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Akbari, Mohammad Amin ; Aghaei, Jamshid; Barani, Mostafa; Savaghebi, Mehdi; Shafie-khah, Miadreza; Guerrero, Josep M.; Catalao, Joao P. S.

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New Metrics for Evaluating Technical Benefits and Risks of DGs Increasing Penetration

Mohammad Amin Akbari, Jamshid Aghaei, *Senior Member, IEEE,* Mostafa Barani, Mehdi Savaghebi, *Senior Member, IEEE,* Miadreza Shafie-khah, *Member, IEEE,* Josep M. Guerrero, *Fellow, IEEE,* and João P. S. Catalão, *Senior Member, IEEE*

***Abstract*—Increasing penetration of distributed generation (DG), may be interesting from several points of view, but it raises important challenges about distribution system operation and planning practices. To optimal allocation of DG, which play an important role in construction of microgrids, the benefits and risks should be qualified and quantified. This paper introduces several probabilistic indices to evaluate the potential operational effects of increasing penetration of renewable DG units such as wind power and photovoltaic on rural distribution network with the aid of evaluating technical benefits and risks trade-offs. A probabilistic generation-load model is suggested to calculate these indices which combine a large number of possible operating conditions of renewable DG units with their probabilities. Temporal and annual indices of voltage profile and line flow related attributes such as Interest Voltage Rise (IVR), Risky Voltage Rise (RVR), Risky Voltage Down (RVD), Line Loss Reduction (LLR), Line Loss Increment (LLI) and Line overload flow (LOF) are introduced using probability and expected values of their occurrence. Also, to measure the overall interests and risks of installing DG, composite indices are presented. The implementation of the proposed framework in a 4-bus and IEEE 33-bus radial distribution systems shows the effectiveness of the benefits and risks assessment technique with the proposed metrics.**

***Index Terms*—Distributed generation, microgrid design, probabilistic indices, voltage profile, losses, overloading, benefits and risks.**

NOMENCLATURE

It should be mentioned that $\mathbb{A}$ stands for the attributes, i.e., IVR, RVR, RVD, LLR, LLI and LOF, e.g., $P\mathbb{A}$ can be $PIVR$.

A. Indices (Sets)

$t\ (\Omega^T)$	Index (set) for time.
$s\ (\Omega^t)$	Index (set) for scenarios at time period t.
$b/l\ (\Omega^B/\Omega^L)$	Index (set) for buses/lines.

B. Acronym of Proposed Indices

$P\mathbb{A}^{\text{BUS/LINE}}$	Probability of each attribute at each bus/line.
$P\mathbb{A}^{\text{SYS}}$	Probability of each attribute in the system.
$E\mathbb{A}^{\text{BUS/LINE}}$	Expected value of each attribute at each bus/line.
$E\mathbb{A}^{\text{SYS}}$	Expected value of each attribute in the system.
$AP\mathbb{A}^{\text{BUS/LINE}}$	Annual probability of each attribute at each bus/line.
$AP\mathbb{A}^{\text{SYS}}$	Annual probability of each attribute in the system.
$AE\mathbb{A}^{\text{BUS/LINE}}$	Annual expected value of each attribute at each bus/line.
$AE\mathbb{A}^{\text{SYS}}$	Annual expected value of each attribute in the system.
$B\mathbb{A}^{\text{BUS/LINE}}$	Binary value of each attribute at each bus/line.
$D\mathbb{A}^{\text{BUS/LINE}}$	Amount of each attribute at each bus/line.

M. A. Akbari, J. Aghaei and M. Barani are with the Department of Electrical and Electronics Engineering, Shiraz University of Technology, Shiraz, Iran (e-mail: m.akbari@sutech.ac.ir; aghaei@sutech.ac.ir; m.barani@sutech.ac.ir).

M. Shafie-khah is with C-MAST, University of Beira Interior, Covilh 6201-001, Portugal (miadreza@ubi.pt).

M. Savaghebi and J. M. Guerrero are with the Department of Energy Technology, Aalborg University, DK-9220, Aalborg East, Denmark (e-mail: mes@et.aau.dk; joz@et.aau.dk).

J.P.S. Catalão is with INESC TEC and the Faculty of Engineering of the University of Porto, Porto 4200-465, Portugal, also with C-MAST, University of Beira Interior, Covilhã 6201-001, Portugal, and also with INESC-ID, Instituto Superior Tcnico, University of Lisbon, Lisbon 1049-001, Portugal (e-mail: catalao@ubi.pt).

I. INTRODUCTION

DISTRIBUTED generation (DG) in power distribution networks has rapidly increased due to the deregulation and environmental concerns. The implementation of DG units such as wind and solar photovoltaic (PV)-based units in existing distribution system, provides various technical and/or economic benefits, however, high levels of penetration may bring additional challenges for traditional electric power systems [1]–[9]. Power injections from DG change magnitude and even direction of network power flow. This result in, for example, potential of improving voltage profile and reducing losses, and/or causes too high/low voltage magnitude, losses increment, transformers and lines overloads [9]–[11]. Also, network operation and planning practices of distribution network operators (DNOs) and/or distribution companies (DISCOs) affected by DG integration with both technical and economic implications [4], [9], [11].

In order to increase the potential and value of DG penetration, these benefits and risks should be clearly understood, analyzed and quantified. Traditionally, the DNOs try to maximize the technical performance of the distribution network, but it is evident that the first step in optimizing a quantity is being able to calculate it and the next one would be optimizing them with different remedial or preventive actions like network reconfiguration, generation curtailments, distributed reactive sources (DRSs) through capacitor placement or smart operation of renewable resources [10]–[15]. Note that, introducing DRSs to distribution systems can enhance the self-healing of micro grids [12]–[14].

Practically, in order to get the maximum benefits from DGs and DRSs, determination of their optimal size and location in the system is necessary [3], [5]–[8]. In this case, distribution engineers may present some limitations in determining DG size and location. Hence, the existence of indices based on probabilistic technical impacts to indicate *"time"*, *"size"*, *"site"* and *"type"* of DG which will be more beneficial for the distribution network is needed (i.e., for the electric utility, helping distribution engineers take decisions and even shape the nature of the contract that might be established between the DNOs and the distributed generator owners [16]).

Evaluating and quantifying the benefits and risks of DG increasing penetration have attracted the attention of researchers, but to the best of authors knowledge, only a few literatures have attempted to develop indices to assess the impacts of DGs on the distribution systems [3], [6], [7]. A "static" approach aimed at quantifying the benefits of DGs such as voltage profile improvement, line loss reduction, and environmental impact reduction via several indices were introduced in [3]. The ratio of a measure of an attribute with and without DG (with the same load) was derived as an index. Nonetheless, technical issues that could measure the negative impacts of DG were not considered. The voltage improvement index of this work, considering DG and load uncertainties, was implemented in [5] for optimal placement and sizing of DG to improve voltage stability margin in the distribution networks. Another "static" approach aimed at evaluating the impacts of DG on real and reactive power losses, voltage profile, current capacity of conductors and short-circuit current with a multiobjective index was presented in [6]. A distributed "time-varying" generation model of [6] was addressed in [7]. This approach was considered the analysis of both load and generation hourly intervals for the horizon of a year. Nonetheless, exhaustive 8760 analysis intervals per year was employed to evaluating the impacts of DG which computationally complicated and time consuming method. Besides, the uncertainties of load and generation were not included. A "static" model of load and generation was implemented in [10] aimed at determining maximum DG penetration limits considering both voltage rise and line overloading criteria.

The major drawback of these types of indices is that they were computed deterministically. In this situation, the probabilistic nature of load and generation were neglected. Furthermore, for a time horizon considered, they could not measure both benefits and risks of introducing DG. That is, *"when"*, *"where"*, *"how much"*, and *"which type"* of DG could be more beneficial or risky. For example, the voltage profile improvement index which was proposed in [3], [5] should be used only after making sure that the voltages at all load busses are within allowable minimum and maximum limits, typically between 0.95 and 1.05 pu. Thus, it cannot be used to evaluate the risk of voltage deviations (due to large-scale DG penetration) to cope with the standards such as BS EN50160 [17]. In other words, these indices cannot measure the net value of benefits and risks. For instance, line-loss reduction index in [3], [6], [7] measure the average value of both loss reduction and increment in the system.

There is a lack of knowledge on what is the probabilistic evolution of attributes in a feeder as a function of different parameters, such as DG penetration, DG technologies mix, DG dispersion and location. Besides, there are trade-offs between benefits and risks that the DNOs or DISCOs may be willing to take into account. Therefore, definition of new indices to evaluate these benefits and risks, separately, are evident.

This paper covers such drawbacks through the analysis of the impacts of DGs on the radial distribution networks and on time bases of temporally and annual, by several probabilistic indices. Indeed, several new indices are proposed in this paper which comprehensively evaluate the steady state technical impacts of DG increasing penetration on the radial distribution networks.

It should be mentioned that all of these indices consider the uncertainty of the DGs by characterizing them via a discrete set of scenarios. The value of these indices over all buses and lines of the network can provide some information about the overall system conditions and severity of attributes through a time horizon considered. Also, these indices can provide scientific and comparative information for the planning and operation of distribution system including microgrids, for optimal deployment of different types of DGs to assure an acceptable level of security, quality and reliability [1], [2], [4], [12], [13]. Besides, these indices can help DNOs and/or DISCOs to make proper network operation and planning decisions with both technical and economic implications.

The rest of the paper is organized as follows: Section II describes the modeling of the renewable DGs, load, network and generation-load. Section III presents the benefits and risks conditions. Section IV introduces the definition of proposed benefits and risks metrics. Simulation results and case studies are presented in Section V. Some relevant conclusions are outlined in section VI.

II. Model Description

A. Modeling of Renewable Resources

1) Data: In this paper, probabilistic generation of each DG unit has been modeled according to the hourly historical data of the site under study, during two whole years, as well as specific characteristic of DGs. On this basis, each year is divided into four seasons. In order to characterize the random behavior of the Renewable energy resources during each season, a typical day with 24-h time periods is considered. Hence, there are 96 time periods ($4 \times 24 - h$) during a year. For each season, the data related to the same hours of the day are utilized to obtain the probability distribution functions (PDFs) corresponding to each time period. Accordingly, by assuming a month to be 30 days, there are 180 samples (2 years$\times$3 months$\times$30 days) of wind speed and solar irradiance to generate the related hourly PDFs. The probabilistic model of DGs including wind generators (WGs) and PV system are characterized as follows.

2) Probabilistic Model of WGs: Generated power of a wind turbine (WT) rely on the wind speed and its own characteristics. The wind speed is regularly modeled using Weibull distribution function [8], specially with shape index equal 2 which is called Rayleigh distribution function [18]. Accordingly, in this study, the hourly wind speed data for the site under study have been utilized to generate the Rayleigh PDFs which can be formulated as,

$$f_r(v) = \left(\frac{2v}{c^2}\right) \exp\left[-\left(\frac{v}{c}\right)^2\right] \tag{1}$$

where $f_r(\cdot)$ indicates Rayleigh distribution function and c is Rayleigh scale index which is determined based on the historical data for each time period.

These continuous PDFs are sliced into several segments where each segment yields a mean value and a probability of occurrence. Note that the probability of each segment during any specific hour can be expressed as follows:

$$\text{prob}_i^w = \int_{ws_i}^{ws_{i+1}} f_r(v)\, dv_i \qquad (2)$$

here, ws_i and ws_{i+1} indicate wind speed limits of segment i and prob_i^w denotes the probability occurrence of segment i.

3) Probabilistic Model of PV System: The hourly solar irradiance data for the site under study have been utilized to generate a Beta PDF [19] for each time period. Therefore, the PDF of irradiance can be calculated as:

$$f_b(s) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\cdot\Gamma(\beta)} s^{(\alpha-1)} \\ \quad (1-s)^{(\beta-1)} & : 0 \le s \le 1; \alpha, \beta \ge 0 \\ 0 & : \text{otherwise.} \end{cases} \qquad (3)$$

where $f_b(\cdot)$ denotes the Beta distribution function. α and β are the parameters of the Beta function and for each time period, can be determined using the historical data.

In the same way, the Beta PDFs are split into several segments which the occurrence probability of each segment during any specific hour can be expressed as follows:

$$\text{prob}_i^s = \int_{S_i}^{S_{i+1}} f_s(s)\, ds_i \qquad (4)$$

where S_i and S_{i+1} indicate the starting and ending points of the interval i, respectively. prob_i^s denotes the probability occurrence of interval i.

B. Load Data

From the hourly load data for the system under study and the IEEE-RTS system [20], the load profile is considered as a percentage of the annual peak load and can be found in [8].

C. Whole System Characterization

It should be noted that for the site under study two different wind profiles, i.e., WP1 and WP2 are considered in this paper.

- *Generating related PDFs*
  Firstly, the PDFs for solar irradiance and wind speed of WP1 and WP2 are obtained using historical data (24 PDFs for each season related to 24-h of a typical day). As it was discussed in previous section, these continuous PDFs are sliced into several segments for each time period.

- *Developing scenarios with their own probability*
  Next, different realization of the random variables, i.e., solar irradiance and wind speed of WP1 and WP2 are generated using the roulette wheel mechanism (RWM) and Monte Carlo simulation (MCS) [21], separately. By way of illustration consider winter which is modeled through a typical day with a 24-h time period. In this case, N_s, N_{ws1} and N_{ws2} scenarios are generated for solar irradiance, wind speed of WP1 and WP2, respectively. For example, for solar irradiance, each scenario contains 24 values of solar irradiance related to 24-h time period of the typical day. It should be noted that each scenario has its own probability of occurrence.

- *Calculating the output power of the DGs*
  Then based on the characteristics of DG units, the wind speed and solar irradiance of each state is transformed to the output power of wind and PV-based unit through equations (5) and (6), respectively.

$$P_{y,t}^w(v_{y,t}) = \begin{cases} 0 & : v_{y,t} \le v_{in}^c \text{ or } v_{y,t} \ge v_{out}^c \\ P_r^w \cdot \dfrac{v_{y,t} - v_{in}^c}{v_r^c - v_{in}^c} & : v_{in}^c \le v_{y,t} \le v_r \\ P_r^w & : \text{otherwise} \end{cases} \qquad (5)$$

where v_{in}^c, v_{out}^c, v_r and P_r^w represent cut in, cut out, and rated speed and rated power of WT, respectively. $P_{y,t}^w$ denotes the output power of WT associated with wind speed $v_{y,t}$ at time period t and state y.

$$\begin{aligned} P_{y,t}^S(s_{y,t}) &= N \times FF \times V_{y,t} \times I_{y,t} \\ FF &= \frac{V_{MPP} \times I_{MPP}}{V_{oc} \times I_{sc}} \\ V_{y,t} &= V_{oc} - K_v \times T_{y,t}^c \\ I_{y,t} &= s_{y,t}\left[I_{sc} + K_i \times \left(T_{y,t}^c - 25\right)\right] \\ T_{y,t}^c &= T_A + s_{y,t}\left(\frac{N_{OT} - 20}{0.8}\right) \end{aligned} \qquad (6)$$

where $T_{y,t}^c$ is cell temperature (^oC); T_A is ambient temperature (^oC); K_v and K_i are voltage and current temperature coefficient ($V/^oC$ and $A/^oC$), respectively; N_{OT} denotes nominal operating temperature of cell in (^oC); FF is fill factor; I_{sc} and V_{oc} indicates short circuit current and open circuit voltage (in A and V), respectively; I_{MPP} and V_{MPP} are, respectively current and voltage at maximum power point (A and V); $P_{y,t}^S$ is output power of the PV module; $s_{y,t}$ solar irradiance; t and y are the indices of time periods and states.

- *Reducing the number of scenarios*
  A large number of scenarios may contribute to a more accurate model of the random variables. Nevertheless, this increases the computational burden of the problem. Thus, finally, a fast forward scenario reduction method based on Kontorwish distance [22] employed to reduce the number of scenarios while provides a reasonable approximation of random variable of the system.

III. Characterization of Benefit and Risk Indices

The attributes evaluated in this paper are clustered into two categories:

1) **Benefits**—Interest Voltage Rise (IVR) and Line Loss Reduction (LLR) attributes.
2) **Risks**—Risky Voltage Rise (RVR), Risky Voltage Down (RVD), Line Loss Increment (LLI) and Line Overload Flow (LOF) attributes.

However, other technical effects of introducing DG such as benefits or risks of reliability, power quality, emission, congestion, etc can be considered if needed. The purpose of these metrics is to measure how the voltage profiles and line power flows change with increasing penetration of DGs, for instance, how much more often benefits and/or risks conditions occur and with which probabilities.

A. Voltage Profile Related Attributes

By introducing DGs in the system, voltage profile can be improved, because DGs can provide a portion of the real and reactive power to the load, thus helping to decrease current along a section of the distribution line, which, in turn, will result in a boost in the voltage magnitude at the customer site. One of the justifications for introducing DGs is to improve the voltage profile of the system and maintain the voltage at customer terminals within an acceptable range.

Considering the same loads before and after adding DGs, the conditions for evaluating IVR, RVR and RVD attributes are given in (7) to (9), respectively:

$$V_{b,t}^{\text{WODG}} < V_{b,t,s}^{\text{WDG}} < V_b^{\max} : \forall b, \forall t, \forall s \quad (7)$$
$$V_{b,t}^{\text{WODG}} < V_{b,t,s}^{\text{WDG}} \text{ and } V_{b,t,s}^{\text{WDG}} > V_b^{\max} : \forall b, \forall t, \forall s \quad (8)$$
$$V_{b,t}^{\text{WODG}} > V_{b,t,s}^{\text{WDG}} \text{ and } V_{b,t,s}^{\text{WDG}} < V_b^{\min} : \forall b, \forall t, \forall s \quad (9)$$

where, $V_{b,t,s}^{\text{WDG}}$ is the voltage magnitude with DG installation, at bus b for the time period t of state s. $V_{b,t}^{\text{WODG}}$ is the voltage magnitude without DG installation at bus b for the time period t. $V_b^{\min}$ and $V_b^{\max}$ are the minimum and maximum voltage at bus b, respectively.

B. Power Flow Related Attributes

Another major potential benefit offered by DGs is the reduction in electrical line losses. When the line losses after DG connection is lower than before DG penetration, there will be benefit of LLR. On the contrary, when the line losses after DG installation is increased with respect to the line losses without DG, then the risk of LLI will occur. The last situation arises with a high penetration of DG, if the reverse power flow is higher than the power flow without DG. Also, in the case of DG units with induction-machine interface, the reactive-power consumption could actually result in the increase of reactive power flow and hence be the occasion of reactive line loss across the feeder.

The conditions to be fulfilled for LLR and LLI can be given in (10) and (5), respectively.

$$LL_{l,t,s}^{\text{WDG}} < LL_{l,t}^{\text{WODG}} : \forall l, \forall t, \forall s \quad (10)$$
$$LL_{l,t,s}^{\text{WDG}} > LL_{l,t}^{\text{WODG}} : \forall l, \forall t, \forall s \quad (11)$$

where, $LL_{l,t,s}^{\text{WDG}}$ denotes the power losses with DG at distribution line l at time period t at state s. $LL_{l,t}^{\text{WODG}}$ denotes the power losses without DG at distribution line l at time period t.

Besides, power injected by the DG may cause to be lines overloaded. The following condition may be considered for the evaluation of the risk of LOF.

$$S_{l,t,s}^{\text{WDG}} > S_{l,t}^{\text{WODG}} \text{ and } S_{l,t,s}^{\text{WDG}} > S_l^{\max} : \forall l, \forall t, \forall s \quad (12)$$

where, $S_{l,t,s}^{\text{WDG}}$ is the magnitude of line power flow with DG at distribution line l at time period t at state s. $S_{l,t}^{\text{WODG}}$ is the magnitude of line power flow without DG at distribution line l at time period t. $S_l^{\max}$ is the maximum capacity of line l. It should be noted that there may be overloading situation in many lines before adding DG, so, we consider only the lines that overloaded with DG employment.

IV. Indices Definition

The indices are defined via the probability of occurrence of attributes and the expected values of them. They evaluate the benefits and risks of DG penetration on the whole system and elements (buses and lines), on the time bases of temporary (an hour) and annual. Therefore, they can give overall information about temporal and annual influence and severity of deploying DG in the radial distribution systems. Also, to quantify the overall benefits and risks of DGs, the composite indices are proposed too. The composite indices can help the planner to decide the sitting and sizing of DGs with the highest benefits and lowest risks. It is noted that in the following formulations, $\mathbb{A}$ stands for all the defined attributes, i.e., IVR, RVR, RVD, LLR, LLI and LOF.

A. Temporal Indices

The probability of the attributes for distribution elements (bus or line, b/l) at time period t, $P\mathbb{A}_{b/l,t}^{\text{BUS/LINE}}$, is defined as follows:

$$P\mathbb{A}_{b/l,t}^{\text{BUS/LINE}} = \sum_{s \in \Omega^t} \rho_{t,s} \times B\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}} : \forall b/l, \forall t \quad (13)$$

where, $\rho_{t,s}$ is the probability of each state at time period t. Ω^t is the set of the states at time period t. The binary value associated to each attribute at each bus/line at time period t at state s, i.e., $B\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}}$, denotes that the conditions related to that attribute are satisfied or not. That is, it is equal to 1, if the conditions are satisfied and 0, otherwise. In other words, this binary value denotes the occurrence of each attribute at distribution bus b or line l at time period t for state s.

Since $P\mathbb{A}_{b/l,t}^{\text{BUS/LINE}}$ can be calculated for every bus/line in the distribution system, accordingly, aggregated attribute probability of the system at time period t, $P\mathbb{A}_t^{\text{SYS}}$, is introduced here and can be defined as follows:

$$P\mathbb{A}_t^{\text{SYS}} = \sum_{b/l} k_{b/l,t} \times \rho_{t,s} \times B\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}} : \forall t \quad (14)$$

where, weighting factor k ($\sum_{b/l} k_{b/l,t} = 1$) is chosen based on the importance and criticality of the distribution system elements at each time period [3], [5]. For example, the weighting factor k_b can be determined as the pu value of load connected to bus b. By using this weighting factor, voltage related indices recognizes that bus with highest load demand will have the highest factor.

As this metric does not take into account the severity of the attributes, we introduce the expected value measures. The attributes expected value at distribution elements (bus or line) at time period t, $E\mathbb{A}_{b/l,t}^{\text{BUS/LINE}}$, can be given as follows:

$$E\mathbb{A}_{b/l,t}^{\text{BUS/LINE}} = \sum_{s \in \Omega^t} \rho_{t,s} \times D\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}} : \forall b/l, \forall t \quad (15)$$

where, the amount of each attribute at time period t at state s, $D\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}}$, can be given in (16)-(21), for IVR, RVR, RVD, LLR, LLI and LOF attributes, respectively. For the voltage related attributes, $\forall b, \forall t, \forall s$ we have:

$$DIVR_{b,t,s}^{\text{BUS}} = BIVR_{b,t,s}^{\text{BUS}} \times (V_{b,t,s}^{\text{WDG}} - V_{b,t}^{\text{WODG}}) \quad (16)$$
$$DRVR_{b,t,s}^{\text{BUS}} = BRVR_{b,t,s}^{\text{BUS}} \times (V_{b,t,s}^{\text{WDG}} - V_b^{\max}) \quad (17)$$

$$DRVD_{b,t,s}^{\text{BUS}} = BRVD_{b,t,s}^{\text{BUS}} \times (V_b^{\min} - V_{b,t,s}^{\text{WDG}}) \tag{18}$$

and for the line flow related attributes, $\forall l, \forall t, \forall s$ we have:

$$DLLR_{l,t,s}^{\text{LINE}} = BLLR_{l,t,s}^{\text{LINE}} \times (LL_{l,t}^{\text{WODG}} - LL_{l,t,s}^{\text{WDG}}) \tag{19}$$

$$DLLI_{l,t,s}^{\text{LINE}} = BLLI_{l,t,s}^{\text{LINE}} \times (LL_{l,t,s}^{\text{WDG}} - LL_{l,t}^{\text{WODG}}) \tag{20}$$

$$DLOF_{l,t,s}^{\text{LINE}} = BLOF_{l,t,s}^{\text{LINE}} \times (I_{l,t,s}^{\text{WDG}} - I_{l,t}^{\text{WODG}}). \tag{21}$$

Note that, the binary values $B\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}}$ ensure that for the calculation of the specified attribute values, only the states that cause the occurrence of this attribute should be considered in the evaluation of attribute expected metrics.

Since $E\mathbb{A}_{b/l,t}^{\text{BUS/LINE}}$ can be calculated for every bus/line in the distribution systems, an aggregated expected attribute metrics of the system at time period t, $E\mathbb{A}_t^{\text{SYS}}$, is introduced here and can be defined as follows:

$$E\mathbb{A}_t^{\text{SYS}} = \sum_{b/l} k_{b/l,t} \times \rho_{t,s} \times D\mathbb{A}_{b/l,t,s}^{\text{BUS/LINE}} : \forall t. \tag{22}$$

B. Annual Indices

The above proposed indices can measure temporal effects of DGs on distribution system and can be run for each time period (for example second (sec.), minutes or hour). Also, these indices can be obtained for each distribution element and for each time period. As wind, solar radiation and system demand changes following daily, weekly, and seasonal cycles, the injected power from DGs and flows in distribution elements will vary and accordingly the attributes will be changed. If we calculate the average of the $P\mathbb{A}_{b/l,t}^{\text{BUS/LINE}}$ values of a distribution element across the time horizon considered (e.g., one year), we will obtain the annual attribute probabilities of that element, $AP\mathbb{A}_{b/l}^{\text{BUS/LINE}}$, as follows:

$$AP\mathbb{A}_{b/l}^{\text{BUS/LINE}} = \frac{1}{T} \times \sum_{t \in \Omega^T} P\mathbb{A}_{b/l,t}^{\text{BUS/LINE}} : \forall b/l \tag{23}$$

where, T is the total number of time periods during a year. Averaging $P\mathbb{A}_t^{\text{SYS}}$ over all time periods gives overall probability of each attribute for the time horizon considered, $AP\mathbb{A}^{\text{SYS}}$, and mathematically is given as follows:

$$AP\mathbb{A}^{\text{SYS}} = \frac{1}{T} \times \sum_{t \in \Omega^T} P\mathbb{A}_t^{\text{SYS}}. \tag{24}$$

Similarly, the annual expected values of each attribute for distribution elements, $AE\mathbb{A}_{b/l}^{\text{BUS/LINE}}$, and for system, $AE\mathbb{A}^{\text{SYS}}$, can be obtained as given in (25) and (26), respectively.

$$AE\mathbb{A}_{b/l}^{\text{BUS/LINE}} = \frac{1}{T} \times \sum_{t \in \Omega^T} E\mathbb{A}_{b/l,t}^{\text{BUS/LINE}} : \forall b/l \tag{25}$$

$$AE\mathbb{A}^{\text{SYS}} = \frac{1}{T} \times \sum_{t \in \Omega^T} E\mathbb{A}_t^{\text{SYS}}. \tag{26}$$

Note that, in order to calculating the line flow related indices of (25) and (26) in the unit of kWh, these two equation should be multiplied by $T \times D_t$ (D_t is the duration of time period t). Fig. 1 depicts the calculation procedure of indices related to IVR attribute, for example. Other metrics can be calculated using the same procedure.

Require: solar and wind historical data, load data and network data

define DG type, size and locations (e.g., cases 1 to 9)
provide generation-load model, refer to the section II
for $b = 1$ to total number of buses **do**
  for $t = 1$ to total number of time periods **do**
    run load flow without DG and calculate $V_{b,t}^{\text{WODG}}$
    for $s = 1$ to total number of states in each time period **do**
      run load flow with DG and calculate $V_{b,t,s}^{\text{WDG}}$
      if $V_{b,t}^{\text{WODG}} < V_{b,t,s}^{\text{WDG}} < V_b^{\max}$ **then**
        $BIVR_{b,t,s}^{\text{BUS}} = 1$
      else
        $BIVR_{b,t,s}^{\text{BUS}} = 0$
      end if
      calculate $DIVR_{b,t,s}^{\text{BUS}}$ using (16)
    end for
    calculate buses temporal metrics using (13) and (15)

$$PIVR_{b,t}^{\text{BUS}} = \sum_{s \in \Omega^t} \rho_{t,s} \times BIVR_{b,t,s}^{\text{BUS}}$$
$$EIVR_{b,t}^{\text{BUS}} = \sum_{s \in \Omega^t} \rho_{t,s} \times DIVR_{b,t,s}^{\text{BUS}}$$

    calculate system temporal metrics using (14) and (22)

$$PIVR_t^{\text{SYS}} = \sum_{j \in \Omega^B} k_{j,t} \times \rho_{t,s} \times BIVR_{j,t,s}^{\text{BUS}}$$
$$EIVR_t^{\text{SYS}} = \sum_{j \in \Omega^B} k_{j,t} \times \rho_{t,s} \times DIVR_{j,t,s}^{\text{BUS}}$$

  end for
end for
for $b = 1$ to total number of buses **do**
  calculate buses annual metrics using (23) and (25)

$$APIVR_b^{\text{BUS}} = \frac{1}{T} \times \sum_{t \in \Omega^T} PIVR_{b,t}^{\text{BUS}}$$
$$AEIVR_b^{\text{BUS}} = \frac{1}{T} \times \sum_{t \in \Omega^T} EIVR_{b,t}^{\text{BUS}}$$

end for
calculate system annual metrics using (24) and (26)

$$APIVR^{\text{SYS}} = \frac{1}{T} \times \sum_{t \in \Omega^T} PIVR_t^{\text{SYS}}$$
$$AEIVR^{\text{SYS}} = \frac{1}{T} \times \sum_{t \in \Omega^T} EIVR_t^{\text{SYS}}$$

Fig. 1. Algorithm of Calculating indices related to IVR attribute.

C. Composite Indices

By designating the proposed annual probabilities of system for the benefits and risks indices as AP_i^{SYS} and AP_r^{SYS} for the different attributes in categories 1 and 2, respectively, an overall composite benefits index (CBI) and composite risks index (CRI) can be formulated as follows:

$$CBI = \sum_i w_i \times AP_i^{\text{SYS}} \tag{27}$$

$$CRI = \sum_r w_r \times AP_r^{\text{SYS}} \tag{28}$$

where w_i and w_r are the benefits and risks weighting factors, respectively and $\sum_i w_i = \sum_r w_r = 1$. In the evaluation of composite indices (which can be called multi-objective indices), once again, the choice of weighting factors may come into question. The weights are intended to give the relative importance to each impact index for DG penetration and depend on the analysis purpose (e.g., planning or operation). The determination of proper values for the weighting factors will also depend on the experience and concerns of the system planner or DNO. The simplest approach is to give equal weights to the three indices considered in this study. If more

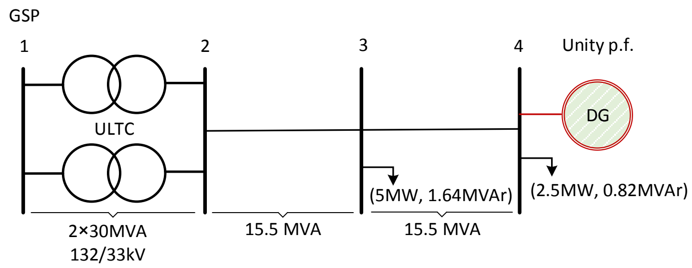

Fig. 2. One-line diagram for the four-bus test feeder at maximum load.

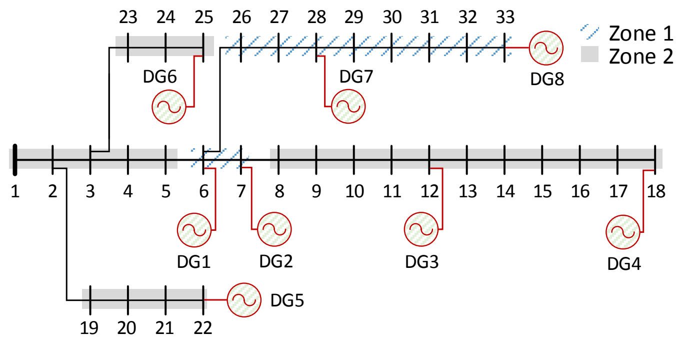

Fig. 3. One-line diagram of the modified 33-bus distribution grid.

indices are included, they can all be given equal weights. However, if DG is introduced to mitigate a certain specific problem (such as voltage profile improvement or lowering losses), then the corresponding index can be assigned a greater weight as compared to others. In short, the weighting factors should be selected carefully by DNO or planner depending on their preferences over different attributes according to the system operational conditions.

V. Simulation Results and Discussion

This paper presents the first attempt to qualify and quantify the possible technical impacts of different penetration levels of utility-owned DGs in radial distribution systems. In this case, DG type, size, and location are known, so it can be considered as a deterministic input. Note that in the decentralized market, the high penetration of renewable DGs in the distribution system can be user-owned resources (small and private wind turbine, solar rooftop bars). Without suitable incentive offerings, utilities may not have control over these resources and DGs become widespread so it will be referred to as nondeterministic [23]. The nondeterministic DGs are probabilistically located at the customer sites to perform analysis of different "what if" (hypothetical) scenarios (i.e., to study the influence of type, size, and location of the DGs on the voltage profile related and line flow related metrics). In this analysis, each scenario corresponds to a different distribution of DGs. This topic is beyond the scope of this paper and will be our future study. However, to address this point, we will study the effects of a "what if" scenario in the end of case study.

A. Distribution System

Two radial test feeders as a simulations, benchmarks for analysing the increasing penetration of DGs are used in this study. A unity power factor is adopted for all DGs based on IEEE std. 1547-2008. In addition, the same weighting factors are assumed for k_l, w_i and w_r, respectively. The weighting factor k_b is set to the per unit value of load at bus b.

1) 4-bus test feeder: A simple 4-bus test feeder is shown in Fig. 2. The network peak load is 7.5 MW. The voltage at the grid supply point (GSP) secondary busbar is set at 1 pu. The line between buses 1 and 2 (considering the two parallel transformers) has the reactance of 0.125 pu and the maximum thermal limit of 0.6 pu on 100-MVA base. These parameters are similar for lines 2-3 and 3-4 with the resistance of 0.196 pu, the reactance of 0.1427 pu and the maximum thermal limit of 0.155 pu.

2) Modified 33-bus radial test system: Single line diagram of this system can be seen in Fig. 3. Detailed load and branch data of this test system is obtained from [24]. Base values of this system are 12.66 kV and 100 MVA. The peak load is 3.715 MW and 2.3 MVAr. The minimum load is 34% of the peak. This radial test system was modified to evaluate the effects of DG penetration. Eight candidate buses of DGs (DG1 to DG8) are assumed to be installed in the system [9], [15], as shown in Fig. 3. The maximum thermal limits of lines between bus 1 to bus 7 are set to 6.6 MVA (which corresponds to a current of 300 A), and other lines are set to 4.4 MVA. Two wind speed zones are considered in this system. Generators DG1, DG2, DG7, and DG8 are assumed to follow WP1 whereas DG3, DG4, DG5, and DG6 are assumed to behave according to WP2.

B. Power Losses Versus Energy Losses

DG impact on losses is an aspect of great interest, as shown by the research community in the last 20 years. The studies found in the literature have concentrated on studying the *power* losses [3], [6] and *energy* [7], [8], [11] losses evaluations. Neglecting the uncertainties of load demand and generation in the planning problems lead to "suboptimal" solutions. For the sake of simple analysis, the impact of the wind-based DG increasing penetration on the line losses is investigated on the 4-bus test feeder, see Fig. 2.

Three cases are evaluated here:

1) **Static**—a snapshot of generation-load model (peak load demand and maximum wind power generation scenario) as defined in [3], [6];
2) **Time varying**—a time varying generation-load demand for hourly intervals for one year as presented in [7]; and,
3) **Stochastic**—a probabilistic generation-load model for one year time horizon as proposed in this paper.

Note that, while indices of this paper cannot be compared by the indices proposed in the previous works ([3], [6], [7]), because they were calculated differently, the focus should be given to the same losses index calculating the ratio of total line losses in the system with DG to the total line losses in the system without DG.

Fig. 4 shows the results by the aforementioned models with a DG plant connected at node 4. In the all cases, a distinct *u-shape* loss curve [11] can be observed by increasing penetration of DG. The results indicate that the snapshot or "power only" analysis depending on the DG capacity leads to over/under estimating solutions. Also, the lowest capacity of 5 MW with the most benefit (with the losses index of

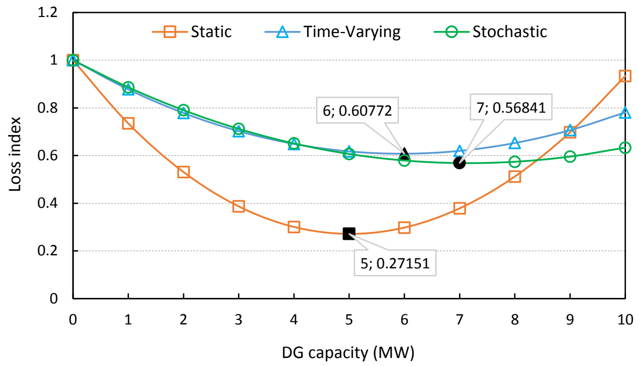

Fig. 4. Effects of DG increasing penetration on the losses index obtained by different generation-load models: snapshot [3], [6], time varying [7] and proposed stochastic.

0.27) and computational time (5 sec.) was observed by this model. When the realistic "energy" basis assessing, i.e., time varying and probabilistic models of generation and load were considered, the losses index of 0.6 and 0.56 were obtained by DG capacity of 6 MW and 7 MW, respectively. The explanation is that, at the most of the time, the actual power injection are lower than the nominal capacity. However, the losses reduction in the most realistic probabilistic model are greater than the time varying model. Finally, in comparison to the probabilistic analysis, the time varying method provides accurate results if DG penetration levels are lower than 5 MW, the losses estimation error increases with the DG penetration level. On a computational burden, with the time varying approach, the analysis is exhaustive using 8760 intervals which is computationally complicated and time consuming method (it takes 180 sec.). The proposed probabilistic model takes only 16 sec. to run which practically is an effective approach in the problems of DG assessing and planning.

The overall conditions and trends of energy losses in the system (or at each line) cannot be measured by this metric. By proposed probabilistic-based indices we can define which line, when and how much often influenced by the DG installation. These information can help DNOs to manage their network by remedial or preventive actions. For example, they can decide about the time of generation curtailments reduce energy losses at the specified time periods.

Energy losses analysis indicates that integration of 5 MW or 9 MW DG in the system will get the same value of the losses index equal to 0.6 (see Fig.4). A question is that, which of these capacities is more beneficial from energy losses reduction point of view. For these capacities, the proposed losses-related indices in the line/system through a year are given in Table I. As can be expected, line 2-3 experiments higher losses reduction and lower losses increment than line 3-4. However, the net energy losses, i.e., the difference between the values of losses reduction and losses increment, are the same with these two DG options. The proposed probabilistic-base metric $APLLR^{SYS}$ indicates that employment of 5 MW DG because of its greater probability is more reliable choice than 9 MW DG installation. However, the value of $AELLR^{SYS}$ by 9 MW is 60 MWh greater than that of 5 MW case, the value of $APLLR^{SYS}$ is 8% lower and $APLLI^{SYS}$ is 8% greater than that of 5 MW case.

TABLE I
PROPOSED EXPECTED LINE LOSSES REDUCTION AND INCREMENT (MWh) BY DG ADDITION, BASE CASE ENERGY LOSSES IS 486 MWh.

DG size	5 MW		9 MW	
Line	2-3	3-4	2-3	3-4
$AELLR^{LINE}$	169	29	232	26
$AELLI^{LINE}$	0.0	6.0	4.8	61.2
$AELLR^{SYS}$	198		258	
$AELLI^{SYS}$	6		66	
$APLLR^{LINE}$	1.0	0.9	0.98	0.68
$APLLI^{LINE}$	0.0	0.1	0.12	0.32
$APLLR^{SYS}$	0.97		0.89	
$APLLI^{SYS}$	0.03		0.11	

C. Assessing Limiting Factors of DG Penetration Level

Employment of DG in existing systems can cause several potential operating issues such as voltage flicker, misoperation of protection, and reverse power flow. The reverse power flow from load bus bars to the substation may cause voltage rise and line overload risks [3], [6], [7], [9], [10]. Therefore, such issues must be taken into consideration to assure an acceptable level of security and reliability.

As mentioned, another deficiency of the previous works in the area is that they can not measure these potential risks associated to increasing penetration of DG in the distribution systems. Simulations were carried out on the 4-bus test feeder (Fig. 2) to determine DG increasing penetration limits, considering both voltage rise and line thermal criteria. Several cases were analyzed using the proposed risk-based probabilistic metrics, with regard to the changes at the substation voltage, VS, ranging from 1.05 pu to 1.00 pu. Fig. 5 summarizes the results of the several simulations aimed to find the limiting factors when installing DG. We plot the probability of having RVR and LOF versus the wind-base DG penetration levels varying from 0 to 80% (30 MW with the capacity factor of 0.2).

One can see that as DG penetration increases, the probability of having RVR at load bus 4 (i.e., $APRVR_4^{\mathrm{BUS}}$) also increases. This probability further rises by increasing the substation voltage. For example, looking at Fig. 5, it can be seen that for a penetration level of 80%, $APRVR_4^{\mathrm{BUS}}$ at $VS = 1.05$ pu is 77%, while at $VS = 1.00$ pu it will be about 7%. It can be observed that RVR at load bus 4 is a serious limiting factor when installing DG. The simulations shows that with $VS = 1.04$ pu, up to 8 MW DG permit to be installed in the feeder. This represents an increase of 33% in DG over the amount in the case of $VS = 1.05$ pu, with only a 0.010 pu reduction in the voltage at the substation. It can be demonstrated that reducing the substation voltage permits higher DG penetration level. However, the voltage at the substation must ensure the loads are always supplied within the allowable voltage limits. As a comparison, the maximum DG penetration level by implementing the "static" approach [10], is about 12% greater than that of the proposed stochastic method. For example, with $VS = 1.05$, the maximum amount of DG to be installed which obtained by static method is 7.04 MW, while the stochastic method allows the maximum DG installation of 2.54 MW.

One can also see that, in this test system, the risk of line overloading is the second major technical issue. It can be observed from Fig. 5 that the starting point of this technical

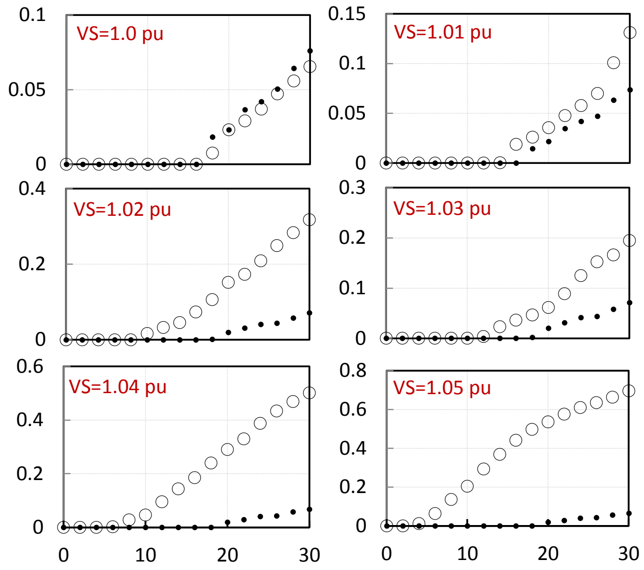

Fig. 5. DG increasing penetration limits: $APRVR_4^{\text{BUS}}$ ("○") and $APLOF_{3-4}^{\text{LINE}}$ ("•"), x-axis: DG size (MW) and y-axis: probability value.

issue is the DG penetration level of 48% (18 MW DG). Since DG injects only active power, the active component of the load (2.5 MW) is thus supplied locally, and the surplus 15.5 MW (this capacity is the line thermal limit) is injected into the grid.

Recently, an strategy to accommodate large-scale DG deployment is based on the Smart Grid-based control schemes such as coordinated voltage control and dispatchable DG power factor. [9], [15]. However, A fast and reliable communications system must be installed throughout the entire system, interacting with DG units in order to enable the centralized control of the entire system [10]. In this control mechanism, the cost effectiveness of using further control mechanisms is questionable. Nevertheless, planning studies must take high DG penetration levels into consideration, so that impacts on the distribution network may be analyzed and control techniques defined.

D. DG Penetration

In this subsection, we aimed to find *"where"*, *"when"*, *"how much"*, and *"which type"* of DG could be more beneficial or risky. Several simulations were performed for analyzing.

1) Effect of DG location: In order to investigate the effects of DG location on each attribute by using the proposed probabilistic indices, DGs were located at candidate buses of 33-bus test system (see Fig. 3). This study performed to analysis "*which*" element, "*how much*" and "*when*" may be influenced by DG integration. Three cases are considered for connection of DGs (50% wind and 50% PV DG units):

Case 1: only two sites are available (DG5 and DG8 with the installation capacities of 3 MW);

Case 2: only six sites are available (DG1, DG2, DG3, DG4, DG7 and DG8 with the installation capacities of 1 MW);

Case 3: all eight buses are available (DG1 to DG8 with the installation capacities of 750 kW).

Note that in all cases the total DGs capacity of 6 MW (30% DG penetration) is considered to be installed in the system. This can be translated into the same energy harvest is all cases. Results of four benefit indices related to the IVR and LLR attributes are shown in Fig. 6 and Fig. 7. A similar trend is followed by indices related to the IVR and LLR, respectively. Better IVR and LLR are obtained in case 3 due to the larger number of degrees of freedom for DG location than in cases 1 and 2. It can be observed that, in cases 1 to 3, the similar values of $APIVR^{\text{BUS}}$ obtained for all buses while $EIVR^{\text{BUS}}$ metrics indicate that the severities of IVR are considerably differ from each other in the cases. This metric confirmed that DG penetration in case 2 has the highest effect on voltage profile. However, the results of risks analysis illustrate that this case causes RVR in some scenarios.

The results of temporal indices on buses/lines show that "*which*" element, "*how much*" and "*when*" often influenced by DG integration, see Fig. 8. For example, the results of case 2 indicates that the voltages of buses 17 and 18 have reached their upper limits in some states at midday in winter and fall seasons (light load high with generation scenarios). Also, bus 33 experiments RVR at the midday of fall in case 1. Same results can be concluded for other attributes.

Comparing the results to those obtained for cases 1 to 3, it is clear that the significant LLR occurs when the DGs with proper sizes are located close to the loads, i.e., case 3. From the results of $AELLR^{\text{SYS}}$ and $AELLI^{\text{SYS}}$ for these cases, energy losses diminished to 42.1 MWh, 176.2 MWh, and 188.7 MWh, respectively.

The results of proposed probabilistic-based impact indices are useful for visualizing the trends and actual impact on each technical attribute. Nonetheless, these individual metrics may be an insufficient tool for decision making. Therefore, to enhance distribution engineers in the technical and economic assessment of DG penetration comprehensively, the composite indices become an effective tool. In addition to the previously mentioned probabilistic based composite indices, i.e., CBI and CRI, we introduce the following new composite indices based on $AE\mathbb{A}^{SYS}$ metrics related to the attributes in categories 1 and 2. By normalizing the indices based on the best possible value obtained in different cases and aggregating them by giving a proper weighting factor to each one, the following composite performance indices can be calculated:

$$EBI = \sum_i w_i \times \frac{AE_i^{\text{SYS}}}{\max(AE_{i,c}^{\text{SYS}})_{c=1}^{Nc}} \tag{29}$$

$$ERI = \sum_i w_r \times \frac{AE_r^{\text{SYS}}}{\max(AE_{r,c}^{\text{SYS}})_{c=1}^{Nc}} \tag{30}$$

here, $\max(AE_{i,c}^{\text{SYS}})$ is the maximum value of AE_i^{SYS} related to the benefit attribute i among all cases ($c = 1, 2, ..., Nc$). Also, $\max(AE_{r,c}^{\text{SYS}})$ is the maximum value of AE_r^{SYS} related to the risk attribute r among all cases. A high beneficial and risky cases mean close-to-unity values for the EBI and ERI, respectively.

As previously mentioned, to select the best location, specified DG units are sited at various buses (cases 1 to 3) after running one base case load flow and proposed probabilistic load flow the corresponding composite indices for each case is calculated. The best location is one with the highest EBI and consequently the lowest ERI, i.e., case 3, see Table II. Furthermore, the results of CBI index confirmed that based on DG size and location, case 3 is the most beneficial case with CBI equal to 0.532 for 30% penetration level. Case 2 with CBI = 0.487 gives the benefit between case 1 with

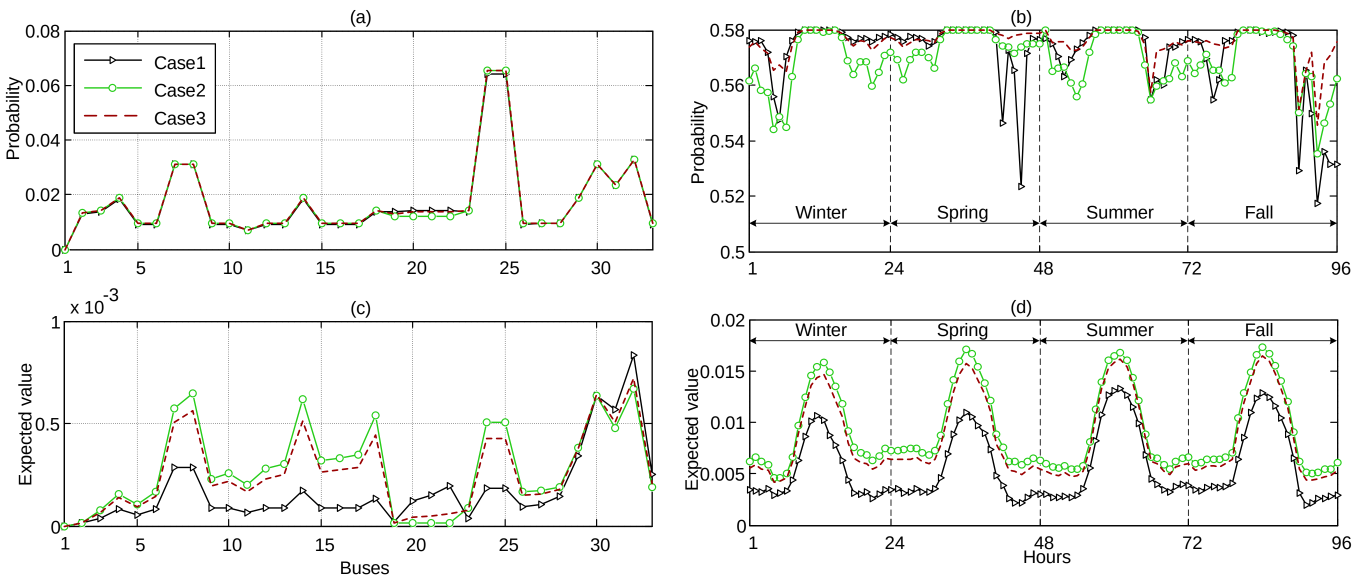

Fig. 6. Effects of DG location on IVR obtained in cases 1 to 3, (a) $APIVR^{\mathrm{BUS}}$, (b) $PIVR^{\mathrm{SYS}}$, (c) $AEIVR^{\mathrm{BUS}}$ and (d) $EIVR^{\mathrm{SYS}}$.

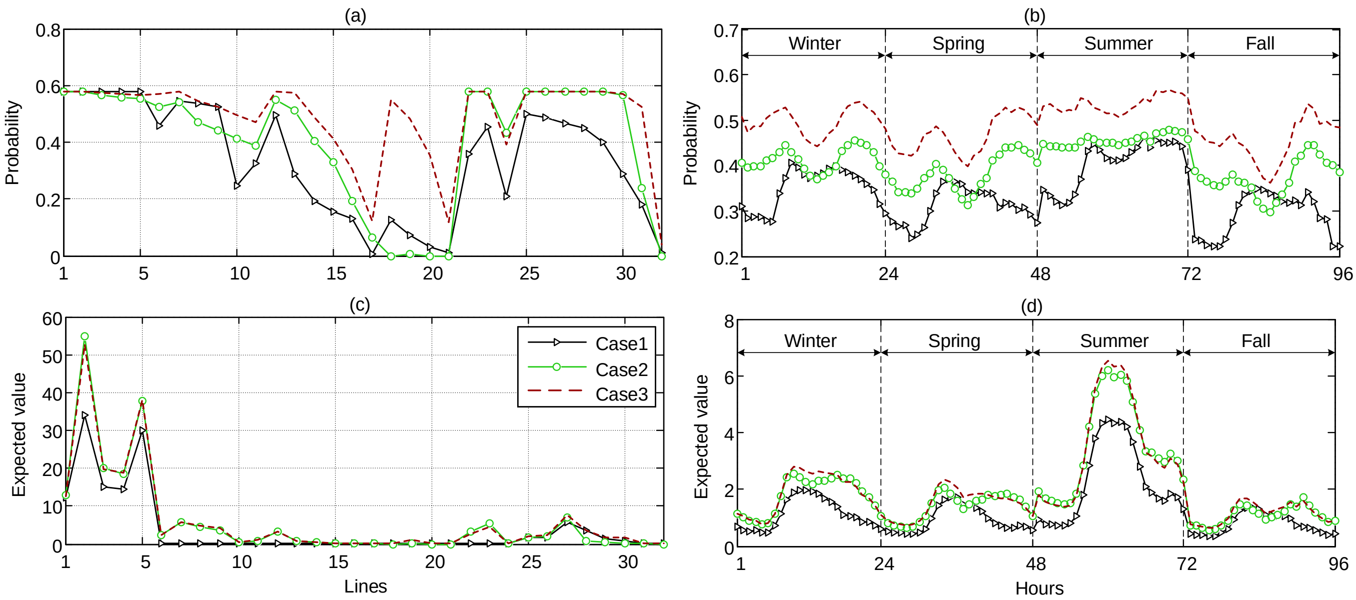

Fig. 7. Effects of DG location on LLR obtained in cases 1 to 3, (a) $APLLR^{\mathrm{LINE}}$, (b) $PLLR^{\mathrm{SYS}}$, (c) $AELLR^{\mathrm{LINE}}$ and (d) $ELLR^{\mathrm{SYS}}$.

TABLE II
EFFECT OF DG LOCATION ON COMPOSITE INDICES.

Index	Case 1	Case 2	Case 3
CBI	0.455	0.487	0.532
CRI	6.01E-02	3.34E-02	3.80E-02
EBI	0.625	0.982	0.956
ERI	0.987	0.562	0.026

$CBI = 0.455$ and case 3, see Table II.

2) Effect of DG type: The effects of wind-base and solar-based PV DG units on the attributes are evaluated via cases 4 to 6.

Case 4: only wind-based DG units (750 kW at each candidate node);

Case 5: only PV DG unit (750 kW at each candidate node);

Case 6: mix of wind-based and PV DG units (750 kW at each candidate node, 50% wind-based and 50% PV).

We will show that the performance of distribution system will be affected by DG energy production patterns. The results of these cases are shown in Table III. The results of cases 4 to 6 show that for 30% penetration level and available sites, considering both technical benefits and risks attributes, the introduction of wind-based DG (case 4) is the worst and the mix of wind-based and solar-based DGs (case 6) is the best choice for installation.

Although, solar radiation and wind speed involve great levels of uncertainty, the attributes of LLR, LLI, IVR and RVR that outcomes in case 4 (only wind-based DG) is higher than for case 5 (only solar DG). A description is that for at least 30% of the year (at night), the output power of the solar DG units is almost zero, as shown in Fig. 9. Within these durations, the system acts similarly to the way it does in the base case, i.e., without DG, which has no effect on the

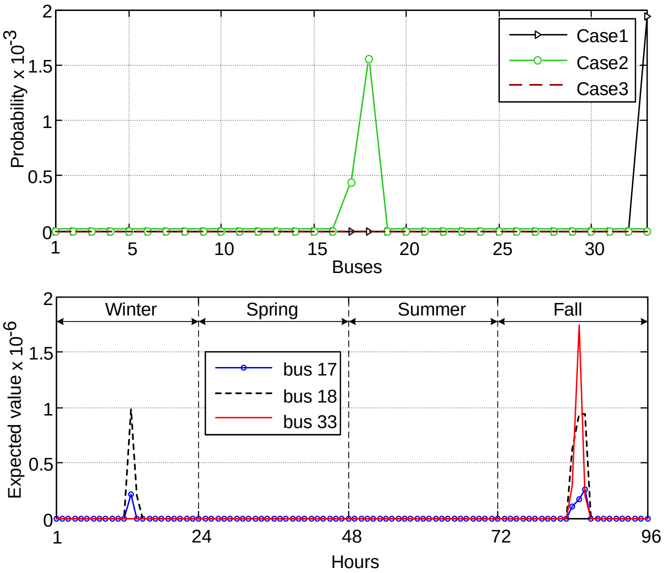

Fig. 8. Evaluation of RVR attribute in cases 1 to 3, (top) $APRVR_4^{\mathrm{BUS}}$ and (bottom) $ERVR^{\mathrm{BUS}}$.

TABLE III
EFFECT OF DG TYPE ON COMPOSITE INDICES.

Index	Case 4	Case 5	Case 6
CBI	0.453	0.235	0.531
CRI	7.45E-02	1.83E-02	3.80E-02
EBI	1.00	0.450	0.836
ERI	1.00	0.0549	0.0863

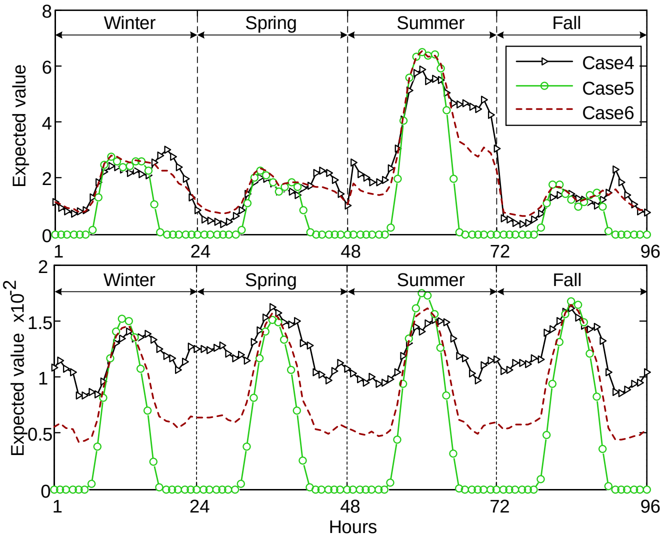

Fig. 9. Effect of DG type on IVR and LLR, (top) $ELLR^{\mathrm{SYS}}$ and (bottom) $EIVR^{\mathrm{SYS}}$

TABLE IV
EFFECTS OF DG INCREASING PENETRATION CAPACITY ON THE ATTRIBUTES.

Index	Case 7 (6 MW)	Case 8 (12 MW)	Case 9 (18 MW)
$AEIVR^{\mathrm{SYS}}(pu)$	0.0084	0.0150	0.0170
$AERVR^{\mathrm{SYS}}(pu)$	0.00	1.49E-04	0.0014
$AELLR^{\mathrm{SYS}}(MWh)$	193.05	170.90	121.92
$AELLI^{\mathrm{SYS}}(MWh)$	4.32	119.25	479.42
CBI	0.531	0.464	0.393
CRI	3.80E-02	1.11E-01	1.84E-01
EBI	0.746	0.882	0.815
ERI	0.004	0.178	1.00

mentioned attributes obtained in this case.

As shown in Table IV, by increasing the size of installed DGs from 6 MW (30% penetration) to 18 MW (90% penetration) the benefits are reduced and the risks are increased.

E. Probabilistic DGs Penetration

In the previous DG penetration studies, only utility-owned DGs were considered. If customers are allowed to freely install DGs on their location and DGs become widespread, the penetration of DG will be nondeterministic. Hence, the effects of unpredictable, uncontrollable, and scattering distributions of user-owned resources on the attributes may be considerable. By applying the algorithm of [23] using the Gibbs sampler algorithm and Monte Carlo methods [25] two "what if" scenarios of the nondeterministic user-owned DG penetration are generated. In this method, it is assumed that the size of user-owned DGs is highly depending on their power consumptions. The maximum capacity of user-owned DGs in the distribution system is assumed to be 2 MW (in this example 1 MW wind-based and 1 MW solar-based DG units). This capacity is 10% penetration level of the peak demand. The results of case 6 and the mentioned two scenarios are shown in Table V. The results from these scenarios show that user-owned DG penetration could give rise the attributes. The voltage profile is improved and losses are reduced. Nonetheless, RVR and LLI are increased. In comparison to the deterministic DG case (i.e., case 6), if scenario 1 happen with case 6, CBI increases and CRI decreases. Conversely, if scenario 2 happen with case 6, CBI decreases and CRI increases.

VI. CONCLUSION

New probabilistic-based indices associated to the voltage profile and line flow have been developed in this paper to facilitate the evaluation of the benefits and risks of increasing penetration of DGs in the distribution systems. These indices are derived based on probabilities of occurrence and expected values of each attribute. For the sake of avoiding over or underestimating the potential benefits or risks of DG penetration, a probabilistic generation-load model was utilized to reflect the probabilistic nature of both load and DGs in the calculation of the indices.

TABLE V
EFFECT OF USER-OWNED DGS PENETRATION ON THE ATTRIBUTES.

Index	Case 6	Case 6 and Scen.1	Case 6 and Scen.2
$AEIVR^{\mathrm{SYS}}(pu)$	0.0084	0.0104	0.0113
$AERVR^{\mathrm{SYS}}(pu)$	0.00	0.00	6.94E-07
$AELLR^{\mathrm{SYS}}(MWh)$	193.05	196.17	197.72
$AELLI^{\mathrm{SYS}}(MWh)$	4.32	8.02	16.36
CBI	0.531	0.5376	0.5175
CRI	0.038	0.0192	0.0559
EBI	0.8659	0.9564	1.00
ERI	0.13	0.24	1.00

The effectiveness of the proposed model for assessing the impacts of DG increasing penetration over the previous models in the area, i.e., "static" and "time varying" models, were examined in the case studies. It was determined in this study that the voltage rise and line overloading are the restricting factors for maximum DG penetration that manifest themselves under different conditions. Through computational simulations, it was proven that the voltage rise was more restrictive than line overload.

Several cases have been studied to evaluate the effects of DG location, type, penetration level and dispersion on the attributes. The results of proposed probabilistic-based impact indices provide useful information for visualizing the trends and actual impact on each technical attribute. The composite indices were introduced as an effective tool to enhance distribution engineers in decision making process. The proposed indices provides the knowledge of "*which type*" of DG "*where*" and "*when*" could be beneficial or risky in the distribution systems considering critical issues of generation and load patterns.

The results show that the attributes could be influenced by user-owned resources. The effects of these nondeterministic DGs should be considered in the operation and planning studies of DGs.

VII. Acknowledgement

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Mohammad Amin Akbari was born in Shiraz, Iran in 1985. He received the B.Sc. degree from Hormozgan University, Iran, in 2009, and the M.Sc. degree from Shiraz University of Technology, Shiraz, Iran, in 2013, both in electrical engineering. He is currently pursuing the Ph.D. degree at the Department of Electronics and Electrical Engineering, Shiraz University of Technology, Shiraz, Iran. His research interests are power system operation and planning, reliability, distributed energy resources and optimization of microgrids.

Jamshid Aghaei (M'12) received the B.Sc. degree in electrical engineering from Power and Water Institute of Technology, Tehran, Iran, in 2003 and the M.Sc. and Ph.D. degrees from Iran University of Science and Technology, Tehran, in 2005 and 2009, respectively. His research interests include renewable energy systems, smart grids, electricity markets, and power system operation and restructuring. Dr. Aghaei is a member of the Iranian Association of Electrical and Electronic Engineers.

Mostafa Barani received the B.Sc. degree from Bu-Ali Sina University of Hamedan, Iran, in 2012, and the M.Sc. degree from Shiraz University of Technology, Shiraz, Iran, in 2015, both in electrical engineering. His current research interests include stochastic modeling, renewable energy resources, operation of electricity market, forecasting and demand side management.

Mehdi Savaghebi (S'06–M'15–SM'15) was born in Karaj, Iran, in 1983. He received the B.Sc. degree from the University of Tehran, Tehran, Iran, in 2004, and the M.Sc. and Ph.D. degrees with highest honors from the Iran University of Science and Technology, Tehran, Iran, in 2006 and 2012, respectively, all in electrical engineering. From 2007 to 2014, he was a Lecturer in the Department of Electrical Engineering, Karaj Branch, Azad University, where he taught various courses and conducted research on power systems and electrical machines. In 2010, he was a Visiting Ph.D. Student with the Department of Energy Technology, Aalborg University, Aalborg, Denmark, and with the Department of Automatic Control Systems and Computer Engineering, Technical University of Catalonia, Barcelona, Spain. He is currently a Postdoctoral Researcher with the Department of Energy Technology, Aalborg University. His main research interests include distributed generation systems, microgrids, and power quality issues of electrical systems. He is a Member of the Technical Committee of Renewable Energy Systems and the IEEE Industrial Electronics Society, and also the IEEE Task Force on Microgrids Stability, Analysis, and Modeling.

Miadreza Shafie-khah (S'08–M'13) received the M.Sc. and Ph.D. degrees in electrical engineering from Tarbiat Modares University, Tehran, Iran, in 2008 and 2012, respectively. He received his first postdoc from the University of Beira Interior (UBI), Covilha, Portugal in 2015, while working on the 5.2-million-euro FP7 project SiNGULAR ("Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration"). He received his second postdoc from the University of Salerno, Salerno, Italy in 2016. He is currently a Visiting Scientist (position only awarded to PhD holders who have scientific curricula of high merit, equivalent to Assistant Professor) and Senior Researcher at C-MAST/UBI, where he has a major role of co-coordinating a WP in the 2.1-million-euro national project ESGRIDS ("Enhancing Smart GRIDS for Sustainability"), while co-supervising 5 PhD students and 2 post-doctoral fellows. He was considered one of the Outstanding Reviewers of IEEE TSTE, in 2014, and one of the IEEE TSG Best Reviewers in 2016. His research interests include power market simulation, market power monitoring, power system optimization, demand response, electric vehicles, price forecasting and smart grids.

Josep M. Guerrero (S'01–M'04–SM'08–F'15) received the B.S. degree in telecommunications engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in power electronics from the Technical University of Catalonia, Barcelona, Spain, in 1997, 2000, and 2003, respectively. Since 2011, he has been a Full Professor with the Department of Energy Technology, Aalborg University, Denmark, where he is responsible for the Microgrid Research Program. Since 2012, he has been a Guest Professor with the Chinese Academy of Science and the Nanjing University of Aeronautics and Astronautics; since 2014, he has been a Chair Professor with Shandong University; and since 2015, he has been a Distinguished Guest Professor with Hunan University. His research interests include different microgrid aspects, including power electronics, distributed energy-storage systems, hierarchical and cooperative control, energy management systems, and optimization of microgrids and islanded minigrids; recently, he has been specially focused on maritime microgrids for electrical ships, vessels, ferries, and seaports. He is an Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS, and IEEE INDUSTRIAL ELECTRONICS MAGAZINE, and an Editor for the IEEE TRANSACTIONS ON SMART GRID and the IEEE TRANSACTIONS ON ENERGY CONVERSION. He has been Guest Editor of the IEEE TRANSACTIONS ON POWER ELECTRONICS Special Issues on Power Electronics for Wind Energy Conversion and Power Electronics for Microgrids; the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS Special Sections on Uninterruptible Power Supplies systems, Renewable Energy Systems, Distributed Generation, and Microgrids, and Industrial Applications and Implementation Issues of the Kalman Filter; and the IEEE TRANSACTIONS ON SMART GRID Special Issue on Smart DC Distribution Systems. He was the Chair of the Renewable Energy Systems Technical Committee of the IEEE Industrial Electronics Society. He received the 2014 Best Paper Award of the IEEE TRANSACTIONS ON ENERGY CONVERSION. In 2014 and 2015, he was awarded by Thomson Reuters as a Highly Cited Researcher, and in 2015, he was elevated as to IEEE Fellow for his contributions on distributed power systems and microgrids.

João P. S. Catalão (M'04–SM'12) received the M.Sc. degree from the Instituto Superior Tcnico (IST), Lisbon, Portugal, in 2003, and the Ph.D. degree and Habilitation for Full Professor ("Agregao") from the University of Beira Interior (UBI), Covilha, Portugal, in 2007 and 2013, respectively. Currently, he is a Professor at the Faculty of Engineering of the University of Porto (FEUP), Porto, Portugal, and Researcher at INESC TEC, INESC-ID/IST-UL, and C-MAST/UBI. He was the Primary Coordinator of the EU-funded FP7 project SiNGULAR ("Smart and Sustainable Insular Electricity Grids Under Large-Scale Renewable Integration"), a 5.2-million-euro project involving 11 industry partners. He has authored or coauthored more than 500 publications, including 168 journal papers, 303 conference proceedings papers, 23 book chapters, and 14 technical reports, with an h-index of 29 and over 3500 citations (according to Google Scholar), having supervised more than 45 post-docs, Ph.D. and M.Sc. students. He is the Editor of the books entitled Electric Power Systems: Advanced Forecasting Techniques and Optimal Generation Scheduling and Smart and Sustainable Power Systems: Operations, Planning and Economics of Insular Electricity Grids (Boca Raton, FL, USA: CRC Press, 2012 and 2015, respectively). His research interests include power system operations and planning, hydro and thermal scheduling, wind and price forecasting, distributed renewable generation, demand response and smart grids. Prof. Catalão is an Editor of the IEEE TRANSACTIONS ON SMART GRID, an Editor of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, an Editor of the IEEE TRANSACTIONS ON POWER SYSTEMS, and an Associate Editor of the IET Renewable Power Generation. He was the Guest Editor-in-Chief for the Special Section on "Real-Time Demand Response" of the IEEE TRANSACTIONS ON SMART GRID, published in December 2012, and the Guest Editor-in-Chief for the Special Section on "Reserve and Flexibility for Handling Variability and Uncertainty of Renewable Generation" of the IEEE TRANSACTIONS ON SUSTAINABLE ENERGY, published in April 2016. He was the recipient of the 2011 Scientific Merit Award UBI-FE/Santander Universities and the 2012 Scientific Award UTL/Santander Totta. Also, he has won 4 Best Paper Awards at IEEE Conferences.