Wind farm incorporation in reliability assessment of power systems from the viewpoint of reactive power management

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The development and utilization of wind power to meet the electrical demand has recently received significant consideration. Additionally, one of the substantial roles of transmission system operators is to balance reactive power within a network in the sense that with the development of wind energy, wind turbines are expected to contribute towards reactive power generation. So far, there is not a wide range of attention being paid to reactive power in reliability evaluation including wind farms contribution. In this article, wind farms with several identical wind turbines are incorporated in reliability assessment while considering reactive power shortage. Fuzzy C-Means clustering method is used for the output power of wind turbines for analyzing power system reliability with wind farms integration. The application of this concept has been also utilized in developing multistep load levels in the illustrated load buses. Reactive power deficiency and the relevant voltage violations caused by the failure of reactive power generations are studied in this article. Load shedding and power injection techniques are employed to determine possible reactive power shortage required for alleviating network violations with and without wind power integration. Composite system reliability analysis in the existence of wind farms is implemented to assess indices affiliated with curtailed energy at various load points. The RBTS 6-bus system has been proportionally modified and studied to demonstrate the procedure. The results indicate the importance of wind power integration in improving both active and reactive reliability indices which in turn provide system planners with long-range planning for system development.

keywords: *Wind farm, Fuzzy C-Means, Load shedding, Power system reliability, Reactive power.*

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NOMENCLATURE

φ_i Auto-regressive parameter at order i
θ_i Moving average parameter at order j
V_{SW} Hourly simulated wind speed
μ_t Mean wind speed at time t
σ_t Wind speed standard deviation at time t
y_t Time series for wind speed at time t
α_t Normal white noise at time t
V_{OW} Hourly observed wind speed
ν_i Mean of the ith cluster
Ψ Fuzzification parameter
D_{ki} Euclidean interval from the kth load point to the ith cluster mean
M_{ij} Initial cluster mean of ith cluster and jth curve
L_{kj} Load on the jth curve at the kth load point
NLC Number of load curves
NLL Number of load levels
v_{cin} Cut-in wind speed
v_r Rated wind speed
v_{co} Cut-out wind speed
P_r Rated wind power
P_{out} Wind turbine generator output power
ρ_i Probability of state i
λ_i Departure rate of state i
F_i Frequency of state i
P_i Available active power of total system capacity for state i
A_j Availability of component j
U_j Unavailability of component j

λ_j Failure rate of component j

μ_j Repair rate of component j

pk Capacity of active power of generator k

N_{gi} Available generator numbers for state i

NC Total number of considered contingencies

LC_{Pi} Active load reduction due to lack of active power for state i

QC_{Pi} Reactive load reduction due to lack of active power for state i

LC_{Qi} Active load reduction due to lack of reactive power for state i

QC_{Qi} Reactive load reduction due to lack of reactive power of state i

$VarS_{Qi}$ Var shortage causing voltage violation for state i

1. INTRODUCTION

Since wind is a clean source of energy and is not diminished in even a long-term utilization, it is taken into consideration as a significant alternative to main conventional sources. The attraction in the use of wind electricity as a renewable source of energy has been in progress noticeably throughout the world for the last three decades. Important influences on power system reliability has been emerged through wind power penetration increment. According to the wind power unpredictability, security survey might lead to uncertainty. This could justify the importance of wind power incorporation in the reliability assessment methods that were recently applied via electric power utilities for evaluating the overall generating capacity adequacy so as to serve the future load requirements [1, 2].

For modeling wind farms in reliability evaluation, numerous probabilistic and analytical techniques have been recently developed [3–5]. Amongst some of the common models being utilized, multistate unit [3–5] and probabilistic distribution [6] are popular. These models are conveniently fast but might not be able to preserve the correlations and also the chronological characteristics between the datasets.

Wind farms tend to have a profound influence on the reliability of power system particularly when reactive power is considered as a substantial necessity for maintining the voltage stability of the system. Having taken into consideration random failures of reactive power generation including wind turbines, sufficient reserve of reactive power is expected to keep the system exactitude. The impact of reactive power on system security and stability has been comprehensively analyzed [7–9].

A zone containing heavy loads in a system without adequate reactive power reserve could subsequently lead to a pervasively immense blackout due to a great deal of reactive power demand and loss in transmission section. Since a drop in bus voltage as a result of a component failure could reduce the generation of reactive power of shunt capacitors and the charging of line, reactive power flow has much highly tendency to change than active power component of line loading during a contingency. Accordingly, sufficient reactive reserve is required to be available to fulfil the *Var* needs after a contingency, and wind farms could play a supportive role in implementing such a vital task to alleviate voltage violations caused by reactive power shortage in system operation. This should be taken into account in reliability studies [10].

Reliability assessment procedures have been well investigated [11, 12] in which the values of fixed minimum and maximum limits are utilized. The expected value of voltage violation and the kWh curtailed expected value caused by insufficient reactive power source were computed [13]. System violations caused by the lack of active power have been differentiated from those resulted from the deficiency of reactive power during the post contingency load shedding. These violations have been subtracted through active power load shedding when taking into consideration the role of reactive power [14]. Reliability issues regarding reactive power inadequacy illustrating corresponding indices have been widely discussed in [14]. Although reactive power resource failures including *Var* compensators and synchronous condensers are rarely used, measures have to be taken to employ the support of wind farm in incorporation of voltage stability as well as its partnership in meeting reliability requirements for the whole power system. Consequently, this could provide planners and operators with sufficient information in order to make appropriate planning and operation intentions.

This article discusses a procedure to assess reliability indices which basically take into consideration both active and reactive power deficiency caused by failures due to active and reactive power generating sources including wind turbines. First in Section 2, a brief description about the utilization of wind turbine as *PQ* sources is considered and the capabilities of wind turbines based upon doubly fed induction generators (DFIG) in providing active and reactive power is studied from reliability evaluation viewpoint using wind turbine *P*-*Q* curve. Then, auto-correlation and moving average (ARMA) time series is illustrated to model wind speed for developing a multi-step wind turbine utilizing Fuzzy C-Means clustering method (FCM), after which the aggregated results would lead to a probabilistic wind farm in Section 4. While reactive power deficiency and its relevant voltage violations caused by insufficient reactive power sources are studied, a technique called "injection of reactive power" is employed to specify shortage of reactive power and its zone which is studied along with the reliability indices in Section 5.

Reactive power matters regarding reliability of power system and load shedding related to voltage set point are investigated in Section 6. In the same Section, the contingency screening method for reliability assessment is also described. The method of reliability analysis is in Section 7. The reactive power injection and load shedding procedures including lack of both active and reactive powers are also illustrated as two distinctive scenarios for evaluating reliability indices relevant to expected *Var* not supplied caused by voltage violation and reactive power deficiencies, respectively. The modified Roy Billinton Test System (RBTS), a 6-bus system, has been studied utilizing the stated methods and the results in which the analysis of the effect of importing wind farms to the case study system are presented in Section 8. In Section 9, the brief conclusion of the paper has been discussed.

2. WIND FARM AS *PQ* POWER RESOURCE

Basically, active and reactive power output of a DFIG-based wind turbine system could be adjusted independently in such a way that active power output is generally specified by wind patterns whereas to determine the reactive power capability for a specific active power output, a number of boundaries in the system have to be taken into account [15]. The rotor side converter (RSC) generally supplies active and reactive power control of the generator whereas the line-side converter (LSC) maintains constant at the DC-link voltage. Both converters could be overloaded in a short period of time. Therefore, the DFIG is

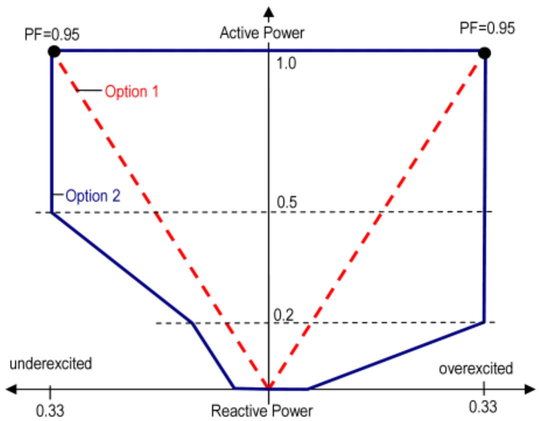

Fig. 1. Reactive power characteristics of DFIG wind turbine [16].

capable for providing a remarkable contribution in supporting voltage of the grid during short circuit period [15].

Manufacturers proposes various options for *Var* generated by DFIG according to steady state of the wind turbines. Fig. 1 demonstrates an instance of an active power versus reactive power features. Interest is being concentrated on the range development of the reactive power generation employing reactive power sufficiency of the DFIG in a better way. As illustrated in Fig. 1, DFIG-based wind turbines could provide reactive power even when there is no wind i.e at zero active power. Accordingly, the option to be performed is substantially dependent on the exact place of the wind turbine in the network. One alternative for the development of generating source of reactive power is to utilize the LSC which could also be functioning as a STATCOM [16].

In addition to the influence of wind farms in transmission system losses based on the distance from generation and load centers, wind power is capable in providing benefits for system reliability. Thus, the total beneficial from a wind farm potential in a system is based upon four main purposes, known as reduction in generation cost of units, reduction in consuming fossil fuels, decrease in the losses of transmission system, and reduction in customer interruption owing to providing active and reactive power. Consequently, in addition to generating a never-pollutant and renewable energy that is a reasonable substitution for traditional power plants, the location of wind farms in large-scale tends to have vital influence on security and adequacy of the system. Study of a wind farm influence on the indices of system reliability is basically dependent on the regime of the wind site as well as the connection tie of the wind farm in the network.

3. WIND SPEED CHARACTERISTIC

As the wind regime of each site is disparate from another, the *ARMA* time series models for various places alter accordingly. Statistical test has proved that the *ARMA* (*n, n-1*) is the appropriate model for simulating wind speed in several regimes [3]. The *ARMA* is usually described via [3]:

$$y_t = \sum_{i=1}^{n} \varphi_i y_{t-i} + \alpha_t - \sum_{j=1}^{m} \theta_j \alpha_{t-j} \tag{1}$$

where auto-regressive and moving average parameters are represented as φ_i $(i = 1, \ldots, n)$ and θ_j $(j = 1, \ldots, m)$, respectively with n and m orders. The time series for wind speed model at time t is defined by y_t and the α_t denotes to a normal white noise with a zero mean and associated variance defined as σ_a^2, having independent normal distribution.

The wind speed V_{SW}, simulated hourly at time t, is acquired from the mean speed (μ_t), standard deviation (σ_t), and the time series y_t such as the equation below:

$$V_{SW} = \mu_t + \sigma_t y_t \tag{2}$$

Using (1), updated amounts of y_t could be accounted from the random white noise (α_t) and prior amounts of y_{t-i}. Equation (2) is utilized in order to produce the wind speeds in hourly interval with the incorporation of time series for wind speed. The standard deviation and mean of the wind speeds in hourly interval from a 12 year database (from 1st March 2006 to 30th February 2018) for the location called Mandan were obtained [17]. These data were employed in order to make the models of *ARMA* time series using the following equation. Then, using the following equation, the data relevant to the wind speed being observed is taken for standardization.

$$y_t = \frac{V_{OW} - \mu_t}{\sigma_t} \tag{3}$$

Hence, V_{OW} denotes to the observed wind speed in hourly interval. Standardized time series (y_t) is utilized to construct *ARMA* (3, 2). The *ARMA* model is acquired as follows:

$$\begin{aligned} y_t &= 0.8320 y_{t-1} - 0.1372 y_{t-2} + 0.0667 y_{t-3} \\ &+ \alpha_t + 0.0321 \alpha_{t-1} + 0.0348 \alpha_{t-2} \end{aligned} \tag{4}$$

When the time series is acquired, the simulated wind speed is accounted by employing the Eq. (2).

4. WIND FARM MODEL

The output power (P_{out}) affiliated with the wind turbine generator (WTG) could be obtained utilizing the wind speed (v) as the following equation:

$$p_{out} = \begin{cases} 0 & 0 \le v \le v_{Cin} \\ (A + B\,v + C\,v^2) & v_{Cin} \le v \le v_r \\ P_r & v_r \le v \le v_{Co} \\ 0 & v \ge v_{Co} \end{cases} \tag{5}$$

Hence, v_r and P_r are described as the speed at rated power and the corresponding power of rated output, whereas v_{Cin} and v_{Co} are cut-in and cut-out speeds, respectively. The constants A, B and C tend to be determined as associated with v_{Cin} and v_r [18]. The Cut-in wind speed, Rated wind speed, and Cut-out wind speed for a 2.5-MW *Nordex*-90 are 3 m/s, 13.5 m/s and 25 m/s respectively, which are demonstrated in Fig. 2 [19].

A. Clustering procedure of Fuzzy C-Means (FCM)

The detection process in groups for a lot of data is presented as the clustering procedure [20]. This unsupervised assortment of schemes makes an effort for categorizing data into similar and well-distinguished clusters according to the similar indices. In this article, clustering procedure of Fuzzy C-Means as a practical model considering clustering techniques in

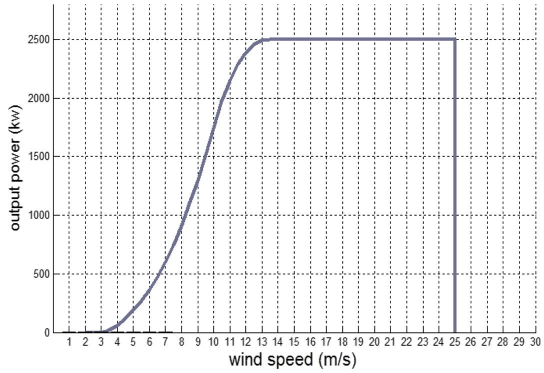

Fig. 2. Wind speed versus output power of a 2.5-MW Nordex-N90.

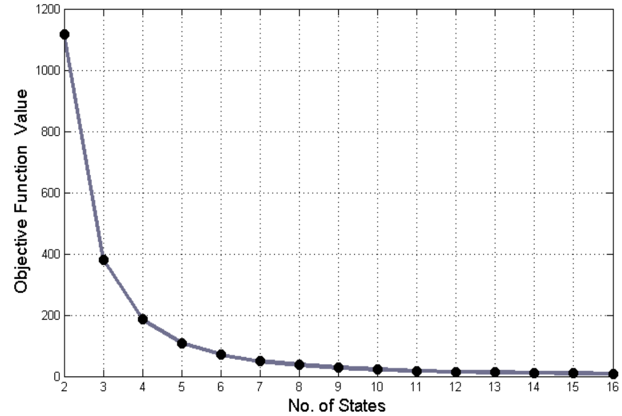

Fig. 3. Cluster number versus value of objective function.

fuzzy objective function is utilized in order to partition object data (wind power) $x_1, x_2, ..., x_k, ..., x_n \subset R^S$ into C fuzzy clusters $v_1, v_2, ..., v_i, ..., v_C \subset R^S$ solving a minimization optimization problem, which is demonstrated as the following equation [4, 21]:

$$J_\psi(\mu, v) = \sum_{i=1}^{C} \sum_{k=1}^{n} \mu_{ik}^{\psi} \|x_k - v_i\|_2^2 \quad \textbf{(6)}$$

where ψ parameter of fuzzification;
v_i the ith cluster mean;
$\mu_{ik} \in [0, 1]$ fuzzy degree to which x_k belongs to the ith cluster;
$v = [v_i]$ cluster means vector;
$\mu = [\mu_{ik}]$ matrix of partition;
$\|*\|_2^2$ 2-norm squared.

Obtaining more information about FCM clustering method, the fond researchers are recommended to read [21].

B. Wind farm generation probabilistic model

The output power of a wind turbine ought to be nourished to the FCM method as the input data to reach appropriate states associated with the wind turbine model. Utilizing the FCM algorithm, the most proper clusters which demonstrate the different states regarding the generation levels of turbine could be acquired. This process is utilized for a wind turbine with 2.5-MW rated power. Fig. 3 points out that as there is an increase in the affiliated cluster numbers, the value of objective function see a dramatic decrease. However, the decline in the objective function seems to be negligible when the number of considered clusters is 7 or more.

Therefore, it could be found out that a 7-cluster model could be considered as an appropriate model for the above-mentioned turbine. These considered 7 clusters are demonstrated in Table 1 along with the corresponding probability of these clusters (wind turbine states) [4].

Fig. 4 shows an n-step cluster model of a single 2.5 MW wind turbine. As an FCM 7-step output power model is used in this study, the clusters between zero and the rated power output clusters are determined as demonstrated in Table 1 in which state n is the 7^{th} cluster.

The Markov equivalent model of a wind farm with N identical turbines could be developed utilizing the mentioned model of a single turbine [22]. Fig. 5 shows the wind farm probabilistic model including N similar turbines.

Table 1. Wind turbine clustering

Cluster number	Centre (MW)	Probability	Range (MW)
n=7	2.5	0.20833	2.23-2.5
6	E=2.0	0.06723	1.75-2.23
5	D=1.5	0.0839	1.32-1.75
4	C=1.1	0.10388	0.91-1.32
3	B=0.7	0.12386	0.53-0.9
2	A=0.4	0.15502	0.2-0.53
1	0	0.25776	0-0.2

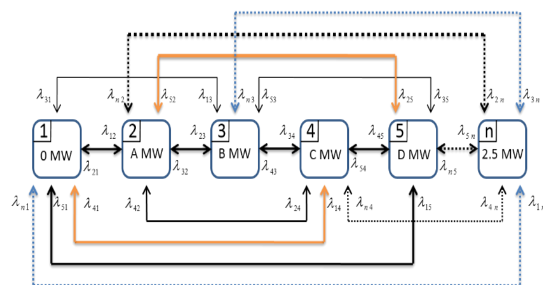

Fig. 4. Output power Markov model of a single 2.5-MW wind turbine.

The transitions rates (λ) between the states placed in non-neighborhood are not illustrated in Fig. 5 because of clarity [23, 24]. It ought to be considered that the discussed model might undergo some identical states in which the final states of the wind farm with different output levels could be resulted when these states are combined together. For instance, this scheme is carried out on a 50-MW wind farm containing twenty (2.5-MW *Nordex*-90) turbines and the final states with their corresponding probabilities are shown in Table 2. The FOR (Force Outage Rate) for each turbine is assumed to be 0.04. Although, the accurate study represents that an 11-state model of wind farm is acceptable enough for planning aims, the number of states is relevant to the required model accuracy [17, 25].

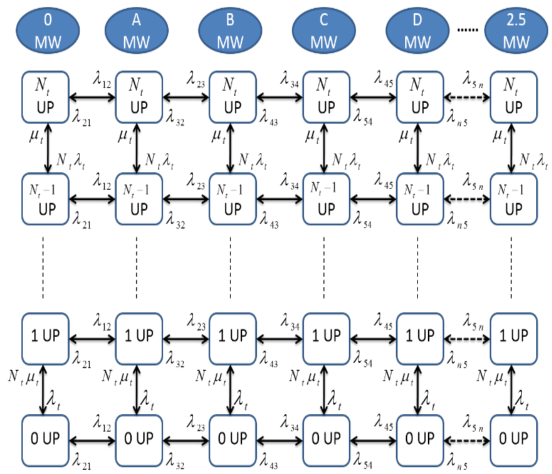

Fig. 5. Output power Markov model of a wind farm containing N_t wind turbines.

Table 2. Probability model of an 11-state 50-MW wind farm

State	Capacity (MW)	Probability	λ_+ (occ/yr)	λ_- (occ/yr)	Frequency (occ/yr)
1	50	0.09208	0	2233.6	205.68
2	45	0.10711	68.776	2202.7	243.3
3	40	0.06342	850.94	1408.2	143.28
4	35	0.01245	1093.4	1282.7	29.587
5	30	0.06849	1205.4	1497.9	185.14
6	25	0.01583	1353.2	1484	44.923
7	20	0.10386	1545.7	1694.4	336.52
8	15	0.11853	1824.1	1795.2	428.98
9	10	0.13105	2188.2	1773.9	519.24
10	5	0.0294	2341.2	1756.8	120.49
11	0	0.25776	2462.4	0	634.71

5. RELIABILITY ASSESSMENT OF COMPOSITE POWER SYSTEM

Taking into account both deficiency of generation and transmission line in the contingency analysis of power system, reliability assessment of composite system is possible to be implemented [26]. Basically, two main procedures for evaluating power system reliability are existing which are popular as analytical and simulation-based techniques. It is true that simulating the system performance could be readily performed in a computer program, but it suffers from great deal of computational endeavors in several cases [27]. On the contrary, although analytical procedures suffer more from intricacy due to the number of elements in power system probabilistic model as well as load characteristics, they are highly and conveniently fast and thoroughly appropriate for planning targets. As an extensive wind farm could be generally modeled as a generation unit with multiple states, analytical procedures could be employed for evaluating the composite system from reliability viewpoint when wind farm exists in the system. The methods employs AC load flow algorithm for any contingency considered. In extremely high stressed power systems, re-dispatching of generation and load shedding are implemented for resolving constraints of voltage violation related to the operation [28].

A. Load model with multiple steps

The FCM clustering method could be employed to build load model curves with multiple steps where each curve demonstrates a bus curve. It is definitely considered that a load duration curve is separated into *NLL* load levels [29]. Each one indicates those load points mean value regarding a cluster. The FCM clustering is implemented utilizing the equations below for the considered load model:

$$D_{ki} = \left| \sum_{j=1}^{NC} \left(M_{ij} - L_{kj} \right)^2 \right|^{\frac{1}{2}} \quad (7)$$

$$M_{ij} = \frac{\sum_{k=1}^{N_i} L_{kj}}{N_i} \qquad (j = 1, ..., NLC) \quad (8)$$

Hence, Dk_i indicates the Euclidean interval from the *k*th load point to the *i*th cluster mean, and L_{kj} is the load at the *k*th load point on the *j*th curve. *NLC* and *NLL* are described as the number of load curves and number of load levels, respectively. M_{ij} is the initial cluster mean of ith cluster (i=1,. . . ,*NLL*) and *j*th curve (j=1,. . . ,*NLC*). The means of clusters are also counted for any of the considered *NC* curves.

The means of clusters are utilized as the levels of load in any cluster for any curve. Any level of the load illustrates NS_i load points in the proportionate cluster in the case of mean amount. It could be found out that the correlation existing between means of clusters of any cluster in the load curves is done in the techniques of load clustering.

B. Reliability model of system elements

Elements of a system including generators, overhead transmission lines and reactive power compensators could be demonstrated utilizing a reliability model with two states [3] as demonstrated in Fig. 6. For an element, the availability *A* and unavailability *U* could be measured according to its failure rate λ and repair rate μ employing the equations below:

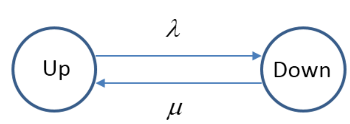

Fig. 6. Two-state Markov model of a system element.

$$A = \frac{\mu}{\lambda + \mu} \quad (9)$$

$$U = \frac{\lambda}{\lambda + \mu} \quad (10)$$

6. SPECIFICATIONS OF REACTIVE POWER

There are some significant aspects which make reactive power noticeably different from the active one in the operation of power system and this issue ought to be taken into consideration while evaluating the reliability of power system.

Firstly, it does not seem to be effective to transport reactive power beyond a long distance due to crucial losses of reactive power in the overhead lines and susceptible voltage of buses concerned to reactive power variation. Accordingly, reactive power deficiency in grids is locally compensated in general which suffer from feeble necessities. Secondly, reactive power has a considerable role in maintaining the voltage stability in a power system. Thus, reactive power impact on the reliability of power system considering the energy not supplied is not direct and has to be investigated based upon voltage violations and reactive power deficiency. Finally, the losses of reactive power alter with operation conditions and also configuration of the system [10]. Reactive power reserve distributions will highly meet voltage restoration if there is a contingency in the system.

In order to appropriately define dispatching the active and reactive power and also load shedding related to post-contingency, active and reactive power features associated with the voltage of the bus and their correlation have to be taken into consideration. Such characteristics have been comprehensively surveyed in [30].

A. Load shedding and under-Voltage control

An extremely vital problem in the operation of power system would be bus voltage stability which ought to be investigated in the reliability assessment. There could be some existing approaches for solving voltage stability problems due to shortage of reactive power. Overall, corrective or preventive control could alleviate the voltage violations. The preventive control tends to deter instability in voltage before it occurs indeed, whilst the corrective control turns out to be used for stabilizing a post-contingency strenuous system with implementations including switching compensation reactors, control of secondary voltage, pick-point increment of generator voltage, re-dispatch of generation and etc. To solve severe voltage problems, the final resort, which is used in this article, is under-voltage load shedding to specify the load curtailments resulted from the lack of reactive power [31]. In this article, the voltage set points in the load shedding are utilized as both 0.97 pu and 0.9 pu.

B. Parameters of system reliability

In a power system containing N elements which are substantially independent, the probability of state i is described as ρ_i, the state departure rate is introduced as λ_i, the parameter F_i denotes to the frequency of occurrence of state i in contingency analysis, and P_i is described as the whole capacity of available active power of the system for state i with M failed elements that could be specified utilizing the following equations listed below:

$$p_i = \prod_{j=M+1}^{N} A_j \prod_{j=1}^{M} U_j \tag{11}$$

$$\lambda_i = \sum_{j=M+1}^{N} \lambda_j + \sum_{j=1}^{M} \mu_j \tag{12}$$

$$F_i = p_i \lambda_i \tag{13}$$

$$P_i = \sum_{k=1}^{N_{gi}} P_k \tag{14}$$

Hence A_j denotes to the availability and U_j denotes to the unavailability of the element j. The failure and repair rates are described as λ_j, and μ_j, respectively. Active power capacity of generator k is introduced as P_k and N_{gi} is considered to be the available generator numbers for state i in the system [14].

C. Active and reactive power reliability indices

For providing reliability information regarding active and reactive power for system planners, the expected load curtailments of both active and reactive power caused by the deficiency of active power are described as ELC_P and EQC_P, respectively. The expected load curtailments associated with active and reactive power caused by the deficiency of reactive power or also violations of voltage are described as ELC_Q and EQC_Q, respectively. Additionally, the expected energy not supplied due to the shortage of both active and reactive powers are represented by $EENS_P$ and $EENS_Q$, respectively. Besides, the expected *Var* not supplied owing to active power deficiency is defined as $EVNS_P$, while the one owing to reactive power is defined as $EVNS_Q$. Moreover, the expected *Var* shortage because of voltage violation is determined as $EVarS$. The expected duration of load curtailment is represented by $EDLC$. These indices could be defined employing the equations as the following [27]:

$$ELC_P = \sum_{i=1}^{NC} LC_{Pi} \times F_i \tag{15}$$

$$ELC_Q = \sum_{i=1}^{NC} LC_{Qi} \times F_i \tag{16}$$

$$EQC_P = \sum_{i=1}^{NC} QC_{Pi} \times F_i \tag{17}$$

$$EQC_Q = \sum_{i=1}^{NC} QC_{Qi} \times F_i \tag{18}$$

$$EENS_P = \sum_{i=1}^{NC} LC_{Pi} \times p_i \times 8760 \tag{19}$$

$$EENS_Q = \sum_{i=1}^{NC} LC_{Qi} \times p_i \times 8760 \tag{20}$$

$$EVNS_P = \sum_{i=1}^{NC} QC_{Pi} \times p_i \times 8760 \tag{21}$$

$$EVNS_Q = \sum_{i=1}^{NC} QC_{Qi} \times p_i \times 8760 \tag{22}$$

$$EVarS = \sum_{i=1}^{NC} VarS_{Qi} \times p_i \times 8760 \tag{23}$$

$$EDLC = \sum_{i=1}^{NC} p_i \times 8760 \tag{24}$$

where the whole number of considered contingencies is defined as NC, and the active and reactive load curtailments caused by the lack of active power for state i are LC_{Pi} and QC_{Pi}, respectively. The active and reactive load curtailments caused by the deficiency of reactive power for state i are LC_{Qi} and QC_{Qi}, respectively, and $VarS_{Qi}$ is defined as the *Var* deficiency which creates voltage violation in state i. Substantially, the expected *Var* deficiency at any bus could be utilized to choose the best place for installing the extra compensators of reactive power required for planning and operation of the whole system [14].

D. Reduction method and contingency filtering

The quantity of system states for an actual huge power system would burst enormously while taking into account up to the third-order failures and load duration curve with annual hourly format as well. Accordingly, for the reduction of the numeral of calculated states based upon the specific precision, contingency filtering or screening is required to be utilized. The majority of available contingency election procedures in reliability assessment are according to the probabilities of contingency states. The contingencies having greater probabilities than a specific amount would be investigated and specified utilizing the state election procedure [32]. From viewpoint of security evaluation, various methods [33] have been surveyed to decrease the screening computing time.

Considering the particular prerequisite of reliability study, a contingency filtering index based upon the combination of the performance index and state probability is utilized that is identical to those used in [27] for the election of the contingency states. For various types of system states whether there are isolated buses caused by line failures or not, the filtering index for up to the third-order failures could be calculated utilizing the state probability and the severity index for any contingency demonstrating combination of various lines and generators failures [14].

7. RELIABILITY EVALUATION PROCEDURE

For making reliability analysis of a power system, the contingency states should be determined so as to consider whether or not system demand P_{di} has exceeded the active power capacity P_i using ac power flow. If it occurs, active and reactive load ought to be cut proportionally until P_i and P_{di} are balanced. For separating reliability indices caused by the deficiency of reactive power from those due to the active power shortage, load shedding has to be done at two different stages so that detailed information are provided for system planners concerning present and future PQ resources. The initial stage is mentioned as above for curtailing active loads and corresponding reactive ones based upon the specified power factor.

After the initial stage as load shedding, any maximum limit of Q injection at all PV buses and voltage violations at other buses need to be checked utilizing ac power flow so that the necessity of changing such PV buses to PQ ones is detected and then conducted. If the voltage at some of the load buses reaches to below the voltage set point, the problem would be concerned to the deficiency of local reactive power. Therefore, the second stage in load shedding being illustrated in Fig. 7 as "Scenario A" is required to eliminate problems associated with the shortage of Q in the system. Owing to the reactive power low efficiency being delivered through a long distance, at any nodes suffering voltage violations, the load shedding is usually implemented. Both the active and reactive power loads are curtailed continuously within the step of 1% and also the fixed power factor until the voltage violation is solved. Since the voltage in the system is greatly susceptible to reactive power load, the decision to choose a miniature step of 1% of the reactive load in duration of the process related to the iterative load shedding is acceptable. The low voltage constraint could not be readily obtained in the iteration process unless the step would not exceed further than what considered. After the loads are completely curtailed, if a violation is still found within the voltage at these buses, it is compulsory to reduce the loads within their neighbor nodes based upon the reactive power configuration in the local zone. It ought to be mentioned that stability of voltage is extremely depended on the distribution of network active load [14].

In order to provide extra data for system planners and operators by creating new reactive power sources in the prospective planning and operation, the voltage violations concerned to the deficiency of Var could also be eliminated by extra local Q that is injected. In this procedure, which is being illustrated in Fig. 7 as "Scenario B", at those nodes which are suffering from violations in the voltages, reactive power is injected for retrieving the voltage. As soon as the voltage gets into the voltage set point, $VarS_Q$ is calculated as the corresponding injected reactive power due to the deficiency of Q. It ought to be mentioned that the influence of injecting reactive power onto the voltage of the bus is very susceptible to the nature of network and also the distribution of reactive power sources. In this article, the reactive power in step of 1% of the reactive load is injected into any bus getting violated via the voltage, until when the voltage concern is thoroughly eliminated [14].

The trend of the stated procedure indicates the steps illustrated in Fig. 7. Although, each of the two above mentioned scenarios are taken into consideration individually and regardless to the other one, it should be noted that they are only being illustrated in one diagram in order to prevent from diagram repetition.

As could be seen from the illustrated process of adding wind farms into the considered system in Fig. 7, in the steps of the accuracy of the probabilistic model of the wind farm, the network is supported with additional active power. This could be built by the incorporation of wind power in the sense that reactive power shortage would be alleviated due to the capability of wind turbines in providing reactive power for the bus being extremely violated even when there is no wind flowing. Although the stochastic behavior of wind power would not seem to be highly certain for balancing the reactive and active power of the power system compared to higher deterministic reactive power compensators, it is believed that this renewable source of energy tends to be acceptable enough to be pressing in reliability studies while considering reactive issues.

8. SYSTEM STUDIES

The single line diagram of the modified RBTS is illustrated in Fig. 8. This system includes 2 generator buses, 4 buses for loads, 9 overhead transmission lines, and 11 units for generation. In this system, 230 kV is regarded as the level of voltage. The voltage constraints for the buses of the system are presumed to be ranging from 0.97 pu to 1.05 pu. The peak active and reactive loads of the system are presumed to be 185 MW and 60 MVAr, respectively, assuming the power factor of 0.95 for all loads. The whole capacity of the installed generation is 240 MW. The locations of the units and the network shown in Fig. 8 have been illustrated to present a geographical interpretation.

Generators and overhead lines reliability parameters [34] are utilized in this article and are represented in Tables A1 and A2 in the appendix Section. The power factor is 0.95 and the reactive load MVAr necessities at any bus is about 33% of the relevant MW load. Table A3 demonstrates bus load data in the appendix Section.

Consequently, two identical wind farms with a 50 MW capacity for each were regarded to be connected into the network. These wind farms integration and the required transmission network reinforcements for absorbing the extra wind power as to optimize the whole power system reliability depend on the

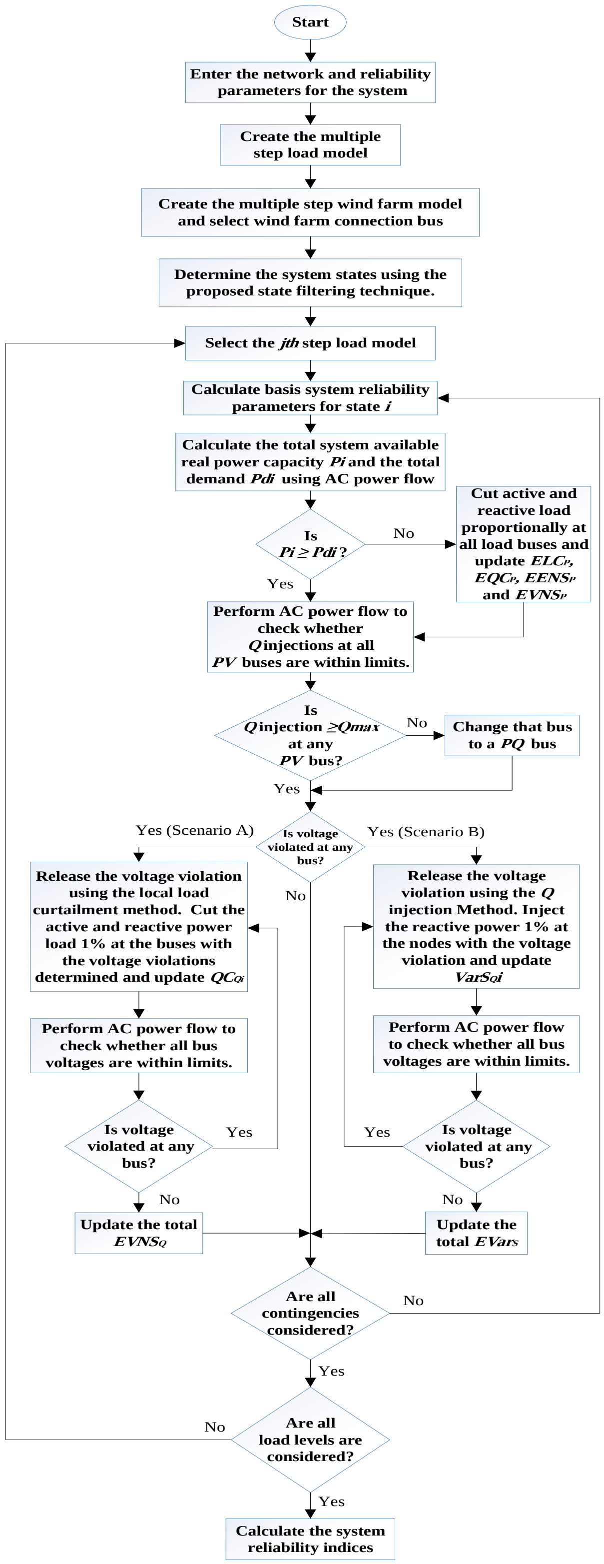

Fig. 7. Calculation of reactive and active indices in the presence of wind power.

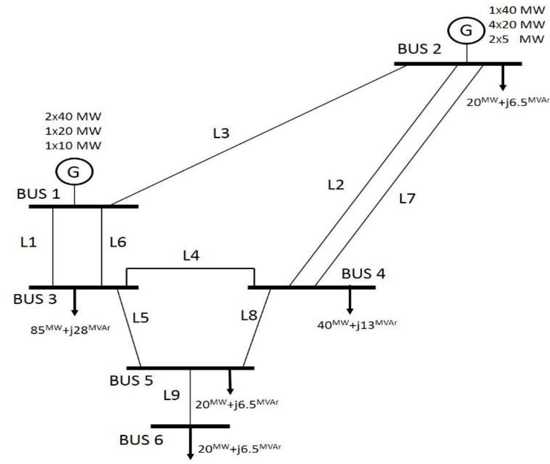

Fig. 8. Single line diagram of modified RBTS system.

network reinforcement plan options, which are determined by the network planners. The impacts of various aspects regarding reactive power issues on the network and reliability of load points are investigated and shown in this part of the article.

A. Analysis of reliability results

The reactive power constraints are illustrated in Table A1, in the appendix Section, for the generators and are also used in the analysis. Load duration curve using FCM is applied in this issue. During the load shedding, both loads of active and reactive power at any bus is bundled utilizing the fixed power factor. Then, the states up to third order failures have been taken into consideration for several combination of both generation units and transmission lines. The annual load and system $EENS_P$, $EENS_Q$, ELC_P, and ELC_Q are demonstrated in Table 3 as the voltage set point tends to be presumed 0.97 pu.

As shown in Table 3, it could be figured out that bus 6 has the most prominent $EENS_P$ pursued by both buses 5 and 3 for this index. The greater $EENS_P$ at such buses is caused by a much greater level of load and these buses are also in more distant from the power resources compared with other load points. Bus 6 has the most prominent $EENS_Q$ pursued by bus 5. The reason behind this is due to the lack of compensator for local reactive power at those buses in the most adjacent neighborhood. The other reason is that the overhead lines are extremely long from the place of other compensators to these two buses. Such results almost indicate that the $EENS_Q$ of the system is approximately 31.30% of the $EENS_P$. It is shown that 29.39% of the total $EENS$ at bus 5 and 24.01% at bus 6 are reached as the result of reactive power deficiency. This implies that the compensation required for the reactive power in some load points is influential for post contingency retrieval. The system $EENS_Q$ resulted from the constraint of reactive generation and the voltage violation is calculated to be 23.84% of the whole $EENS$.

Table 4 shows bus Var and reactive load indices including system $EVNS_P$, $EVNS_Q$, EQC_P, EQC_Q, and $EVarS$. The system expected Var curtailment caused by the deficiency of reactive power is inconsiderable compared with that caused by the deficiency of active power. The reason behind this is due to the reduction of reactive power load in the initial stage which was introduced as load shedding. In an actual power system, active and reactive power ought to be shed according to the load features.

Table 3. Annual bus energy and active load indices

BUS	$EENS_P$ (MWh/yr)	$EENS_Q$ (MWh/yr)	ELC_P (MW/yr)	ELC_Q (MW/yr)	$EDLC$ (hr/yr)
2	0.4356	0	0.0207	0	0.0001
3	4.7123	0.6572	0.2783	0.0772	0.0006
4	4.2408	1.1398	0.2419	0.2054	0.0006
5	6.9818	2.9062	0.4392	0.4173	0.0011
6	140.3521	44.3568	10.3297	6.7347	0.021
System	156.7226	49.06	11.3098	7.4346	0.0234

Table 4. Annual bus *Var* and reactive load indices

BUS	$EVNS_P$ (MVarh/yr)	$EVNS_Q$ (MVarh/yr)	EQC_P (MVar/yr)	EQC_Q (MVar/yr)	$EVarS$ (MVarh/yr)
2	0.2576	0	0.0164	0	0.0131
3	1.3632	0.1036	0.0857	0.0146	0.3495
4	1.478	0.5031	0.0936	0.0668	1.0602
5	2.4327	1.0762	0.1632	0.1678	9.9136
6	34.5013	14.221	2.9357	2.8347	23.7819
System	40.0328	15.9039	3.2946	3.0839	35.1183

Table 5. System reliability indices

BUS	$EENS$ (MWh/yr)	ELC (MW/yr)	$EVNS$ (MVarh/yr)	EQC (MVar/yr)	$EVarS$ (MVarh/yr)	$EDLC$ (hr/yr)
2	0.4356	0.0207	0.2576	0.0164	0.0131	0.0001
3	5.3695	0.3555	1.4668	0.1003	0.3495	0.0006
4	5.3806	0.4473	1.9811	0.1604	1.0602	0.0006
5	9.888	0.8565	3.5089	0.331	9.9136	0.0011
6	184.708	17.0644	48.722	5.7704	23.781	0.021
System	**205.782**	**18.744**	**55.936**	**6.378**	**35.118**	**0.023**

Total system reliability indices in combination of active and reactive indices are demonstrated in Table 5.

B. Load shedding and *Var* compensation

The majority of common reliability assessment procedures reduce voltage violations by load shedding within active and reactive power (Scenario A). Injection of the reactive power (Scenario B) is also investigated in this article in order to eliminate the occurred obstacle. The aim of the general load shedding or injection of *Var* is to retrieve voltage at any bus to its low constraint. Table 5 demonstrates total system *EENS* acquired utilizing the mentioned procedures. The curtailments of the relevant load for active and reactive power in "Scenario A" and compensation of *Var* for "Scenario B" caused by voltage violations are also illustrated in Fig. 9. The total system *EENS* would be decreased approximately by 3.5% in comparison with that from the load shedding procedure if the injection of reactive power is performed in the relevant buses for solving the violation occurred within the voltage.

The whole system *EENS* is decreased whenever the load level is reduced from one hundred percent to the percentage of eighty for the peak level in the two mentioned scenarios. An utterly small distinction between these two scenarios is found out and the relevant results would be reached. The system *EENS* for "Scenario A" and "Scenario B" are identical due to no violations within the network for the majority of the contingency states except those having isolated buses, while the levels of loads are generally less than or actually equal to eighty percent of the peak load.

The whole injection of the expected reactive power described by *EVarS* is 35.1183 MVarh/yr. The injection of almost the highest reactive power would be at bus 6 and after that at bus 5. These results give additional data to planners of the system for prospective placement related to the compensators of reactive power.

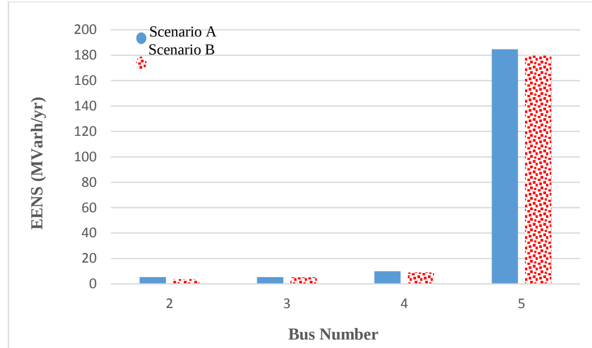

Fig. 9. *EENS* of different buses using load shedding (Scenario A) and *Var* compensation (Scenario B).

Consequently, the results show that for a specific voltage threshold the system total risk index extremely depends on that of bus 6. The reason behind this is that bus 6 is located in a long distance from generation sources and might be disconnected from the grid by even a single contingency.

C. Voltage set point effect

The voltage set point impact on the reliability indices is also surveyed in this article. These indices for the voltage set point of 0.9 pu is also counted. The system $EENS_Q$ associated with the voltage set point of 0.9 pu is noticeably decreased down to 12.6789 MWh/yr from 49.06 MWh/yr when the voltage set point is 0.97 pu. The system *EVarS* associated with the voltage set point of 0.9 pu is considerably decreased down to 3.4621 from 35.1183 MVar/yr when the voltage set point is 0.97 pu. The results show that if the system is preserved in the stable mode of operation at the voltage of 0.9 pu, much less load will be curtailed and less *Var* injection is needed. It ought to be mentioned that the associated margin of reliability relevant to a post-contingency will be decreased because of the much lower voltage set point.

D. Effects of wind farm size and location

Regarding the above acquired results from the reliability analysis, two identical wind farms experiencing the same wind regime with the capacity of 50 MW for each (totally 100 MW) are modeled to be connected into buses 5 and 6 employing procedure stated in Fig. 7. The results which are being showed in Tables 6-8 describe how much beneficial these wind farms could be regarded by their contribution in power system reliability from the viewpoint of both active and reactive adequacy. Table 8 shows a considerable reduction in *EENS* when a total of 100 MW wind power capacities are included into the system at buses 5 and 6. Since bus 2 is regarded as a generator bus that is able to provide locally light load, the interconnection of a 100-MW wind farm into bus 2 connecting point may cause an overload on the cables between bus 2 and the far located bus 4.

If a wind farm is injected to bus 4, because of the essence of much heavier power flow from the north to the south of the system after interconnection of wind farm at this bus, it could be estimated that reliability improvement in this case would not

Table 6. Annual bus energy and active load Indices with wind farm

BUS	$EENS_P$ (MWh/yr)	$EENS_Q$ (MWh/yr)	ELC_P (MW/yr)	ELC_Q (MW/yr)	$EDNS$ (hr/yr)
2	0.3703	0	0.0176	0	0.0001
3	3.5813	0.4456	0.2143	0.051	0.0005
4	2.5445	0.8993	0.15	0.1582	0.0004
5	2.4087	1.6478	0.1581	0.2087	0.0004
6	50.5268	15.0813	2.2725	2.0204	0.0048
System	59.4316	18.074	2.8125	2.4382	0.0061

Table 7. Annual bus *Var* and reactive load indices with wind farm

BUS	$EVNS_P$ (MVarh/yr)	$EVNS_Q$ (MVarh/yr)	EQC_P (MVar/yr)	EQC_Q (MVar/yr)	$EVarS$ (MVarh/yr)
2	0.2293	0	0.0144	0	0.0109
3	1.1724	0.0806	0.0737	0.0107	0.2621
4	1.0346	0.2963	0.0702	0.0387	0.6361
5	1.0826	0.5026	0.0685	0.0722	3.5689
6	3.4501	3.5553	0.2936	0.7937	6.8968
System	6.9689	4.4348	0.5204	0.9153	11.3748

Table 8. System reliability indices with wind farm

BUS	$EENS$ (MWh/yr)	ELC (MW/yr)	$EVNS$ (MVarh/yr)	EQC (MVar/yr)	$EVarS$ (MVarh/yr)	$EDLC$ (hr/yr)
2	0.3703	0.0176	0.2293	0.0144	0.0109	0.0001
3	4.0269	0.2652	1.253	0.0844	0.2621	0.0005
4	3.4438	0.3081	1.3309	0.1089	0.6361	0.0004
5	4.0565	0.3668	1.5851	0.1407	3.5689	0.0004
6	65.6081	4.2929	7.0054	1.0873	6.8968	0.0048
System	77.5056	5.2507	11.4037	1.4357	11.3748	0.0061

be considerable.

The wind farms at both buses 5 and 6 would have a remarkable improvement in the system reliability compared with other buses if integrated with wind farms. A zone with heavy load is placed at these two buses, which could absorb wind energy of these wind farms. Besides, these wind farms could provide loads at central buses 3 and 4.

On the contrary, the distribution of reactive power between all *Var* sources that are available, including also wind turbines, demonstrates an optimization problem in reliability studies indicating that wind turbines are capable in controlling and supporting the features of reactive power continuously such as voltage control, whether required.

9. CONCLUSION

Since wind farms have become much extensive and extremely huge in recent years, they are susceptible to play a significant role in analyzing power system reliability and associated power system planning. Wind farm integrated system reliability analysis, along with the investigation of operating requirements and transmission characteristics, could be able to prove reasonable factors in order to help policy makers to put wind farm projects in high priority according to the whole reliability benefits. It is been a controversial matter that how wind farm is incorporated in reactive power compensation while it's effect from the aspect of active adequacy had been only considered.

In this paper, Fuzzy C-Means clustering procedure was engaged to find out the most appropriate clusters affiliated with the output power of wind farms. Using this technique, it could be interpreted that the given objective function value would not have a considerable change as the number of clusters rises. The analytical procedure of wind farm was developed by establishing state space model for turbines according to the specified states for each turbine.

To make reliability evaluation of power system including reactive power adequacy, which has a significantly influential factor in reliability assessment, the acquired model of wind farm is employed to investigate the amount of reliability improvement that could be resulted by adding 2 wind farms to the modified RBTS 6-bus test system. To do so, the reliability indices caused by the deficiency of reactive power are distinguished with those caused by that of active power.

Load shedding and reactive power injection are also employed at the buses with the voltage violation as two distinctive scenarios for the determination of reactive power deficiency. There is not a noticeable change when comparing the *EENP* of the system applying these two scenarios.

Finally the effect of adding 2 wind farms into the system from the active and reactive reliability indices has been compared to the system without wind integration. The results indicate that not only do a wind farm play a considerable role in contribution of power system reliability from active power adequacy, but it could also support reactive power shortage occurred in contingencies due to reactive shortage caused by voltage violation or insufficient reactive power resources even at zero wind power.

APPENDIX

Table A2. Transmission line length and outage data

Line	From bus	To bus	Length (km)	λ	μ
1	1	3	75	1.5	876
2	2	4	250	5	876
3	1	2	200	4	876
4	3	4	50	1	876
5	3	5	50	1	876
6	1	3	75	1.5	876
7	2	4	250	5	876
8	4	5	50	1	876
9	5	6	50	1	876

Table A3. Bus load data

Bus	Load (MW)	Load (MVAr)
2	20	6.5
3	85	27.5
4	40	13
5	20	6.5
6	20	6.5
Total	185	60

Table A1 includes the reliability parameters and also reactive power constraints, Table A2 includes the parameters concerned to the reliability of transmission lines and Table A3 consists of the buses' loads [34].

Table A1. Rating of Generating units and their reliability data

Unit Size (MW)	Type	No. of Units	Q_min (MVAr)	Q_max (MVAr)	Forced Outage Rate	Failure Rate (f/yr)	Failure Rate (r/yr)
5	Hydro	2	0	5	0.01	2	198
10	Thermal	1	0	7	0.02	4	196
20	Hydro	4	-7	12	0.015	2.4	157.6
20	Thermal	1	-7	12	0.035	5	195
40	Hydro	1	-15	17	0.02	3	147
40	Thermal	2	-15	17	0.03	6	194

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