The Journal of Energy: Engineering & Management
Vol. 12, No. 4, Winter 2023, P. 2-17
Research Article

The Impact of Vanadium-Redox Batteries on the Reliability of Power Systems Integrated with Current-Type Tidal-Turbines

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Accepted: 11/12/2022 **Received:** 11/01/2023

Abstract

To reduce the uncertainty nature of tidal stream turbines connected to the bulk power system, energy storage systems with high capacity should be used. Among different energy storage systems, vanadium redox flow batteries with large capacity can be used in power systems. In this paper, an economic analysis is performed, and the impact of vanadium redox batteries on the power system containing tidal turbines considering reliability effect is evaluated. For this purpose, a multi-state reliability model is developed for tidal-stream turbines connected to battery units. The multi-state reliability model is used to study the adequacy of the power systems containing tidal turbines in conjunction with vanadium redox batteries. In the proposed reliability model, the failure rate of the composed components and variation in the generated power arisen from variation in tidal current speed are taken into account. Fuzzy c-means clustering technique and Xie-Beni index are utilized to determine an optimal number of clusters and probability of them in the reliability model of the system including tidal stream turbines and vanadium redox batteries. Numerical results of Roy-Billinton and IEEE reliability test systems are evaluated to study the effect of tidal stream turbines and vanadium redox batteries on the reliability of power systems and verify the effectiveness of the proposed model.

Keywords: reliability, tidal-stream-turbines, Vanadium-redox battery, fuzzy c-means clustering, XB-index.

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doi: 10.22052/JEEM.2023.113677

1. Introduction

The tidal level and the tidal current speed can be predicted based on astronomical relationships with reasonable accuracy. Hence, the value of generated power of barrage type tidal power plants and tidal stream turbines can approximately be evaluated. Among different renewable resources, tidal stream turbines are increasingly utilized for electric power production due to high accuracy of predictability and negligible environmental effects. In recent years, large-scale current type tidal farms which are based on tidal stream turbines are installed around the world. It is estimated that 100TWh/yr electric energy can be extracted from tidal current using tidal stream turbines [1]. Hence, this type of renewable energy can play a significant role in future power systems. However, the generated power of tidal stream turbines is dependent on the tidal current speed. The output power of tidal turbines changes widely due to the wide variation in tidal current speed. Thus, different aspects of a power system such as reliability may be affected in case of significant penetration level of tidal turbines in the power system. Energy storage systems can be used in power systems for reducing the uncertain nature of tidal turbines such as the pumped-storage power plant, the battery, the compressed air system, hydrogen tank/electrolyze/fuel cell, the flywheel, and the capacitor. In recent years, flow batteries such as vanadium redox batteries (VRB) with high capacities are developed. These batteries can be used in conjunction with tidal stream turbines to reduce the variation of the generated power. Several studies have been performed to examine the effects of tidal stream turbines and energy storage devices on power systems. In [2], in addition to the current status of wind and tidal stream turbines, the impacts of offshore wind and tidal stream turbines on the grid, different types of generators used in these turbines, and the dynamic modeling of them are studied. In this paper, fault-ride through methods are proposed to improve the generator and grid integration performance. Also, the stability and control problems of wind and tidal turbines are studied. In [3], the state of the art and the current status of current type tidal technologies are discussed. In this paper, the fundamental concepts of tidal energy and the main projects around the world focusing on tidal turbines are reviewed.

In [4], the impact of vanadium redox battery on the stand- alone current type tidal turbine from stability point of view of is studied. In this paper, the optimal design of the vanadium redox battery with the goal of cost reduction is performed, and a comparison between the lead-acid batteries and the these vanadium redox batteries in terms of different characteristics is made. In [5], the fuzzy modeling approach is used to allocate the wind turbines connected to the battery energy storage system in the distribution networks in regard to risk criteria. In this paper, a new risk-based technique considering monetary cost as well as technical and economic risk is suggested to determine the optimum location and capacity of energy storage units and wind turbines simultaneously. The uncertainties, including the future load growth of the system, the generated power of the wind turbine, and the electricity market price are implemented to the optimization problem. The best solution among the obtained Pareto optimal set is selected using the non-dominated storing genetic algorithm and max-min technique. In [6], an optimal stochastic scheduling of a virtual power plant considering sodium-sulfur battery storage system as well as combined heat and power plants is performed. In this paper, the virtual power plant, including wind turbine, combined heat and power plants, sodium-sulfur battery, heat storage and boiler unit, are modeled to determine optimal participate into the day-ahead market and response to the local heat demand. In [7], a distributed control is proposed to achieve the constant power generation of the grid-connected system, including photovoltaic arrays connected to the battery energy storage unit. In this paper, a distributed power management system is suggested to control the amount of the power generated by a micro grid including photovoltaic panels and a battery storage system. The proposed technique is used to solve the problems of the centralized controllers and provide the constant power transferred to the grid. In [8], new economic indices based on the value of electrical energy storage system in the power network are proposed aiming to investigate the economic value of the battery for three different applications, including the capacity benefit, the avoidance of carbon emission and loss reduction in Kerman, Iran. In this paper, the opportunity cost, as a new economic term, is determined by the comparison between the levelized value of energy and the levelized cost of energy. This index is suggested to study the techno-economic analysis of the understudied power system. In [9], a new technique is proposed to determine the value of emission based on economic dispatch in an energy hub concept, including tidal power plants. In this paper, the optimal operation of the energy hub is performed based on the mixed integer linear programming approach for optimizing the cost of different energy carriers and the generation cost of the environmental pollutant produced by each carrier. In [10], a multi-objective function is proposed to optimally integrate renewable resources such as photovoltaic panels, wind turbine, and battery energy storage system to distribution networks, which takes into account the energy price, transmission access fee, energy losses, power quality associated with the voltage regulation, and environmental emissions. In this paper, the combination of a genetic multi-objective solver with a linear programming approach is proposed to determine optimally the placement, sizing, and operation of the renewable resources and energy storage systems.

In [11], the conceptual design of a tidal power plant located in Taiwan is discussed. In this paper, due to the large tidal range of the understudied region on the northwestern of Taiwan, a current type tidal turbine is chosen, and its dynamic characteristic, performance, and related design are investigated. In [12], the reliability of large-scale current type tidal turbines in UK is evaluated. The potential of tidal stream resource in UK is estimated to be 95TWh/year. Hence, the reliability model of devices of tidal power plant is established in order to study the effect of environmental site conditions on the failure rate of associated components and reliability levels. A practical tidal stream device reliability prediction method is proposed in [13] for reliability modeling of current type tidal turbines equipped with the horizontal-axis turbines. Historical reliability data associated with similarly rated wind turbines and other relevant marine databases are utilized for developing the proposed reliability model. In [14], a multi-state reliability model is developed for current type tidal power plants, in which both failure rate of composed components and uncertain nature of tidal current speeds are considered. The proposed model is used for adequacy assessment of power systems containing large-scale current type tidal power plants. In [15], reliability evaluation of a current type tidal power plant equipped with double-fed induction generator is performed, and the effects of variation of tidal current speeds on the failure rate of components are studied. In this paper, among various components of tidal stream plants, the failure rate of a back-to-back converter is considered to be affected by variation of tidal current speeds. Hence, the failure rate of composed components, including generator side converter and grid side converter, is determined considering the current speed. In [16], the resource assessment of tidal stream energy in Korea, based on observational data and numerical simulation of water circulation, is discussed. In this paper, the theoretical tidal current potential of south coastal areas of Korea is calculated using average power intercepted. In [17], a reliability model is developed for barrage type tidal power plants, in which the failure of composed components and variation in the generated power are taken into account. The resulted multi-state reliability model is used for adequacy assessment of power system integrated into barrage type tidal power plants. The research investigates the reliability of wind turbines in the presence of energy storage systems. It can be used for studying the reliability of tidal stream turbines connected to the energy storage system due to the similarity between current type tidal turbines and wind turbines. In [18], the optimum capacity of energy storage system from reliability point of view is determined in a power system containing wind power plants. In this paper, a method based on the equivalent firm capacity approach is proposed to model the capacity value of energy storage device in the power systems integrated with wind turbines. In [19], Monte Carlo simulation method is used to perform the reliability evaluation of integrated wind-storage systems. In this paper, random outages are imposed to load chronological data for simulating the grid failures using Monte Carlo simulation approach. Also, a comparison among different states-- including grid-connected load, the hybrid system including the wind turbine with and without energy storage, and the stand-alone wind power system-- is made. In [20], the reliability assessment of generating system containing wind turbines and energy storage system is performed. In this paper, a simulation technique is proposed that can take into account wind farm and energy storage operating strategies. Based on this technique, different operating strategies are compared, and the resulting benefits are investigated.

In [21], the reliability modeling of battery energy storage systems, considering lithium-ion battery lifetime degradation, is performed. In this paper, universal generating function algorithm based on the weak-link analytical approach is proposed to investigate the reliability of lithium-ion batteries considering battery lifetime degradation. To determine the degradation rate of solid electrolyte interface film formation and capacity plummeting, a novel lithium-ion battery model is suggested. In [22], operation strategies for coordinating wind power plants with battery energy storage systems, considering the reliability of system, are introduced. For this purpose, a computation model is proposed for batteries that consider the main aspects and operation limitations of batteries. In this paper, the reliability indices of composite power system including the loss of load probability and expected unsupplied energy are calculated. In [23], a comprehensive reliability assessment of the battery energy storage systems, considering its role in the operation of the power network, is illustrated. The degradation of battery cells and thermal runaway propagation as two important factors in the reliability performance of battery modules are considered. In [24], to enhance the reliability performance of radial distribution systems, the optimal siting of batteries is performed, and their best location is determined. For this purpose, utility hierarchical load, outage, and project-data are used to determine the energy capacities of each battery energy storage system.

Furthermore, the mixed-integer programming method is implemented as an optimization technique. In [25], the reliability analysis and financial viability of a micro-grid system, located in KwaZulu-Natal, including renewable resources and energy storage systems are elaborated. The main objective of this paper is to optimize the operations of the micro-grid, including photovoltaic panels and wind turbines combined with batteries, to improve the reliability, to reduce the greenhouse gas emission, and to balance the demand and supply of energy through renewable energy resources and battery energy storage system. In table 1, the comparison of reviewed papers and the current paper is given.

Table 1: The comparison of published papers and the current paper

References	Research topics	Drawbacks
[2-3]-[11]	The current status and dynamic characteristic of tidal turbines are studied	Reliability evaluation and the impact of batteries are not considered.
[4]	Stability analysis of vanadium-redox batteries connected to the tidal turbines is discussed	Reliability analysis is not elaborated.
[5-6]	Reliability assessment of wind turbines connected to batteries are elaborated.	The impact of tidal turbines on the reliability performance is not considered.
[7]-[10]	Energy management of renewable resources connected to the batteries is discussed.	The impact of tidal turbines and reliability performance are not considered.
[8]	Economic studies of energy storage systems are illustrated.	Reliability performance and the impact of tidal turbines are not address
[9]	Economic dispatch of an energy hub containing tidal turbines is studied.	The impact of batteries and reliability performance is not considered.
[12-15]	Reliability evaluation of current-type tidal turbines is studied.	The impact of vanadium-redox batteries is not addressed.
[16-17]	Tidal potential and reliability evaluation of barrage-type tidal power plants is studied.	Current-type tidal turbines and the impacts of batteries are not considered.
[18-20]	Reliability evaluation of wind turbines connected to batteries is performed.	The impact of tidal turbines is not considered.
[21-25]	Reliability assessment of energy storage systems is performed.	The impact of tidal turbines is not considered.

It is concluded from the reviewed papers that reliability and economic analysis of current type tidal turbines, connected to the high-capacity battery energy storage systems, were not discussed in the past studies. For this purpose, the adequacy and economic assessment of a power system integrated with the current type tidal turbines and energy storage system have been examined, in the current paper. Thus, the main contributions of the paper would be:

- Performing an economic analysis to investigate the impact of the vanadium redox batteries on the power system containing tidal turbines considering reliability effect.
- Developing a multi-state reliability model for large-scale tidal turbines, connected to the vanadium redox flow batteries, which take into account the failure of composed components and variation in the generated power.

To determine this reliability model, the number of power states should be reduced. For obtaining an appropriate model, in this paper, XB index is calculated to determine the optimal number of reduced states, and a fuzzy c-means clustering method is used to calculate the center of states and their probability. Thus, other contributions of the paper would be:

- Xie-Beni index is calculated to determine the optimal number of states in the reliability model of the current type tidal turbine connected to the vanadium redox battery.
- A fuzzy c-means clustering technique is proposed for reducing the number of states in the reliability model of the current type tidal turbine connected to the vanadium redox battery.

Due to the unavailability of real data associated with the output power of a current-type tidal farm connected to the vanadium redox battery, this paper simulates the behavior of these systems. Thus, the other contribution of the paper is:

- The Monte Carlo simulation approach is suggested for evaluating the behavior of the current type tidal turbine connected to the vanadium redox battery.

To reach these aims, the paper is organized into seven sections. In the second section the tidal stream turbines are explained. The concept of power system reliability is discussed in the third section; also, the reliability model of current stream turbines is developed in this section. The technique to study the economic and reliability aspects of power system, integrated with the current type tidal turbines and energy storage systems, is introduced in the fourth section. The numerical results of the Roy-Billinton test system (RBTS) and IEEE reliability test system (IEEE-RTS), which are two well-known reliability test systems, are presented in the fifth section for proving the effectiveness of the proposed method. The discussion and the conclusion to the study are preseted in the sixth and seventh sections.

2. Tidal Stream Turbines

The density of water is about 832 times of air density. Hence, the generated energy of a tidal stream turbine is almost four times of energy per m^2 of rotor of a wind turbine [26]. Thus, tidal stream turbines have high energy intensity, and the potential of tidal streams is estimated to be about 75GW worldwide. Tides are occurred due to the relative motion of the earth and moon to the sun. Thus, the tidal height and tidal currents speed can be predicted accurately based on the astronomical relationships. Tidal power plants can play a significant role in electricity generation in future power systems due to high energy intensity and predictability of tides. There are two methods for extracting the energy of tides, which are used in the tidal power plants. The potential energy of tides is utilized to generate electricity in the barrage type tidal power plant. In this type of power plant, a dam is constructed between sea or estuary and reservoir. In the barrage of the dam, several sluices are located in such a way that water can be transfered between the sea and reservoir through these sluices. In flood state, water is transferred from the sea to the reservoir through the sluices and fills the reservoir. In ebb states, water is transferred from the reservoir to the sea passing from the turbines located in the sluices, and electricity is generated. In the second type of tidal power plants, named current-type tidal power plants, the kinetic energy of tidal streams is utilized for generating electricity in a way similar to wind turbines. The current type tidal turbines are installed under water surface for extracting the kinetic energy of tidal currents.

The relation of the generated power of current type tidal turbines and the tidal currents speed can be illustrated as the power curve of turbine. A typical power curve of tidal stream turbines is shown in Fig. 1. As seen in the figure, the generated power would be zero for tidal current speeds less than the cut-in speed, while for the speeds between the cut-in speed and rated speed, the generated power is proportional to v^3, and the generated power would be constant and equal to the rated power for speeds more than rate speed. Despite wind turbines, tidal current speeds are low and do not reach the cut-out speed. Thus, the generated power of a moving mass of water in tidal turbines can be calculated as (1) [27].

$$P=\begin{cases} 0 & 0\le v\le V_{cut-in} \\ \frac{1}{2}C_P\rho A v^3 & V_{cut-in}<v\le V_{rated} \\ P_{rated} & V_{rated}<v \end{cases} \tag{1}$$

where ρ is the seawater density (1025 kg/m^3); A is the area of turbine; v is the velocity of tidal currents; V_{cut-in} and V_{rated} are cut-in and rated velocities; P_{rated} is rated power, and C_P is the Betz coefficient.

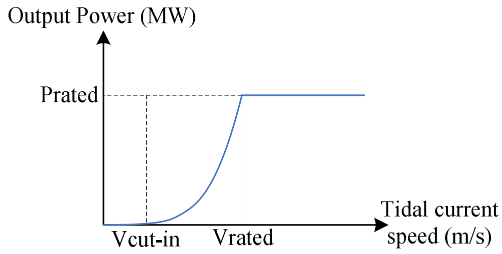

Fig. 1: The power curve of tidal stream turbines [27]

The structure of a typical current-type tidal power plant and its composed components are depicted in Fig. 2. As seen in the figure, a tidal stream power plant is composed of a current-type tidal turbine, including blades, shaft, bearing, gearbox, generator, electrical converter, cable, transformer, and control system for mechanical and electrical controlling. Different types of generators can be used in the structure of tidal stream power plants including permanent magnet synchronous generator, electrically excited synchronous generator, double fed induction generator, and squirrel cage induction generator [14].

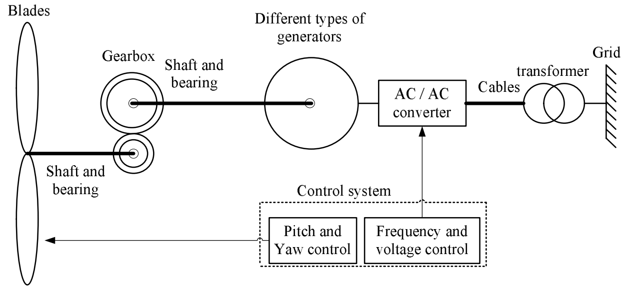

Fig. 2. The structure of tidal stream power plants [14]

3. Power System Reliability

In this section, power system reliability concept and reliability modeling of current type tidal turbines are explained with considering both failure rate of composed components and variation in the generated power.

3.1. The Concept of Power System Reliability

Power system reliability is the ability of a power system to supply the required load and is studied in two aspects, including adequacy and security. In power system adequacy, adequate facilities must be provided in the generation, transmission, and distribution parts of the power system to supply the required loads based on the predicted values. In power system security, the response of the power system to sudden disturbances, including the outage of generation units or transmission lines, is investigated [28]. Three hierarchical levels (HL) can be considered in the reliability evaluation of power systems. In HLI, only generation system is considered, and reliability of generation units connected to the loads through a common bus is studied. In HLII studies, the reliability of composite power system including generation and transmission networks is evaluated, and in HLIII reliability studies, all parts of the power system including generation, transmission, and distribution subsystems are considered. Two approaches including analytical and numerical methods can be used for calculating the reliability indices of the power system. In the analytical approach, a reliability model is developed for each element of the system, and the reliability indices can be calculated using mathematical equations. However, in the numerical methods such as Monte Carlo simulation approach, the reliability indices can be estimated by simulation of real process and random behavior of system components. In simulation-based methods, the problem is investigated through the real experiment and experience considering all possible states and contingencies. Thus, numerical methods require to be repeated for several thousand years and will have a large computational volume. In this paper, an analytical approach is used to study the reliability of power system integrated with the tidal stream turbine and energy storage system. For this purpose, a reliability model for current-type tidal power plants is developed.

3.2. Reliability Modeling of Tidal Stream Turbines

In this sub-section, a multi-state reliability model is developed for tidal stream turbines considering both failure of composed components and variation in the generated power arisen from variation in the tidal currents speed. The failure of any component of tidal unit results in zero production of the plant. Hence, from reliability point of view, all components are series in the reliability model of tidal stream unit. A two-state Marco model with up and down states is considered for composed components of tidal unit. It can be seen in Fig. 3. In this model, λ_c and μ_c, are the failure rate and the repair rate of the component respectively. The probability of up and down states of Marco model can be calculated as (2) [28].

$$P_c^{UP} = \frac{\mu_c}{\lambda_c + \mu_c}, P_c^{DOWN} = \frac{\lambda_c}{\lambda_c + \mu_c} \tag{2}$$

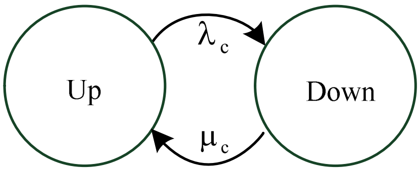

Fig. 3: A two-state Marco model [28]

The reliability model of tidal unit can be presented as an equivalent two-state model; its reliability parameters including equivalent failure and repair rates are calculated by (3) [28].

$$\lambda_{equivalent} = \sum \lambda_i, \mu_{equivalent} = \frac{\sum \lambda_i}{\sum (\frac{\lambda_i}{\mu_i})} \tag{3}$$

The reliability model of a tidal farm composed of *m* tidal stream turbines that include *m+1* states; each turbine with *C* capacity is presented in Fig. 4. The capacity and probability of state *k* with *k* up turbines can be calculated as:

$$capacity = k \times C\, MW, k\, is\, number\, of\, up\, units$$

$$probability = \binom{m}{k} A^k (1-A)^{m-k} \tag{4}$$

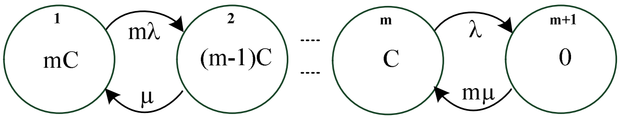

Fig. 4: The reliability model of a tidal stream farm [14]

The generated power of tidal stream turbines is dependent on the speed of tidal currents. The output power of tidal units has numerous values due to a wide variation in the speed of tidal currents. Thus, the number of states of generated power of tidal units is numerous. this situation is not suitable for analytical reliability evaluation. Therefore, the number of states in the reliability model of tidal stream turbines is reduced using fuzzy c-means clustering technique, as a robust clustering method [29]. This clustering method, classifies *n* generated power data **X**=[x_1, x_2,…, x_n] into *c* fuzzy clusters through minimizing the following objective function.

$$J = \sum_{i=1}^{c} \sum_{k=1}^{n} u_{ik}^{m} \left| x_k - v_i \right| \tag{5}$$

where $v_i$and $u_{ik}^{m}$are the center of i^{th} cluster and fuzzification parameter (fuzzy degree between x_k and i^{th} cluster) respectively. The probability of appropriate clusters can be obtained by applying historical data of generated power of tidal stream turbine as input data of fuzzy c-means clustering algorithm. Such data represent the various states of the current-type tidal turbine generation levels. In advance, the number of clusters as an input parameter of algorithm must be specified in the fuzzy c-means clustering technique. Xie-Beni (*XB)* index is calculated as (6) for determining the optimum number of reduced states [30].

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

where x_k is hourly output power of the tidal unit during one or several years as input parameter for calculation of *XB* index. To calculate *XB* index, the value of this index is obtained with variation of the number of clusters. The optimum number of clusters is selected when XB index is minimal. Having optimal number of clusters, the centers of clusters and matrix associated with the fuzzy degree between the power data and the obtained clusters are determined the use of fuzzy c-means clustering algorithm. After clustering procedure, the probability associated with state k of c resulted clusters can be calculated using (7).

$$P_k = \sum_{i=1}^{n} u_{ik}^{m} \tag{7}$$

Complete reliability model of tidal farm can be determined by combining the reliability model of composed component failures and that of variable generated power. If fuzzy c-means clustering algorithm results in h clusters, the complete reliability model of current-type tidal farms will be as shown in Fig. 5.

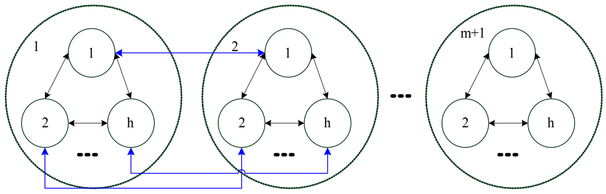

Fig. 5: The complete reliability model of a tidal farm [14]

4. Reliability Evaluation of Power System including Tidal Farm and Vanadium Redox Battery

In this section, an analytical approach is proposed to study the reliability of power systems incorporating large-scale current-type tidal power plants and vanadium redox battery. Due to the uncertain nature of tidal stream turbines, which leads to variation in the generated power of them, energy storage devices such as vanadium redox batteries can be used to reduce the variation of generated power of these turbines.

4.1. Vanadium Redox Batteries

Due to the variation in wind speed, solar radiation, height, and period of waves, tidal levels, and tidal current speeds, the generated power of renewable resources such as wind, photovoltaic, wave, and tidal units varies with time and is not controllable. Thus, renewable resources may generate more electricity in the case of low consuming load, or they may generate zero or low power when the connected load requires high power. To address this challenge, energy storage systems can be used in the renewable-based power system including the battery, the pumped-storage power plant, the electrolyze/hydrogen tank/fuel cell, the large capacitor, the compressed air system and flywheel. The VRB is a flow-type battery with large capacity that can be used in the bulk power system. The main advantages of this battery are: low environmental effect with no solution contamination, the full capacity of charging and discharging capability, high lifetime about 10-20 years or 10000 charging/discharging cycles, and the high efficiency associated with the charging and discharging process, e.g. about 70-90% [31]. In the VRB, a type of vanadium is used that can be stored in two separate solutions; one which is charged by receiving energy, and the other which is discharged by returning energy. This battery is constructed based on the ability of vanadium, which can be present in 4 different oxidation states in a solution, and it uses an active chemical element instead of two elements. One of the main advantages of this battery is that its capacity can be increased by increasing the number of storage tanks. The structure of a VRB is shown in Fig. 6.

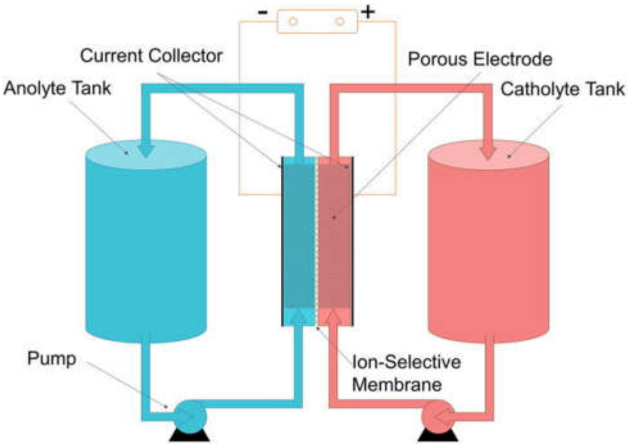

Fig. 6: The structure of a VRB [26]

A VRB is made of a set of power cells consisting of two electrolytes separated by a proton exchange membrane, which exchanges protons and prevents the combination of two electrodes, i.e. anode and cathode. There are two main tanks and two storage tanks in the VRB, and the electrolyte can be circulated between the main and storage tanks using two pumps. Both electrolytes are based on a vanadium that exists in the positive electrolytes (VO_2^{+} and VO^{2+}) and in the negative electrolytes (V^{3+} and V^{2+}). The electrolyte is prepared as a solution of V_2O_5 in H_2SO_4 acidic. In charging state and in positive part, the VO^{2+} ions are converted to VO_2^{+}. In the discharge state and in the negative part, the ions V^{3+} are converted to V^{2+} when the battery is disconnected from the supply; this event produces an electrical voltage difference between battery terminals. The chemical reactions of anode, cathode, and total reaction taking place in a VRB are stated in (8-10) [31].

$$Anode:\ VO^{2+} + H_2O - e \leftrightarrow VO_2^{+} + 2H^{+} \tag{8}$$

$$Cathode:\ V^{3+} + e \leftrightarrow V^{2+} \tag{9}$$

$$Total\ reaction: VO^{2+} + V^{3+} + H_2O \leftrightarrow VO_2^{+} + V^{2+} + 2H^{+} \tag{10}$$

The advantages of these batteries are that they can respond quickly to load changes, for example, they respond to 100% load changes in several milliseconds; and they can withstand over 400% overload (4 times as much as the rated current) for 10 seconds. These batteries are environmentally friendly apparatus and have high levels of performance safety. The energy density of these batteries is lower than other conventional batteries. The energy density for leaded acid batteries is between 30 and 40 watt-hours per kilogram and for lithium batteries is between 80 to 200 watt-hours per kilogram, while for vanadium batteries is 24 watts-hours per kilogram. The VRBs have large energy storage capacity, and, therefore, they can be used as electrical energy storage systems along with renewable resources such as tidal turbines in the power system.

4.2. Reliability Evaluation Technique

For evaluating the adequacy of a power system integrated with tidal stream turbines and VRBs in HLI, all generation units and loads are considered to be connected to a common bus as shown in Fig. 7. As seen in this figure, transmission and distribution systems are considered to be with 100% availability, and, thus, it is neglected from transmission and distribution systems in the reliability analysis. Reliability studies are performed in terms of generation level, and, thus, all power plants including renewable and non- renewable units are considered in the analysis. Thus, for adequacy assessment, the capacity outage probability table (COPT) of conventional units with two states, including up and down states, is determined. The COPT includes the capacity of all states and their associated probabilities. The uncertain nature of tidal stream turbines results in COPT of these units with more than two states, which can be determined based on the proposed technique.

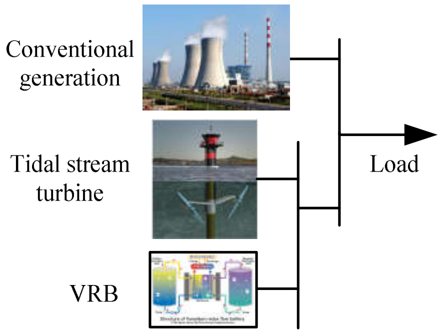

Fig. 7: Adequacy assessment of a power system integrated with tidal stream turbine and VRB in generation level neglecting transmission and distribution networks

Because the efficiency of VRB is less than 100%, it is not cost-effective to store generated power of conventional units for use in other times. However, in case of renewable units such as tidal stream turbines, which have negligible operating cost, this is an affordable choice. Therefore, in cases where the production is more than the load requirement, the surplus production of renewable units is stored in the battery, and in cases where the production is less than the load power, the battery is discharged and supplies the remaining part or the load. Accordingly, the storage batteries are incorporated in conjunction with the renewable units, and a reliability model should be assigned to the system composed of tidal stream turbine connected to the VRB. At this stage, the reliability model of VRB is obtained based on the failure of composed components, which results in the battery components in series with each other in terms of reliability studies. The uncertainty of the battery's output power must now be considered. If a renewable unit is connected to the power grid next to a VRB and the hourly output power data of this set is available for several years, it is possible to determine the reliability model of set using fuzzy c-means clustering technique and frequency-duration method. Since the output power data is resulted from the real operation of the system, the advantage of this method is that the limitations of the set-- including the failure of the renewable unit or the energy storage system, the efficiency of the energy storage system, the maximum and minimum limitations of battery capacity-- and the speeds of battery charging and discharging are taken into account in the model:

$$P_{VRB}(t)=\frac{E(t)-E(t+1)}{\Delta t} \tag{11}$$

$$P_{\min}\le P_{VRB}(t)\le P_{\max} \tag{12}$$

$$E_{\min}\le E(t)\le E_{\max} \tag{13}$$

$$\left|\frac{P_{VRB}(t+1)-P_{VRB}(t)}{\Delta t}\right|\le R_{\max} \tag{14}$$

where $P_{VRB}(t)$, $E(t)$, P_{min}, P_{max}, E_{min}, E_{max}, R_{max} and Δt respectively denote: the power and stored energy of the VRB, the minimum and maximum of power that can be stored in the battery, the minimum and maximum energy that can be stored in the VRB, the maximum charging and discharging rates of the battery, and the time step between two states of charge of the battery..

In this research, the real data associated with the operation of the system is not available. Hence, the output power values of the set, including tidal stream turbine and VRB, which are used for reliability modeling are created using Monte Carlo simulation. In this way, by applying the associated limitations, the hourly output power of set is determined, and, consequently, its reliability model is obtained. In this simulation, the failure of conventional and tidal stream units, the failure of VRB, VRB efficiency, minimum and maximum capacities of VRB and its charging and discharging rates are considered. The total COPT of generation system is determined for evaluating the adequacy of power systems integrated with tidal stream turbine and VRB. Then, different reliability indices such as the loss of load expectation (*LOLE*), the expected energy not supplied (*EENS*), the peak load carrying capability (*PLCC*), and an increase in peak load carrying capability (*IPLCC*) are calculated by convolving the resulted COPT and the load model. The flowchart of the proposed method for determining the reliability indices of the power system containing current-type tidal turbines connected to the VRB is shown in Fig. 8.

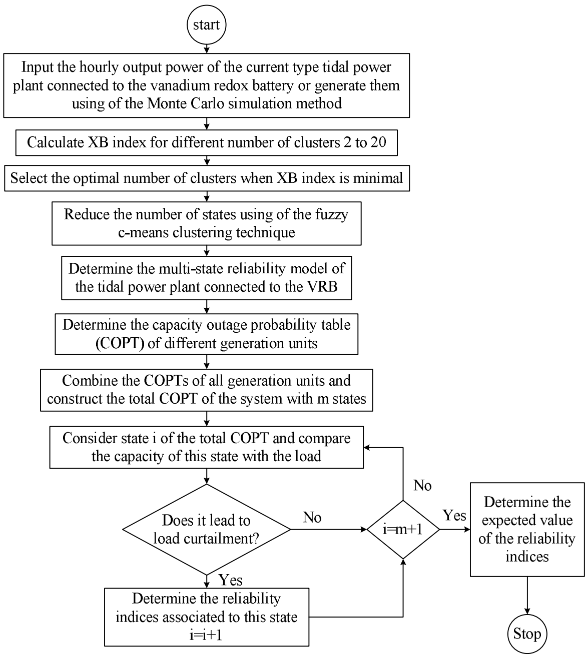

Fig. 8: The flowchart of the proposed method for adequacy evaluation of a power system integrated with tidal stream turbine and VRB

4.3. Economic Analysis

To study of the impact of VRB on the power system containing tidal turbines, a cost function including investment cost, operation, and maintenance cost of the VRB and reliability cost is calculated as:

$$C = C_{invest.} + C_{oper.main.} + C_{reliability} \qquad (15)$$

Where, $C_{invest.}$, $C_{oper.main}$. and $C_{reliability}$ are investment costs of VRB; the operation and the maintenance cost of VRB, and the reliability cost of the power system is calculated as:

$$C_{reliability} = EENS \times VOLL \qquad (16)$$

Where, *EENS* is the expected energy not supplied in *MWh/yr,* and *VOLL* is the value of lost load in *\$/(MWh/yr).* To study the impact of VRB on the power system containing tidal farms, all costs of (15) are put in present value as:

$$present\ value = c[\frac{(1+i)^n - 1}{i(1+i)^n}] \qquad (17)$$

Where, c is the operation and maintenance cost or the reliability cost associated with the penalty of the interrupted loads, i is the interest rate and n is the number of years associated with the cost analysis.

5. Numerical Results

In this section, numerical results of reliability evaluation of RBTS and IEEE-RTS, as two well-known reliability test systems, are presented to study the effect of tidal stream turbine and VRB on the reliability indices of power system.

5.1. Understudied Tidal Stream Farm

A 30MW tidal farm, composed of 15×2MW SeaGen tidal stream turbines, is considered to be located in Lake St. Clair somewhere between Ontario in Canada and the state of Michigan in the U.S. The power curve of SeaGen turbine [32] and the hourly tidal current speed [33] are shown in Figs. 9 and 10 respectively. Based on the hourly tidal currents speed and the power curve of understudied turbine, the generated power of the tidal stream turbine is calculated and presented in Fig. 11.

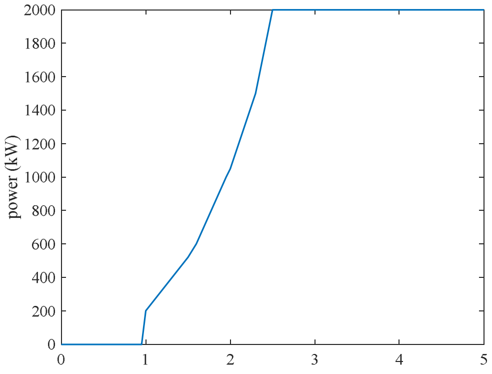

Fig. 9: The power curve of 2MW SeaGen turbine [32]

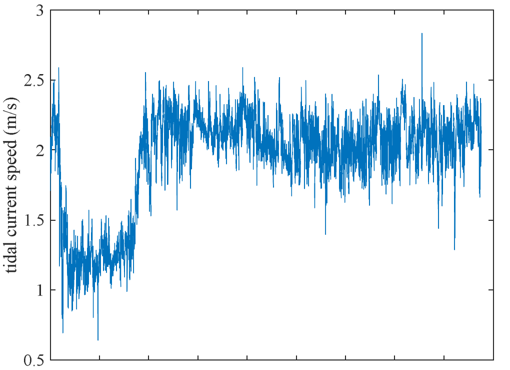

Fig. 10: The hourly tidal currents speed in St. Clair Lake [33]

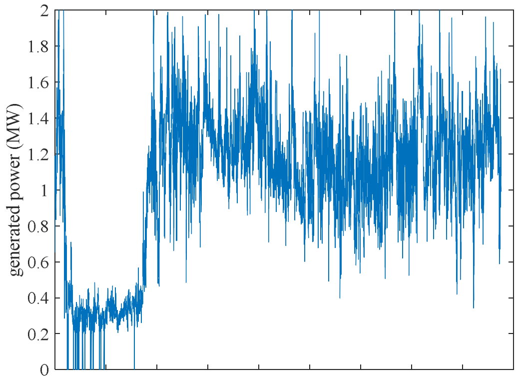

Fig. 11: The hourly-generated power of tidal stream turbine

The equivalent failure and repair rates of tidal stream turbine are considered to be 1.425 and 43.4 times per year respectively [14]. Thus, the availability of turbine would be 0.97. The XB index for generated power data is calculated and presented in Fig. 12. As seen in the figure, when the number of clusters is three, XB index is minimum. Hence, three clusters are considered for the modeling of the uncertainty nature of generated power of tidal turbine. By applying fuzzy c-means clustering method to the generated power data, the capacity and probability of these states are obtained and given in Table 2.

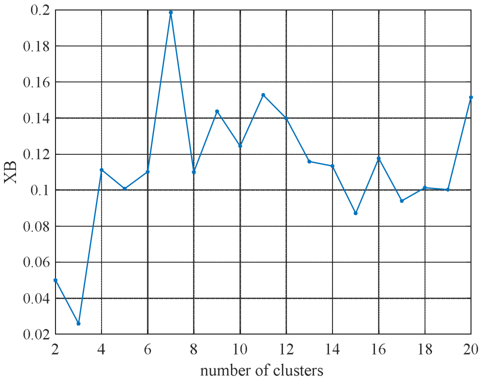

Fig. 12: The XB index for generated power of tidal turbine

Table 2: The center and probability of clusters

Capacity (MW)	Probability
0.33	0.2020
1.04	0.4297
1.40	0.3683

The complete reliability model including 48 states is determined by combining a 3-state model of tidal turbine associated with the variation in the generated power and 16-state model associated with the failure of composed components. In this stage, the states with probability less than 10^{-4} are neglected. Hence, a reliability model, including 15 states, is resulted with the states written in Table 3.

Table 3: The reliability model of understudied tidal farm

State	Capacity (MW)	Probability
1	3.63	0.000160
2	3.96	0.001722
3	4.29	0.012847
4	4.62	0.059343
5	4.95	0.127917
6	11.44	0.000340
7	12.48	0.003663
8	13.52	0.027329
9	14.56	0.126236
10	15.6	0.272108
11	15.4	0.000291
12	16.8	0.003139
13	18.2	0.023424
14	19.6	0.108198
15	21	0.233226

5.2. Reliability Model of Tidal Farm Connected to Vanadium Redox Battery

In this part, a 5MW VRB with 10MWh energy storage capacity composed of 500×10kw batteries with charging-discharging efficiency of 75% is considered to be installed next to tidal farm. The mean time of battery failure is considered to be 1235 days. Hence, its failure rate would be 0.3 failures per year. The battery repair time is considered to be 100 hours. The VRB may fail due to the failure of electrolyte circulating pumps, connection wires, separating membrane, and other components. The VRB is connected to a charging/discharging control system and an inverter. The failure and repair rates of the control system are assumed to be 0.1 and 87.6 times per year; these rates for the inverter are considered to be 0.2 and 87.6 times per year respectively. From reliability point of view, all components of VRB are in series. Hence, the equivalent failure and repair rates of VRB are obtained as 0.5 and 87.6 times per year respectively. In this stage, a 30MW tidal stream farm connected to a 5MW VRB are considered to be integrated with RBTS. The hourly load is considered to be based on the IEEE pattern with 185 MW peak load as shown in Fig. 13.

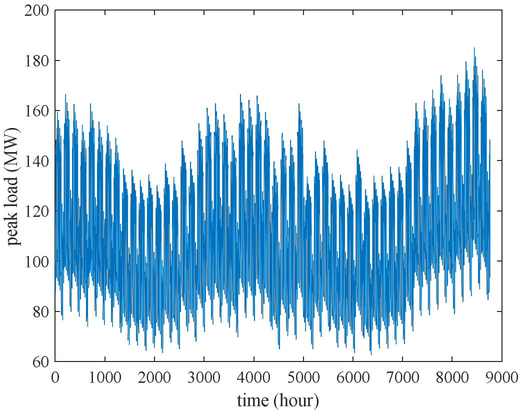

Fig. 13: The hourly peak load [34]

To determine the reliability model of tidal farm connected to VRB, the generated power of tidal farm is obtained based on the hourly tidal currents speed and the power curve of turbine. In each hour, by generating random numbers for tidal farm and VRB components, the conditions of components, i.e. health or damage, are determined, and the generated power of tidal farm is obtained. A Monte Carlo simulation is performed with 1000 repetitions for determining the hourly output power of the set including tidal farm and VRB considering 75% VRB efficiency, 5MW maximum capacity, 10MWh energy storage capacity, 5MW per-hour maximum charging and discharging rates. In simulation process, if the generated power is more than the required load demand and if the generated power of tidal farm is non-zero, the surplus power is stored in the VRB. Also, when the generated power is less than the required load, VRB can provide a portion or the entire required load based on its stored energy. It is assumed that the battery can fully be discharged. The XB index is calculated for the resulted output power data and determining optimum number of states in the reliability model of the set including tidal farm and VRB, which are shown in Fig. 14.

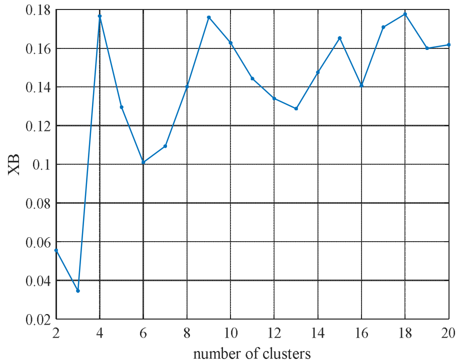

Fig. 14: The XB index for output power of set including tidal farm and VRB

It is deduced from Fig. 14 that 3 clusters can optimally model the output power of tidal farm connected to the VRB. The fuzzy c-means clustering technique is implemented on output power data and the centers of clusters and the associated probabilities are determined and presented in Table 4. This reliability model can be used for adequacy studies of the power system containing understudied tidal farm connected to the VRB.

Table 4: The clusters and their probability

Cluster number	Cluster center (MW)	Probability
1	29.74	0.3767
2	24.65	0.4271
3	14.31	0.1962

5. 3. Adequacy Assessment of Roy Billinton Test System

In this sub-section, reliability evaluation of RBTS integrated with understudied tidal farm and VRB is performed. The characteristics of RBTS including capacity and reliability parameters of the generation units are presented in [34]. The load duration curve is considered to be a straight line from 100% to 60% of peak load. Four cases are considered to study the effects of tidal farm and VRB on the reliability indices of power system: case I is the RBTS; case II is the RBTS integrated with a 30MW conventional generation unit with availability of 0.98; case III is RBTS integrated with understudied tidal farm. Case IV is RBTS integrated with understudied tidal farm connected to the VRB. The *LOLE* and *EENS* of these four cases are calculated and compared in Figs. 15 and 16 respectively.

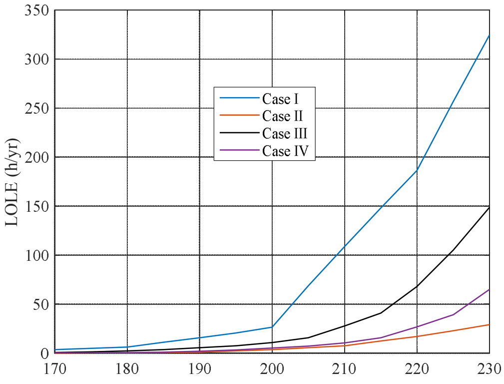

Fig. 15: The LOLE considering peak load

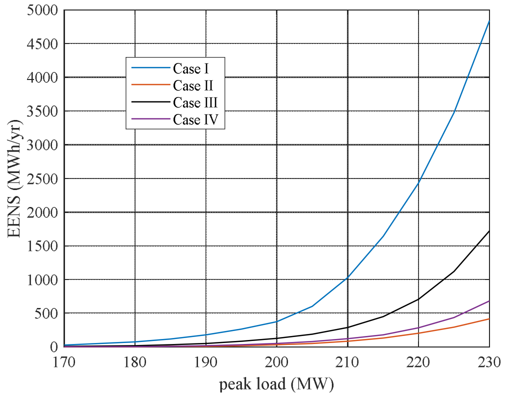

Fig. 16: The EENS considering peak load

It is concluded from these figures that the reliability of power system is improved when a new generation unit is added to the system. However, due to the uncertain nature of tidal turbines-- arisen from variations in the speed of tidal currents and, consequently, the generated power-- the installation of a tidal farm results in less improvement in the reliability indices in comparison with a conventional generation unit with the same capacity. However, the utilization of the VRB connected to tidal farm results in the reduction of uncertainty of tidal power and the reliability indices are improved.

5.4. Economic Analysis of RBTS connected to tidal turbine and VRB

In this part, to investigate the impact of VRB on power system containing tidal farms, an economic analysis is performed. In this study, the values of different costs and the characteristics of understudied VRB are considered to be as shown in Table 5 [35].

Table 5: characteristics of VRB and different costs [35]

Life time	Investment and installation cost	Operation and maintenance cost	VOLL
15 years	3430 $/kw	10 $/kw/yr	7.41 $/kwh

To study the impact of VRB on RBTS, total costs for two peak load values 200 and 230MW are calculated and presented in Table 6. As seen in the table, because the cost of battery is higher than the cost of curtailed load during its useful life, using batteries at a peak load of 200 MW is not cost-effective. However, at peak load of 230MW, VRB can significantly reduce the cost of curtailed load and, thus, using VRB would be cost-effective. In Fig. 17, the total cost versus peak load considering the impact of VRB is shown. As seen in the figure, the use of VRB is cost-effective for peak loads more than 213MW.

Table 6: Total costs versus peak load

Different quantities	Peak load=200MW		Peak load=230MW	
	Without VRB	With VRB	Without VRB	With VRB
EENS (MWh/yr)	126.0774	50.94564	1722.5	863.7441
Penalty of interrupted load per year ($)	934234	377507	127640955	6400344
Investment and installation cost of VRB ($)	0	17150000	0	17150000
Annual operation and maintenance cost ($)	0	50000	0	50000
Present value of total cost ($)	9697029	21587376	1324869465	84102365

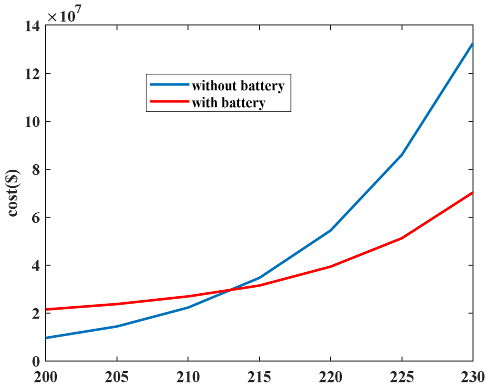

Fig. 17: The total cost considering peak load

In this part, another effective factor, i.e. the value of lost load, varies, and the total cost for peak load of 200MW is calculated and presented in Fig. 18. As seen in the figure, the use of VRB is cost-effective for VOLLs more than 23 $/kWh.

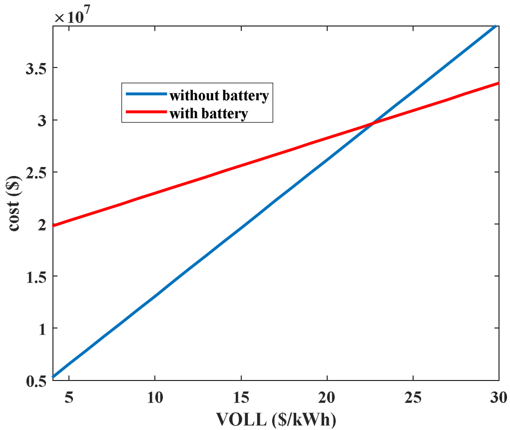

Fig. 18: The total cost considering VOLL

5.5. Adequacy Assessment of IEEE Reliability Test System

It this part, the IEEE-RTS as a large reliability test system is considered to study the effects of current type tidal farm and vanadium redox battery on the reliability indices of power system. The characteristics of generation units of IEEE-RTS are illustrated in [36]. The load duration curve is considered to be a straight line from 100% to 60% of peak load. In this study four cases are considered, including IEEE-RTS, IEEE-RTS integrated with a 30MW conventional generation unit with availability 0.98, IEEE-RTS integrated with understudied tidal farm, and IEEE-RTS integrated with tidal farm connected to VRB as case I to IV respectively. Based on the proposed technique, *LOLE* and *EENS* of these cases are calculated and presented in Figs. 19 and 20 respectively. It is deduced from the numerical results of IEEE-RTS that the reliability of the system is improved when new generation units are added to the system. However, the addition of conventional generation units improves the reliability of the system more than the addition of tidal farm. Besides, VRB reduces the uncertainty of output produced power of tidal farms, and thus, the addition of tidal farm connected to VRB improves the reliability of the system more than the addition of tidal farm without VRB.

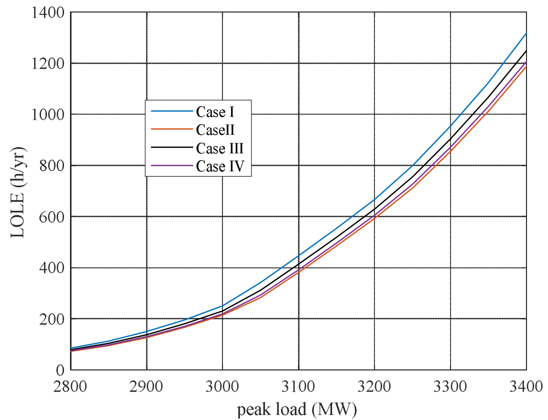

Fig. 19: The LOLE considering peak load

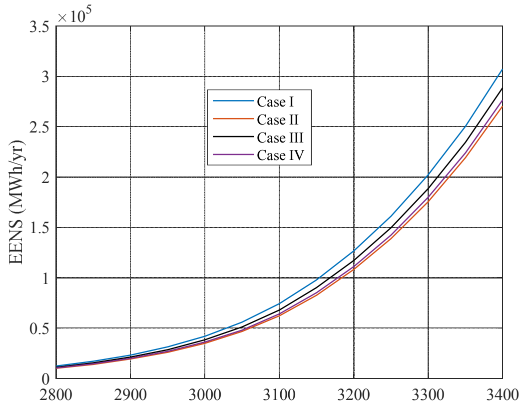

Fig. 20: The EENS considering peak load

6. Discussion

In previous sections, a multi-state reliability model was developed for current type tidal turbines considering both the failure of composed components and the variation in the generated power arisen from variations in the speed of the tidal current. Then, the proposed model was used to study the effects of tidal stream turbines on the power system reliability. The failures of composed components of the tidal stream turbine, including blades, main shaft, and bearing, gearbox, generator, electrical converter, cable, transformer and control system, led to the failure of the entire system. Hence, these components are in series from reliability point of view. The generated power of tidal turbines is dependent on the speed of the tidal current. The generated power of the tidal turbines, due to a wide variation in the speed of the tidal current changes widely. Thus, the states of the reliability model of tidal unit are reduced using a fuzzy c-means clustering method. The real data associated with the output power of this set is required for determining the reliability model of tidal farm connected to the VRB. As the real data associated with the output power of tidal farm connected to the VRB is not available, Monte Carlo simulation is used for collecting the required data and the reliability modeling of the set including tidal farm and VRB.

In this paper, the hourly data of tidal current speed during a year is used for the reliability modeling of the tidal turbine connected to the VRB. The reliability evaluation of RBTS and IEEE-RTS, considering a tidal farm and a VRB, is performed in order to study the effectiveness of the proposed method. It is deduced from the numerical results that when a new generation unit is added to the power system the reliability indices are improved. However, the improvement in reliability indices in the case of adding a conventional generation unit is more than adding the tidal farm. It is due to the uncertain nature of tidal stream turbines, arisen from the variation in the tidal currents speed, that it results in the variation of the generated power of tidal farms. Because the generated power of tidal stream turbines is less than rated capacity in most of times. The VRB can reduce the uncertainty nature of tidal farms. Hence, the installation of a tidal farm connected to the VRB yields an enhancement of the reliability indices of the power system more than an addition of a tidal farm without VRB. In [12-15], the reliability assessment of power systems including tidal turbines is performed. In the current paper, the impacts of vanadium redox batteries on reliability indices of power system containing tidal turbinesare studied. For this purpose, peak load carrying capability (*PLCC*) of the power system for four cases mentioned in 5.3 are calculated and shown in Table. 7. To calculate the *PLCC* of the system, the peak load is increased until the reliability criterion is satisfied. Thus, the *PLCC* is maximum peak load that the system can supply provided that the reliability criterion is satisfied. In this study, the *EENS* is used as the reliability criterion, and the *PLCC* is calculated based on this index. An increase in the peak load carrying capability (*IPLCC*) associated with the addition of new generation units are calculated and presented in Table. 8.

Table 7: The PLCC (MW)

Cases	100 MWh/yr	200 MWh/yr	300 MWh/yr
Case I	180	190	195
Case II	210	215	225
Case III	195	205	210
Case IV	205	215	220

Table 8: The IPLCC (MW)

Cases	100 MWh/yr	200 MWh/yr	300 MWh/yr
Case II	30	25	20
Case III	15	15	15
Case IV	25	25	25

It is deduced from these tables that the maximum load that can be supplied by the system is increased with the addition of new generation units. However, the *IPLCC* associated with the addition of conventional generation units is more than tidal stream farm. Besides, the VRB reduces the uncertainty of current type tidal turbines and, thus, the *IPLCC* of the case IV is more than case III. Thus, vanadium redox battery can improve the reliability performance of power systems containing tidal turbines.

Also, to study the impact of vanadium redox batteries on the reliability performance of IEEE-RTS, the *PLCC* associated with four cases mentioned in 5.5, and the *IPLCC* associated with the insertion of new generation units (cases II to IV) are calculated and presented in tables 9 and 10 respectively.

Table 9: The PLCC (MW)

Cases	20 GWh/yr	50 GWh/yr	100 GWh/yr
Case I	2875	3031	3155
Case II	2904	3060	3184
Case III	2891	3046	3169
Case IV	2901	3057	3179

Table 10: The IPLCC (MW)

Cases	20 GWh/yr	50 GWh/yr	100 GWh/yr
Case II	29	29	29
Case III	16	15	14
Case IV	26	26	24

As seen in the tables, vanadium redox batteries can improve the reliability performance of the power systems including tidal turbines.

In this paper, multi-state reliability models are developed to represent different states of tidal farms and tidal farms connected to vanadium redox batteries. The reliability model of understudied farm has 15 states, and the reliability model of understudied tidal farm connected to vanadium redox battery has 3 states. To study the adequacy of power system including tidal units, historical tidal current speed in each hour associated with one or more years are used. Thus, the generated power of tidal units may have numerous states, and, thus, analytical approach for reliability evaluation of large-scale power systems containing tidal farms requires a lot of calculations, which is very time-consuming. In this paper, the number of states is reduced to the optimal value by fuzzy c-means clustering technique suitable for analytical reliability evaluation of the power systems containing tidal farms connected to vanadium redox batteries.

7. Conclusion

In this paper, the adequacy studies of power system integrated with large-scale tidal turbines and vanadium redox flow batteries was performed. Due to the variation in tidal current speed, it was necessary to improve the reliability performance of tidal turbines connected to bulk power system through energy storage devices with high capacity. Among different types of batteries, vanadium redox flow batteries could be used with high capacity in the power systems with large-scale tidal turbines. To construct the reliability model of tidal turbines connected to the vanadium redox battery, the failure of composed components and the variation in the generated power were considered. In the reliability model, it was proposed to calculate the *XB* index to determine an optimum number of reduced states. The optimum number of states was determined when the *XB* index is minimal. Then, the probability of states was determined through fuzzy c-means clustering approach. To study the impact of vanadium redox battery on the reliability performance of power systems integrated with tidal turbines, the adequacy assessment of RBTS and IEEE-RTS were examined. To determine the reliability model of tidal farms connected to vanadium redox battery, historical data associated with tidal current speed was used. The more hourly data available on output power or tidal current speeds, the more accurate the multi-state reliability model was obtained. Numerical results show vanadium redox battery could improve the reliability performance of power systems with tidal turbines. It was also deduced from the economic analysis of power systems, containing tidal farms, that the VRB could reduce the penalty associated to the load interruption. However, the cost-effectiveness of the battery in the power system including current type tidal power plants was dependent on different parameters such as peak load and the value of lost load.

To study the impacts of vanadium redox battery on the reliability of tidal turbines, due to the unavailability of real data, Monte Carlo simulation method was used to generate the associated data. It was one of the limitations of this paper. Another limitation of this work in practical application was the high cost of the transmission line required to transfer power between the battery and the tidal turbines.

Nomenclature

$P_{VRB}(t)$: stored power in battery

$E(t)$:stored energy in battery

P_{min}: minimum power of battery

P_{max}: maximum power of battery

E_{min}: minimum energy of battery

E_{max}: maximum energy of battery

R_{max}: maximum charging and discharging rate of battery

Δt: time step

P_k: probability of state k

J: objective function in clustering

x_k: input data for clustering

u_{ik}^{m}: fuzzification parameter

v_i: center of ith cluster

XB: Xie-Beni index

$\mu_{equivalent}$: equivalent repair rate
$\lambda_{equivalent}$: equivalent failure rate
P_c^{down}: probability of down state
P_c^{up}: probability of up state
μ_c: repair rate of component
λ_c: failure rate of component
P_{rated}: rated power
V_{rated}: rated speed
$V_{cut\text{-}in}$: cut-in speed
C_P: Betz coefficient
v: velocity of tidal current
A: area of turbine
P: generated power of tidal turbine
$C_{invest.}$: investment cost of battery
$C_{oper.main}$: operation and maintenance cost of battery
$C_{reliability}$: reliability cost of the power system
i: interest rate
n: number of years

Acronyms

VRB: vanadium redox battery
RBTS: Roy Billinton test system
IEEE-RTS: IEEE reliability test system
HL: hierarchical level
XB: Xie-Beni
COPT: capacity outage probability table
IPLCC: increase in peak load carrying capability
PLCC: peak load carrying capability
LOLE: loss of load expectation
EENS: expected energy not suppliedf
VOLL: value of lost load

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