Reliability Evaluation of Power Systems Containing Ocean Thermal Energy Conversion Power Plants

Khodakhast Nasiriani\textsuperscript{1}, Amir Ghaedi\textsuperscript{2,}\textsuperscript{*}, Mehdi Nafar\textsuperscript{1}
\textsuperscript{1}Islamic Azad University, Marvdasht Branch, Marvdasht, Iran (e-mail: kh.nasiriani@miau.ac.ir, mehdfanafar@yahoo.com).
\textsuperscript{2}Islamic Azad University, Dariun Branch, Dariun, Iran (e-mail: amir_ghaedi_63@yahoo.com, P. O. Box: 7145168598).

Abstract—Recently, renewable power plants, utilize from clean and sustainable resources for electricity generation in the world. The ocean thermal energy conversion (OTEC) system uses from the ocean surface water as high temperature source and the water in the depth of the ocean as low temperature source. The difference between these temperatures is 20\degree C or more and a working fluid with low boiling point can be used for electricity generation. In a close cycle OTEC system, working fluid through a thermodynamic cycle based on the Rankine cycle can rotate the turbine and generate electricity. Due to the variation in the ocean surface temperature, the output power of the OTEC system changes and results in the numerous states in the generated power of this plant. Thus, in integrating the OTEC systems to the power system, many aspects of power system such as reliability may be affected and so new approaches must be developed for investigation these effects. In this paper, the reliability of the power system containing OTEC system based on the multi-state reliability model and also based on the conditional value at risk concept is evaluated and the valuable indices used for generation expansion planning of the power system are calculated.

Index Terms—Adequacy, clustering, ocean thermal energy conversion, reliability, conditional value at risk.

1 INTRODUCTION

In recent years the renewable energy resources specially wind, solar and ocean, instead of the fuel-based power plants, are increasingly utilized for electrical power generation in the modern power systems. It is due to the different problems that arisen from the fossil fuels such as sudden increase in their prices, non-sustainable nature of these resources and greenhouse gas emission of them that results in the climate change, earth warming and other environmental effects. Among renewable resources, because of the vast area of the oceans, different kinds of ocean energies such as wave, tidal and ocean thermal energies can play a vital role in the generation sector of the future power systems. The surface area of the oceans is very large and with receiving solar radiation, ocean thermal energy conversion (OTEC) systems can be used for supplying significant consumers in the world.

\textsuperscript{*}corresponding author: Amir Ghaedi is with the Islamic Azad University, Dariun Branch, Dariun, Iran (e-mail: amir_ghaedi_63@yahoo.com, Fax: 07132746390, Tel: +98912794861, P. O. Box: 7145168598).
For integrating the OTEC system to the power grids, many works were done in the past. In [1], principles and equations associated to the calculation of generated power of an OTEC system are explained. In this paper, from the numerical analysis, it is concluded that the overall efficiency of the system is 3.97%. In [2], history, different types, different applications and environmental impacts of OTEC technology are given. In [3], it is used from organic isobutene as working fluid in a 110 MW on-shore, closed cycle OTEC power plant. In this paper the generation power process, energy calculation and cost analysis are studied. In [4], different types of OTEC systems, environmental considerations and economics of different applications of OTEC including producing of fresh water, refrigeration and air conditioning, Mari culture, agriculture and energy carriers are illustrated. In [5], the performance evaluation and optimal design of a 50 MW OTEC power plant based on the Rankine cycle with R-22 as working fluid is obtained. In [6], the sensitivity analysis of a closed cycle OTEC power plant is performed and the effects of variation in warm and cold water temperatures, warm and cold water pipe diameters, warm and cold water velocity in pipes and evaporator and condenser working temperatures on the net generated power and efficiency of the system is analyzed. In [7], using of the genetic algorithm, a multi-objective optimization problem is solved and optimal designs of OTEC power plants with 10, 50 and 100 MW capacities are resulted. In this study, the warm sea water velocity, warm water pipe diameter, temperatures of sea water, condenser and evaporator are considered as optimization parameters. In [8], it is suggested that the discharge water of nuclear or fossil power plants can be used as high temperature source in the OTEC power plant instead of ocean surface water and so using of this method, the environmental impact of power plant discharge is mitigated. In [9], the combination of OTEC system with solar energy in an organic Rankine cycle to generate electric power is studied and the effects of variation in different effective parameters including turbine inlet temperature, turbine exit quality, turbine inlet pressure and condenser exit temperature on system efficiency is investigated. In [10], the potential of South China Sea encompassing a large area over 3.5 km² with the surface temperature around 24 to 30°C throughout the year in electric power generation based on the OTEC system is investigated and it is concluded about 0.5 TW electric power can be generated with consideration of Carnot efficiency. In [11], low efficiency and high energy consumption are considered as two main drawbacks of the OTEC system and so in this paper, wave, solar and OTEC systems are integrated to construct water-electricity cogeneration system and improve the efficiency and reduce energy consumption of this system. In [12], techno-economic characteristics of some renewable resources including wave, tidal, geothermal and ocean thermal are studied. The global capacity of ocean thermal energy and its long term cost are estimated to be 5000 GW and 0.1-0.18 $/kWh, respectively. The generated power of an OTEC system is dependent on the temperature of ocean waters and due to the variation in these temperatures throughout the year, the generated power of OTEC power plants varies too and so it affects different aspects of integration OTEC power plants in the power system such as reliability indices.
Variation in the output power of the renewable resources including wind, solar, tidal, wave and so on is the main drawback of these clean energies and so many researches have been devoted to studying the effects of these resources on the different aspects of power systems [13-20]. The reliability evaluation of OTEC systems is not performed so far and so in this regard, the researches associated to the reliability assessment of other renewable resources such as wind, solar, wave, tidal and so on can be utilized. In [21], sequential Monte Carlo simulation technique and fuzzy theory are used to calculate the reliability indices (based on the well-being approach) of a system with a high penetration of wind resources considering the impacts of demand response program. In [22], a novel generation rescheduling algorithm is used to improve the reliability of a power system containing high renewable energy penetration. In [23], Monte Carlo simulation approach based on the cross-entropy and Copula techniques is utilized for adequacy studies of the generation system containing high share of wind power considering the correlation between wind farms. In [24], reliability evaluation of distribution network containing photovoltaic systems considering time-varying failure rate of conventional power equipment, variation in the radiation intensity, failure and degradation of photovoltaic modules is performed. In [25], reliability assessment of distribution network containing renewable resources and parking lots using of the non-sequential Monte Carlo simulation approach is performed and it is concluded that parking lots can improve the reliability of renewable-based distribution networks. In [26], a new robust and easy to use model is developed for simulation solar radiation that can be used for reliability assessment of power systems containing solar generation systems. In [27], a new approach is proposed to evaluate the reliability of wind farms considering the correlation between wind speed and wind turbine reliability. In [28], a reliability model is constructed for the wind farms considering wind variability, failure of turbines and correlation between turbine outputs. The proposed model includes both probability and frequency distribution of the power output associated to the wind farms. In [29], the optimal layout of an offshore wind farms based on the constant number of wind turbines and a constant area of coverage is determined using of the mixed integer linear programming method. This optimal layout is determined by maximization the output power, minimization the cable cost and maximization the reliability. In [30], a stochastic multi-objective model to optimally exchange the energy of renewable-based micro grids under risk-based strategies is developed. In the objective function, the economic and reliability factors are considered and to address the uncertainty nature associated to the loads and renewable resources three various risk-based strategies based on the conditional value at risk (CVaR) approach are utilized. In [31], the value at risk (VaR) and CVaR approaches are used to calculate the long-term operational reserve of the renewable-based power system. In this paper, to analyze the medium and long-term operation studies of the power system considering the variability and uncertainty of the renewable generation capacity, risk-based technique is proposed to result is the more robust and flexible generating configurations. In [32], a robust optimization approach based on the CVaR is proposed to perform the unit
commitment in a market with probabilistic offers. This paper proposes a risk-aware market clearing strategy to consider the uncertainty nature of wind power and other stochastic resources by accepting probabilistic offers based on the conditional value at risk in a power system containing large-scale renewable resources. In [33], the optimal control of energy storage in a micro grid is performed by minimizing conditional value at risk. In this paper, two methods, based on the concept of rolling horizon control are proposed to optimally control an energy storage system in a grid connected micro grid considering the uncertainty of demand and electricity pricing. The control is performed based on the scenario-based stochastic CVaR optimization, and in the cost function, electricity usage cost, operation cost of the battery and grid signal smoothing objectives are taken into account. In [34], capacity configuration optimization is carried out for stand-alone micro grids taken into account the uncertainties of wind and solar resources. In this paper, a micro grid including wind, photovoltaic, diesel and battery is considered and a stochastic optimization model based on the CVaR is proposed to taken into account the operation risk of micro grid arisen from uncertainties of wind and solar resources. As mentioned, reliability assessment of OTEC systems is not studied so far and so, in this regard, in this paper for the first time, the reliability evaluation of a power system containing OTEC power plants is performed. For this purpose, a reliability model is constructed for OTEC power plants with considering both failure rates of composed components and variation in the generated power arisen from uncertainty nature of ocean water temperature. The failure rate of the OTEC system varies with time and so an average failure rate is calculated to use in the associated model. Based on this reliability model a multi-state generation unit is obtained and utilized for adequacy studies of a power system containing OTEC power plants. The fuzzy c-means clustering method and Xie and Beni (XB) index are implemented for determining appropriate states of this reliability model. To study the effect of the uncertainty nature associated to the variation in the ocean temperature, the reliability indices based on the CVaR are also calculated. Thus, the contributions of this paper are as below:

- An analytical multi-state model taken into account both failure of composed components and variation in the generated power arisen from variation in the temperature of ocean surface is developed for OTEC systems.
- To reduce the number of states in the reliability model of OTEC systems, fuzzy c-means clustering technique is utilized.
- To determine the optimum number of states in the reliability model of OTEC system, the XB index is calculated.
- The large-scale OTEC system is integrated to the power system, and the adequacy indices are calculated.
- To consider the uncertainty nature of ocean surface temperature, the adequacy indices of power system in presence of OTEC system is calculated based on the CVaR concept.

Based on the aims of the study, this paper is organized as below: the structure, principle and different types of the OTEC systems are illustrated in the second part. In the third part, related equations associated to the generated power in OTEC power
plant are presented and a suitable working fluid among ammonia, R-22 and R-134a is selected to be utilized in the OTEC power plant. The proposed multi-state reliability model of OTEC power plants is developed in the first subsection of fourth section. In the second subsection, the $CVaR$ concept to model the uncertainty nature of ocean surface temperature is introduced and in the third subsection, the proposed technique to evaluate the adequacy of a power system containing OTEC power plants based on the multi-state model and also $CVaR$ is introduced. The technique to study the effect of transmission network on the reliability of renewable-based power system is introduced in the fourth subsection. In fifth section, the numerical results associated to Roy Billinton Test System (RBTS) and IEEE Reliability Test System (IEEE-RTS) as two well-known test systems with considering the effects of OTEC power plants based on the multi-state reliability model and also $CVaR$ concept are investigated. The conclusion of the paper is summarized in the sixth section.

2 OTEC SYSTEMS

Greenhouse gas emission of burning fossil fuels results in climate change and earth warming and because of these effects; global organizations act some laws to reduce the use of fossil fuels in the world. So, many of countries in their generation expansion planning put some encouragements to use from renewable resources for electric power generation. One of these renewable energies that are utilized from the sun is OTEC systems. The temperature of oceans with very large area can be increased to 20-30 $^\circ$C by receiving the thermal energy from the sun. The temperature of the water at 1000 meters deep is about 4-5 $^\circ$C and because of this difference between temperatures of water in the surface and the water at 1000 meters deep, a thermodynamic Rankine cycle can be used for electric power generation.

2.1 Different types of OTEC systems

Three types of OTEC power plants including closed cycle, open cycle and hybrid cycle can be constructed. In an open cycle OTEC power plant, the seawater is used as working fluid and warm sea water (water in the surface) is pumped into a flash evaporator with 0.03 bar pressure that causes the water to boil at 22 $^\circ$C temperature. The resulted steam expands through a low pressure turbine that is connected to a synchronous generator for electric power generation. Then, the steam passes through a condenser that is used from the cold seawater of the depths of the ocean to condense the steam into desalinized water. In a closed cycle OTEC power plant, a low boiling point liquid such as ammonia, R-22, R-134a or another type of refrigerant is used as the working fluid in a Rankine cycle. The heat of warm seawater of ocean surface flowing through an evaporator causes the working fluid to vaporize. Then, the vapor expands through a turbine and generates the electric power using of the generator connected to
the turbine. The steam flows into a condenser and the cold seawater condenses it into a liquid. A hybrid cycle OTEC power plant is a combination of both closed and open cycles. In this system, the fresh water is initially flashed into steam, similar to the closed-cycle approach that occurs in a vacuum vessel. In the same vessel the ammonia or other working fluid is evaporated through heat exchange using of the warm water from the surface of ocean. The working fluid is then physically mixed with the warm seawater in a two-phase, two-substance mixture. The evaporated working fluid is then separated from the steam/water and re-condensed and re-introduced into the closed loop cycle. The phase change of the water/working fluid vapor rotates a turbine generating the electric power.

2.2 The structure of the close cycle OTEC system

In this paper the close cycle OTEC power plant is studied and the reliability model of this plant is developed. In Fig. 1 the structure and composed components of this system is presented. As can be seen in the figure, in close cycle OTEC systems, the working fluid is pumped, and then its temperature in a heat exchanger exposed to the surface water is increased and converted to the vapor. The resulted vapor turns the turbine and consequently the generator connected to the turbine and so produces the electric power. The output vapor of turbine is converted to the liquid in the heat exchanger using of the cold seawater that is pumped from the 1000 meters deep.

3 GENERATED POWER OF CLOSED CYCLE OTEC SYSTEMS

In this section, different thermodynamic equations associated to the Rankine cycle are evaluated and the generated power of a closed cycle OTEC power plant is determined.

3.1 Thermodynamic relations of generated power

The temperature-entropy (T-S) diagram of Rankine cycle associated to a closed cycle OTEC system is presented in Fig. 2. The entropy (kJ/(kg °K)) is a thermodynamic quantity to present the unavailability of a system’s thermal energy for conversion into mechanical work, often interpreted as the degree of disorder or randomness in the system. The pure generation power of an OTEC power plant can be calculated as:

\[ P_N = P_G - P_{WFP} - P_{WWP} - P_{CWP} \]  \hspace{1cm} (1)

Where, \( P_G \) is the generated power of generator and \( P_{WFP} \), \( P_{WWP} \) and \( P_{CWP} \) are the power required for pumping working fluid, warm water and cold water, respectively. The generated power of the generator connected to the turbine can be calculated as:

\[ P_G = \dot{m}_{WF} \eta_G \eta_T (h_1 - h_2) \]  \hspace{1cm} (2)
Where, $m_{WF}$ is mass flow rate of the working fluid (kg/s), $\eta_G$ and $\eta_T$ are generator and turbine efficiency, $h_1$ and $h_2$ are the enthalpies of evaporator outlet (turbine inlet) and condenser inlet (turbine outlet), respectively (J/kg). The enthalpy is a thermodynamic quantity equivalent to the total heat content of a system. It is equal to the internal energy of the system plus the product of pressure and volume. For power generation in the Rankine cycle, the turbine expands in adiabatic process (constant entropy).

The power required for pumping working fluid, warm water and cold water are determined as:

\[ P_{WFP} = \dot{m}_{WF}g h_{WF} / \eta_{WFP} \]  
\[ P_{WWP} = \dot{m}_{WW}g h_{WW} / \eta_{WWP} \]  
\[ P_{CWP} = \dot{m}_{CW}g h_{CW} / \eta_{CWP} \]

Where, $\dot{m}_{WF}$, $\dot{m}_{WW}$ and $\dot{m}_{CW}$ are mass flow rate of working fluid, warm water (ocean surface water) and cold water (water at 1000 meters deep), $g$ is acceleration of gravity (m/s$^2$), $h_{WF}$, $h_{WW}$ and $h_{CW}$ are total pressure difference (arisen from the difference in the height of the plant or friction of the pipes) associated to the working fluid, warm seawater and cold seawater, $\eta_{WFP}$, $\eta_{WWP}$ and $\eta_{CWP}$ are efficiencies of pumping of working fluid, warm water and cold water. The heat transfer rate (J/s) of the evaporator ($Q_E$) and the condenser ($Q_C$) are calculated as:

\[ Q_E = \dot{m}_{WF}(h_1 - h_4) \]  
\[ Q_C = \dot{m}_{WF}(h_2 - h_3) \]

Where, $h_1$ and $h_4$ are the enthalpies associated to the inlet and outlet of the working fluid pump, respectively. In addition to the Equation (3), the power that is required for pumping working fluid can be calculated as:

\[ R_{WFP} = \dot{m}_{WF}(h_4 - h_3) \]

In this part, three working fluid including ammonia, R-22 and R-134a are considered and the generated power of these working fluids in a closed cycle OTEC power plant with the same working fluid mass flow rate is calculated. Thermodynamic properties of saturated ammonia, R-22 and R-134a are illustrated in [35]. In table 1, the thermodynamic properties of ammonia in temperatures between 20 to 26 °C including temperature, pressure, specific volume, enthalpy and entropy are given. It is assumed that a closed cycle OTEC power plant is constructed in the Hawaii. The hour to hour data associated to temperature of ocean surface in this region for 2016 is presented in Fig. 3.
For calculating the generated power of the power plant in each hour, the temperatures of the warm and cold waters are considered as the temperature of the saturated vapor in state 1 and the temperature of saturated liquid in state 3 of Fig. 2, respectively and so using of the thermodynamic table of working fluid [35], the pressure, enthalpy and entropy of these two states can be obtained. With considering state 1 in saturated vapor and state 3 in saturated liquid, in Rankine cycle of Fig. 2, \( h_1 = h_g, \ s_1 = s_g, \ v_1 = v_g, \ P_3 = P_{3b}, \ P_1 = P_4, \ h_1 = h_g, \ s_1 = s_g \). The subscripts \( f, fg \) and \( g \) are respectively used for saturated liquid (a liquid that is about to vaporize), saturated liquid–vapor mixture (the state at which the liquid and vapor phases coexist in equilibrium) and saturated vapor (a vapor that is about to condense). From the adiabatic process of turbine expansion, \( s_1 = s_2 \). If the state is a mixture of liquid and vapor, the entropy can be determined as: \( s = s_f + x s_{fg} \), where \( x \) is the quality and \( s_f \) and \( s_{fg} \) are saturated values listed in the saturation table [35], and so the quality \( (x) \) of state 2 can be calculated as:

\[
x = \frac{s_{2} - s_f}{s_{fg}} = \frac{s_{1} - s_3}{s_{fg}} \tag{9}
\]

When a substance exists as part liquid and vapor at saturation conditions, its quality \( (x) \) is defined as the ratio of the mass of the vapor to the total mass of both vapor and liquid. Thus, the enthalpy of state 2 can be calculated as:

\[
h_2 = h_f + x h_{fg} = h_3 + x h_{fg} \tag{10}
\]

The required power for pumping working fluid in \( kJ/kg \) can be calculated as:

\[
p_{WFP} = h_{4e} - h_3 = v_f(P_e - P_3) \tag{11}
\]

Thus, the enthalpy of state 4 can be calculated as:

\[
h_4 = h_3 + p_{WFP} \tag{12}
\]

Based on the thermodynamic equations of the Rankine cycle (1) to (12), the generated power of a closed cycle OTEC power plant can be calculated.

### 3.2 Comparison of different working fluids

The generated power of OTEC power plants that use from ammonia, R-22 and R-134a as three working fluids in 2016 is calculated and presented in Fig. 4. As can be seen in the figure, the maximum generated power associated to ammonia is 30MW, while for the other two working fluids, it is about 5MW. Thus, with the same mass flow rate, the OTEC plant that utilizes from ammonia can produce the electric power about 6 times more than the OTEC power plant that uses from R-22 and R-134a. The generated power of OTEC power plants that use from R-22 and R-134a working fluids are approximately the same.
In this section, a multi-state reliability model of closed cycle OTEC power plants is developed that can be used for adequacy studies of a power system containing these renewable resources. Power system reliability is the ability of a power system to supply the required demand of the consumers and it comprises of two aspects: adequacy and security. Adequacy of a power system is satisfied when adequate facilities in the generation, transmission and distribution parts of that power system are available to supply the loads and the security of a power system is the ability of the system to respond to different events such as outage of the generation units or transmission lines and so on. For reliability evaluation of power systems two approaches including analytic and numerical methods are available. The numerical approaches are based on the Monte Carlo simulation and require huge volume of computation due to the numerous repetitions.

### 4.1 Reliability modeling of OTEC system

In this paper, an analytic reliability model of OTEC power plants is introduced that considers both failure of composed components and variation in the generated power. The main components of a closed cycle OTEC power plant are main structure, mooring system (for maintaining the main structure and the pipes in the ocean), pipes, turbine, generator, evaporator, condenser, three pumps (for pumping working fluid, warm and cold water), electrical converter, control system, transformer and cable. With failing of these components the operation of the system must be stopped and so the generated power of the system would be zero. Thus from reliability point of view, these components are connected in series in the reliability model of the power plant as can be seen in the Fig. 5. A two-state (up and down) Marco model as can be seen in Fig. 6 can be used for reliability modeling of each component of model Fig. 5. In this model \( \lambda \) and \( \mu \) are failure and repair rate of the components [36]. The probabilities associated to up and down state can be determined as Relation (13).

\[
P_{up} = \frac{\mu}{\lambda + \mu}, \quad P_{down} = \frac{\lambda}{\lambda + \mu}
\]

The temperature of water in the surface of the ocean varies between 20 to 30 °C that affects the failure rate of components in contact with this water. Based on the Arrhenius theorem, the failure rate of these components in different temperatures is calculated as:

\[
\lambda(T) = \lambda_0 e^{\frac{E_a}{RT}}
\]

In Equation (14), \( \lambda(T) \), \( \lambda_0 \), \( E_a \), \( k \) and \( T \) are respectively failure rate associated to temperature \( T \) (in Kelvin degree), failure rate in the base temperature, activation energy, Boltzman constant and temperature [37]. For the components in contact with the water in the surface of the ocean, based on the temperature of each hour in the year, the average failure rate is calculated as:
\[
\lambda = \frac{\sum_{i=1}^{8760} \lambda(T_{ik})}{8760}
\]  

(15)

The equivalent failure and repair rate of the OTEC system can simplicity be determined based on the series components as Relation (16) [36].

\[
\lambda_{eq} = \sum_{i=1}^{k} \lambda_i, \quad r_{eq} = \sum_{i=1}^{k} r_i = \frac{1}{\lambda_{eq}}, \quad \mu_{eq} = \frac{1}{r_{eq}}
\]  

(16)

In Relation (16) \(\lambda_{eq}\), \(\mu_{eq}\) and \(r_{eq}\) are equivalent failure rate, equivalent repair rate and equivalent repair time. The generated power of an OTEC system is dependent on the temperature of ocean surface water and because of the variation in these temperatures as can be seen in Fig. 3, the generated powers are not fixed and vary with time as can be seen in Fig. 4. In this figure the generated power of a 30MW closed OTEC power plant utilizes from ammonia as working fluid constructed in the Hawaii with temperature data of 2016, can be utilized for reliability studying of the power system.

As can be seen in the figure, the generated power of plant has numerous states that are not suitable for analytic reliability evaluation of a power system. Thus, the states of the power must be reduced using of an appropriate clustering technique. The clustering methods are classified in two categories including hierarchical and partitioning clustering methods. The partitioning clustering method is categorized into the K-means clustering, fuzzy c-means (FCM) clustering, Gaussian expectation-maximization, K-harmonic means and hybrid 2 algorithms. Among these clustering techniques, FCM clustering method allocates each data to each cluster with some degree of membership (i.e. fuzzy clustering) that is more appropriate in the real applications where there are some overlaps between the clusters in the data set. The performance of the FCM clustering method is better than other clustering techniques and the effect of data uncertainty on this method is less [38]. Thus, due to the uncertainty nature of ocean surface temperature, this technique can be used to reduce the number of states in the reliability model of OTEC power plant. However, as in K-means it requires the user to specify the number of clusters in the data set. Applying this robust approach, for a preset number of clusters, center of clusters can be determined. This method categorizes object data \(X = \{x_1, x_2, ..., x_n\}\) into \(m\) fuzzy clusters minimizing the following objective function [39].

\[
J_m(U,v) = \sum_{l=1}^{m} \sum_{k=1}^{n} U_{ik} f \left| x_k - v_k \right|
\]  

(17)

where \(f, v_k\) and \(U_{ik}\) are fuzzy parameter, center of the \(i^{th}\) cluster and fuzzy degree between \(x_k\) and \(i^{th}\) cluster. In the FCM clustering approach, it requires the user to specify the number of clusters in the data set. To determine the optimal number of
clusters, various indices including the least Square Error (SE), Partition Coefficient (PC), Partition Entropy (PE), Fukuyama and Sugeno (FS), Xie-Beni (XB), Dunns Index (DI), Partition Coefficient and Exponential Separation (PCAES) [40-41], and techniques including using the Information Theoretic Criterion have been taken [42]. Due to the suitability and good performance of XB index for obtaining the optimal number of reduced states resulted in the frequent applications of this index in the literature review, in this paper, the XB index is used to determine the optimal number of clusters in the reliability model of OTEC system which is obtained when XB is minimal. Thus, for determining appropriate number of clusters, XB index is calculated as [43]:

$$XB = \frac{J_m(U,v)}{n \times \min_{i \neq j} (|v_i - v_j|^2)}$$  \hspace{1cm} (18)

The optimal number of clusters is determined when XB index is in the minimum value. Utilizing the generated power associated to historical data as the input data of FCM clustering method, the number and probability of suitable clusters, which represent the appropriate states associated to the OTEC power plant, can be determined. If the clustering algorithm results in $h$ clusters the complete reliability model of closed cycle OTEC power plant would be obtained as can be seen in Fig. 7. The states with zero capacity can be merged and a model with $(h+1)$ states can be obtained.

### 4.2 The CVaR concept in the OTEC systems

The generated power of OTEC systems depend on the temperature of ocean surface and due to the variation in the ocean surface temperature, the output power of OTEC systems has stochastic behavior. The uncertainty nature of OTEC units put the system at risk due to this probabilistic behavior. Thus, in this stage, risk-based adequacy study of the power system integrated to the OTEC units is proposed. For a random variable such as ocean surface temperature $(T)$, in a given time horizon such as a year, for $0<\alpha<1$, the $\alpha$-value at risk $(VaR_\alpha(T))$ can be calculated as (19). The $VaR_\alpha(T)$ is the minimum ocean temperature that the probability of occurrence of the temperature below it is equal to $\alpha$.

$$VaR_\alpha(T) = \min \{ c | P(T \leq c) \geq \alpha \}$$  \hspace{1cm} (19)

For the random variable ocean temperature, the $\alpha$-conditional value at risk $(CVaR_\alpha(T))$ can be calculated as (20). The $CVaR_\alpha(T)$ is the expected value of the ocean temperatures that are more than $VaR_\alpha(T)$.

$$CVaR_\alpha(T) = \frac{1}{1-\alpha} \sum_{T_{\alpha(T)}}^T (T \times P(T))$$  \hspace{1cm} (20)

Where, $P(T)$ is the probability of occurrence temperature $T$ and $T_{\max}$ is the maximum ocean temperature occurred during time horizon. The concept of $VaR$ and $CVaR$ is presented in Fig. 8.
In this paper, the variation in the ocean temperature leads to the variation in the generated power and consequently the variation in the reliability indices. To study the effect of variation in the ocean temperature on the adequacy studies of the power system containing OTEC units, the reliability indices including loss of load expectation (LOLE) and expected energy not supplied (EENS) considering different CVaR associated to the different value of $\alpha$, are determined. For this purpose, the generated power associated to different CVaR is calculated and used for determining the LOLE and EENS values.

4.3 The technique to evaluate the adequacy of the power system containing OTEC system

For adequacy studies of a generation power system containing OTEC power plants with large capacity that can be integrated to the bulk power system, all generation units are considered to connect to a common bus and the total load is connected to it too. A capacity outage probability table (COPT), including different capacities and associated probabilities of the power plants, is constructed for the conventional generation units including two states (up and down). Then the multi-state reliability model of the OTEC power plants are added to this table and the total COPT of the system is constructed. With convolving the load model and the generation model, the adequacy indices including LOLE, EENS, peak load carrying capability (PLCC) and increase in peak load carrying capability (IPLCC) are simplicity obtained. The LOLE is the hours in a year that part or all of the electric load is curtailed, the EENS is the value of the energy in a year that the system cannot supply, the PLCC is the value of the peak load that the system can supply provided that the reliability criterion is satisfied and IPLCC is the amount of peak load that can be added provided that the reliability criterion is satisfied, when a new generation unit is added to the system. If the peak load is modeled through load duration curve with a straight line, the LOLE and EENS can be calculated as Relations (21) and (22) based on the Fig. 9.

$$\text{LOLE} = \sum_{i=1}^{n} t_i \times P_i \text{ hours/year} \quad (21)$$

$$\text{EENS} = \sum_{i=1}^{m} ENS_i \times P_i \quad (22)$$

4.4 The effect of transmission system on the adequacy studies

In this part, the effect of transmission network on the reliability of power system containing OTEC units is investigated. In this paper, to study the composite (generation and transmission) system reliability, contingency analysis approach is proposed. Each conventional generation units and transmission lines can be presented by two states including up and down states. However, due to the uncertainty nature of OTEC systems arisen from variation in the generated power, each OTEC system can be presented by multi-state model. Thus, a composite power system including $n$ generation units and $m$ transmission lines will have $2^{n+m}$
contingencies. The number of contingencies in the large-scale composite power system is very high that is not suitable for adequacy studies of the composite power system and so, using of the state selection, it is neglected from the contingencies with low probabilities and the number of contingencies are reduced. If an OTEC system with \(h\) states is added to the composite system, the number of contingencies would be \(h \times 2^{n+h}\). After reducing the contingencies using of state selection, each selected contingency is evaluated. In this paper, to evaluate the contingencies, DC load flow considered the capacity of transmission lines is performed. If a contingency result in the load curtailment, using of the load shedding program to minimize the cost of interrupted loads, optimum load curtailment is determined. The objective function of load shedding program is considered to be:

\[
\text{objective function} = \sum_{i=1}^{n} C_i VOLL_i \quad (23)
\]

Where, \(C_i\) and \(VOLL_i\) are respectively the curtailed load and the value of lost load in ($/MWh) associated to the load point \(i\). In this paper, linear programming approach based on the interior point method is utilized to optimize the objective function. To optimize the cost function, the problem constraints (including the power balance equation must be established, the generated power of generation units must be within the permissible range, the interrupted load must be less than the maximum load and the transmitted power of the transmission lines must be less than nominal capacity) must be satisfied. Based on the contingency analysis, adequacy studies of composite power system containing OTEC systems are performed and reliability indices such as the probability of lost load \((Q_S)\), \(LOLE\) and \(EENS\) associated to each load point can be determined using of Relations (24), (25) and (26), respectively. Where, \(P_i\) is the probability of state \(i\), \(B_i\) is a binary number with two values of 0 and 1 that 1 represents the state results in the load curtailment of understudied bus, \(n\) is the number of all states and \(L_i\) is the value of lost load of understudied load point associated to the state \(i\). The flowchart associated to the adequacy assessment of a composite power system containing large-scale OTEC systems is presented in Fig. 10.

\[
Q_S = \sum_{i=1}^{n} P_i B_i \quad (24)
\]

\[
LOLE = \sum_{i=1}^{n} P_i B_i \times 8760 \quad (25)
\]

\[
EENS = \sum_{i=1}^{n} L_i P_i \times 8760 \quad (26)
\]
5 NUMERICAL RESULTS

In this section the proposed multi-state reliability model of closed cycle OTEC power plants is developed to use for adequacy studies of RBTS and IEEE-RTS systems containing OTEC power plants. The reliability indices based on the CVaR concept are also calculated to study the effect of uncertainty nature of ocean temperature on the reliability performance of the power system.

5.1 Reliability modeling of the understudied OTEC system

The generated power of a 30 MW closed cycle OTEC power plant is presented in Fig. 4. The histogram of the generated power is obtained and presented in Fig. 11. Applying FCM clustering method to the generated power data and calculation of XB index as can be seen in Fig. 12, it is resulted that 3 clusters can model the generated power of under studies OTEC power plant. In Fig. 13, the fuzzy number of different generated power data associated to every cluster is represented. As can be seen in this figure, all data are concentrated around the clusters and the FCM clustering method can successfully model all generated power with three clusters. The 3-state reliability model of the OTEC power plant arisen from uncertainty nature of variation in the temperature of the ocean surface is presented in table 2.

The failure rate and repair time of different components can be collected from the manufactures or the operators during the operation of the power plant. In table 3, these reliability data are given [1-7]. The equivalent failure rate and repair time are calculated based on Relations (14), (15) and (16). The availability and unavailability of the understudied power plant are calculated based on Relation (13) that are 0.86 and 0.14, respectively. The 6-state complete reliability model of OTEC power plant with capacity 30 MW is obtained with combining the 3-state model of table 2 with 2-state model arisen from failure of components (including full capacity with probability 0.86 and zero capacity with probability 0.14). With merging zero-capacity states, a 4-state model that is presented in table 4 is obtained for reliability modelling of understudied OTEC power plant. Based on the CVaR approach, the VaR and CVaR associated to the different values of alpha are calculated and presented in Fig. 14 to model the uncertainty nature of ocean temperature variation. It is deduced from this figure that the value of CVaR is higher than the VaR.

5.2 Adequacy assessment of RBTS

In this part, adequacy studies of RBTS containing understudied OTEC power plant are performed. The generation and reliability parameters of RBTS, with capacity 240 MW, including generation capacity, failure rate and repair time of the units are given in [44]. The load is modeled based on the load duration curve and is considered to be a straight line from maximum to
minimum hourly peak load. Three cases including original RBTS, RBTS containing a new 30 MW conventional unit with availability 0.95 and RBTS containing understudied OTEC unit are considered as cases 1 to 3, respectively to evaluate the effect of OTEC units on the adequacy indices of power systems. The \textit{LOLE} and \textit{EENS} of three cases considering the peak load are calculated and presented in Figs. 15 and 16, respectively. As can be seen in the figures, increasing the peak load results in the increasing of the \textit{LOLE} and \textit{EENS} indices, and so the reliability of power system gets worse. Although, the addition of a new generation unit improves the reliability indices, conventional units can improve the reliability indices more than OTEC units. It is arisen from the uncertainty nature of OTEC power plants that makes the generation capacity of the OTEC units due to the variation in the ocean temperature would be less than full capacity in the most times of the year. To clearly compare the OTEC units with conventional ones with the same capacity from reliability point of view, the \textit{PLCC} and \textit{IPLCC} are calculated based on the \textit{EENS} criteria and presented in Tables 5 and 6. To calculate the \textit{PLCC}, the peak load is increased as far as the \textit{EENS} of the system is less than the permissible value. As can be seen from these tables, addition of a new generation unit results in the increase in the capability of the power system to supply loads. However, due to the uncertainty nature of the OTEC units, the increase in the capability of the power system, with addition of conventional units, is more than the cases including addition of the same capacity OTEC power plants.

To study the effect of uncertainty nature of ocean temperature variation on the adequacy indices of the power system, in this stage, the reliability indices including \textit{LOLE} and \textit{EENS} considering different value of CVaR are calculated and presented respectively in Figs. 17 and 18. It is concluded from the figure that due to the variation in the ocean temperature, the effect of OTEC system on the reliability indices that is dependent on the temperature value is different. When, the ocean temperature is higher associated to the higher alpha, the generated power of OTEC system would be higher and consequently the \textit{LOLE} and \textit{EENS} of power system would be less.

\subsection*{5.3 Adequacy assessment of IEEE-RTS}

In this part, the IEEE-RTS with more generation capacity than RBTS is considered as a test system to evaluate the impacts of the OTEC units on the power system adequacy studies. The generation capacity and the reliability data of this system is given in [45]. The \textit{LOLE} and \textit{EENS} value considering different peak loads in three cases including original IEEE-RTS as case I, IEEE-RTS with a 30 MW conventional unit with 0.95 availability as case II and IEEE-RTS containing a 30 MW OTEC unit as case III are calculated and presented in Figs. 19 and 20, respectively. Also, the \textit{PLCC} and \textit{IPLCC} of these cases based on the \textit{EENS} criteria are calculated in tables 7 and 8. As can be seen in the figure and tables, addition of a new generation unit results in
improvement in the reliability indices. However, due to the uncertainty nature of the OTEC power plants arisen from the variation in the ocean temperature, OTEC power plant can less improve the reliability indices than conventional units with the same capacity.

5.4 Adequacy assessment of composite power system

In this part, based on the proposed technique, adequacy studies of the RBTS system as a composite power system are performed to evaluate the effect of OTEC systems on the reliability of composite power systems. In this study the transmission network of RBTS that is given in [44] is considered to the reliability computations. To evaluate the composite power system containing OTEC system, the contingencies associated to the simultaneous failures of up to 4 generation units, up to 3 transmission lines and up to 3 generation units and transmission lines are considered. Based on the proposed technique, the reliability indices of the composite RBTS are calculated and presented in Table 9. As can be seen in the table the reliability indices of load point 3 are very poor and so, the understudied OTEC unit is added to the RBTS system at this bus. The reliability indices of the RBTS integrated to the OTEC system is calculated and presented in Table 10. As can be seen in the table, addition of OTEC system to the load point 3 results in the improvement in the reliability indices of this bus.

6 CONCLUSION

In this paper for the first time integrating OTEC power plants to the power system from reliability point of view is investigated. For this purpose, a multi-state reliability model considering both failure of composed components and variation in the generated power arisen from the variation in the ocean temperature for these units is developed. For state reduction of the model, FCM clustering technique is applied and for determination the proper number of clusters, the XB index is implemented. The proposed multi-state model is used for adequacy studies of the power systems in presence of the OTEC power plants. It is deduced from the numerical results associated to the adequacy studies of RBTS and IEEE-RTS in presence of OTEC power plant that OTEC power plants can improve the reliability indices of the power system, however due to the uncertainty nature of these plants arisen from variation in the generated power, this improvement is less than the conventional generation units with the same capacity. The numerical results indicate that the CVaR models the uncertainty nature of ocean surface temperature and can be used in the renewable-based power systems to study the effect of variation in the generated power of renewable resources on the adequacy indices of the power system. It is deduced from the numerical results that the proposed technique effectively calculates the reliability indices. This analytical technique has smaller computational volume than numerical methods such as Monte Carlo and
does not have the problems of the simulation based approach such as low convergence speed, high computation time and large memory volume required.

**NOMENCLATURE**

**Symbols**

- $P_G$: produced power of generator
- $P_{WFP}$: the power needed for pumping working fluid
- $P_{WWP}$: the power needed for pumping warm waters
- $P_{CWP}$: the power needed for pumping cold waters
- $m_{WF}$: mass flow rate of the working fluid in kg/s
- $\eta_G$: generator efficiency
- $\eta_T$: turbine efficiency
- $h_1$: the enthalpy of evaporator outlet (turbine inlet)
- $h_2$: the enthalpy of condenser inlet (turbine outlet)
- $m_{WT}$: mass flow rate of working fluid
- $m_{WW}$: mass flow rate of warm water (ocean surface water)
- $m_{CW}$: cold water mass flow rate (water at 800-1000 meters deep)
- $g$: acceleration of gravity in m/s$^2$
- $h_{WF}$: total pressure difference associated to the working fluid
- $h_{WW}$: total pressure difference associated to the warm seawater
- $h_{CW}$: total pressure difference associated to the cold seawater
- $\eta_{WFP}$: efficiency of pumping of working fluid
- $\eta_{WWP}$: efficiency of pumping of warm water
- $\eta_{CWP}$: efficiency of pumping of cold water
- $Q_E$: the heat transfer rate of the evaporator
- $Q_C$: the heat transfer rate of the condenser
- $h_3$: enthalpy of the input of the working fluid pump
- $h_4$: enthalpy of the output of the working fluid pump
- $s$: entropy
- $x$: quality
- $\lambda$: failure rate of the components
- $\mu$: repair rate of the components
- $P_{up}$: the probabilities associated to up state
- $P_{down}$: the probabilities associated to down state
- $\lambda_{eq}$: equivalent failure rate
- $\mu_{eq}$: equivalent repair rate
- $r_{eq}$: equivalent repair time
- $C$: capacity
- $f$: fuzzy parameter
- $v_i$: center of the $i_{th}$ state
- $U_{ik}$: fuzzy degree between data $x_k$ and the $i_{th}$ state
- $P_f$: probability of failure of component

**ABBREVIATIONS**

- OTEC: Ocean Thermal Energy Conversion
- EENS: Expected Energy Not Supplied
- FCM: Fuzzy C-Means
- COPT: Capacity Outage Probability Table
- MCS: Monte Carlo Simulation
- VaR: Value at Risk
- CVaR: Conditional Value at Risk
- LOLE: Loss of Load Expectation
- LOLP: Loss of Load Probability
- XB: Xie-Beni
- PLCC: Peak Load Carrying Capability
- IPLCC: Increase in Peak Load Carrying Capability
- RBTS: Roy Billinton Test System
- IEEE-RTS: IEEE Reliability Test System
REFERENCES


Khodakhast Nasirian was born on April 24, 1984 in Kheirabad, a village of Shiraz, and received the Ph.D. degree in 2013 in electrical engineering, power field, from Shiraz University if Technology. He is currently the faculty member and also the head of the Islamic Azad University, Dariun branch, Iran. His main research interests are the power quality, power system reliability, smart grids, renewable resources and high voltage engineering.

Amir Ghaedi was born in 1984 in Kheirabad, a village of Shiraz, and received the Ph.D. degree in 2013 in electrical engineering, power field, from Shiraz University if Technology. He is currently the faculty member and also the head of the Islamic Azad University, Dariun branch, Iran. His main research interests are the power quality, power system reliability, smart grids, renewable resources and high voltage engineering.

Mehdi Nafar was born on April 24, 1979 in Marvdasht, Iran. He received his BS, MS and Ph.D. degrees in electrical engineering in 2002, 2004 and 2011 from PWIT University, Tehran, Iran and Amirkabir University of Technology (AUT), Tehran, Iran and Islamic Azad University, Science and research Branch, Tehran, Iran, respectively, graduating all with First Class Honors. He is an assistant professor of Electrical Engineering Department, Marvdasht Branch, Islamic Azad University, Marvdasht, Iran. He is the author of more than 50 journal and conference papers. His teaching and research interest include power system and transformers transients, lightening protection system of oil tank, reliability, renewable resources and high voltage engineering.

Figure captions:

Fig. 1. the structure of the closed cycle ocean thermal energy conversion (OTEC) power plant
Fig. 2. the temperature-entropy (T-S) diagram of the closed cycle ocean thermal energy conversion (OTEC) power plant
Fig. 3. the temperature of ocean surface of Hawaii in 2016
Fig. 4. the generated power of ocean thermal energy conversion (OTEC) power plants that utilizes from ammonia, R-22 and R-134a as working fluid
Fig. 5. series connection of composed components of closed cycle ocean thermal energy conversion (OTEC) power plants in reliability model
Fig. 6. two-state Marco model for each component
Fig. 7. Complete reliability model of closed cycle ocean thermal energy conversion (OTEC) power plants
Fig. 8. The concept of value at risk (VaR) and conditional value at risk (CVaR)
Fig. 9. The method to calculate the loss of load expectation (LOLE) and expected energy not supplied (EENS)
Fig. 10. The flowchart associated to the adequacy assessment of composite power system
Fig. 11. Histogram of generated power
Fig. 12. The Xie-Beni (XB) index associated to the generated power data
Fig. 13. Fuzzy number associated to the generated power associated to the clusters
Fig. 14. Value at risk (VaR) and conditional value at risk (CVaR) associated to the ocean temperature considering alpha
Fig. 15. The loss of load expectation (LOLE) considering peak load.
Fig. 16. The expected energy not supplied (EENS) considering peak load
Fig. 17. The loss of load expectation (LOLE) considering CVaR
Fig. 18. The expected energy not supplied (EENS) considering CVaR
Fig. 19. The loss of load expectation (LOLE) considering peak load.
Fig. 20. The expected energy not supplied (EENS) considering peak load

Table captions:

Table 1. thermodynamic properties of saturated ammonia [35]
Table 2. 3-state model of the ocean thermal energy conversion (OTEC) unit arisen from uncertainty nature of variation in the temperature of the ocean surface
Table 3. The Failure Rate and Repair Time of ocean thermal energy conversion (OTEC) power plant components
Table 4.4-state model of the ocean thermal energy conversion (OTEC) power plant
Table 5. the peak load carrying capability (PLCC) for Three Cases
Table 6. the increase in peak load carrying capability (IPLCC) for Cases II and III
Table 7. the peak load carrying capability (PLCC) for Three Cases
Table 8. the increase in peak load carrying capability (IPLCC) for Cases II and III
Table 9. Reliability indices of composite RBTS
Table 10. Reliability indices of composite RBTS integrated to the ocean thermal energy conversion (OTEC) unit at bus 3
Figures:

1. Schematic diagram of a seawater-based heat pump system.
   - Warm seawater discharge
   - Cold seawater at 1000 meters deep
   - Warm seawater of ocean surface
   - Working fluid vapor
   - Working fluid condensate
   - Turbine
   - Condenser
   - Generator
   - Pumps

2. Graph showing temperature (T) and entropy (s) relationships.
   - Points 1, 2, 3
   - Energies Qf, Qc, Pe
   - Temperatures Tc

3. Time series plot of temperature (°C) over time (days).
   - Temperature range 30 to 28
Closed cycle OTEC power plant reliability model

1- turbine
2- generator
3- electrical converter
4- control system
5- transformer
6- cable
7- main structure
8- mooring system
9- evaporator
10- condenser
11- working fluid pump
12- warm water pump
13- cold water pump
14- pipes

Fig. 4.

Fig. 5.

Fig. 6.

Fig. 7.
Fig. 8.

Fig. 9.

start
Develop a multi state model for each OTEC system
The OTEC systems are connected to the composite system with M load points
Determine the contingencies based on the multi-state model of OTEC systems and two-state model of conventional generation units and transmission lines
Reduce the number of contingencies to N using of the state selection method
Investigate the contingency k
Does it lead to load curtailment?
Run the load shedding program using of the linear programming
Determine the amount of lost load at each bus
k=k+1
No
k=N
Yes
Calculate the various indices for all load points
Stop

Fig. 10.
Fig. 15.

Fig. 16.

Fig. 17.
Tables:

Table 1.

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<tr>
<th>Temp. (°C)</th>
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<td>Spec. vol. v_f (m³/kg)</td>
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<td>Spec. vol. v_g (m³/kg)</td>
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<td>Enthalpy h_f (kJ/kg)</td>
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Table 2.

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Table 3.

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<td>Mooring system</td>
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