Abstract—expanded integration of wind energy implies technical
confronts to maintain system reliability. Thus, comprehensive
reliability models for wind turbines and related features are
required. Composite and precise wind farms (WFs) reliability
analysis includes wind turbine generator (WTG) detailed models
besides wind speed (WS) probabilistic variations considering
wake effects. This paper is considered as an extension to the
proposed multi-state duration sampling model to assess WTG
reliability integrated with a comprehensive representation for WF
[1]. The paper investigates the impacts of two WTG frequency
support operation algorithms on capacity factors and first
hierarchical level indices. LOEE is evaluated using a novel
method to emphasis the chronological coordination between load
and WS attitudes. System and load points’ reliability indices are
estimated at moderate penetration levels of wind energy using a
simplified technique. Results insure the feasibility of the
composite WTG reliability model and provide reasonable
indicators for WFs integration influence.

Keywords—Wind power, reliability, frequency support, Monte Carlo
simulation

I. INTRODUCTION

Renewable energies continue to make a strong foothold to
contribute to the rapidly rising share of energy supply in this
decade with wind power accounting for 39% from the
integrated capacity in 2012 [2]. Independent organizations and
governmental bodies have instilled the enforcement of a well-
developed framework to secure energy supply by allowing high
levels of wind power penetration in the next years. Multiple
investigations on WFs reliability assessment have been
conducted. Research work [3, 4] focused on the development of
a reliability schema for WFs and composite power systems.
Literatures made use of WS models but commonly implied the
basic Jensen model for wind streams propagation [2]. Kim and
Singh applied the Markov model to simulate WSs dynamics
[5], and the pitfalls of using this model are addressed in [6].
The participation of WTGs and WFs in frequency drops
mitigation is the second topic involved in this paper. System
operators (SOs) face problems during frequency dips, because
the traditional primary and secondary responses scenarios could
not be applied by WFs. As an illustration, conventional plants
respond easily and efficiently to deviations by controlling the
output active power using governors [7]. This return to the
stable and controllable amounts of fossil fuels burnt to provide
steam to the turbine, and in turn the mechanical power running
generator shaft. On the contrary, WS is neither controlled nor
expected with high accuracy. Researchers offered several
algorithms which make WTG able to mitigate frequency
excursion or nearly neutralizes the negative influence of WS
intermittency during frequency excursions [9, 10]. For this aim,
WTGs are not operated based on maximum power tracking
(MPT [11]) but other speed and/or power control methods.
WTG de-loading technique is highlighted in [12], such that
WTG output power is reduced by certain percentage; hence the
frequency support is insured by the deficit between optimum
and de-loaded power values. Further strategy is presented in
[13], where pitch angle control is utilized to keep WT output
de-loaded to a predetermined reference. Completely different
point of view rejects any de-loading or reduction in WFs
output, but it counts on energy storage mediums. Wide range of
energy storage facilities are discussed in literature, mainly,
hydro pumping stations, batteries banks and flywheels.

Nevertheless, economic constrains halt the expansion of storage
solutions, especially batteries.

WF capacity factor (CF) is considered the nexus between the
two previously mentioned topics. As an illustration, the retired
conventional capacities which are replaced by WFs have a great
impact on the post balance between generation and load
demand (i.e., imbalance is the main cause for frequency drops
[14]). Thus, it is mandatory to find an accurate method to assess
CF, and at the same time acknowledges the reliability impact.
In the light of previous survey, this paper investigates the
impact of conventional generation replacement by WFs on
selected reliability indices. The capacities of displaced
conventional units are decided based on the estimated CFs.
LOEE index is evaluated using a modified method to insure the
chronological synchronization between load demand attitude
and WSs. The influence of the implied WTG operation method
(i.e. integrated WTG power curve, for example MPT or de-
loaded operation for possible frequency support) is
acknowledged. Thus, the highlighted operation methods are
compared from reliability and CF point of views.

II. THEORETICAL BACKGROUND

A. WTG and WF reliability

WTG is a collection of an estimated 8,000 components out of
which ten main components play a crucial role in determining
the overall functioning and performance of WTG [7]. The ten
components are designated under two groups namely Critical
and Non-critical in accordance to their contribution in the
failure of WTG. The Critical group includes; tower, pitch
control and blades, gearbox, generator, converters, control
system and transformer. A failure of one of these components
switches the WTG to the downstate. Thus, these components
are assigned an equal high priority level. On the other side,
Non-critical group constitutes the yaw system, brake system and sensors [6]. Failure of one or more of non-critical components results in a de-rated operation (e.g., 70% from WTG rated power). Each of these components causes different de-rating factor when it fails.

The WF reliability is involved with other components, for example, substation(s) equipment and internal cables. However, the inclusion of these components exerts huge additional computational and time burdens. Meanwhile, its influence on wind energy reliability assessment is minor [15]. Conversely, WS forecasting mechanisms are effective, especially when the reliability indices counting on harvested energy are estimated. Moreover, it is relevant to estimate the WS magnitude incident on each WTG according to its position with respect to the WF layout and WTGs geographical distribution.

**B. WTG operation method**

This subsection explains briefly WTG operation in de-loading and the authors published proposed algorithm (it will be called now on “partial de-loading”) [10].

1) **De-loading operation**

WTG is operated such that its output power is always less than the optimum available power by a certain predefined ratio or absolute value. Thus, the deficit between the actual output power and optimum one is a strategic reserve to support the system during frequency drops. De-loading could be applied by two methods:

- Running WTG at rotational speed higher than the optimum speed. This method is called WT over-speeding which is valid for variable speed WTGs.
- Continuous activation of pitch control so that the output power is reduced based on the implied pitch angle. This technique is applicable for any WTG equipped with pitch angle controls [11].

In both methods a predefined de-loading factor \( D_p \) is selected according to the target WTGs contribution in frequency drops mitigation. \( D_p \) numerical value is adjusted based on several givens including the level of WFs penetration and the history of frequency excursions in the system. In this paper, \( D_p = 15\% \).

2) **Partial de-loading algorithm**

The major merits and uniqueness of this algorithm lie in three points; 1) It correlates between WTG type and WS conditions in the WF location, 2) The de-loading is activated only within certain range of WS which is determined based on certain procedure. 3) Its capability to handle WS drops intersecting with frequency events, reducing possible negative consequences. The first step is to evaluate the pivot three parameters of proposed algorithm, namely, 1) base rotational speed, 2) base WS \( (WS_{bo}) \) and 3) low WS \( (WS_{low}) \) [10].

The proposed algorithm operates WTG in de-loaded operation within the WS range \( (WS_{low} < WS < WS_{bo}) \) using pitch angle control. It is worth mentioning that when WS exceeds \( WS_{bo} \) by certain margin, rotor speed is allowed to accelerate above its base value, hence higher output is guaranteed. When output reaches its rated value (i.e., 1 p.u.) the de-loading is deactivated to utilize all the available wind energy. However, supporting the system, in case of frequency excursions is achieved by overloading the WTG for a predefined duration. When instantaneous WS drops, kinetic energy is extracted from WT rotating parts by fixing the former output and decelerating rotor speed to a new speed which avoids loss of synchronism. In words, de-loading is applied at the following conditions: 1) \( WS_{low} < WS < WS_{bo} \) and 2) normal output is less than 1 p.u. Further details about this algorithm are not prerequisites to comprehend offered reliability analysis.

3) **Manufacturer power curve**

WTG fabricating companies provide standard power curves for each WTG type where the expected output power at each WS is indicated within the margin between cut-in and cut-out WSs. These values are based on continuous monitoring for WTG performance where the average value of several records at the same WS is considered. MPT can be manipulated into a lookup table with appropriate interpolation method; hence optimum output is obtained at any WS. The most critical region of this curve is between cut-in and rated WSs, elsewhere the output is either rated or zero. Operating WTG in MPT mode cancels any contribution for the WTG in frequency drops curtailment. Further illustrating figures comparing between the three algorithms are shown in Subsection IV. For further details please refer to [16].

### III. INTEGRATED RELIABILITY ASSESSMENT ALGORITHMS

Subsections A and B summarize the method proposed in [1].

**A. WTG reliability**

A two-state operation cycle based on state duration sampling is used to obtain an artificial operating history of WTG components. The failure and the repair rates (\( \lambda \) and \( \mu \) respectively) of each component are assumed to be exponentially distributed for calculating the Time to Fail (TTF) and Time to Repair (TTR) using (1). Aggregate values for \( \lambda \) and \( \mu \) are estimated for critical group components using method of series-component reliability [17]. Since the failure of one of Critical components leads to complete breakdown. Each Non-critical component is considered as a single group while all Critical components are aggregated in one group. As an illustration, a Non-critical component, during its down state, has a different impact on WTG output where a de-rated percentage is given with respect to component priority. De-rating factors caused by each non-critical component are 25, 15 and 5% for Sensors,Yaw system and Brake system respectively. In conclusion, nine states (seven of them are de-rated) are defined for WTG. Obtained curves are timely added to get the WTG transition multi-state array (i.e., Availability).

\[
TTF = -1 / \lambda \cdot \ln(R), \quad TTR = -1 / \mu \cdot \ln(R)
\]

**B. WF layout and reliability**

1) **WTGs positioning, WS forecasting and propagation**

WTGs are uniformly distributed across WFs’ terrains for simplicity and acknowledging the almost flat ground of the candidate locations to host WFs in Egypt. In other words, the WFs borders length and width are equally sectionized to keep a fixed distance between any two neighbor WTGs, namely, six times the rotor diameter \( (d) \) of installed WTG type [18]. Each WF is composed of one type of WTGs distributed in regular rows so that all rows have equal number of WTGs.

WS data are available for all locations in the form of time series average readings in 10 minutes resolution for 1 year. However,
the proposed analysis accuracy is improved by generating different WSs arrays, for each simulation sample, with 15 minutes resolution through Weibull distribution using (2) where α and β are the shape and scale parameters respectively. A vector \( y \) consisting of uniformly distributed random numbers in the range \( (0, 1) \) are simulated and applied to the transformation function to obtain the WS array for the desired simulation period.

\[
W(y) = \alpha \cdot \beta \cdot y^{\beta-1} \cdot \exp(-\alpha y^\beta)
\]

(2)

The wake effect produced by the propagation of wind streams is also considered. The upstream WS at each WTG is estimated using (3) where \( W_{S_i} \) and \( W_{S_j} \) are the upstream WS magnitudes at the previous WTG and the next one respectively. Thrust coefficient \( (C_T) \) equals 7/\( W_{S_i} \) and \( k \) is 0.075 for onshore WTGs [19]. The distance at which the wake WS is calculated is \( \chi \) (i.e., \( x = 6\chi \)) depending on WTG size. WS stream direction is always perpendicular on WF rows. Hence, for simplicity, the WS incident on the WTGs of the same row is typical and it is evaluated using (3). The time delay consumed by wind stream to cover the separating distance between each two successive rows is \( W_{S}/\chi \).

\[
W_{S_i} = W_{S} \left[ 1 - \left(1 - \sqrt{1 - C_T}\right) \right] \left( \frac{d}{d + 2 \cdot k \cdot \chi} \right)
\]

(3)

C. Impact of WTG Operation method

The power curve of each WTG type is integrated to evaluate the output power at any WS. Three different operation methods are investigated as explained earlier in Section II.B. However, in case of continuous de-loading, MTTF of pitching converter subsystems are reduced by 15%. This assumption reflects the nature of this operation method which imposes intensive variations for rotor speed and pitch angle leading to higher failure rate for the responsible components. Meanwhile, partial de-loading reduces MTTF by 8% since de-loading is not continuous. Generally, operation method mainly affects the amounts of harvested wind energy.

D. Simulation sequence

The following steps describe briefly how the proposed algorithms are simulated using MATLAB and Simulink.

- Generate the initial incident WS time series in the considered WF within T. The actual chronological WSs data in concerned location are processed through (4).
- For each row \( (i) \), generate the state transition chronological arrays of installed WTGs. Keep in mind that, WTGs in the same row face the typical WS as explained at the end of subsection B. Hence, aggregate state array of a row \( \text{State}_{\text{row}_i} \) is the summation of all WTG arrays in this row.
- Repeat for all WF rows (number of rows/WF is \( N_{\text{row}} \)).
- Repeat for all WFs.
- Run a Simulink model to generate: a) WS time series arrays incident on each row, in each WF, acknowledging wake effect, hence, b) output power array of a single WTG in row \( (i) \) is obtained based on the applied operation method look-up table \( (P_{\text{row}_i}) \).
- Evaluate WF availability and output time arrays using (4) and (5) resp., where \( N_{\text{WTG}} \) is the number of WTG in the WF.

- Repeat previous steps for ‘\( N_{s} \)’ samples until the error stopping criteria of Monte Carlo method is achieved.

\[
WF_{\text{availability}} = \sum_{i=1}^{N_{\text{WTG}}} \text{State}_{\text{row}_i}
\]

(4)

\[
WF_{\text{avl}_{p}} = \sum_{i=1}^{N_{\text{WTG}}} (\text{State}_{\text{row}_i} \cdot P_{\text{row}_i})
\]

(5)

IV. CASE STUDY

Proposed algorithms are applied on 12 different locations which are candidates to host WFs. Due to lack of geographical information; it is assumed that all WFs have the same terrain area, namely, 50 km\(^2\) in analogy to Za‘afra WFs which is already constructed [24]. Three different WTGs types are installed; N-117, E-101 and G-90 whose main characteristics are depicted in Table I and the Partial de-loading power curves are obtained [10, 16]. The selection of WTG type for each location is based on [14]. As explained in Subsection III.B, \( N_{\text{WTG}} \) counts on WF terrain dimensions and \( d \). Since all WFs have the same area thus, every type has equal \( N_{\text{WTG}} \) in all locations. Moreover, each WF is divided into 6 to 8 rows facing wind streams (14 to 16 WTGs/row). Types and numbers of installed WTGs in each WF, and WF fixed layout are in Fig. 1. The failure and repair rates of integrated WTGs types are not published by their vendors. Thus, standard reliability data for WTG components given in Table II [6] are assigned for G-90. Meanwhile, the reliability data of the other two types are proportional to their rotor diameter. For example, standard tower MTTR is 104 hours then G-90 tower has same value, while N-117 scaled value is 104*117/90. This simplified criterion assumed that larger WTGs require more reliable components, but failures take longer time to be fixed due to larger size complications.

V. CAPACITY FACTOR ASSESSMENT

The CFs for the 12 WFs is estimated through Monte Carlo simulation method as in [1]. The CF values for several locations with the integration of the three investigated operation methods are depicted in Fig. 2. The evaluated CFs show great variation mainly based on WS conditions in each location. The locations characterized with high average WS (e.g., NW and Ras Ghareb) CF is about 60%.
Conversely, lowest CF is achieved by Kossier with 24% which is still in the acceptable worth limits. On the other hand, the operation algorithm causes slight deviations in the estimated CF. However, the locations of better WS conditions have large gaps between different algorithms. For example, Ras Ghareb location has showed a 9% deficit between MPT and de-loaded operation. Meanwhile, partial de-loaded method mitigates energy loss by 4% which is considerable value (202 GWh/year). The partial de-loaded algorithm proves superiority over de-loaded method in most of locations. Nevertheless, locations of poor WS conditions (i.e., average WS is dramatically less than WTG rated WS) have a minor deficit for the favor of de-loaded algorithm. As an illustration, the operation of WTG at base rotational speed, which deviates from optimum speed sometimes especially at very low WS, waste more energy compared to de-loaded operation. Moreover, the durations of rated WTG operation in such locations are mitigated. Thus, the advantage of partial de-loading which avoids de-loading at rated output is lost. It is worth mentioning that lower reliability levels of some components in de-loaded operation alleviate the difference between the two frequency support algorithms in poor WS locations. In addition, higher N_{WTG} increases failure probability which aggravate the WF availability but the other positive factors overcome this point.

VI. WIND ENERGY IMPACT ON SYSTEM RELIABILITY

A. Case studies
Estimated CFs in the previous section are utilized to decide the number and location of the conventional units which are forced to retire. In other words, planned WFs replace certain conventional capacity. Replacement procedure focused on conventional plants which are geographically near from intended WFs sites (i.e. WFs are integrated to the present network without the assessment of possible expansions). The Egyptian grid composite layout is presented in Fig. 3 before and after WFs integration. Steam generation participates with 76% from the total generation capacity. The average annual load demand was 12.25 GW in 2010 based on hourly records. The failure and repair rates for all conventional units, about 186 units, are provided by the concerned authorities.

| TABLE I. INTEGRATED WTG TYPES MAJOR SPECIFICATIONS |
|---------------------------------|---------------|---------------|---------------|
| WTG type | G-90 | E-101 | N-117 |
| d, m | 90 | 101 | 117 |
| Cut-in WS, m/s | 3 | 3 | 3 |
| Cut-out WS, m/s | 21 | 28 | 20 |
| Rated WS, m/s | 16 | 13 | 11 |
| Rotor speed, r./s | 0.94 - 1.99 | 0.67 - 2.31 | 1.19 - 2.1 |

| TABLE II. STANDARD WTG COMPONENTS RELIABILITY DATA |
|-----------------|--------------|---------------|
| WTG Component | Failure rate λ | Repair rate μ |
| Tower | 0.006 | 104.1 | 0.73 |
| Blades/Pitch | 0.052 | 91.6 | 5.43 |
| Gearbox | 0.045 | 256.7 | 13.17 |
| Generator | 0.021 | 210.7 | 5.05 |
| Converters | 0.067 | 106.6 | 8.15 |
| Controllers | 0.05 | 184.6 | 10.53 |
| Transformer | 0.02 | 210 | 4.26 |
| Yaw system | 0.026 | 259.4 | 7.09 |
| Brake system | 0.024 | 128.4 | 7.46 |
| Sensors | 0.054 | 49.4 | 3.24 |

Sample data for certain conventional plants are depicted in Table III. Conventional units’ reliability is represented by two-state model to mitigate computational efforts. However, an independent state transition time series array is generated for each unit within each simulation sample. Likewise, state transition arrays are also generated for transformers and transmission lines.

The lack of reliability data of transformers and transmission lines implied three assumptions: 1) transmission lines failure and repair rates are similar for the same transmission voltage level, 2) all transformers have the same failure and repair rates, 3) other system components are assumed to be healthy all the time. These assumptions will not deeply affect the relevance of obtained results since this paper mainly compares between pre and post WFs integration cases.

The evaluation of load points and overall system reliability is based on the methodology offered in [20]. However, taking into consideration the grid complexity (65 buses and 56 transmission lines), the maximum considered number of possible paths to feed certain load point is 10 paths.

The selected load points are divided into four categories as in Table IV. The expression ‘Higher WFs feed’ means that these points’ demands are covered by high number of paths fed by WFs (i.e. 7 paths out of 10). Meanwhile, the high and low customers’ number points are evenly supplied by WFs and conventional plants to highlight only the influence of customer count. Keep in mind that, in base case, load points are fed from conventional units only and sometimes number of paths is less than 10. An illustrative example for the applied ‘paths’ concept is depicted in Fig. 5. Points characterized by high number of customers have slightly higher feed from conventional units compared to WFs, and low-customers points have balanced feed. The approximate number of customers at each load point is assumed to be proportional to the population density [21].

The constant of proportionality is the total number of customers in the system.

Two indices from first hierarchical level, as well as CAIDI and CAIFI from third hierarchical level are estimated [22]. All indices are evaluated without, and with WFs integration (with former conventional capacity and also after replacement) plus the testing of the three highlighted operation methods (only for LOLE and LOEOD). LOEOD is evaluated using a modified method, where the load demand failures are obtained by subtracting the chronological load array from the available aggregate generation. Actual load chronological array is used to
generate a different load array in each sample year through Weibull probability function. Thus, the seasonal natures of load demand and wind power production are synchronized. On the contrary, standard method classifies system load into several levels where each level has its own annual occurrence probability (AOP). Egyptian grid load levels AOP are included in Fig. 4 in the left corner (average load levels are highlighted). It is worth mentioning that, the simulation process for 1000 samples, continued for 43 hours using a 2.53 GHz core-i3 CPU and 4 GB RAM DDR3.

B. Results

1) Impact of conventional capacity replacement

The results of load points that belong to the same category are combined together for simplicity and to get a wider view (e.g., CAIDI indices of load points of each category are aggregated in one average value). Results reveal that WFs integration does not have positive or negative impact all the time. But, the influence is affected by the nature of load point. For example, in first category CAIDI slightly increased after WFs integration before and after replacement as depicted in Fig. 6. This return to shutting down some conventional units, hence the loss of demand probability is higher as this category counts more on conventional generation. On the contrary, in the third category, WFs integration reduced CAIDI by 2 hours (improved by 6% for high density customers regions). Nevertheless, conventional plant retirement ruined CAIDI by 16.7%. Likewise, the load points which count on WFs generation suffered worsened index especially, after conventional units’ displacement (i.e., increased by 13.7%). However, the difference between pre and post replacement almost vanishes at lower density customer points. Only a minor improvement occurred since CAIDI is shortened by 90 minutes compared to base case. Most of the realized drawbacks are normal consequences for WS intermittency. Switching to CAIFI results displayed in Fig. 7, the impact of WFs integration is minor. This returns to the high reliability of WTGs which are available 98% from the year. Thus, the interruptions caused by their unhealthy states are very limited and interruptions are mainly caused by conventional units. This is insured by ASAI (Annual system availability index) results which are not fully included in this paper.
The deviations after WFs integration are also minor. It should be highlighted that, the WF is considered unavailable, from ASAI point of view, when the ‘real recorded’ value in 2012 is considered, namely, 70 GWh [23]. The WFs 9% added (i.e., before replacements) capacity solidly improved LOEE by 98% even from Standard method point of view. Generally, Chronological method is always more optimistic by about 50% from standard (e.g., 56 GWh using Standard method and 25 GWh using Chronological one in Base case). Conventional units’ retirement caused average increase in LOEE by 3.3 times compared to pre-retirement cases (e.g., at MPT; 0.75 enlarged to 2.46 GWh). However, evaluating LOEE using the proposed modified method has dramatically alleviated the former value.

### Table III. Real failure data for some plants in Egyptian grid

<table>
<thead>
<tr>
<th>Plant name, no. and type</th>
<th>MTTF, hours</th>
<th>MTTR, hours</th>
</tr>
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<tbody>
<tr>
<td>Talkha, no. 20 in Fig. 2 Steam, 2 units</td>
<td>7963</td>
<td>596</td>
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<td>Nubirua, no. 25 in Fig. 2 Gas, 4 units</td>
<td>6982</td>
<td>1901</td>
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<td>North Cairo, no. 34 in Fig. 2 Steam, 3 units</td>
<td>6789</td>
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### Table IV. Selected load points categories

<table>
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<tr>
<td>1</td>
<td>Higher conventional feed</td>
<td>21, 20, 8</td>
</tr>
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<td>2</td>
<td>Higher WFs feed</td>
<td>4, 18, 23</td>
</tr>
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<td>3</td>
<td>High customers no.</td>
<td>18, 21, 15</td>
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### Table V. System indices results

<table>
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<th>Case study</th>
<th>LOLE (hours/year)</th>
<th>LOEE (GWh/year)</th>
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<tbody>
<tr>
<td>Base case</td>
<td>55.88</td>
<td>55.97</td>
</tr>
<tr>
<td>WFs integrated - No replacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPT</td>
<td>1.01</td>
<td>0.75</td>
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<tr>
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<td>1.599</td>
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<tr>
<td>WFs integrated - After replacements</td>
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<tr>
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<td>3.07</td>
<td>2.46</td>
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<tr>
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<td>4.93</td>
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Figure 4 AOP of major load levels and customer density at the main load points

Figure 5 Example for ‘paths’ method used to estimate load points’ reliability indices

The deviations after WFs integration are also minor. It should be highlighted that, the WF is considered unavailable, from ASAI point of view, when the ‘real recorded’ value in 2012 is considered, namely, 70 GWh [23]. The WFs 9% added (i.e., before replacements) capacity solidly improved LOEE by 98% even from Standard method point of view. Generally, Chronological method is always more optimistic by about 50% from standard (e.g., 56 GWh using Standard method and 25 GWh using Chronological one in Base case). Conventional units’ retirement caused average increase in LOEE by 3.3 times compared to pre-retirement cases (e.g., at MPT; 0.75 enlarged to 2.46 GWh). However, evaluating LOEE using the proposed modified method has dramatically alleviated the former value.

2) Impact of WTG operation method

Results highlight the impact of WSSs conditions and WTG integrated operation algorithm. First of all, the relatively high base LOEE value found in Table V is not surprising, especially, when the ‘real recorded’ value in 2012 is considered, namely, 70 GWh [23]. The WFs 9% added (i.e., before replacements) capacity solidly improved LOEE by 98% even from Standard method point of view. Generally, Chronological method is always more optimistic by about 50% from standard (e.g., 56 GWh using Standard method and 25 GWh using Chronological one in Base case). Conventional units’ retirement caused average increase in LOEE by 3.3 times compared to pre-retirement cases (e.g., at MPT; 0.75 enlarged to 2.46 GWh). However, evaluating LOEE using the proposed modified method has dramatically alleviated the former value.

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<td>0.75</td>
</tr>
<tr>
<td>De-loaded</td>
<td>1.99</td>
<td>1.599</td>
</tr>
<tr>
<td>Partially de-loaded</td>
<td>1.98</td>
<td>1.598</td>
</tr>
<tr>
<td>WFs integrated - After replacements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MPT</td>
<td>3.07</td>
<td>2.46</td>
</tr>
<tr>
<td>De-loaded</td>
<td>5.77</td>
<td>4.92</td>
</tr>
<tr>
<td>Partially de-loaded</td>
<td>5.82</td>
<td>4.93</td>
</tr>
</tbody>
</table>

Figure 6 CAIDI for the selected categories in all cases studies
Results also reveal the considerable impact of the good matching between WTG type and WF location. Likewise, LOLE index insured the same performance with almost the same ratios. The impact of operation algorithm is clearer in LOEE results. For example, MPT achieved the best results as expected in all cases. The MPT superiority is always in the range of 50%. Meanwhile, the two frequency support methods have minor deviations between each other. This might return to the homogeneous WS conditions in WFs locations. In other words, WS averages are evenly distributed between low and high levels among all sites. Thus, partial de-loading is preferred in locations of high and moderate WS conditions.

VII. CONCLUSIONS

This paper applies an innovative and detailed reliability multi-state model for WTG to build a WF reliability model including WS propagation influence and physical configuration of WTG inside the WF terrain. The WF comprehensive model is implemented to estimate the influence of frequency support algorithms on capacity factor and system reliability. Frequency support algorithms caused moderate reduction for capacity factors. However, the difference between the two support algorithms is noticeable in regions of good WS conditions. Thus, WS nature in WF location determines the favorite frequency support algorithm between partial de-loading and de-loading. The reliability indices analysis proved that wind energy integration solidly mitigated Standard LOEE. The improvements are clearer in the Modified LOEE. The operation method has a relatively minor impact on LOEE value.

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