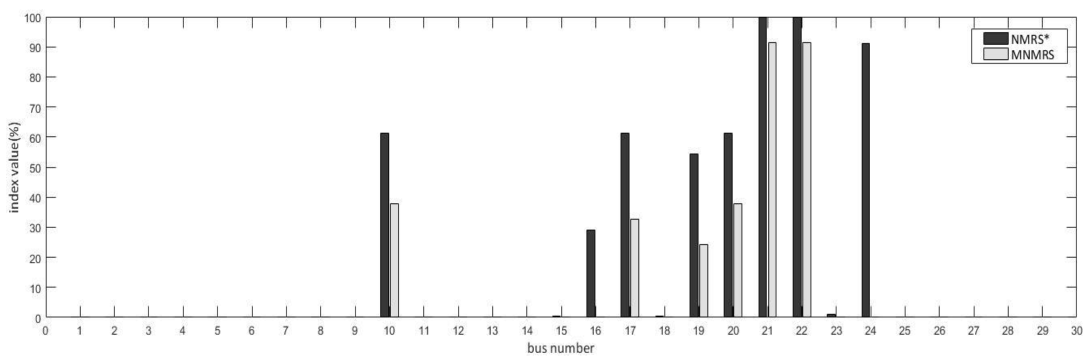

Fig. 6. Comparison of NMRS* and MNMRS (analyze of unit 3 at each node)

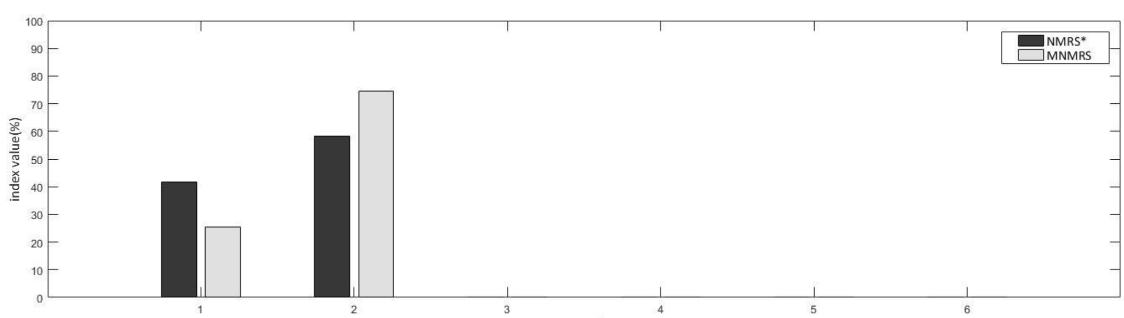

Fig. 7. Comparison of NMRS* and MNMRS (analyze of each unit at node 2)

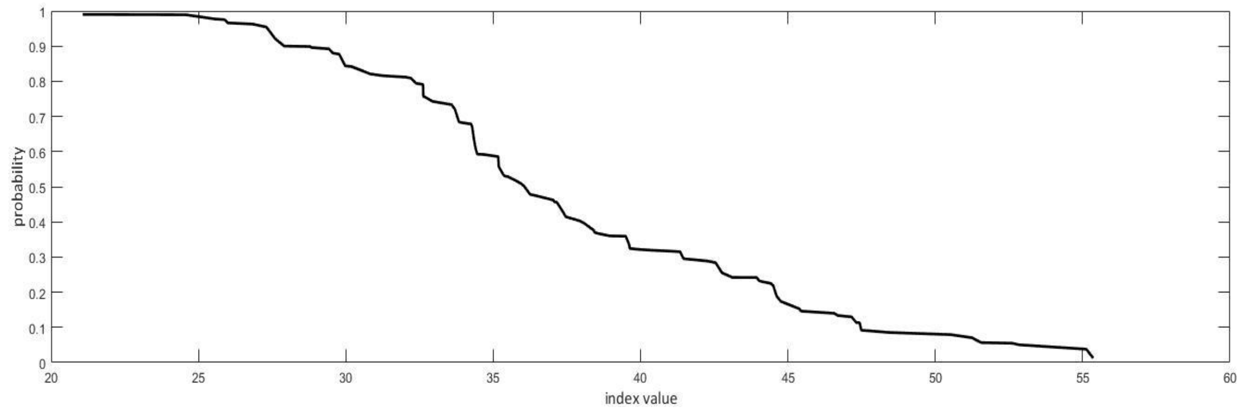

Fig. 8. Cumulative distribution factor curve for MNMRS of unit 3 at node 10

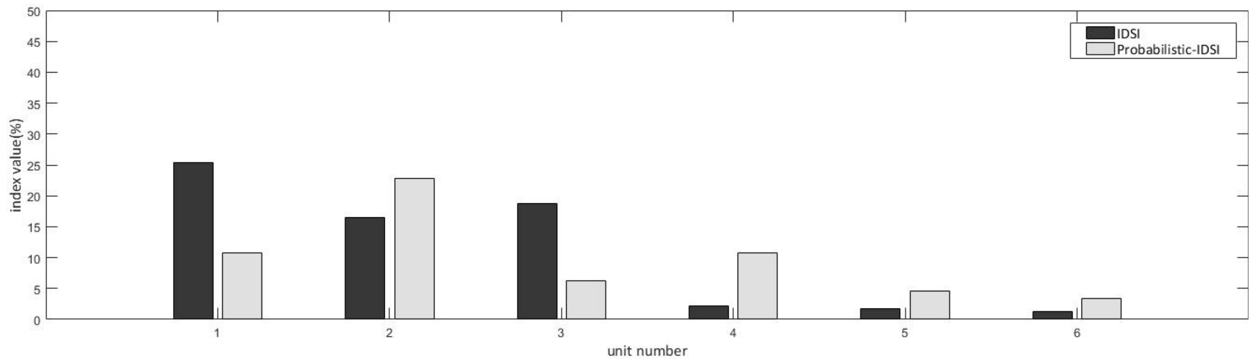

Fig. 9. Comparison of IDSI in deterministic and probabilistic terms

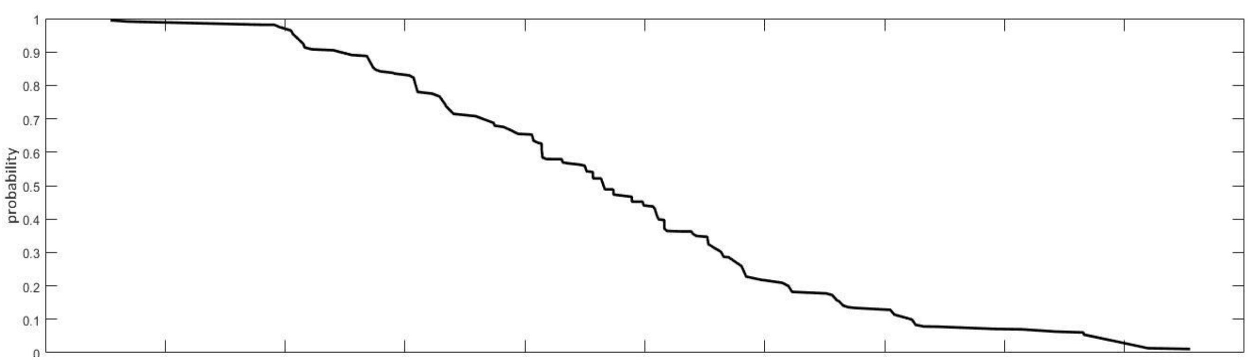

Fig. 10. Cumulative distribution factor curve for probabilistic IDSI of unit 1

2) Results of the NIDSI

The proposed NIDSI index is calculated in both deterministic and probabilistic terms, and results are compared. Furthermore, the NMRS index and its modified type for a probabilistic term called MNMRS are examined and compared in this section.

According to Fig.11, it can be seen that the deterministic and probabilistic terms of IDSI are calculated for unit 3 at each node. It illustrates that NIDSI for unit 3 varies from zero to %84.33 on the system's nodes, and probabilistic NIDSI for unit 3 varies from zero to %44.65. It can be concluded that the rate of the potential of market power is dramatically decreased for unit 3, which is modeled as an uncertain resource. As can be seen from Fig.12, the rate of market power for all units at node 2 is indicated. It can be concluded that only units 1 and 2 can possess the potential of market power and unit 2 is the dominant supplier at this node. The rate of NIDSI for unit 1 at node 2 is expected to be %32.44, whereas, in probabilistic terms, it is expected to be %12.90; so, it has decreased dramatically. The rate on NIDSI for unit 2 at node 1 is expected to be %36.35, whereas, in probabilistic terms, it is resulted in %54.86 and has increased dramatically.

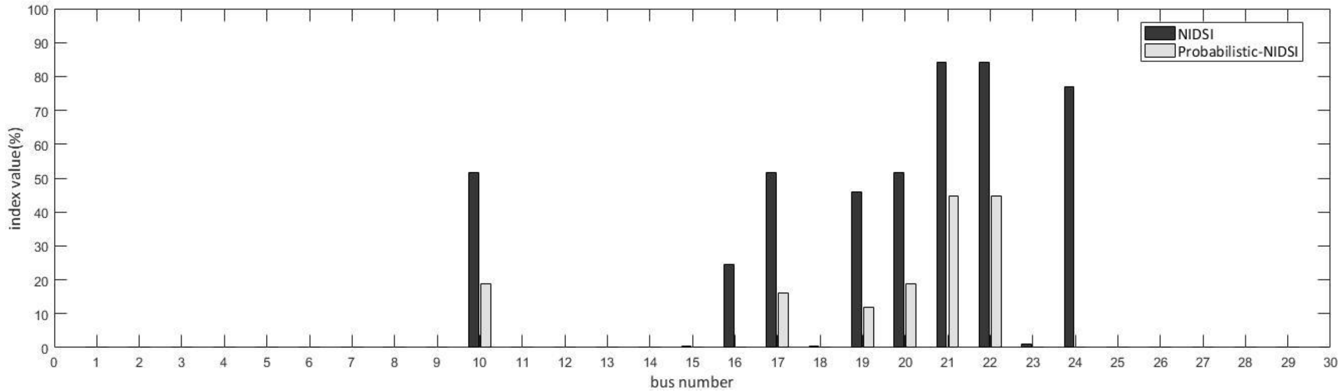

Fig. 11. Comparison of NIDSI and probabilistic NIDSI (analyze of unit 3 at each node)

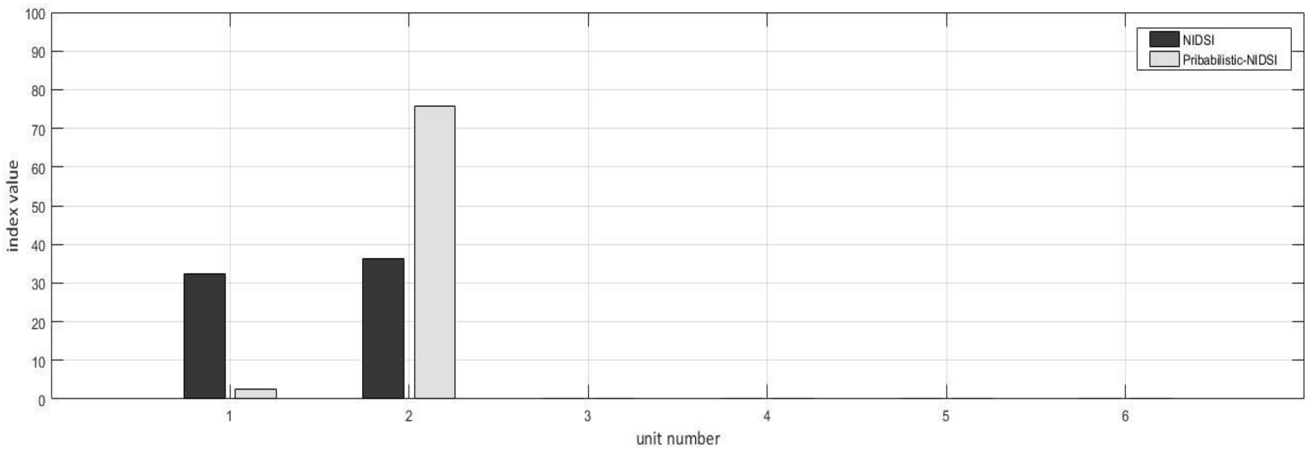

Fig. 12. Comparison of NIDSI and probabilistic NIDSI (analyze of each unit at node 2)

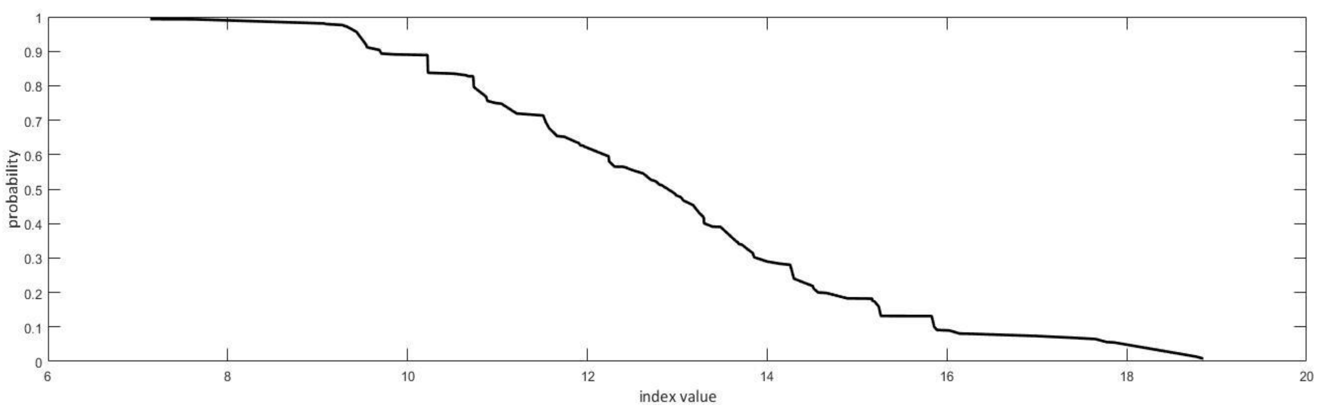

Fig. 13. Cumulative distribution factor curve for probabilistic NIDSI of unit 1 at node 2

Fig.13 represents an example of CDF for probabilistic NIDSI that relates to unit 1 at node 2, which describes that with a probability of about %85, its rate is about %8.9 or larger with a probability of about under %0.07 it is about %14. Therefore, the effective application of the proposed index and performed method to evaluate market power potential by considering different conditions is shown clearly.

C. Comparing the results

In this section, the proposed indices of market power assessment are compared with the conventional or modified ex-ante indices in both deterministic and probabilistic terms.

1) Comparing the IDSI and MRS in both deterministic and probabilistic terms*

As shown in Fig.14, which compares the IDSI with the MRS*, the MRS* of each unit is reached about zero, and it can be noted that when MRS* is not equal to zero, it means that the market is not competitive. Units possess the potential of market power, and the IDSI has an identical opinion about the market power of units. However, the IDSI with different and acceptable amounts represents the rate of market power for each unit, as expected of its formulation and definition. It often has lower amounts than MRS* index. Although the MRS* can determine the potential of market power for all units, IDSI by completing and modifying its acceptable concept and definition related to the size (total capacity) of each unit assesses the market power by covering the weakness of the MRS*. Where the MRS* results same incentive to exercise the potential of market power for units 5 and 6, and it cannot detect the size (total capacity) difference of these units but as it can be seen, the proposed IDSI solves this problem and results in that unit 5 has a higher incentive to use of its potential of market power than unit 6.

In probabilistic terms, as shown in Fig.15, different scenarios are considered by performing the MCM method on the indices. The comparison results represent that the value of probabilistic IDSI is lower than MMRS for each unit. It can be concluded that although MMRS determines the expectation of possessing market power for each unit effectively, they cannot measure its amount effectively and accurately because of expressed weakness for this index. The probabilistic term of these indices by considering explained conditions and effects of system and units have effective performance. Thus, they can calculate each unit's market power with more acceptable amounts and accuracy.

2) Comparison of NIDSI and NMRS in both deterministic and probabilistic terms

The NIDSI and NMRS* for unit 3 at each node are represented in Fig.16. The results of these indices are compared together. Fig. 17 illustrates that the NIDSI and NMRS* of each unit at node 2. It can be concluded that the proposed NIDSI has a lower or maybe the same amount in comparison with NMRS* because it considers the described concept of unit's size as a factor for each unit in its calculations and analyzes the potential of the market power more effective. So, the NIDSI examines more acceptable quantities and real rates than NMRS to analyze the market power level effectively.

The probabilistic NIDSI and MNMRS of unit 3 at each node are compared and shown in Fig.18. The rate of these indices for all units at node 2 is compared in Fig.19. As it can be seen from Fig.18, both indices represent that unit 3 have more ability to exercise the market power at nodes 10, 17, 19, 20, 21, 22 rather than other nodes and Fig.19 represent that from both indices, unit 2 is expected dominant supplier at node 2 but a difference between them is the rate of market power as described previously.

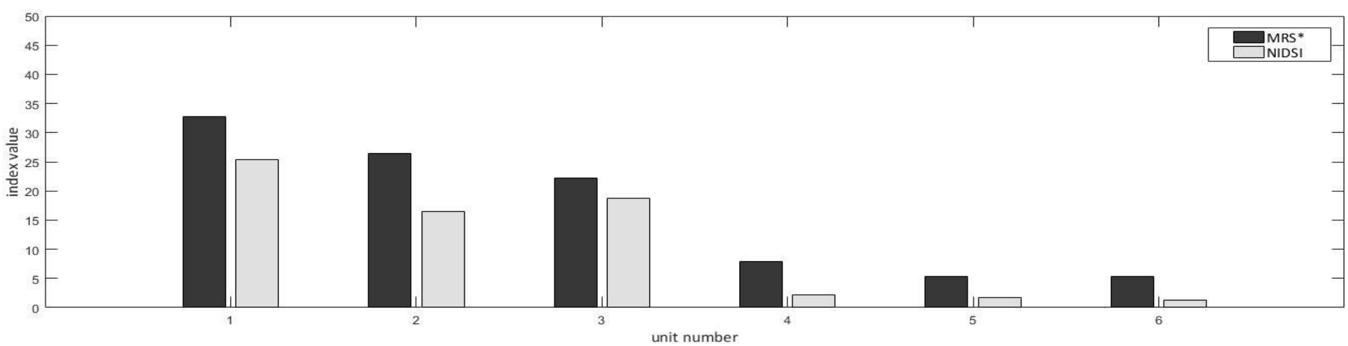

Fig. 14. Comparison of IDSI and MRS*

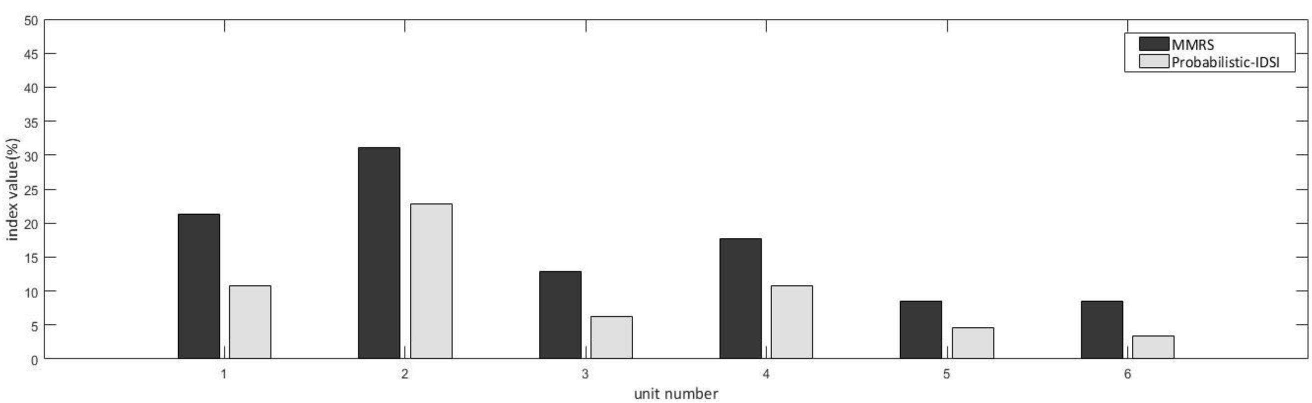

Fig. 15. Comparison of probabilistic IDSI and MMRS

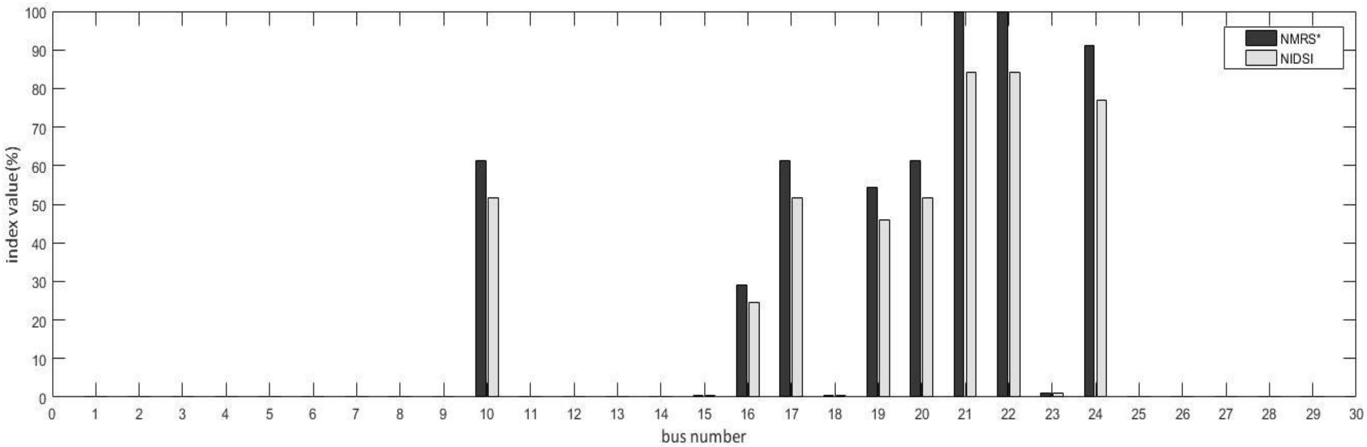

Fig. 16. Comparison of NIDSI and NMRS* (analyze of unit 3 on each node)

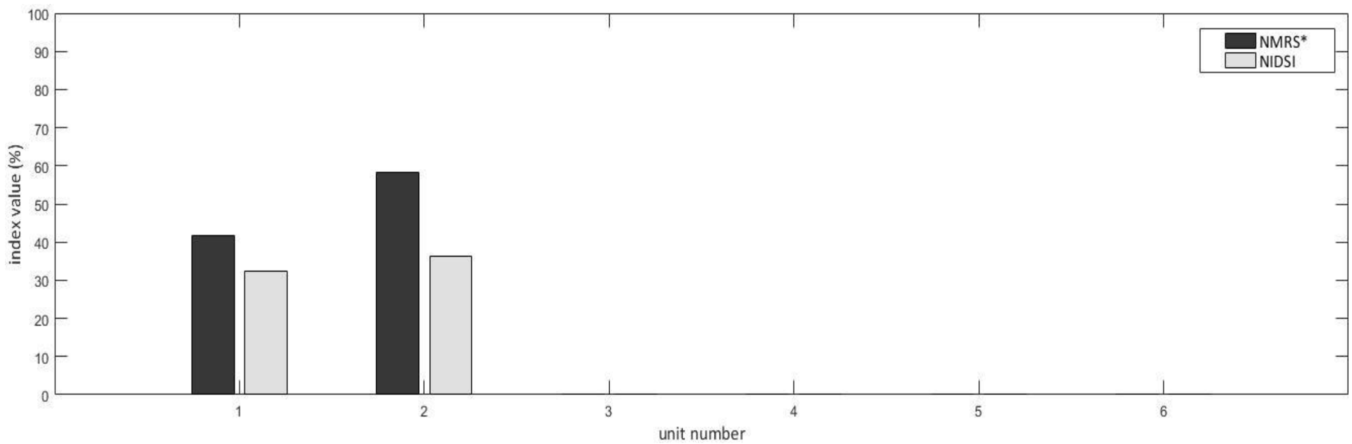

Fig. 17. Comparison of NIDSI and NMRS* (analyze of each unit at node 2)

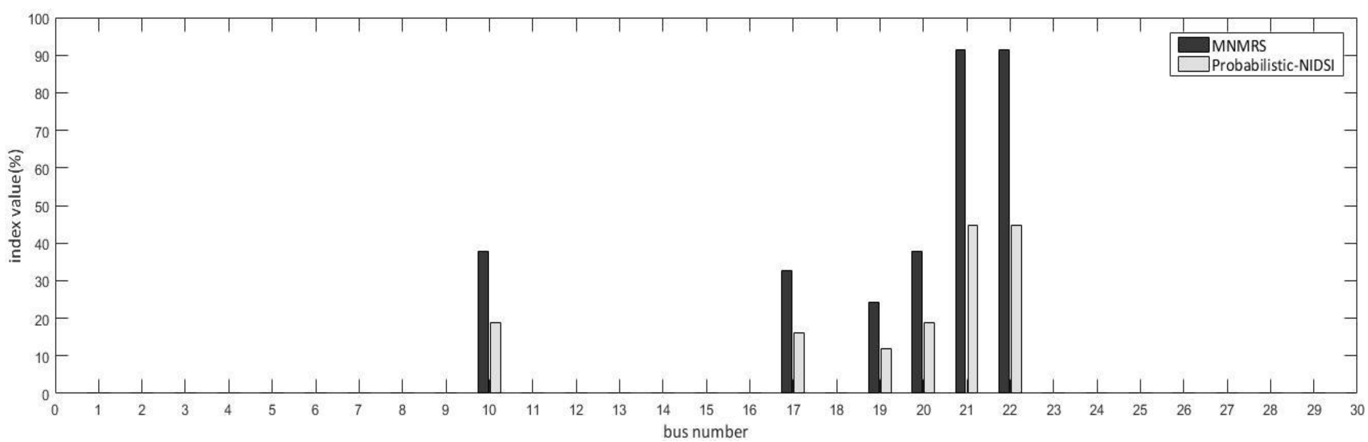

Fig. 18. Comparison of Probabilistic NIDSI and MNMRS (analyze of unit 3 at each node)

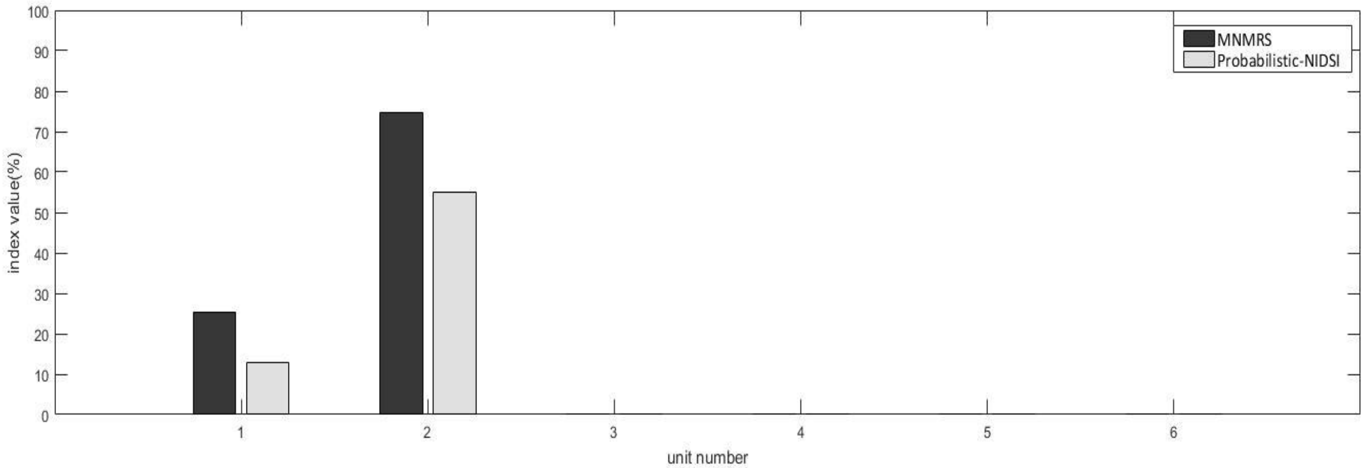

Fig. 19. Comparison of probabilistic NIDSI and MNMRS (analyze of each unit at node 2)

3) Sensitivity analysis

Sensitivity analysis in our study is clearly verified because the different situations are considered via probabilistic term and the deterministic term is compared to the probabilistic term. The probabilistic case calculations include different deterministic terms, so it's a method for verification of the results. Nevertheless, we implement a sensitivity analysis to verifying the results. For this purpose, the generation level of wind units is decreased (units 1 and 3) and the generation level of unit 2 (non-renewable unit) is increased to meet the load. The NIDSI of unit 3 at each node is expected to decrease with respect to the base case. In Fig 20 the NIDSI of unit 3 is represented at each node in the case that generation of unit 3 is decreased. By comparing Fig 20 with Fig. 11 we see that the amount of NIDSI at each node is reduced as expected. Also, by comparing the NIDSI of units at node 2 after changing their generation (Fig 21) with the base case (Fig. 12), we see that the NIDSI of unit 1 is decreased while the NIDSI of unit 2 is increased, which both of them are in the direction of changing the generation of corresponding units. So, the outputs have the same behavior as expected.

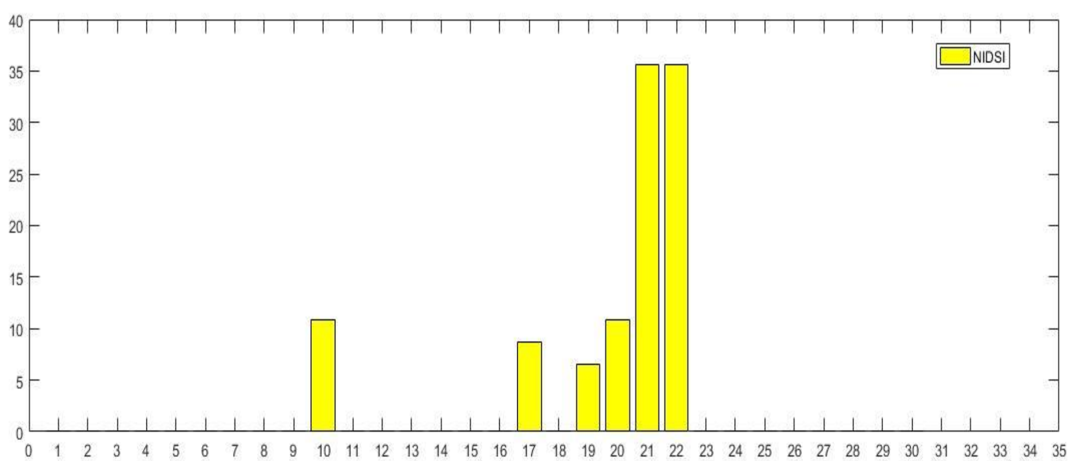

Fig. 20. NIDSI of unit 3 at each node after the decrease in its generation level

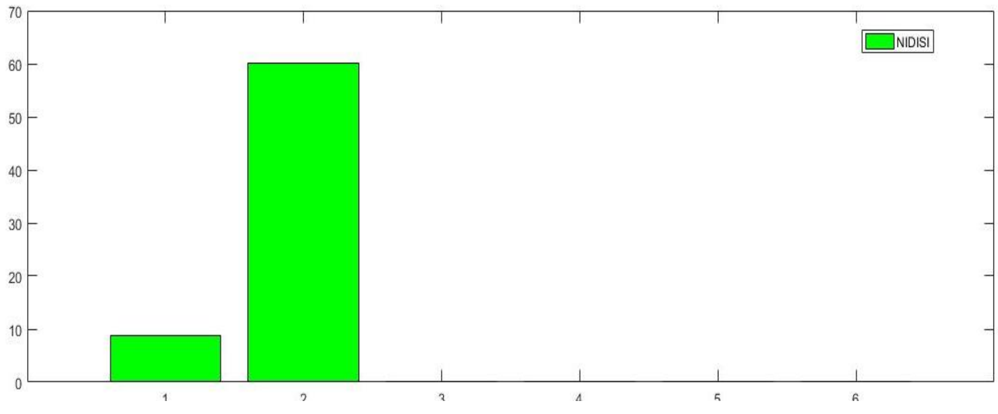

Fig. 21 NIDSI of units 1 and 2 after change in their generation level

V. Conclusion

In this paper, the new indices are proposed, and also some ex-ante indices are modified to overcome the shortcoming of the existing market power assessment indices. In the proposed indices, two types of assessment are considered as deterministic and probabilistic terms. The mentioned proposed indices are completed, an amended form of MRS index and NMRS index, and extends their concept effectively. The MCM is used to model renewable energy resources and is performed to modify some existing ex-ante indices. Also, the cost functions of participants (suppliers) are included in the calculation of indices. The probabilistic term of the proposed indices considers the impact of renewable energy resources' stochastic and uncertain nature. The indices are compared, and the results illustrate that renewable generation dramatically affects the ability or incentive of a participant to exercise market power. The proposed indices have more acceptable results and give a wider view to effective analysis of actual market power in the electricity markets. It is also possible to extend the proposed indices to a system with considering demand side effect and sensitive loads, which is the subject of further work.

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