Reliability evaluation of power systems containing tidal power plant

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Nowadays renewable energy resources have been experiencing rapid progress in electric power networks all over the world. As a result, it is important that these clean electrical power resources be utilized for power generation in the modern power systems in the planning and operation studies. However, the uncertainty related to these energy resources and their intermittent nature result in some challenges when integrating into the power networks. The reliability of power systems is affected when the penetration level of these intermittent renewable power generations is significant. In this regard, this paper introduces an analytical technique to study the adequacy of a power system containing significant tidal power generation. For this purpose, a multi-state reliability model of a tidal plant considering both failure rate of composed components and variation in the generated power arisen from variation in the tidal current speed is developed. At first, an equivalent reliability model considering failure effects of composed components is obtained. Then Fuzzy-C-means clustering method is applied for reducing numerous values of the output power of the plant. For determining the optimum number of states in the model, XB index is calculated. The proposed multi-state model is then used for adequacy studies of RBTS and IEEE-RTS and the related indices of these systems in the presence of tidal units are evaluated.

keywords: *Tidal power plant, Adequacy indices, Fuzzy C-means clustering, Tidal current speed, state reduction.*

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NOMENCLATURE

λ Failure rate of the components
μ Repair rate of the components
P_{up} Up state probability
P_{down} Down state probability
T Set of time intervals
λ_{eq} Equivalent failure rate
μ_{eq} Equivalent repair rate
r_{eq} Repair time
P_{out} Output power of the turbine
C_P Power capture coefficient
ρ Seawater density
A Area swept out by the turbine rotor
P_i Probability of the occurrence of the cluster i
v_i Tidal current speed
RPS Renewable portfolio standard
ROR Run-of-the-river
FCM Fuzzy C-means clustering method
$COPT$ Capacity outage probability table
$LOLE$ Loss of load expectation
$EENS$ Expected energy not supplied
$PLCC$ Peak load carrying capability
$IPLCC$ Increase in peak load carrying capability

1. INTRODUCTION

Recently, renewable energy resources e.g., wind, solar sources, and ocean are widely used for electrical power generation in power systems. The rapid progress of these clean and free energy resources in the generation sector of power systems rises from problems resulted from conventional generation units including concerns about the increase of greenhouse gases, expensive and variant price of fossil fuels and high operation costs of these power plants [1]. In addition, government incentive schemes to encourage investors for the installation of renewable energy-based power plants in some countries result in a significant penetration level of renewable resources in the generation power system. Some of these supportive mechanisms include Renewable Portfolio Standard (RPS), fixed tariffs in some European countries one of whose main goals is picking up the pace in renewable integration and the like so on [2]. Tidal power plant is one among many of the ocean energy technologies used for electrical power generation. The first power plant based on the tidal energy was constructed in 1966 on the Rance River estuary located in Brittany, France. This plant consisted of 24 10 MW tidal turbines and supplied 0.12 percent of the total France electrical demand at that time [3]. In recent years, this type of ocean energy will have a significant share among different electricity generation technologies. The Sihwa tidal plant with 260 MW installed capacity, the largest barrage type tidal plant in the world, was operated in 2011, in South Korea and generates electrical power whenever the water flows from the sea to the basin [4]. One of the large-scale tidal power plants is the Annapolis tidal unit which was operated in 1984 with 18 MW generation capacity in Canada [5]. These three tidal power plants require long dams, several gates or tidal locks for extract and reserve the ocean potential energy. However, another technology of tidal power plants can generate electricity from tidal current speed of moving water which is similar to what is done suing wind speed. In recent years this technology of tidal turbines has grown and matured. For example, recently tidal current turbines with large capacity have been made for which the following can be mentioned as examples: 1.2 MW Alstom/TGL tidal turbine in 2013, 1.1 MW Hammerfest/Andritz Hydro in 2013, 2.2 MW Open Hydro/DCNS in 2012 and 1 MW Voith Hydro in 2013 [6]. Based on the large marine current turbine technologies, pilot tidal current farms were constructed in the past years such as 10 MW Anglesey tidal farm in Wales in 2015, 10 MW Sound of Islay tidal farm in Scotland in 2015 and 12 MW Raz Blanchard tidal farm in 2016 [7]. The generated power of the tidal power plant is a function of the tidal current speed, and because the tidal current speed varies with time, the output power of the plant varies widely. By integrating the tidal power plant in the power system, the intermittent nature of such plants resulted from the variation in their output power may lead to some problems that must be investigated. The reliability, one of the important topics in the modern power systems, is affected when integrating the large-scale tidal power plants in the power grid. Thus, it is essential to analyze the reliability of the power system containing the tidal power plants. The reliability indices of the power system can be used for the generation expansion planning of the power system. Thus, the value of the reliability indices of the power system considering tidal power plants can be utilized for this purpose. In this regard, some efforts are done to evaluate the reliability of tidal power plants. In [8], barrage type tidal power plants are presented with a multi-state model considering the effects of failure of components and also variation in the tidal height. The composed components and also the basis of electricity production in the current type tidal power plants and current type units are different and so, a new technique must be developed for reliability evaluation of current type tidal power plant. In [9], reliability-based operation studies of a power system containing barrage type tidal power plant are performed. In this paper, PJM method is used for calculating operation indices of the power system containing barrage type tidal power plant. However, barrage type tidal power plants are similar to the hydro power plants and current type tidal power plants are similar to the wind power plants and so, the methods used for evaluating these two types of tidal power plants are different.

In this research, an analytical approach is introduced to perform adequacy study of the power system including tidal power plants with large capacity. However, because of the similarity between wind and tidal current turbines, some valuable and useful works performed in conjunction with the reliability analysis of power systems considering wind turbines can be used. In [9, 10], a reliability model of the wind unit containing the doubly-fed induction generator is introduced and a reliability model with several states for these farms is constructed and utilized to analyze the adequacy of an electric power network including wind farms in HLI and HLII. In these two papers, the composed components of the wind power plants based on DFIG are considered and the effects of these components on the reliability model of wind units are investigated. Also, the effect of variation in the wind speed and consequently generated power on the model is considered. In [12] adequacy analysis of a power network in the presence of doubly-fed induction generator-based run of the river (ROR) plant is performed. For this purpose, the reliability model of a ROR unit is introduced as a generation unit with several states. In this model, the failure rate of the composed components as well as the intermittent nature associated to the water flow which led to the variation of the output power of the unit is considered. Based on the obtained multi-state reliability model of the run of the river power plant, the important reliability indices of the power system containing ROR plants are calculated. In [13], the effects of the operation mode of the tidal turbine related to the tidal current speed, on the tidal unit's failure rate based on the doubly-fed induction generator is investigated. Although in the mentioned paper an equivalent failure rate for this type of tidal power plant considering different operation modes and temperatures is determined, a complete reliability model of the tidal power plant with several states suitable for adequacy analysis of the power system, associated to the failure of components and variation in the generated power, is not obtained. In [14], a probabilistic modeling of tidal power generations is performed and it is deduced that Wakeby distribution is the best to model the probabilistic nature associated to the tidal currents speed. Thus, this distribution can be used for tidal current speed forecasting and generated power determination of a current type tidal power plant. In [15], a new approach for performing operation analysis of a power network containing significant wind farms based on reliability criteria is introduced. In this paper, wind farms are modeled as a multi-state unit from reliability point of view and the modified PJM method is employed for spinning reserve determination of the power system in presence of wind farms with large capacity. In [16], the reliability analysis of a power network including wind generation from voltage and power quality criteria is performed. Therein, effects of reactive power compensation through shunt capacitor placement on reliability indices are investigated. In [17], a new approach for wind speed distribution modeling is introduced in whose method the distribution of wind speed is represented based on the first order origin moment and also second to fourth order central moments associated to the historical data of the wind speed as the constraint of maximum value of entropy. With this model combination to other conventional units, the reliability analysis of the power network is evaluated and the loss of load probability index is calculated for the RBTS based on the proposed approach. In [18], adequacy studies of a generation system containing high penetration level wind farms are performed. The reliability model of the wind turbine generator is there developed based on the components' failure rates and the uncertain property of wind speed. Then, a software program for data generation is used to capture the hour-to-hour wind speed data from the seasonal value and then, clustering technique is employed for states reduction of the generation unit model. Using the Marcov process, the probability of each generation state is obtained and the adequacy studies of the RBTS in presence of wind farms using of the proposed approach is performed. In [19], reliability analysis of a power network including large-scale wind power unit is performed based on an algorithm named state-space partitioning. This algorithm is modified and the unit rates forced shutdown and its possible effects on the system reliability, utilization the minimum adjacent state sets along with the service model of the wind turbine and the uncertain nature of the wind speed are considered. In [20], a method for reliability evaluation of a hybrid generation system of wind and tidal powers with battery energy storage is proposed. In case studies of this paper, the effects of various parameters on the system reliability are investigated by Mont Carlo method. LOLE and EENS indices for power system containing tidal and wind generation with battery energy storage system is calculated. In this paper, the number of states in the reliability model of wind and tidal unit is not optimally determined and an arbitrary number is selected.

This paper introduces a reliability model with several states for different technologies of tidal power plants to be used in power system adequacy and planning studies. Different types of tidal power plants based on the types of generators used inside including permanent magnet or electrically excited synchronous generators, double fed or squirrel cage induction generators are studied in this research. The proposed reliability model considers both failure rate of the composed elements and the intermittent nature of the tidal current speed. A proven clustering technique, namely the fuzzy C-means clustering approach (FCM), is applied to determine the feasible mode of tidal units arisen from the intermittent nature of the tidal current speed. The capacity and the probability associated with the reduced states are obtained using historical data. Furthermore, this analytical method provides the possibility to investigate the contribution that tidal energy can supply the required load of a power network. The proposed approach is used for adequacy analysis of two test networks, namely RBTS and IEEE-RTS. The main contributions of this paper can be summarized as below:

- A reliability model considering both components' failure and uncertainty nature associated with the tide velocity is developed for current type tidal power plants.
- For state reduction in the reliability model and determination of optimal number and center of clusters, the XB index and fuzzy c-means clustering method are utilized.

The reliability indices calculated based on the proposed approach can be used for generation expansion planning of the power systems considering the potential and generation capacity associated to the tidal currents. For generation expansion planning of the power system two important aspects must be considered: the cost and also the reliability.

The rest of this research is structured as follows: In Section 2, the tidal power plants and different types of them are introduced. The reliability analysis of the power network and reliability model of different current type tidal power plants is illustrated in Sections 3 and 4. The proposed technique for adequacy analysis of a power system including tidal power plants and numerical results associated with the RBTS and IEEE-RTS are given in Section 5. The conclusions of the research are summarized in Section 6.

2. TIDAL POWER PLANTS

The potential of renewable energy resources, especially wind, oceans, and seas is very high, and they can be used for providing required clean energy of the world. In this regard, different technologies are currently being introduced to convert the kinetic energy of these resources to the electrical energy for satisfying a long-term contribution of these emission-free energies to the future energy sector. Among the various technologies related to ocean energy, tidal power plants are expected to progress rapidly due to resources availability and mature technologies [6]. For extraction of electrical energy from the tides, two approaches can be employed: In the first approach the kinetic energy of the tidal currents or the moving water is used to generate the electrical power in a similar trend to that of wind turbines. These types of tidal power plants do not have damaging effects on the environment since the tidal generators can be built into the structures of existing bridges or are entirely floated in the marine area. In the second approach, the potential energy resulted from the difference in heights of high and low tides are made use of. In this method, the generation system is equipped to the long dams, several gates or locks for extraction and reserve the ocean potential energy. In other words, a barrage type tidal unit requires the construction of a dam named tidal barrage which spans across the tidal inlet entrance, reservoir or estuary making a single enclosed tidal basin that is the same as the hydroelectric reservoir [21]. In this paper, the first type of the tidal units, i.e. the tidal current power plants, is investigated. In this type of system, different technologies have been used for electrical power extraction from the kinetic energy of the ocean currents arisen from the tides. In the present study, four well-known technologies based on different types of generators used are illustrated and their composed components associated with the conversion systems are explained [22–26]. The structure of a typical tidal power plant with different types of generators is presented in Fig. 1. In the first type, the permanent magnet synchronous generator is used for tidal kinetic energy conversion to the electrical power. In this technology, the kinetic energy of the tidal currents results in the rotation of the blades and then the mechanical energy of the blades can be transferred to the gearbox and the generator through the main shafts. The permanent magnet synchronous generator converts the mechanical energy to electrical energy. Since the frequency and voltage amplitude of the generation power are not fixed, a back-to-back converter system consisting of a DC to AC converter, DC bus capacitor and an AC to DC converter is placed at the generator output to integrate the generated power of the tidal unit to the power grid using of a transformer and cables. The control system includes the pitch and yaw control of the turbine and the voltage and frequency control systems of the electrical output power [23]. In the second technology, a double fed induction generator is utilized for electrical power extraction from tidal currents. In this type of power plant, the generator's stator is directly connected to the grid using the transformer. However, the rotor is connected to the grid using of a back-to-back converter (for frequency and voltage control) and the transformer. Except the generator, all components are similar to the previous type [25]. The third tidal power plant technology uses squirrel cage induction generator for tidal energy conversion to electrical power. In these power plants, the rotor is squirrel cage type and

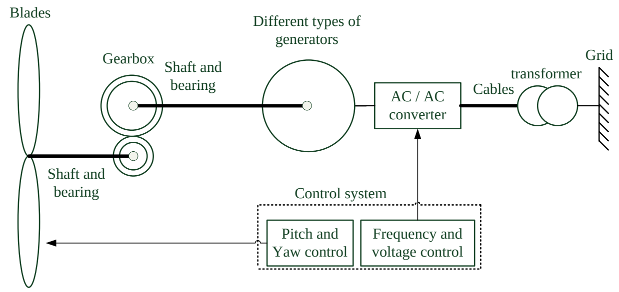

Fig. 1. The typical structure of the tidal power plant with different types of generators.

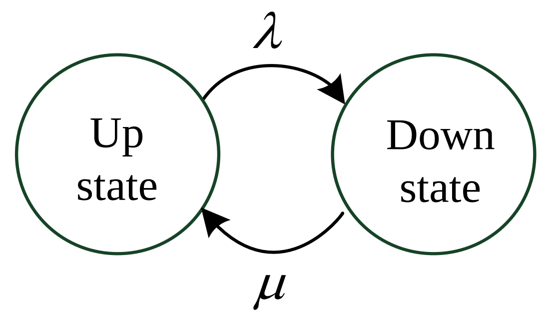

Fig. 2. Two-state Marco model for each component.

has no winding. The stator is connected to the power network using of a back-to-back converter and a transformer. Except the generator, all components are similar to the permanent magnet synchronous generator type. The last technology of tidal power plants utilizes from electrically excited synchronous generator for electrical power generation. In this power plant, the rotor is excited by the DC current and AC three-phase voltages are induced in the stator windings. The stator is connected to the power network by a transformer and a back-to-back converter for voltage and frequency matching.

3. POWER NETWORK RELIABILITY

Power network reliability, which is the ability of the power network in supplying the required loads according to the operation standards, is one of the main aspects of modern power systems. The reliability of the power network is performed in three hierarchical levels including generation level, composite (including generation and transmission) level and the total power network composed of the generation, transmission and distribution systems. Adequacy and security of the power system are two main aspects of reliability studies. In adequacy studies, adequate facilities in generation, transmission or distribution systems must exist to supply the required demand. Security is involved in operation studies of the power network and is required to investigate the response of the system to probable contingencies such as generation unit failure, outage of the transmission lines, etc. [27].

Reliability analysis of the power network can be studied by two approaches. The first approach is the analytical method required to develop a reliability model for each element of the system. The total reliability model developed for the system can be determined by combining the reliability models of the subsystems with associated components. In the second approach, the system reliability indices can be obtained by simulation of the system in a long period and time. Monte Carlo simulation is a well-known method for determining the indices based on the second approach. However, the Monte Carlo simulation method requires a high volume of calculations and is very time-consuming [27]. In this paper, the adequacy analysis of the power network including tidal power plants is studied based on the analytical approach. To this end, it is required to develop the reliability models of the different types of tidal power plants.

4. RELIABILITY MODEL OF TIDAL POWER PLANTS

In the second part of this paper, different technologies associated with the tidal power plants based on different types of related generators are introduced and their associated components are illustrated. The output power of the plants can vary due to the failure of the composed components or the variation in the tidal current speed. For this purpose, for reliability modeling of the tidal power plants, both components including failure rate and the intermittent nature of the tidal current speed must be considered.

A. Conversion system reliability model

In this subsection the effects of component failure on the reliability model of the tidal power plant is investigated. A macro model with two states (down and up states) can be seen in Fig. 2 which can be used for reliability modeling of each component. λ (number of failures per year) and μ (number of repairs per year) represent failure and repair rates of the elements, respectively [27]. The up and down state probabilities can be determined as by Eq. (1).

$$p_{up} = \frac{\mu}{\mu+\lambda} \quad , \quad P_{down} = \frac{\lambda}{\lambda+\mu} \tag{1}$$

In all technologies introduced in the second section, failure of each element leads to the failure of the conversion system and thereafter the tidal unit generates no power. Thus, based on the reliability studies, all elements are series and so the equivalent value for failure and repair rate of the total system can be simply determined based on the series components as in Eq. (2) [27].

$$\lambda_{eq} = \sum_{i=1}^{n} \lambda_i \quad , \quad r_{eq} = \frac{\sum_{i=1}^{n} \lambda_i r_i}{\lambda_{eq}} \quad , \quad \mu_{eq} = \frac{1}{r_{eq}} \tag{2}$$

In Eq.(2) λ_{eq}, μ_{eq} and r_{eq} (hour) are equivalent values for the failure rate, repair rate and repair time and n components are assumed to be in series with each other. The reliability model of the tidal unit considering failure rate of the components is presented in Fig. 3. For each technology, the power curve of the turbine, failure rate and repair time of the components may be different from one other.

In a tidal farm, to output power enhancements, the output power of several tidal turbines are integrated into a common bus and transferred to the power grid. Based on the reliability studies, these turbines are parallel and so the reliability model of the tidal farm with m tidal turbines each with a capacity equal to

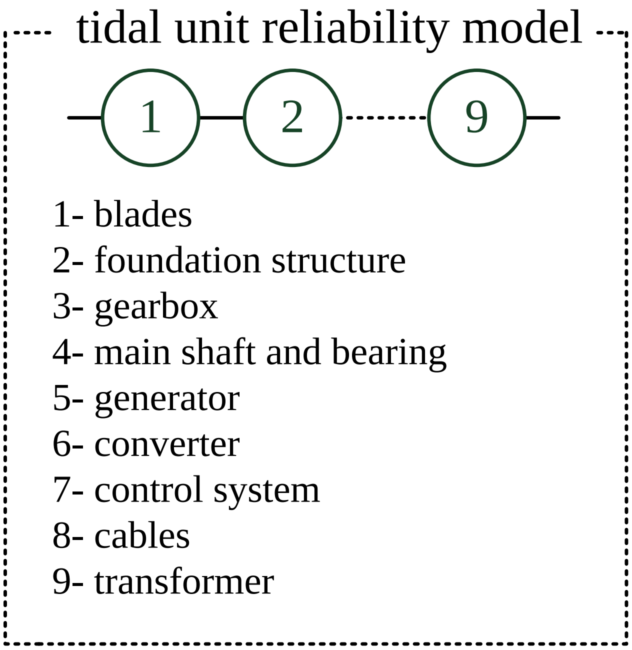

Fig. 3. Reliability model of tidal generation unit considering the failure rate of the component.

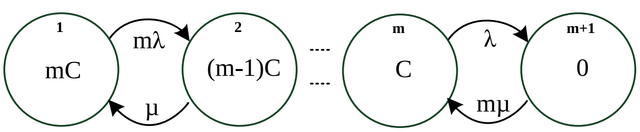

Fig. 4. Reliability model of a tidal farm consisting of *m* turbines.

C (MW) and availability of A can be presented as shown in Fig. 4. The capacity and probability of different states of the farm model can be calculated by Eq. (3).

$$Capacity = k \times C\ MW\ ,\ k : number\ of\ up\ units \tag{3}$$

B. Impacts of the intermittent nature of the tidal current speed

The variation of the tidal current speed results in changes in the output power of the tidal power plant. Similar to the wind turbine, the relation between the tidal current speed and the generated power of the turbine can be obtained by the turbine power curve. As can be seen from Fig. 5, in speeds less than the cut-in speed (m/s) the generated power is zero. With increasing the speed of the tidal current, when it reaches to the cut-in speed, the turbine starts to generate power. The relation between the tidal current speed and the generated power of the turbine is stated as Eq. (4).

$$P_{out} = \begin{cases} 0 & 0 < v_i < v_{cutin} \\ \frac{1}{2} C_p \rho A v_i^3 & v_{cutin} < v_i < v_{rated} \\ P_{rated} & v_i > v_{rated} \end{cases} \tag{4}$$

In Eq. (4), C_p is the power capture coefficient and for a typical turbine is 0.4 0.5, ρ is the density of the sea water (kg/m^3); A

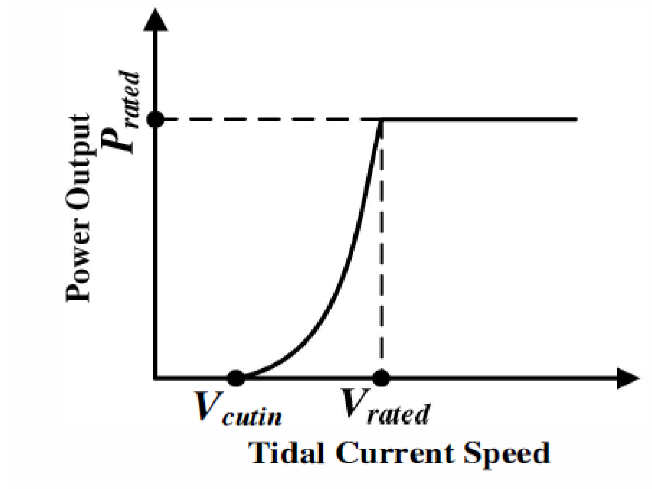

Fig. 5. Power curve of a tidal turbine.

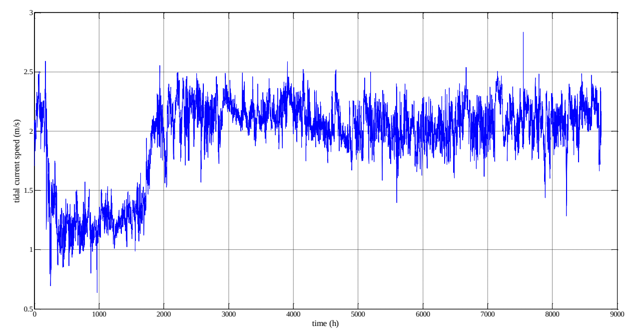

Fig. 6. Tidal current speed of lake St. Clair in one year (2015) ??.

(m^2) is the area of the turbine rotor and v_i is the tidal current speed (m/s). As can be seen from Fig. 5 and Eq. (4), unlike wind turbines, in the tidal current turbines the cut-out speed does not exist and the generated power of the turbine is fixed to the rated value when the tidal current speeds are higher than the rated value. Compared to the wind speed, tidal current speeds are small and their maximum value cannot damage the turbine [25]. These speeds vary in time and location. In Fig. 6 the tidal current speeds of Lake St. Clair located between Ontario in Canada and the state of Michigan in the U.S., in one year (2015) are presented. As can be seen from the figure, speeds have changed a lot in one year and so the generated power of the tidal unit has numerous values which is not good for reliability analysis of the power network. As a result, it is important to decrease the number of states of the model through a suitable clustering method.

Among different clustering techniques, fuzzy C-means clustering method (FCM) is a well-known technique that is utilized in different applications such as image segmentation [29]. Thus, in this research, FCM is selected for state reduction of the tidal power plants. This method was utilized for state reduction of generated power associated with the renewable resources such as wind and the run of the river plants in [8–10]. Using this robust technique, the proper number, centers and range of tidal power states can be determined.

This method categorizes object data $X = [x1, x2, ..., xn]$ into

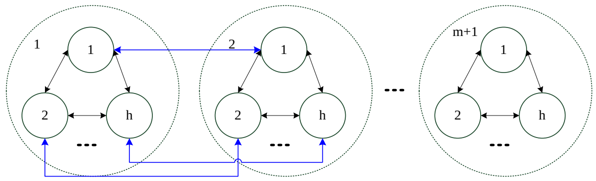

Fig. 7. The multi-state reliability model of a tidal farm.

m fuzzy clusters minimizing the following objective function **??**:

$$J_m(U,v) = \sum_{i=1}^{m}\sum_{k=1}^{n} U_{ik}^{f}\left|x_k - v_i\right| \tag{5}$$

Where f, v_i and U_{ik} are fuzzy parameters, the center of the i^{th} cluster and fuzzy degree between xk and ith cluster, respectively. In this paper, the XB index as represented in Eq. (6) is utilized for obtaining the optimal number of clusters. Xie-Beni (XB) index is defined as the quotient between the minimum of the minimal squared distances between the points (power data) in the clusters and the mean quadratic error. The suitable number of clusters is obtained when XB is minimal.

$$XB = \frac{J_m(U,v)}{n \times min_{i\neq j}\left(\left|v_i - v_j\right|^2\right)} \tag{6}$$

Using the tidal turbine generated power associated to the historical data as the input values of FCM, the number and probability of suitable clusters which represent the appropriate states of the tidal turbine generation powers are obtained.

C. Complete reliability model of tidal power plants

A complete reliability model of the tidal unit is determined considering both failure rate of the components (Model Section A) and variability in the output power arisen from the intermittent nature of the tidal current speed (Model Section B). In this regard, the complete reliability model of a tidal unit including m turbines and h clusters in each state can be shown as in Fig. 7. However, for different technologies associated to the generators used in the current type tidal power plant, the value of failure rate and repair times associated to the components especially generators are different and so the resulted equivalent failure rates and repair times of different tidal units are different. In addition to the equivalent failure and repair rate, the power curve associated to the different technologies of tidal units is different and so the generated power of these units would be different. Thus, for reliability modelling of different technologies of tidal power plants both reliability parameters and generated power of understudied technology must be determined and using the proposed method, the multi-state model can be obtained.

Different types of tidal power plants based on the types of generators used inside including permanent magnet or electrically excited synchronous generators, double fed or squirrel cage induction generators are studied in this research.

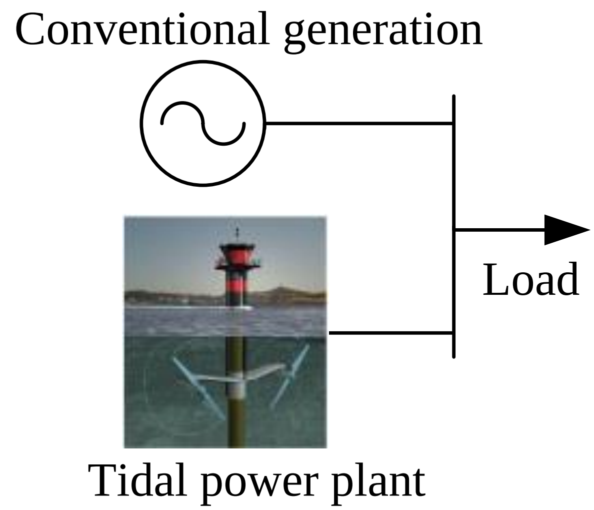

Fig. 8. Adequacy studies of a generation power system containing tidal plants.

5. ADEQUACY STUDY OF POWER SYSTEMS CONSIDERING TIDAL POWER PLANTS

In this section, the proposed technique for performing adequacy analysis of the power network including large-scale tidal units is introduced and the numerical results with the application of the model to well-known test systems are given. Based on the proposed technique, a tidal unit is modeled with more than two states and this multi-state reliability model can be combined with the two-state reliability models of the conventional units and the total model of the power system is obtained. Less memory requirement, no convergence problem, and also evaluation of the effect of different tidal power parameters on the reliability model are the advantages of this method over Mont Carlo.

A. Proposed evaluation technique

For adequacy study of a generation power network including significant tidal units, as can be seen in Fig. 8, all the conventional and renewable units are considering connecting a common bus and the total load is connected too. In this level of the reliability studies, the effects of the transmission network are neglected. A capacity outage probability table (COPT) is developed for the conventional units based on two-state model of them. Further, the multi-state reliability model of the tidal units is added to this table and the total COPT of the system is determined. With convolving the load model and the generation model, the appropriate adequacy indices are simply obtained. In this paper, the loss of load expectation (LOLE) in hours per year, expected energy not supplied (EENS) in MWh per year, peak load carrying capability (PLCC) in MW and increase in peak load carrying capability (IPLCC) in MW are calculated.

B. Numerical results

In this part, two test networks, namely the RBTS and the IEEE-RTS, considering integration of tidal power plants are analyzed. Once the reliability model of the newly added tidal unit considering the proposed technique is obtained, the adequacy analysis of these two test networks can be done and various network reliability indices can be determined. Several sensitivity analysis

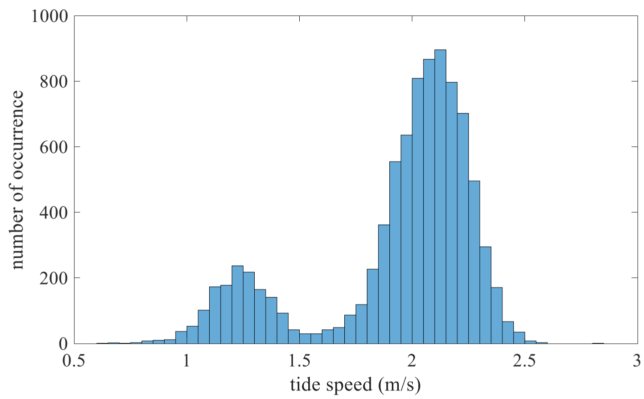

Fig. 9. Histogram of tidal current speed.

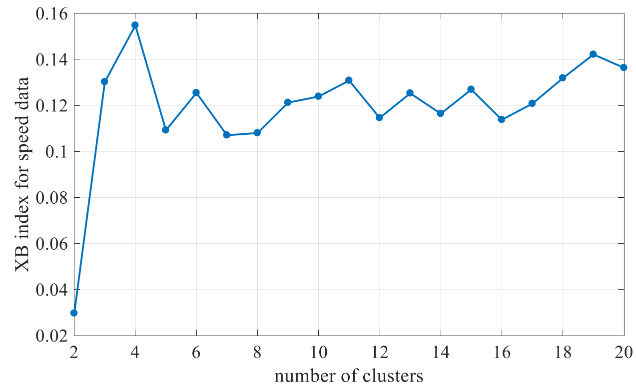

Fig. 10. XB index associated to the tidal current speed data considering number of clusters.

are then conducted to more deeply investigate the impacts of peak load, risk criteria and penetration level of tidal resources on the adequacy studies of power systems.

Here, a 30 MW squirrel cage induction generator-based tidal farm composed of 15 tidal turbines, each with 2 MW capacity, installed in Lake St. Clair is considered to be the added renewable-based unit. The reliability parameters of components can be collected based on manufacture data, expert's comments and recorded data by the operators during the operation that are given in Table 1. These values would be subject to change according to different operating conditions and equipment's manufactures. Utilizing the historical components' failure data as in Table 1 [11], the equivalent values for failure rate and repair time of each tidal turbine are obtained, results in 1.425 failures per year and 202 hours. The tidal farm consists of 15 2 MW turbines and so the 16-state reliability model can represent this farm.

The historical tidal current speed data of this region for a one-year period presented in Fig. 6, is then employed to compute the output power of each turbine based on its power curve characteristic [31]. For reducing the number of states, the FCM can be implemented to the tidal current speed or generated power data. In Figs. **??**-**??**, the histogram of these tidal current speed data, the XB index and Fuzzy frequency distribution function of them associated to the clusters are given. As can be seen in the figures, two clusters are optimal for modelling the entire tidal current speed data, and the distribution of data around these centers is suitable; thus, it is concluded that no outlier data exist.

Table 1. The failure rate and repair time of understudied tidal turbine

Component	Failure rate (occ.yr)	Repair time (h)
Blade	0.1	87.6
Main shaft and bearing	0.05	43.8
Gearbox	0.155	250.3
Generator	0.8	219
Transformer	0.02	219
Control system	0	-
Foundation structure	0	-
Converters	0.3	195
Total	1.425	202

Using the tidal current speed and the power curve of the tidal

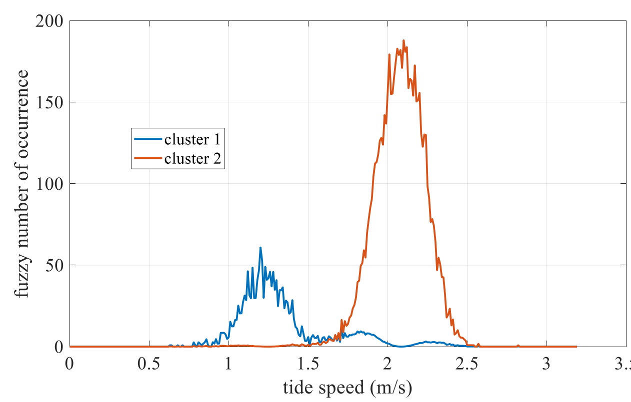

Fig. 11. Fuzzy frequency distribution function of current speed data associated to the clusters.

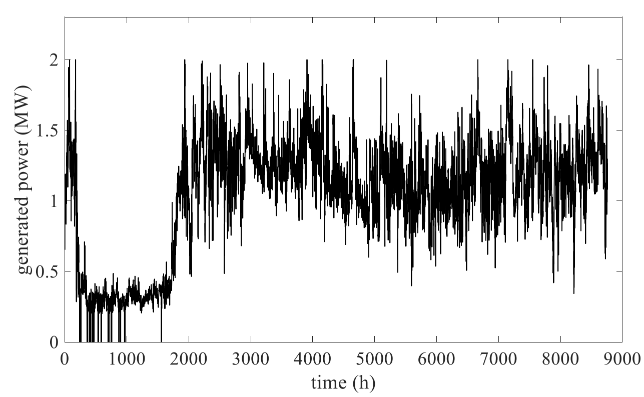

Fig. 12. Generated power of tidal turbines.

turbines, the generated power of tidal turbines is calculated that is presented in Fig. **??**. The histogram of the generated power is shown in Fig. **??**. Applying FCM to the generated power of the tidal plant and calculating XB index as can be seen in Fig. **??**, a three-state model as presented by Table 2 is obtained for modelling the variation in the tidal current speed.

For state reduction in the reliability model of the tidal unit, it is appropriate that FCM be implemented to the power gen-

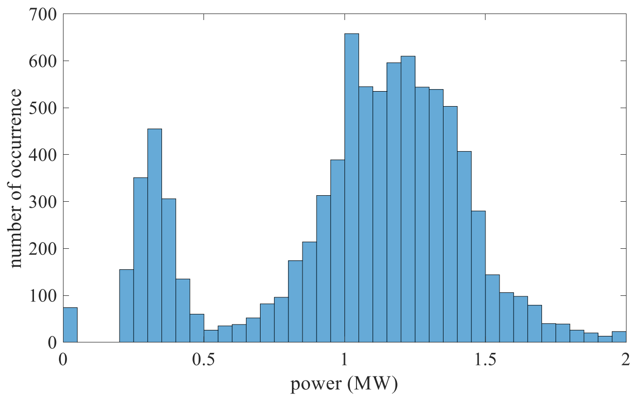

Fig. 13. Histogram of generated power.

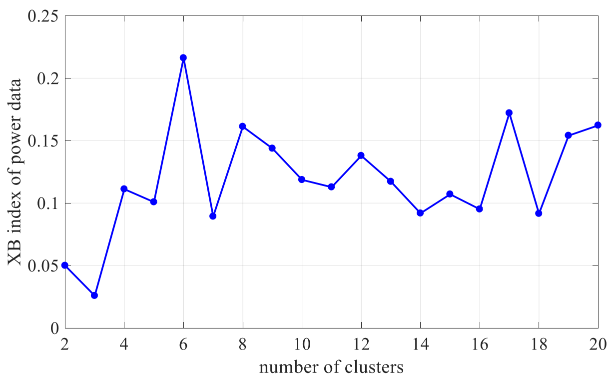

Fig. 14. XB index associated to the generated power data considering number of clusters.

eration data rather than tidal current speed data because the relation between the generated power and tidal current speed is a non-linear function and so it may the generation powers associated to the near current speeds that belong to a similar cluster are different.

By convolving the 3-state model of the tidal turbine arisen from the variation in the tidal current speed with the 16-state reliability model arisen from the failure of the components, the complete reliability model of this farm with 48 states is determined. Neglecting the states with probabilities less than 10-5, leads to a 15-state reliability model presented in Table 3.

In this stage, the RBTS is considered and the adequacy analysis of this system including the tidal unit is done. In [32] the RBTS characteristics with installed capacity equal to 240 MW, including generation capacity, failure rate and repair time of the units are given. The load duration curve is considered for load modelling that is assumed to be a straight line from maximum to minimum hourly peak load. For investigation of the effect of the tidal power plant on adequacy indices, three cases including Case I which is the original RBTS and Case II and Case III in both of which a conventional unit with 30 MW of capacity and availability equal to 0.95 with a 30 MW tidal power plant where the specifications of this section are integrated to the original RBTS are considered. The LOLE and the EENS of these cases are determined and illustrated in Figs. 15 and 16. As can be concluded from these figures, increasing the peak load worsens the adequacy indices of the system and adding new units (conventional or tidal) leads to the improvement of the adequacy of the power system. Thus, the results obtained based on the proposed method investigated by adding the tidal power plants to the power systems, the reliability of the power system is improved and so, the peak load of the system can be increased. However, the adequacy improvement resulted from the tidal power plant in addition to the system is less than the conventional case. It has arisen from the intermittent nature of the tidal current speed that causes the variation in the output power of tidal farms. This is clearly seen from the PLCC and IPLCC that are presented in Tables 4 and 5. The PLCC and IPLCC are determined based on the EENS criteria. In other words, the peak load is increased as far as the EENS of the system is still below the allowed value.

Table 2. 3-state model resulted from FCM associated to current type tidal power plant

Capacity (MW)	Probability
0.33	0.202
1.04	0.4297
1.4	0.4298

Table 3. 15-state complete reliability model of the tidal frame

State	Capacity (MW)	Probability
1	3.63	0.000198
2	3.96	0.002006
3	4.29	0.014091
4	4.62	0.061289
5	4.95	0.124402
6	11.44	0.00042
7	12.48	0.004266
8	13.52	0.029975
9	14.56	0.130375
10	15.4	0.00042
11	15.6	0.264631
12	16.8	0.004267
13	18.2	0.029982
14	19.6	0.130405
15	21	0.264693

Table 4. PLCC for three cases

Cases	EENS<100MWh/yr	EENS<200MWh/yr	EENS<300MWh/yr
Case I	183 MW	191 MW	196 MW
Case II	208 MW	216 MW	221 MW
Case III	197 MW	205 MW	210 MW

It can be seen from the PLCC of the predefined cases, with regard to various risk criteria levels, the capability of the power network to supply loads improved by integrating tidal and conventional plants to its generation network. However, this increment is affected by the intermittent nature of the tidal current speed and the risk criteria levels. Another important index, (IPLCC) is analyzed to compare the effects of tidal plants and conventional units. In so doing, the network peak load is increased as far as the EENS value remains less than the predefined risk criterion level. It is obvious that the addition of tidal units to

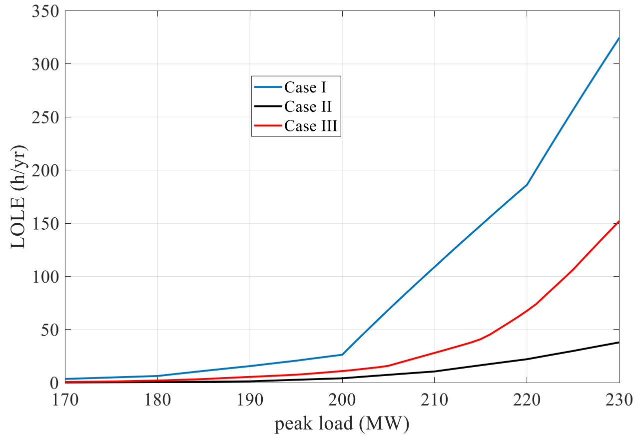

Fig. 15. LOLE considering peak load.

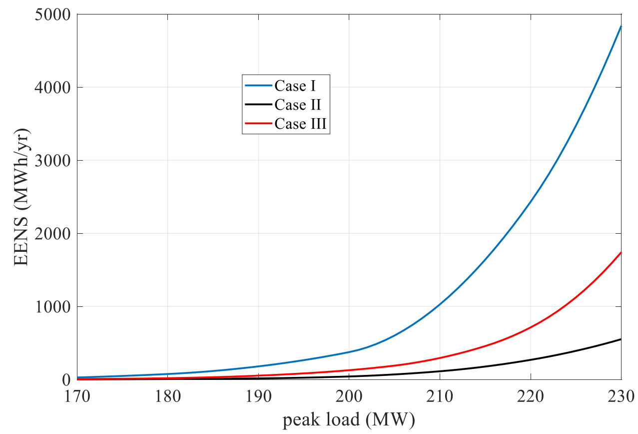

Fig. 16. EENS considering peak load.

the network leads to increase of the peak load carrying capability of the network.

In this stage, the IEEE-RTS is considered analyzing the effects of the penetration levels of tidal resources on the electric power network adequacy analysis. The generation capacity and the reliability data of this network are illustrated in [33]. The LOLE and EENS values for different tidal penetrations are evaluated and illustrated in Figs. 17 and 18. The integration of new tidal power plants improves the adequacy indices of the power network.

In this stage, Monte Carlo (MC) simulation approach is used for adequacy studies of the power system containing current type tidal power plant to justify the applicability and effectiveness of the proposed method for large scale cases such as IEEE-RTS. In the MC method, for an hour, a random number in [0,1] is generated for each component of tidal power plant and also each conventional unit. Based on the availability of the components and conventional units, the state of them (up or down) is determined. In the given hour, the generated power of the current type tidal power plant based on the state of composed components and tidal current speed is determined. Thus, the total generated power of the system in the given hour is obtained, then compared with the peak load and the state of the hour (load curtailment) is determined. With repetition of the simulation in several years, the average reliability indices can be calculated.

Table 5. IPLCC for three cases

Cases	EENS<100MWh/yr	EENS<200MWh/yr	EENS<300MWh/yr
Case II	25 MW	25 MW	25 MW
Case III	14 MW	14 MW	14 MW

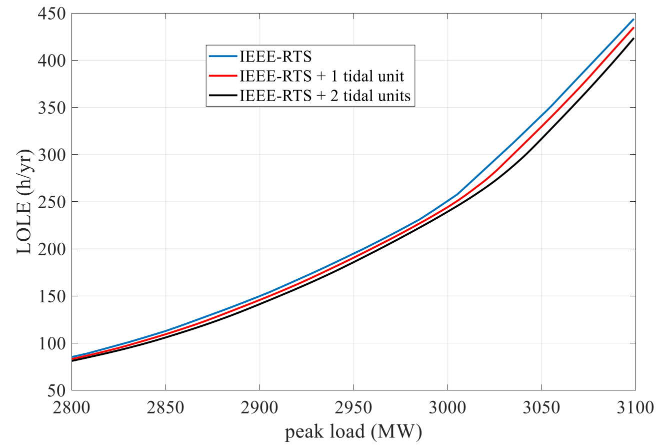

Fig. 17. The LOLE versus peak load.

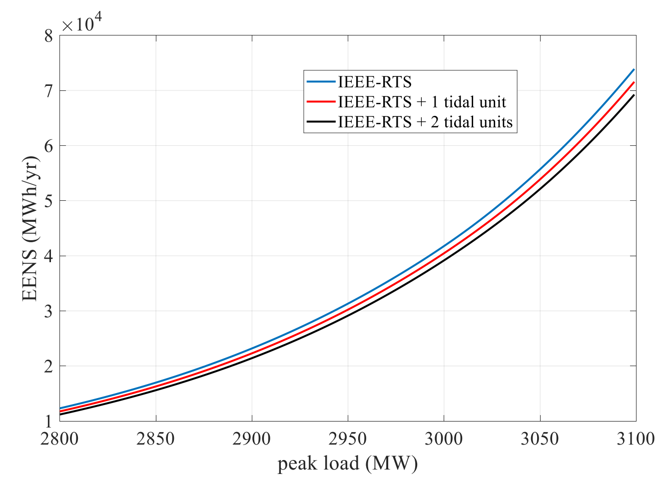

Fig. 18. The EENS versus peak load.

In Table 6, the EENS of the IEEE-RTS system containing one tidal unit in 2850 MW peak load, based on the proposed technique and MC method with different repetition is illustrated. As can be seen from the table, the proposed method can accurately calculate the reliability indices of the large scale power system containing tidal units.

As can be seen from the results of this section, based on the proposed technique a current type tidal power plant considering both failure of composed components and also variation in the generated power arisen from variation in the tidal current speed can be modeled with several states such as 15 states for understudied tidal power plant. However, the number of states of the model for some tidal units may be high and it can be reduced by merging some near states. By adding the tidal unit to the test systems, the reliability indices such as EENS and LOLE are improved and so the peak load carrying capability

Table 6. EENS of IEEE-RTS based on the different method

Methods	Proposed analytical	MC (100 yr repetition)	MC (200 yr repetition)
EENS (MWh/yr)	15364	15842	15387

of the power system by adding the tidal units can be increased. However, due to the variation of the generated power of the current type tidal power plant, improvement in the reliability indices by adding tidal units to the power system is less than the addition of conventional units with the same capacity to the power system.

6. CONCLUSIONS

In this research for the first time, the adequacy analysis of a power network including significant tidal units is done through an analytical approach. For this purpose, a reliability model with several states for different types of tidal current power plants considering different types of generators including squirrel cage or doubly-fed induction generator, permanent magnet or electrically excited synchronous generator is developed. For decreasing the number of states in the resulted reliability model, the fuzzy C-means clustering approach is employed and for obtaining the optimum number of clusters, the XB index is calculated. Then, the resulted multi-state model is utilized for adequacy analysis of power networks including current type tidal power plants.

For better illustration of the proposed technique, two reliability test systems including RBTS and IEEERTS are investigated and a 30 MW tidal unit is added to these systems. Several indices including LOLE, EENS, PLCC, and IPCC for these networks are calculated considering the proposed method. Furthermore, numerous sensitivity analyses are done and it is deduced that the integration of tidal resources in the power networks can enhance the adequacy of the power network in generation level studies. It is deduced from the numerical results that the LOLE of the RBTS system is improved from 11.1228 to 0.9634 and 3.3930 h/yr for addition of conventional and tidal units, respectively. Thus, with addition the conventional and tidal units to the system, the peak load carrying capability of the power system can be increased, for example for RBTS cases considering EENS less than 100 MW h/yr, the peak load of the system can be increased up to 25 and 14 MW for addition conventional and tidal units, respectively. It is also deduced that due to the uncertain nature of the tidal current speed resulted in the variation of the generated power of tidal power plants, the capacity benefit of tidal plants is less than conventional power plants with the same capacity. The proposed analytical method is compared with Monte Carlo approach to calculate the reliability indices of large scale power system such as IEEE-RTS. The results show that the error between the proposed method and MC method with 200 repetition is about %0.1 and so the proposed method accurately calculate the reliability indices of the large scale power systems. Thus, for generation expansion planning of the power system considering tidal power plants, the reliability indices calculated based on the proposed technique alongside the economic indices can be used and concluded to the appropriate plan.

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