International Journal of Industrial Electronics, Control and Optimization © 2020 IECO
Vol. 3, No. 3, pp. 379-392, July (2020)

Spinning Reserve Scheduling in a Power System Containing OTEC Power Plants

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ABSTRACT

Ocean energy, as a renewable resource that covers a large area of the earth, is increasingly used for power generation in forms of wave, tidal and thermal. Ocean thermal energy conversion (OTEC) systems utilize from the difference between the temperatures of surface and deep water and drive a thermodynamic Rankine cycle to generate electric power. The generated power of these plants depends on the temperature of the surface water as warm source. Due to the variation in the temperature of ocean surface, the output power of the OTEC system frequently changes in the year. This uncertainty nature results in the variation in the generated power and so, integration of large-scale OTEC generation units to the power system is a challenging problem. Thus, new techniques must be developed to study the effects of these variable resources on the power system. In operation studies of power systems, the balance between generation and consumption is important and from reliability point of view, some spinning reserve must be scheduled to prevent load curtailment in the events such as forced outages of generation units, transmission lines and so on. In a power system containing large-scale OTEC power plants, the uncertainty nature of these plants must be considered in the reserve scheduling. Thus, for this purpose, a reliability model considering both failure of composed components and variation in the output power, is developed for OTEC units. To determine a suitable multi-state model for OTEC units, fuzzy c-means clustering technique and XB index are utilized. Then, the proposed multi-state model is used to determine spinning reserve value of a power system containing OTEC plants using of the modified PJM method. Numerical results associated to RBTS and IEEE-RTS present the effectiveness of the proposed technique for operation studies of power systems containing OTEC systems.

Article Info

Keywords:
Fuzzy C-means Clustering, Ocean Thermal Energy Conversion, Operation Studies, Reliability Evaluation, Spinning Reserve

Article History:
Received 2019-12-09
Accepted 2020-02-04

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
$\dot{m}_{WF}$	mass flow rate of the working fluid in kg/s
η_G	generator efficiency
η_T	turbine efficiency
h_1	the enthalpy of evaporator outlet (turbine inlet)
h_2	the enthalpy of condenser inlet (turbine outlet)
$\dot{m}_{WF}$	mass flow rate of working fluid
$\dot{m}_{WW}$	mass flow rate of warm water (ocean surface water)
$\dot{m}_{CW}$	mass flow rate of cold water (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
η_{WFP}	efficiency of pumping of working fluid
η_{WWP}	efficiency of pumping of warm water
η_{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

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h_4	enthalpy of the output of the working fluid pump
s	entropy
x	quality
λ	failure rate of the components
μ	repair rate of the components
P_{up}	the probabilities associated to up state
P_{down}	the probabilities associated to down state
T	lead time
UCR	unit commitment risk
λ_{eq}	equivalent failure rate
μ_{eq}	equivalent repair rate
r_{eq}	equivalent repair time
C	capacity
N_{ij}	the number of hours that transition from state i to state j
f	fuzzy parameter
v_k	center of the i_{th} state
U_{ik}	fuzzy degree between data x_k and the i_{th} state
Δt	time span
n	time steps
P_f	probability of failure of component

ABBREVIATIONS

OTEC	Ocean Thermal Energy Conversion
ARMA	Auto Regressive Moving Average
VOLL	Value Of Lost Load
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
ENS	Energy Not Supplied
FCM	Fuzzy C-means Clustering Method
COPT	Capacity Outage Probability Table
MCS	Monte Carlo Simulation
DG	Distributed Generation
PSO	Particle Swarm Optimization
XB	Xie-Beni
VAR	Voltage Ampere Reactive
PJM	Pennsylvania, New Jersey and Maryland
RBTS	Roy Billinton Test System
IEEE-RTS	IEEE Reliability Test System
ORR	Outage Replacement Rate

I. INTRODUCTION

In future power systems, because of the problems associated to the fossil fuels such as environment effects arisen from greenhouse gas emission, concerned about the end of these fuels, variable cost of them and so on, renewable resources would play a key role in the electric power generation. Among different technologies of renewable resources, ocean energy that covers a large area of the earth can be utilized to generate power in forms of waves, tidal and thermal. In the tropical areas, the temperature of the waters in the surface is about 20-30 ºC and the temperature of the waters at 800-1000 meters deep is about 4-5 ºC. The OTEC systems can use from this temperature difference and drive a thermodynamic Rankine cycle. In this cycle, it is utilized from the surface water as warm source and the waters at 800-1000 deep as cold source. A working fluid with low boiling point such as ammonia, R-22, R-134a, isobutene and so on can be used for electric power generation in this Rankine cycle. The generated power of the OTEC power plants is dependent on the temperature of the surface and deep waters. Due to the variation in the temperature of the ocean surface water, the generated power of the OTEC systems is variable. Thus, the integration of large-scale OTEC power plants to the power system affects different aspects of this power system such as reliability, dynamic, power quality, operation and so on. For this reason, new techniques must be developed to study the power systems containing large-scale OTEC power plants. In the past works, OTEC plants are investigated by many researchers. In [1], the principle of OTEC power plants, main components (including platform, mooring system, cold and warm water pipes, warm and cold water discharge pipes, heat exchangers, evaporator, condenser, pumps, turbine. generator, power cable and pipe interface) and some challenges of its application are illustrated. Then, using of the fault tree analysis, reliability of OTEC systems is evaluated. In [2] a new type of ocean energy system, i.e. water-electric power cogeneration, with higher efficiency and lower energy consumption than OTEC systems, is introduced. This proposed system is integrated from OTEC, wave and solar power generation systems. In [3] OTEC systems as advanced electric generation methodology is evaluated and different types, associated thermodynamic equations, composed components and the main limitations are illustrated. In [4] techno-economic assessment of different renewable resources including wave, tidal, OTEC and geothermal energies is performed. It is concluded from the paper, the global capacity of the ocean thermal energy is estimated to be 5000 GW and the cost of this technology is about 0.1-0.18 $/kwh. In [5] different types of OTEC systems, technical limitations and challenges, environmental considerations, economic considerations, market potential and related equations are illustrated. Also, a 5 MW pre-commercial hybrid OTEC power plant is designed. In [6] the constant sunlight and large littoral areas are introduced as two main factors needed for OTEC power plants that can be used to select the suitable site for these renewable resources. It is concluded from this paper that the efficiency of OTEC system is 6.84 percent and the costs of generated electrical power from wave, hydro, diesel and OTEC in the Pacific region are respectively 0.062-0.072, 0.113, 0.126 and 0.149 US $/kw. In [7] environmental assessment of OTEC systems in Hawaii is performed. In [8] development in the heat exchangers as one of the largest cost component in the OTEC system to maximize heat transfer per unit area and minimize pressure losses, corrosion and cost is illustrated. So far, according to the authors' information no significant work is done for spinning reserve scheduling of a power system containing OTEC power plants. However, due to the similarity between OTEC power plants and other variable

power generating resources such as wind farms, it can be utilized from the papers that studied operation of power systems containing wind turbines [9-12]. In [9], using of the Monte Carlo simulation method, the optimal amount of spinning reserve is calculated in a power system containing significant wind power generation. In this paper, the normal distribution is considered to model the error of wind power forecasting. In [10] the effects of large-scale wind farms on the power systems from reliability, cost and environmental points of view are evaluated. This paper utilizes from the time series associated to the observed and predicted average wind speeds with 15-min time spans. In [11] generation unit's outage rate and uncertainty nature associated to the load and wind power forecasts are taken into consideration to calculate the amount of the spinning reserve. For this purpose, the reliability of the power system is considered as the objective function to decide the amount of wind power penetration. It is concluded from the paper that increasing in the wind power penetration results in the increase of required spinning reserve. In [12] based on the historical wind speed data, an auto regressive moving average (ARMA) model is created as the optimal time series model to represent the variation in the wind speeds. Based on this model the important reliability indices such as loss of load expectation, loss of energy expectation and unit commitment risk are calculated to investigate the effect of wind farms on the increase in peak load carrying capability of the power system. In [13] optimal scheduling of a micro grid considering normal and emergency operation is performed. This micro grid is considered to equip with dispatch able distributed units, renewable resources and energy storages. In this paper, the uncertainties associated to the loads and renewable resources are considered in the model and the required reserve is calculated. In [14], economic risk function and load uncertainty are considered and a practical technique for planning reliability based maintenance is proposed in the distribution systems. Using of this method, the reliability of critical devices and system performance are improved and consequently the cost of utilities is reduced. In this paper, the cost associated to the failure of different elements (including overhead lines, underground cables and power switches) and value of lost load (VOLL) are calculated to evaluated the reliability of the system. In [15] reliability assessment of smart grids containing distributed generation resources considering self-healing is performed. In this paper, the effects of distributed generation resources on the reliability indices of smart grids are evaluated. For considering the uncertainties associated to the distributed generation resources, demand load change and system restoration time after the presence of DGs, Monte Carlo Simulation method is utilized and reliability indices such as SAIFI, SAIDI and ENS are calculated. In [16] symbiotic organisms search algorithm is utilized to optimally plan energy storage systems. In this paper, the location, power and capacity of the energy storage systems are determined with consideration of the economic (reduction of investment, operation and maintenance costs of the energy storage system) and technical (loss reduction and voltage profile improvement) aspects, simultaneously. In [17], crow search algorithm is utilized to simultaneously determine the optimal size and location of DGs and shunt capacitors in the radial distribution systems. The goal of this paper is to reduce the distribution system loss. In this problem, the constraints are limitation associated to the bus voltages, current passing of lines, active and reactive powers of DGs. In [18], optimal location and size of dynamic VAR devices are determined to improve short term voltage stability of the system considering high penetration level of wind power and dynamic load model. In this paper, the optimal location and size of static VAR compensator is determined so that the whole investment cost and also the undesirable behavior of transient voltage under multiple probable contingencies are minimized. In [19], control of islanded micro grid using of the particle swarm optimization algorithm is optimized. In this paper, PSO method is utilized to determine the controller parameters by minimizing the errors in the current and voltage controllers. In [20], reliability assessment of a step down DC/DC converter considering thermal effects is performed. In this paper, thermal modeling of temperature-sensitive equipment of these converters, i.e. power semiconductors including diodes and IGBTs is presented. Based on this model, the junction temperature of these elements is calculated to determine the associated failure rates. In [21], the impact of condition monitoring of circuit breakers on the reliability and maintenance cost of high voltage substations is studied. In this paper, a mathematical formulation is proposed to categorize and model failure of equipment considering their severity. By condition monitoring, some of major failures can be detected early and so they can be corrected as minor failures. Thus, this paper studies the effect of condition monitoring program on the outage rate and also predictive maintenance rate of the equipment. In [22], secondary voltage control in a hybrid micro grid containing multiple DC-AC-DC conversions is evaluated. In understudied hybrid micro grids primary and secondary controllers are proposed to compensate demand power fluctuations and control extra demand variations, respectively. By using of this control, the effects of demand fluctuations are eliminated and the system is stabilized. In [23], using of a multi objective particle swarm optimization algorithm, for a power system considering environmental pollution caused by fossil fuels, economic dispatch is performed. In this paper, the PSO algorithm is based on the Pareto criterion and fuzzy logic. It is deduced from the results that the operation and pollution costs with/without power loss are reduced significantly by the proposed technique. In [24], using of the improved artificial bee colony algorithm,

operation of hydrothermal units is optimized. In this paper, multi objective function including economic dispatch considering the valve-point effect and pollution function of power system considering hot water of the hydro system is minimized. The results obtained from the proposed method are compared with other methods including the genetic algorithm, the Basu technique and the improved genetic algorithm. It is deduced that the convergence of proposed method is fast. As can be concluded from the reviewed papers, so far, the operation studies of the power system containing OTEC power plants considering reliability criteria are not performed. To fill this gap, for the first time, reliability-based operation studies of the power system containing OTEC systems are performed in this paper. Thus, the contributions of this paper would be:

- Developing a reliability model for OTEC systems considering both failure of composed components and also variation in the ocean surface temperature.
- Determining optimal number of clusters in the reliability model of OTEC units considering variation of ocean temperature by minimizing XB index.
- Calculating the probability of different clusters using of the fuzzy c-means clustering technique.
- Determining required spinning reserve in a power system containing OTEC power plants using of the proposed technique based on the modified PJM method.

Based on the aims of this paper, it is organized as below: in the second section the principle of OTEC systems, different types of these renewable resources and related equations are illustrated. The PJM technique to study reliability-based operation of the power system is summarized in the third section. The proposed multi-state reliability model of OTEC power plants is developed in the fourth section and the modified PJM technique to consider the OTEC power plants in the spinning reserve scheduling of the future power systems is introduced at the end of this section. Numerical results of two well-known power systems i.e. RBTS and IEEE-RTS when new OTEC power plant is integrated to them are given in the fifth section and the required spinning reserve of these systems with considering the OTEC system effects is calculated. The conclusion of the paper is summarized in the sixth section.

II. OTEC Power Plants

Climate changes and earth warming are arisen from the greenhouse gas emission. These changes that are created from burning fossil fuels, result the global organizations make limitations to prevent gas emissions. Thus, many countries utilize from renewable resources such as wind, solar, ocean and so on to generate the required electric power. Due to the vast area of the oceans in the world, ocean generation power technologies including wave, tidal and ocean thermal energy conversion systems can play an important role in generation expansion planning of the modern power systems. In an OTEC system, it is utilized from the difference between ocean surface water and deep water temperature that this difference reaches about 20 ^{o}C. It can drive a thermodynamic Rankine cycle equipped to the working fluids with low boiling point and generate electric power. The temperature of the waters in the ocean surface is about 20-30 ^{o}C and it can be used as warm source. The temperature of 800-1000 deep water is about 4-5 ^{o}C and so, it can be used as clod source in the Rankie cycle. For utilization of this difference of temperature, three approaches can be used in the OTEC power plants: in the open cycle OTEC power plants, it is used from the seawater as working fluid. The water in the ocean surface is pumped into a flash evaporator with 0.03 bar pressure and this low pressure makes the water to boil at 22 ^{0}C. The generated steam expands through a low pressure turbine connected to a generator and it generates electric power. Then, the steam enters into the condenser containing cold water (seawater that is pumped from the depth of 800-1000 meters) to convert the steam into desalinized water. In the second type OTEC systems i.e. the closed cycle OTEC power plants, a working fluid with low boiling point such as ammonia or another type of refrigerant is utilized in a thermodynamic Rankine cycle. The working fluid is pumped to an evaporator containing the warm seawater that results the working fluid to vaporize. Then, the vapor expands through a turbine connected to the generator and generates the electricity. Then, the steam enters into a condenser containing the cold seawater that makes the steam is converted to the liquid. A hybrid cycle OTEC power plant as the third type of OTEC systems is a combination of closed and open cycle systems. In this power plant, similar to the closed-cycle method that occurs in a vacuum vessel, the fresh water is firstly flashed into steam. In the same vessel, the low boiling point working fluid is evaporated using of the heat exchanger containing ocean surface water as the warm source. Then, the working fluid is mixed with the surface seawater in a two-phase or two-substance mixture. After it, the evaporated working fluid is 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 makes the turbine to rotate and generate the electricity. In this paper, for operation studies of the power systems containing OTEC power plants, it is utilized from the closed cycle OTEC systems and for this purpose, the reliability model of this plant suitable for operation studies, is developed. In Fig. 1 the structure and main components of this power plant is illustrated. As can be seen in the figure, in close cycle OTEC systems, at first, the working fluid is pumped to the evaporator containing the surface water. Heat

transferring from the warm water to the working fluid makes it to vaporize. The generated vapor causes the turbine connected to the generator to rotate and produce electricity. The vapor of turbine outlet is condensed in the heat exchanger containing cold seawater that is pumped from the 800-1000 meters deep.

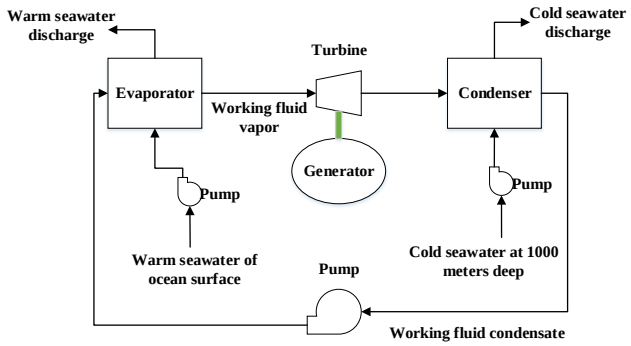


Fig.1. The main components of the closed cycle OTEC system.

In this part, the thermodynamic equations to calculate the generated power of the closed cycle OTEC systems based on the Rankine cycle are illustrated. The temperature-entropy (T-S) diagram associated to the Rankine cycle of the closed cycle OTEC systems is represented in Fig. 2. The Net generating power of OTEC power plants is calculated as:

$$P_N = P_G - P_{WFP} - P_{WWP} - P_{CWP} \quad (1)$$

Where, P_G is the produced power of generator and P_{WFP}, P_{WWP} and P_{CWP} are the power needed for pumping working fluid, warm and cold waters, respectively. The produced power of the generator connected to the turbine can be obtained as:

$$P_G = \dot{m}_{WF}\,\eta_G\eta_T\,(h_1 - h_2) \quad (2)$$

Where, $\dot{m}_{WF}$ is mass flow rate of the working fluid in kg/s, η_G and η_T are generator and turbine efficiencies, h_1 and h_2 are the enthalpies of evaporator outlet (turbine inlet) and condenser inlet (turbine outlet), respectively in J/kg. In the power generation process of the Rankine cycle, the turbine expansion is done in an adiabatic process with constant entropy.

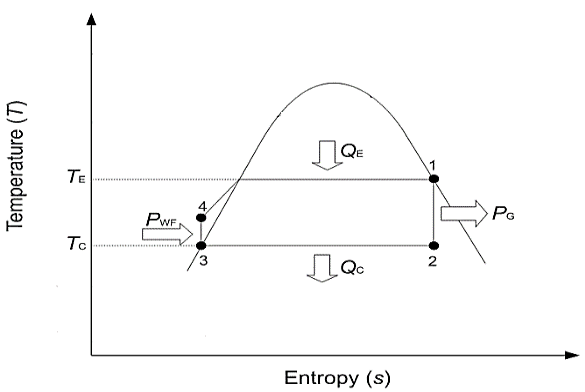


Fig.2. the T-S diagram of a Rankine cycle

The power needed to pump the working fluid, warm water and cold water are calculated as:

$$P_{WFP} = \dot{m}_{WF}\,gh_{WF}\,/\,\eta_{WFP} \quad (3)$$

$$P_{WWP} = \dot{m}_{WW}\,gh_{WW}\,/\,\eta_{WWP} \quad (4)$$

$$P_{CWP} = \dot{m}_{CW}\,gh_{CW}\,/\,\eta_{CWP} \quad (5)$$

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 800-1000 meters deep), g is acceleration of gravity in m/s^2, h_{WF}, h_{WW} and h_{CW} are total pressure difference (considered the difference in the height and friction of the pipes) associated to the working fluid, warm seawater and cold seawater, η_{WFP}, η_{WWP} and η_{CWP} are efficiencies of pumping of working fluid, warm water and cold water. The heat transfer rate of the evaporator (Q_E) and the condenser (Q_C) are calculated as:

$$Q_E = \dot{m}_{WF}\,(h_1 - h_4) \quad (6)$$

$$Q_C = \dot{m}_{WF}\,(h_2 - h_3) \quad (7)$$

Where, h_3 and h_4 are the enthalpies of the input and output of the working fluid pump, respectively. In addition to the (3), the power that is needed to pump the working fluid can be obtained as:

$$P_{WFP} = \dot{m}_{WF}\,(h_4 - h_3) \quad (8)$$

In this part, the ammonia is considered as the working fluid and the produced power of a closed cycle OTEC system is determined. Thermodynamic properties of saturated ammonia are presented in [25]. In table I, the thermodynamic characteristics of ammonia in temperatures between 20 to 26 ^{0}C including temperature, pressure, specific volume, enthalpy and entropy are presented.

TABLE I

THERMODYNAMIC CHARACTERISTIC OF SATURATED AMMONIA[25]

Temp. (°C)	20	22	24	26
Pressure (kPa)	857.6	913.8	972.7	1034.5
Spec. vol. v_f (m^3/kg)	0.001638	0.001646	0.001655	0.001663
Spec. vol. v_{fg} (m^3/kg)	0.1476	0.1387	0.1304	0.1227
Spec. vol. v_g (m^3/kg)	0.1492	0.1403	0.132	0.1243
Enthalpy h_f (kJ/kg)	294.3	303.9	313.5	323.1
Enthalpy h_{fg} (kJ/kg)	1185.7	1177.5	1169.2	1160.8
Enthalpy h_g (kJ/kg)	1479.9	1481.3	1482.7	1483.9
Entropy s_f (kJ/(kg °K)	1.3308	1.363	1.3951	1.4271
Entropy s_{fg} (kJ/(kg °K)	4.0446	3.9894	3.9347	3.8803
Entropy s_g (kJ/(kg °K)	5.3753	5.3524	5.3298	5.3074

It is considered that a closed cycle OTEC system is installed in the Hawaii. The 2016 hour to hour data associated to temperature of ocean surface in this region is presented in Fig. 3. For obtaining the generated power of the system 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. Thus, using of the thermodynamic table of

ammonia, the pressure, enthalpy and entropy of these two states can be determined. With considering state 1 in saturated vapor and state 3 in saturated liquid, in Rankine cycle of Fig. 2, $h_3=h_f$, $s_3=s_f$, $v_3=v_f$, $P_3=P_2$, $P_1=P_4$, $h_1=h_g$, $s_1=s_g$.

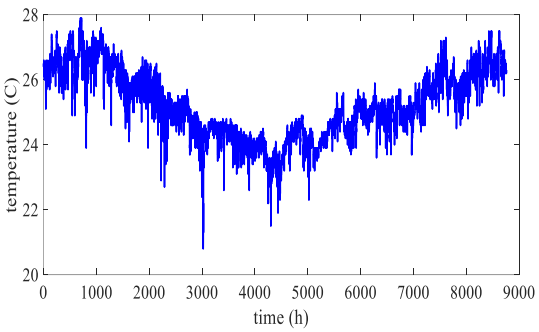


Fig.3. Temperature of water in ocean surface of Hawaii in 2016

Based on the adiabatic process of turbine expansion, $s_1=s_2$ and so the quality (x) of state 2 can be obtained as:

$$x=\frac{s_2-s_f}{s_{fg}}=\frac{s_1-s_3}{s_{fg}} \quad (9)$$

Thus, the enthalpy of state 2 can be determined as:

$$h_2=h_f+xh_{fg}=h_3+xh_{fg} \quad (10)$$

The needed power to pump working fluid, in kJ/kg can be obtained as:

$$p_{WFP}=h_4-h_3=v_3(P_4-P_3) \quad (11)$$

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

$$h_4=h_3+p_{WFP} \quad (12)$$

From the thermodynamic equations of the Rankine cycle Equs. (1) to (12), the produced power of a closed cycle OTEC system can be obtained. The produced power of OTEC power plants that utilize from ammonia, R-22 and R-134a as working fluid in 2016 is calculated and presented in Fig. 4. As can be shown in the figure, with the same mass flow rate, the OTEC power plant that uses from ammonia can generate the electric power about 6 times more than the OTEC power plant that utilizes from R-22 and R-134a. The produced power of OTEC power plants that utilize from R-22 and R-134a working fluids are approximately the same.

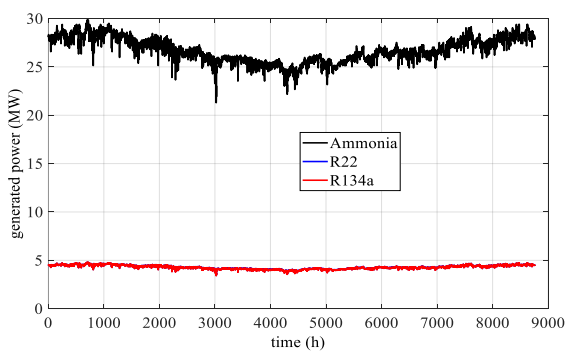


Fig.4. Generated power of OTEC power plants that utilizes from ammonia, R-22 and R-134a as working fluid

III. Operation Studies of the Power Systems Based on the PJM Technique

In this section, the PJM method, for reliability-based operation studies of the power system and spinning reserve scheduling are explained. Power system reliability is the ability of the power systems to supply the loads and it is composed of two aspects including adequacy and security. Power system adequacy is satisfied when adequate facilities in the generation, transmission and distribution sections are available to supply the loads. The power system security is the ability of the system to response to the different events such as sudden outage of the generation units or transmission lines and so on. In the operation phase of the power system, some spinning reserve must be considered in the system to response in the events when the generated power is less than the required loads and so with increasing the generated power associated to the spinning reserve, the balance between generation and consumption is satisfied. In the past, to determine the value of the spinning reserve, deterministic approaches (such as the spinning reserve is considered equal to the capacity of the largest online generation unit) are used that makes the power system more reliable (but not economic) or less reliable. In the PJM technique introduced for reserve scheduling in the power systems of Pennsylvania, New Jersey and Maryland, the value of the spinning reserve is calculated based on the unit commitment risk [26]. For determining the unit commitment risk, all conventional units are represented with two states (up and down) Marco model from reliability point of view as can be seen in the Fig. 5. In this model λ and μ are failure and repair rates of the components [26]. The probabilities associated to up and down states in long term studies can be determined as Equ. (13).

$$P_{up}=\frac{\mu}{\mu+\lambda},\ P_{down}=\frac{\lambda}{\lambda+\mu} \quad (13)$$

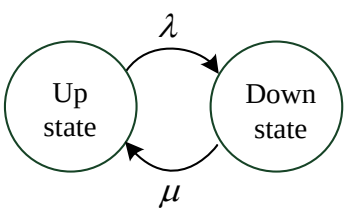


Fig.5. two-state Marco model for each unit

Due to the short time of operation studies of the power systems, the repair cannot be performed and so in this understudied short time, is known as lead time (T), the probability of down state or outage replacement rate (ORR) is:

$$P_{down}=ORR=\lambda T \quad (14)$$

Whit considering all generation units, the total capacity outage probability table (COPT) is constructed and comparing this model with the load model, the unit

commitment risk (UCR) is calculated as the summation of the probabilities of the states with lower capacity than load. In the PJM approach, to determine spinning reserve of the power system in a specific load, the generation units, based on the priority, are added to the system so that the UCR value is less than the permissible value. The spinning reserve is the difference between online generation capacity and the load.

IV. PROPOSED TECHNIQUE FOR OPERATION STUDIES OF THE POWER SYSTEMS CONTAINING, OTEC POWER PLANTS

In this section, the modified PJM approach is introduced to integrate OTEC power plants in the operation scheduling of the power systems. For this purpose, a multi-state reliability model of closed cycle OTEC systems considering both failure rate of composed components and the variation in the generated power arisen from the variation in the ocean surface temperature is developed. The main components of a closed cycle OTEC system are main structure, mooring system, warm and cold pipes, turbine, generator, evaporator, condenser, three pumps (for pumping working fluid, warm and cold water), electrical converter, control system, transformer and power cable. Failure of these components results the operation of the system is stopped and so the output power of the power plant would be zero. Thus, these components are series in the reliability model of the power plant as can be seen in Fig. 6. For considering two-state (up and down) Macro model for reliability modeling of each component of power plant, the equivalent reliability model of the OTEC system is obtained. The failure and repair rate of the OTEC power plant can simplicity be calculated based on the series components as Equ. (15) [26]. In Equ. (15) λ_{eq}, μ_{eq} and r_{eq} are equivalent failure rate, equivalent repair rate and equivalent repair time, respectively. The produced power of the OTEC power plants is dependent on the temperature of waters on the ocean surface and due to the variation in the surface water temperature as can be seen in Fig. 3, the produced powers are not fixed and vary with time as can be seen in Fig. 4. In this figure the produced powers of a 30 MW closed OTEC system uses from ammonia and two other working fluids that is installed in the Hawaii with temperature data associated to 2016, are given. As can be seen in the figure, the produced power of the power plant has numerous states that are not suitable for operation studies of the power systems. Thus, the states of the power must be reduced using of a suitable clustering method. The clustering techniques are categorized in two groups including hierarchical and partitioning clustering approaches. The partitioning clustering technique is divided into the K-means clustering, fuzzy C-means clustering, Gaussian expectation-maximization, K-harmonic means and hybrid 2 algorithms. Among these clustering methods, fuzzy C-means approach assigns each pattern to each cluster with some degree of membership (i.e. fuzzy clustering). This is more suitable for real applications where there are some overlaps between the clusters in the data set. FCM performs better than other clustering algorithms and it is less affected by the presence of uncertainty in the data [27]. Thus, due to the uncertainty nature of ocean surface temperature, this algorithm can be utilized 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. In this paper Fuzzy C-means clustering method is used for obtaining suitable value as center of clusters. Utilizing this robust technique, for a preset number of clusters, center of these clusters can be obtained. This technique categorizes object data $\mathbf{X}=[x_1, x_2,\ldots, x_n]$ into m fuzzy clusters minimizing the following objective function [28].

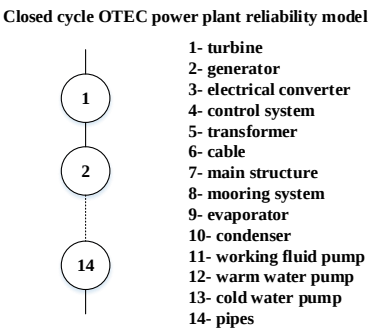


Fig.6. series connection of composed components of closed cycle OTEC systems in reliability model

$$\lambda_{eq}=\sum_{i=1}^{14}\lambda_i,\ r_{eq}=\frac{\sum_{i=1}^{14}\lambda_i r_i}{\lambda_{eq}},\ \mu_{eq}=\frac{1}{r_{eq}} \tag{15}$$

$$J_m(U,v)=\sum_{i=1}^{m}\sum_{k=1}^{n}U_{ik}^{f}\left|x_k-v_k\right| \tag{16}$$

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. To obtain the optimal number of clusters, different indices such as 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) [29-30] and approaches such as using the Information Theoretic Criterion have been implemented [31]. Due to the frequent applications of XB index in different reviewed papers for determining suitable number of clusters, in this paper the XB index is utilized for obtaining the optimal number of clusters in the reliability model of OTEC power plant which is obtained when XB is minimal. For obtaining suitable number of clusters, XB index is

calculated as [32]:

$$XB = \frac{J_m(U,v)}{n \times \min_{i \neq j}(\left|v_i - v_j\right|^2)} \quad (17)$$

The optimal number of clusters is obtained when XB index is minimal. Applying the generated power associated to historical data as the input data of FCM, the number and probabilities of appropriate clusters, which represent the suitable states associated to the OTEC system, can be obtained. When the clustering method results in *h* clusters, the complete reliability model of a closed cycle OTEC system is concluded as can be seen in Fig. 7. As can be seen in the figure, the number of states in the reliability model is 2h. The states in the upper row (states from 1 to h) are resulted from the clustering. The related capacities and associated probabilities of these states are calculated based on the FCM technique. If the failure of composed components of the OTEC power plant is occurred, the transition between upper states to the associated downer states with zero capacity is occurred. The states with zero capacity can be merged and a reliability model with *(h+1)* states can be resulted.

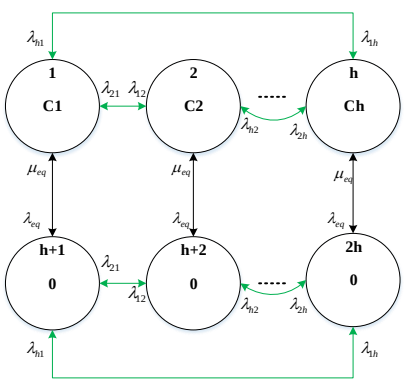


Fig. 7. Complete reliability model of closed cycle OTEC power plants

Due to the short time of operation studies, it is neglected from the repair in the reliability model and so, the complete reliability model of OTEC power plants suitable for operation studies is represented in Fig. 8.

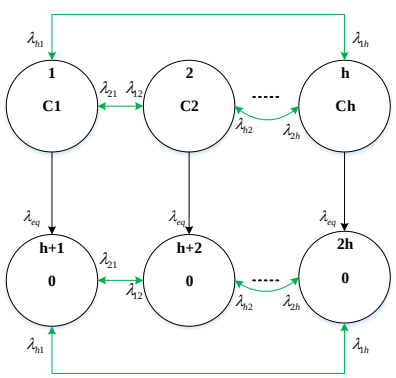


Fig. 8. Complete reliability model of closed cycle OTEC power plants suitable for operation studies of the power systems

As can be seen in the figure, it is neglected from the repair and so only the transition from upper states to the associated downer states due to the failure of composed components is occurred. In this part, the PJM method is modified to consider the multi-state OTEC power plants in reserve scheduling of the power systems. Based on the hour to hour historical temperature data and consequently power data, stochastic transitional probability matrix associated to the different clusters (per hour) is obtained as:

$$[P] = \begin{bmatrix} N_{11} & N_{12} & \dots & N_{1h} \\ N_{21} & N_{22} & \dots & N_{2h} \\ \dots & \dots & \dots & \dots \\ N_{h1} & N_{h2} & \dots & N_{hh} \end{bmatrix} \quad (18)$$

Where, N_{ij} is the number of hours that transition from state i to state j is occurred. In the beginning of the study, the initial temperature of the ocean surface is specified and so the initial matrix associated to the probability of different clusters i.e. [P(0)] can be determined. To determine the probabilities of different clusters associated to the lead time T, this time is divided to n time steps with Δt time span (T=nΔt). Thus, these probabilities can be calculated based on the matrix multiplication technique as (19).

$$[P(t)] = [P(0)][P]^n \quad (19)$$

The stochastic transitional probability matrix for Δt time span can be obtained as Equs. (20) and (21).

$$[P] = \begin{bmatrix} 1-(\sum_{i=2}^{h}\lambda_{1i})\Delta t & \lambda_{12}\Delta t & \dots & \lambda_{1h}\Delta t \\ \lambda_{21}\Delta t & 1-(\sum_{i=1,i\neq 2}^{h}\lambda_{2i})\Delta t & \dots & \lambda_{2h} \\ \dots & \dots & \dots & \dots \\ \lambda_{h1}\Delta t & \lambda_{h2}\Delta t & \dots & 1-(\sum_{i=1,i\neq h}^{h}\lambda_{hi})\Delta t \end{bmatrix} \quad (20)$$

$$\lambda_{ij} = \frac{N_{ij}}{\sum_{k=1}^{m} N_{ik}}, i \neq j \quad (21)$$

V. NUMERICAL RESULTS

In this section the modified PJM method is used for spinning reserve scheduling of the RBTS and IEEEE-RTS considering the effects of closed cycle OTEC systems. The produced power of 30 MW closed cycle OTEC system equipped to the ammonia as working fluid is given in Fig. 4. The histogram of the powers is determined and represented in Fig. 9. With consideration the appropriate values for different parameters as [33-35], FCM is applied to the produced power data and from the XB index as can be seen in Fig. 10, it is concluded that 3 clusters can model the produced power of understudied OTEC system. In Fig. 11, the fuzzy number of different produced power data related to each cluster is presented. As can be seen in this figure, all data are concentrated around the resulted clusters and so, the FCM

successfully models all produced power with these three clusters.

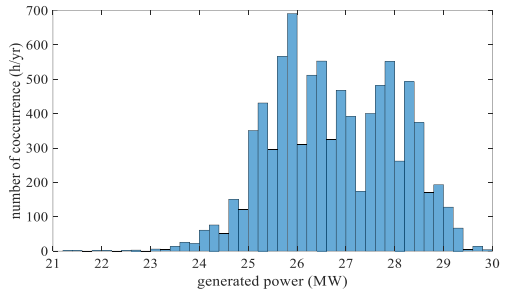


Fig. 9. Histogram of produced power

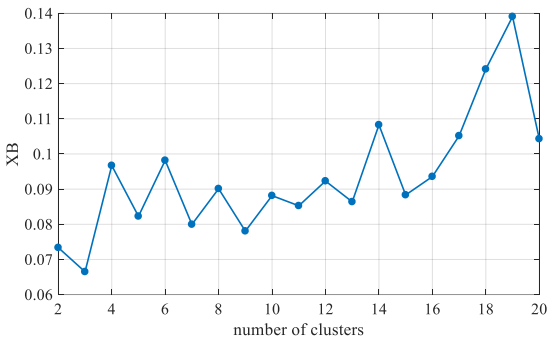


Fig. 10. XB index related to the produced power data

The 3-state reliability model of the OTEC system arisen from uncertainty nature associated to the variation in the temperature of the ocean surface is presented in table II. The reliability parameters of main components can be collected from the manufactures or the operators (during the operation of the power plant and based on the recorded failure data). In table III, these reliability data are presented. The equivalent failure rate is calculated from Equ. (15). The complete reliability model of the understudied OTEC power plant with 6 states is obtained with combining the 3-state model of table II with 2-state model associated to the failure of components. The stochastic transitional probability matrix of this plant (in occurrence per 10 minutes) is calculated and presented as Equ. (22). The flowchart associated to the spinning reserve determination of a power system in presence of OTEC power plants is drawn in Fig. 12. It comprises of determining multi-state reliability model of OTEC plats considering both failure of composed components and variation in the generated power, commitment the conventional generation units in the system based on the priority order of them, construction total COPT of the system, calculation the UCR index and finally obtaining the amount of spinning reserve with satisfying the permissible UCR index.

$$P = \begin{bmatrix} 0.9659 & 0.0335 & 0.0003 & 0.0003 & 0 & 0 \\ 0.0305 & 0.9682 & 0.0011 & 0 & 0.0003 & 0 \\ 0.0055 & 0.0199 & 0.9744 & 0 & 0 & 0.0003 \\ 0 & 0 & 0 & 0.9662 & 0.0335 & 0.0003 \\ 0 & 0 & 0 & 0.0305 & 0.9684 & 0.0011 \\ 0 & 0 & 0 & 0.0055 & 0.0199 & 0.9746 \end{bmatrix} \quad (22)$$

TABLE II

3-STATE MODEL OF THE OTEC SYSTEM ARISEN FROM UNCERTAINTY NATURE OF OCEAN SURFACE TEMPERATURE VARIATION

Capacity (MW)	25.3	26.6	28.2
Probability	0.3619	0.3009	0.3372

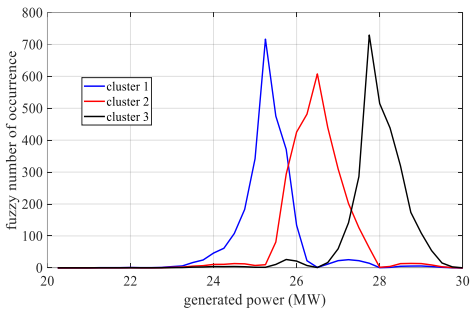


Fig. 11. Fuzzy number of the generated power associated to the clusters

TABLE III

THE FAILURE RATE OF THE OTEC POWER PLANT COMPONENTS

component	Failure rate (occ.yr)
Main structure	2
Mooring system	2
Pipes	2
Turbine	0.5
Generator	0.5
Evaporator	1
Condenser	1
Working fluid pump	1
Warm water pump	1
Cold water pump	1
Electrical converter	0.2
Control system	0.2
Transformer	0.5
Cable	1
total	13.9

To compare the proposed approach with the other methods, Monte Carlo Simulation (MCS) technique is introduced in this part to calculate UCR of the power system containing OTEC units. This method is summarized as below:

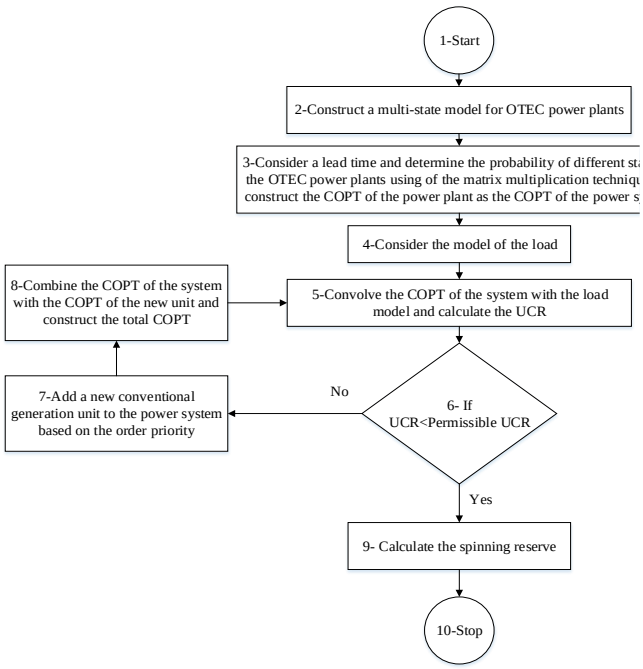
1- For the OTEC units, based on the failure rate of different composed components and the lead time, the probability of failure of component (P_f) in the associated lead time is calculated as Equ. (14).

2- For each component, a random number is generated. If the generated number be in [0, Pf], the components is down.

3- Based on the state of the components (up or down), the state of the OTEC unit is determined.

4- The initial temperature of the ocean surface is known. Based on the transitional probability matrix, the probability of transition from initial state to other states is known. A random number is

generated in this stage and the ocean surface temperature in the desired lead time is determined.



Flow chart for Construction a multi-state model for OTEC power plants

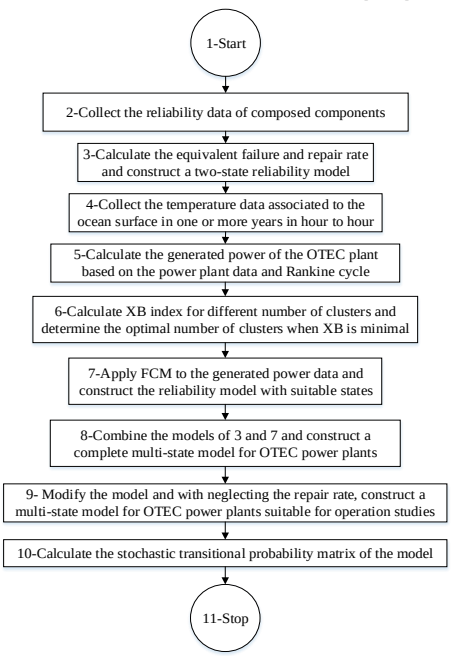


Fig. 12. Flowchart for determining spinning reserve value in the power system containing OTEC power plant

5- Based on the results from 3 (up or down state of the OTEC unit) and 4 (the ocean surface temperature in the desired lead time), the output power of OTEC unit in the desired lead time is calculated.

6- In the desired lead time, for other conventional units a random number is generated and based on the associated failure rates, the state (up or down) of them is determined.

7- In the desired lead time, total generation power of the generation system including OTEC units (based on 5) and conventional units (based on 6) is calculated.

8- With convolving the value of load and the capacity of generated power, the condition of this state (supplying the load or load curtailment) is determined.

9- The simulation is repeated for a suitable number of iterations.

10- The UCR is calculated by dividing the number of load curtailment states to the total number of iteration

Some advantages and drawbacks of the proposed method in comparison with the Monte Carlo Simulation approach are given in table IV.

TABLE IV
ADVANTAGES AND DRAWBACKS OF THE PROPOSED METHOD IN COMPARISON WITH THE MCS APPROACH

Advantages	Drawbacks
It requires less computation time.	The dimension of STPM in the region with high variation is large.
It requires less memory capacity.	The dimension of COPT in large power systems is large.
It is suitable for operation studies with short time.	It is difficult to consider variation of ocean temperature associated to time sequence.
The impact of different components failure on the operation indices can be studied.	In the power systems containing OTEC power plants and other renewable resources such as wind and solar, MCS method is more appropriate.

In this part, operation studies of Roy Billinton test system (RBTS) containing understudied OTEC power plant are performed. The generation and reliability parameters of RBTS, with 240 MW installed capacity including generation capacity, priority order, failure rate and repair time of the units are given in [36]. Due to the short time of study, the load is considered to be constant. Four cases including original RBTS, RBTS containing a new 30 MW conventional unit with failure rate 5 failures per year, RBTS containing understudied 30 MW OTEC unit with initial high ocean surface temperature and the RBTS containing understudied 30 MW OTEC unit with initial low ocean surface temperature are considered as cases 1 to 4, respectively to investigate the effect of OTEC power plants on the operation indices of power systems. The UCR associated to these four cases in lead time 1h considering peak load are calculated and represented in Fig. 13. As can be seen in the figure, increasing the peak load results in the increasing the unit commitment risk and consequently, the reliability of the

system get worse. Although addition a new generation unit makes reduction in the unit commitment risk, however, the conventional units can reduce the risk more than OTEC units with the same capacity. It is arisen from the uncertainty nature of OTEC power plants. Due to the variation of ocean temperature, in more times of the year, the generation capacity of these power plants is less than full capacity. Based on the figure, it is concluded that the initial temperature of the ocean surface affects the reliability performance of the power system containing OTEC units. The OTEC generation units with high ocean surface temperature can more reduce the unit commitment risk of the power system than the OTEC units with less ocean surface temperature.

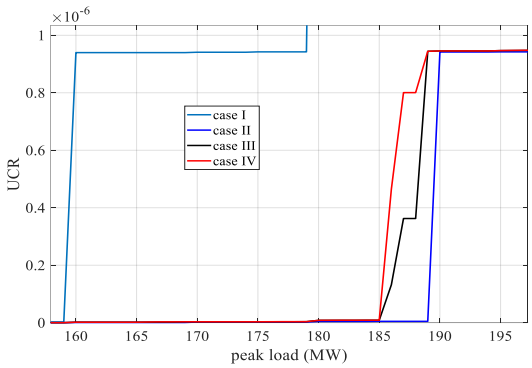


Fig. 13. UCR considering peak load.

For comparison the proposed method with MCS approach, the UCR of RBTS containing understudied OTEC unit with initial high ocean surface temperature (case III) considering different peak loads is calculated using of two methods. The results considering lead time 1h are given in table V. As can be seen in the table, the results from proposed method and MCS approach are very close together. However, increase in the number of iterations in the MCS method, results in the more accurate UCR values. In this part, the scheduled generation capacity and the required spinning reserve of the original RBTS as case I and RBTS containing understudied OTEC unit as case II, for two UCR levels i.e. UCR=0.002 as high risk level and UCR=0.00001 as low risk level, are calculated and represented in Figs. 14 and 15, respectively. The lead time of this study is considered to be 1h. As can be seen in the figures, to reduce the unit commitment risk, more generation capacity and consequently more spinning reserve must be scheduled in the power system. Addition a new OTEC generation unit to the power system results in the reduction of the scheduled generation capacity. This capacity must satisfy the reliability criteria (UCR index). Thus, the required spinning reserve of the power system that is provided by the conventional units reduced too. In this part, the IEEE-RTS with more generation capacity than RBTS is examined as a large test system to investigate the impacts of OTEC power plants on the power system operation studies. The generation capacity and the reliability data of this system is illustrated in [37]. The unit commitment risk value considering different peak loads associated to four cases including original IEEE-RTS as case I, IEEE-RTS with a 30 MW conventional unit with 5 failures per year as case II, IEEE-RTS containing a 30 MW OTEC power plant with high initial ocean surface temperature as case III and IEEE-RTS containing a 30 MW OTEC power plant with low initial ocean surface temperature as case IV is calculated and represented in Fig. 16 for lead time 1h. As can be seen in the figure, addition of a new generation unit results in the reduction of UCR. However, due to the uncertainty nature of the OTEC power plants arisen from the variation in the ocean surface temperature, OTEC power plant can less reduce the UCR than conventional units with the same capacity. It is also deduced from the figure that initial temperature of ocean surface affects the modified UCR values when a new OTEC power plant is added to the power system. As can be seen in the figure, addition the OTEC power plants with high initial ocean surface temperature results in more reduction of UCR index than addition of the OTEC units with less initial ocean surface temperature. Thus, it is recommended that the OTEC power plants must be constructed in the tropical regions with high ocean surface temperature to enhance the reliability performance of the power systems.

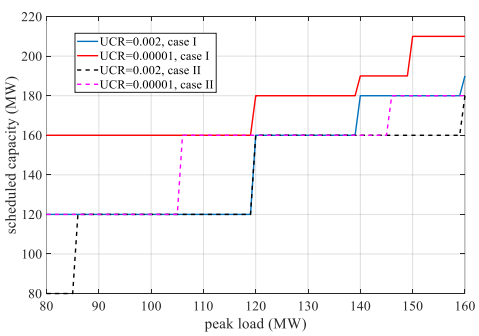


Fig. 14. Scheduled capacity considering peak load.

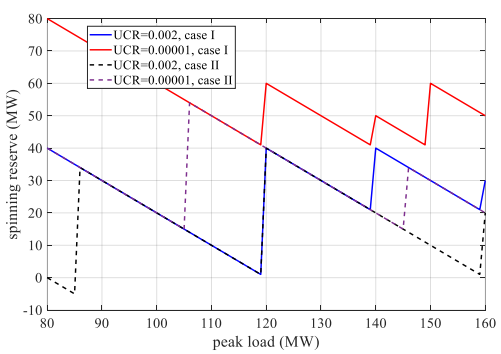


Fig. 15. Spinning reserve considering peak load.

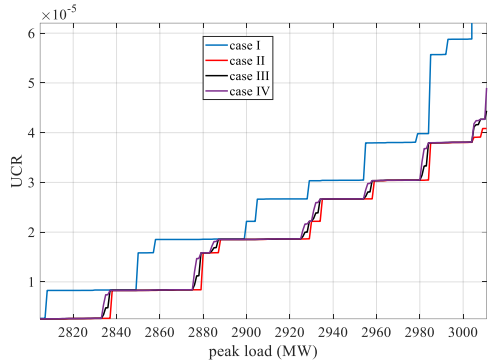


Fig. 16. UCR considering peak load.

TABLE V
UCR VALUE, COMPARISON BETWEEN PROPOSED METHOD AND MCS TECHNIQUE

Peak load (MW)	UCR from proposed method	UCR from MCS method with 10^{11} iterations	%error	UCR from MCS method with 10^{12} iterations	%error
160	1.66e-09	1.91e-09	15.0	1.71e-09	3.0
170	3.23e-09	3.49e-09	8.0	3.29e-09	1.9
180	8.21e-09	8.58e-09	4.5	8.27e-09	0.7
190	9.46e-07	9.97e-07	5.4	9.52e-07	0.6
200	3.68e-06	4.02e-06	9.2	3.77e-06	2.4

VI. CONCLUSION

In this paper for the first time operation studies of the power systems containing closed cycle OTEC power plants are performed. Based on the reliability criteria, i.e. unit commitment risk index, the appropriate amount of spinning reserve is obtained. For this purpose, a multi-state reliability model taking into account both failure of main components and variation in the produced power arisen from the variation in the ocean surface temperature for these units is developed. It is deduced from the reliability model, that failure of each critical component results in the failure of plant and so from reliability point of view, all components are series in the reliability model of OTEC power plant. The variation of ocean surface temperature results in the numerous states in the generated power of OTEC units. For state reduction of the reliability model, fuzzy C-means clustering approach is utilized and for obtaining the proper number of clusters, the XB index is applied. By minimizing the XB index, the number of states in the proposed model is optimal and using of the fuzzy C-means clustering technique, the probabilities of clusters is determined. The proposed multi-state reliability model is modified and with neglecting the repair rate in the model, a multi-state reliability model suitable for operation studies is resulted. Based on the modified PJM method and using of the matrix multiplication technique the probabilities of different states of the multi-state reliability model of OTEC power plant are calculated. With construction the total COPT of the power system important indices such as unit commitment risk are determined. Then, the amount of the required spinning reserve of the power systems in presence of the OTEC power plant is determined based on the unit commitment risk criteria. It is concluded from the numerical results associated to the operation studies of RBTS and IEEE-RTS in presence of closed cycle OTEC power plant that OTEC units can reduce the unit commitment risk and the amount of the required spinning reserve. The effect of OTEC power plant on the reliability-based operation indices is dependent on the initial temperature of the ocean surface. Higher temperature of ocean surface results in more difference between temperatures of warm and cold sources in the Rankine cycle and consequently the generated power of the OTEC plant is more. Thus, the OTEC power plants with higher initial temperature can more improve the reliability-based indices of the power system. However due to the uncertainty nature of these plants arisen from variation in the ocean surface temperature and consequently variation in the generated power, the improvement in the reliability-based operation indices is less than the conventional generation units with the same capacity. To verify the effectiveness and accuracy of the proposed approach, a comparison is performed between this method and Monte Carlo Simulation technique. It is deduced from this comparison that the proposed approach with good accuracy can calculate the reliability-based operation indices of a power system containing OTEC power plants.

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