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Research Article

Reliability Evaluation of Power Systems Including Pumped-Storage Generation Units

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Abstract: In recent years, the energy storage systems are increasingly used in the power systems to store the electricity when the generated power is more than the required load. The advantages of the energy storage systems in the power system include, improved reliability, energy storage in non-peak times and production in peak times that results in the peak reduction of the power system, store at the time of cheap electricity price and generate at the time of high electricity price, and storage of the surplus production capacity of renewable energy resources such as wind turbines and photovoltaic systems that their production is not controllable. Among different energy storage systems, pumped-storage generation units can be integrated into electricity networks with high-energy storage capacity and no environmental effects. For this purpose, in this research, adequacy assessment of power system including pumped-storage generation units is studied. At first, the paper develops a reliability model for these energy storage systems considering failure of composed components including motor-generator, pump-turbine, control, protection and measurement systems, turbine housing, water channel, up and down reservoir and transformer. To consider effect of pumped-storage generation plants on reliability of power system, load duration curve of system is modified. Then, the proposed model is implemented for assessing adequacy of power systems considering effect of generation and transmission networks using analytical method through contingency analysis technique. To study the effectiveness of suggested reliability model, numerical results related to reliability assessment of RBTS and IEEE-RTS are presented. It is concluded from numerical outcomes that pumped storage power plants can improve reliability indices of power system. Integration of understudied pumped storage generation unit into RBTS, system load can increase up to 15 MW.

Keywords: Contingency analysis, load duration curve, pumped-storage power plant, reliability, transmission system.

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1. Introduction

When power system is operated, generated power should be equal to required load for setting frequency of electricity generated within the allowable range. If generated power is more than required demand, frequency of generated electricity increases and so some of generated power of the conventional power plants should be reduced, or generated power of renewable generation units such as photovoltaic systems and wind farms should be wasted. If generated power of power system is less than required load, some of loads must be curtained. To solve this problem, energy storage devices can be used in power systems to store surplus generated power from power plants, especially renewable resources whose output is not controllable. These stored energies can then be used during times when generated power is less than the required load. This leads to a reduction in power fluctuations in the system. Other benefits of the energy storage systems in power system include: reliability of power system is increased, energy storage systems can store the electricity at low costs during off-peak times and sell at high costs during peak times, which are both economically viable and lead to peak reduction of the power system. Among different energy storage systems including batteries, capacitors, water electrolysis device -hydrogen tank- fuel cell system, flywheels, compressed air system, super magnets and pumped-storage systems, pumped-storage generation units can be integrated into power system with high-energy storage capacity. For this purpose, in the current research, impact of pumped-storage generation plants on power system reliability is examined.

For studying impact of pumped-storage systems on different aspects of power system, many researches have been performed. In [1], scheduling plan of a system containing wind units, photovoltaic system and pumped-storage generation unit is performed. In the proposed system, penetration level of renewable energies especially pumped-storage plant is significant and its voltage is extra high level. This paper studied different uncertainties including generated power of wind and photovoltaic units and operating range constraint related to pumped-storage units. Paper [2] proposes an approach for energy management of a hybrid system including wind turbines and pumped-storage generation unit to evaluate economic aspect related to this device. This paper studies economic feasibility related to integration a wind unit into a system containing a pumped-storage generation unit to convert existing system to hybrid system composed of wind and hydro power plants. Paper [3] studies a pumped-storage generation unit with variable speed to determine required reserve of system. To this end, mixed-integer linear programming method considering energy loss of power electronic converters is proposed. Paper [4] studies different electrical converters utilized in pumped-storage generation units with variable speed, especially partial-scale converters used in double fed induction machines. In this research, the topologies, problems and future development of these devices are investigated. In [5], pumped-storage generation plant is used for maximizing generated energy of wind farms in the power systems with transmission constraints. In this paper, transmission congestion and wind power curtailment arisen from mismatch of wind unit and required load are considered. For minimizing the wind power curtailment, pumped-storage generation unit is proposed in the paper. In [6], the characteristics of double fed pumped-storage generation unit with variable speed are performed. This technology is applied to regulate the grid power fluctuations arisen from the renewable resources. In this paper, topology of double fed pumped-storage generation plant is introduced and mathematical presentation associated to plant components is developed. Paper [7] studies operation of pumped-storage generation units at short-circuits conditions. To this end, this paper proposes mixed integer programming method to study the plant at short circuit conditions. Paper [8] studies dynamic characteristics of islanded power systems equipped to pumped-storage generation plants with high penetration level of renewable energies. In the research, understudied pumped-storage generation unit is equipped with Pelton turbines and pumps with fixed speed. In [9], current status of pumped-storage generation units installed in China are studied. In this research, different advantages of these systems are reviewed. In [10], a chronological production simulation platform used for planning of pumped-storage generation plants in power system containing wind units is described. In this research, a unit commitment module is used to simulate daily dispatch related to different kinds of plants, and then, a simulation of the wind farms operation is interconnected to the unit commitment module to consider its variability impact on daily dispatch program. Paper [11] performs a feasibility study to construct a pumped storage generation plant using abandoned mines. In this research, the natural conditions, mine conditions, safety conditions, economic benefits, resource utilization, ecological restoration and population resettlement of pumped storage plant constructed using Shitai mine are investigated. In [12], multi-method combination site selection of pumped storage generation unit is performed, taking into account the power structure optimization. In this paper, a systematic assessment index system of pumped storage generation unit site selection is developed from power grid expansion planning, economic and environmental benefits, hydrological, topographical, and geological and construction conditions. Paper [13] presents nonlinear modeling and operation stability of pumped storage generation unit based on the variable speed technology. For this purpose, basic equations of variable speed pumped storage power plant are developed. To determine dynamic response of variable speed pumped storage power plant, nonlinear state equation in the form of reactive deviation value considering supplementary conditions is derived. In [14], influencing factors associated with modification potential of abandoned coal mine into pumped storage generation unit is analyzed. According to the principle of pumped storage power plant and the characteristics of coal mine roadway conditions, an analytical hierarchy process is utilized in this paper to assess the main influencing factors including elevation difference between the upper and lower basins, basins capacity, roadway surrounding rock stability, and roadway permeability. Paper [15] presents the prospect of new pumped storage generation unit. In this paper, a new type of pumped storage power plant based on the variable speed technology with faster response speed, wider regulation range and better stability is proposed. Paper [16] studies developments and characteristics of pumped storage generation units constructed in China. In this paper, the current development status of the pumped storage generation unit in some different countries, especially in China, based on their own economic loads and network characteristics are introduced. In [17], the operation of pumped storage generation unit is optimized to boost the absorbability of power grid to the renewable energy. In this research, a novel optimization operation framework for a pumped storage generation unit driven by peak-shaving and valley-filling operation is proposed to boost the power system absorbability to renewable energy inputs. Paper [18] analyzes the coupling mechanisms of the pumped storage generation unit and the eco-environment. For this purpose, the fuzzy comprehensive assessment of the cloud model is established, and the economic model is used to evaluate the influence factors. Paper [19] performs an optimal dispatching of a power system containing wind turbines, photovoltaic systems and mine pumped storage generation units. In this paper, the pumped storage generation units are considered to be utilized from Lingxin coal mine located in Ningxia province of China. The genetic algorithm-dog log optimization method is utilized to minimize the operation cost of the system based on the underground reservoir of mine. In [20], load frequency control of pumped storage generation unit is performed based on the second-order linear active disturbance rejection control strategy. In this paper, the load frequency model of the two-area reheats steam turbine under nonlinear conditions such as governor dead zone and generation rate constrains is developed.

In the current research, reliability assessment of power systems containing pumped-storage generation plants, considering impact of transmission network, is performed. To this end, the contributions of the research would be as follows:

- Reliability modeling of pumped storage power plants considering failure of composed components is performed.
- A new technique based on the load duration curve modification is introduced for reliability analysis of the power system containing pumped storage power plant.
- Reliability assessment of power system containing pumped storage power plant in HLI and HLII is performed.

According to the aims of the paper, its organization would be as follows: in the second section, structure of pumped-storage generation plants is described. In third section, reliability model of these units is developed, and section four studies adequacy of the power system containing pumped-storage generation plant. Adequacy assessment of RBTS and IEEE-RTS including pumped-storage power plants are presented in 5th section. The last section of the paper is devoted on the research conclusion.

2. Pumped-Storage Power Plants

Fig. 1 presents topology of a typical pumped-storage generation unit. Pumped-storage generation plant includes the lower and upper reservoirs that are usually found naturally in nature and if these reservoirs want to be made artificially, they have to cost a lot. A channel called the penstock is made to transfer the water between lower and upper reservoirs. When the generated power exceeds the required load during off-peak times, the cost of electricity is cheaper, and the generator-motor machine acts as a motor, consuming the excess electricity. In this condition, water moves from lower basin to upper basin by pumping. If the generated power is less than the required load during peak times, the cost of electricity increases, prompting the release of water from the upper basin to rotate the turbine. Thus, turbine and consequently generator turns to generate electricity. Generated power is transmitted to the main grid using of the transformer.

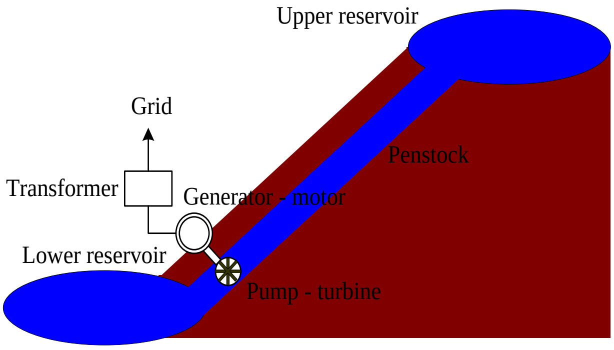


Fig. 1: The structure of pumped-storage generation plant

Thus, main components of a typical pumped storage generation units are upper and lower reservoirs, the penstock, turbine house, pump – turbine, motor – generator, control-protection and measurement systems and transformer. The pump – turbine and the generator – motor can be a single device that they can be rotated in two directions. It is possible to use from the independent motor and generator, and also independent pump and turbine in the pumped-storage power plants. Different electrical and mechanical losses including the friction of the penstock wall, the friction of the pump, the copper and the stray losses of motor lead the efficiency of the pumped-storage power plant to be less than 100% and so, the electrical power consumed by the motor for pumping water from lower reservoir to upper basin is more than power generated by generator.

3. Reliability Model of Pumped-Storage Generation Plants

This section develops a reliability model for pumped storage generation plants considering failure of composed components. All components of pumped-storage generation plant including upper and lower reservoirs, penstock, pump – turbine, motor – generator, control – protection and measurement devices and transformer are presented through Markov model with two states as shown in Fig. 2. The proposed model consists of up and down states. Failure rate (λ) presents transition rates from up to down states, and repair rate (μ) presents rate of transitions from down to up states. Availability (A) and unavailability (U) of each component of pumped-storage generation unit can be obtained as [21]:

$$A = \frac{\mu}{\lambda + \mu}, U = 1 - A \tag{1}$$

Failure of each component of pumped-storage generation unit leads transferring water from lower basin to upper basin, rotation of turbine, the electric power generation, or transmitting the generated power to the grid fail and so, if one or more components fails, the electric power of pumped-storage generation unit transmitted to main grid is zero. Thus, in the reliability modeling of plant, all composed components of pumped-storage generation unit as presented in Fig. 3, are series.

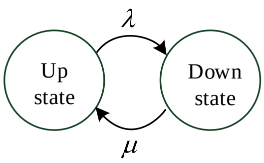
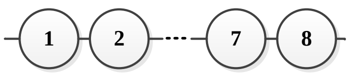


Fig. 2: 2-state Markov model of plant components.



1- motor – generator
2- pump – turbine
3- control, protection and measurement devices
4- turbine house
5- penstock
6- upper reservoir
7- lower reservoir
8- transformer

Fig. 3: Reliability model of pumped-storage generation unit

considering failure of composed components.

Equivalent failure and repair rates of reliability model of pumped storage generation unit is calculated as [21]:

$$\lambda_{eq} = \sum_{k=1}^{8} \lambda_k \tag{2}$$

$$\mu_{eq} = \frac{\lambda_{eq}}{\sum_{k=1}^{8} \frac{\lambda_k}{\mu_k}} \tag{3}$$

Where, λ_{eq} is equivalent failure rate of model, λ_k is failure rate of composed components, μ_{eq} is equivalent repair rate and μ_k is repair rate of composed components. In a power system including N pumped storage generation units, reliability model of these N pumped storage generation units can be presented as Fig. 4. Probability of state k associated to this model including $N+1-k$ up units can be calculated as:

$$P_k = \binom{N}{N+1-k} A^{N+1-k} U^{k-1} \tag{4}$$

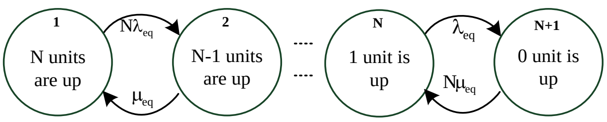


Fig. 4: Reliability model of N pumped storage generation units.

4. Adequacy Analysis of Power Systems Containing Pumped-Storage Generation Units

Reliability of power system is defined as providing required load of the power system according to the associated standards. Two aspects of power system reliability are adequacy and security. In adequacy analysis of power system, adequate facilities must be provided for supplying required load. In security studies of power system, response of the power system to various disturbances such as outages of power plants is investigated. Reliability analysis related to power system can be performed in three hierarchical levels. They are reliability study of the generation part (HLI), reliability evaluation of generation and transmission parts (HLII) and reliability assessment of three sections of power system including generation, transmission and distribution parts (HLIII). This paper introduces proposed techniques used for studying power system adequacy in HLI and HLII.

4.1. Adequacy Assessment of Power System including Pumped-Storage Generation Unit in HLI

For adequacy assessment of power system containing pumped-storage generation plants in HLI, as presented in Fig. 5, all power plants and total load of system are connected to common bus. In this level, reliability of transmission network is considered to be 100% and failure of transmission network is neglected. The model of power plants is presented by capacity outage probability table (COPT). In COPT associated with each unit, capacity and related probability of all possible states are determined. By combining COPTs of different power plants, total COPT of system is constructed. Demand is presented by load duration curve that is a line extended from maximum to minimum peak load during the studied horizon time. By convolving the models of power

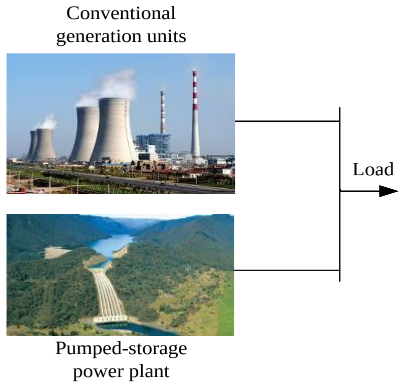


Fig. 5: Adequacy assessment of power system including pumped-storage generation plant in HLI.

plants and demand, reliability indices of power system are obtained. These reliability indices are average times that load is curtailed (loss of load expectation - *LOEE*) and average energy that is not provided (expected energy not supplied - *EENS*). Fig. 6 presents load duration curve of the system. For determining power system reliability indices, each state of total COPT is selected and reliability indices associated to each state can be calculated. Then, reliability indices of the power system are obtained by summing these reliability indices weighted by the related probabilities as equations (5) and (6).

$$LOLE = \sum_{i=1}^{n} t \times P_i \quad hours/year \tag{5}$$

$$EENS = \sum_{i=1}^{n} ENS_i \times P_i \tag{6}$$

Where, t and ENS_i are time of year that system load is curtailed and energy of system that is not supplied related to state with generation capacity i and probability P_i. Other reliability indices are peak demand that system can provide (peak load carrying capability - *PLCC)* and difference in peak demand that system can provide (increase in peak load carrying capability - *IPLCC*). *PLCC* is maximum peak load that power system can provide, so that reliability remains in permissible range. *IPLCC* is amount of increased peak load with addition of new power plant, so that reliability remains in permissible range.

In this part, the impact of pumped storage power plant on the reliability performance of power system is studied. The charging and discharging of storage depends on time and availability of water, which is not independent from load variations. Thus, to accurately study the reliability of power system containing pumped storage power plant, input data including hourly load, hourly generated power of all power plants, and hourly operation of pumped storage power plant in motor or generator states are required. However, in the best case, when the impact of pumped storage power plant on the reliability of power system is maximum, the operation of pumped storage power plant would be as below: the pumped storage power plant acts as load in minimum load to pump water from lower reservoir to the upper reservoir, and acts as generator in maximum load to generate electricity through releasing water from upper reservoir to the lower reservoir. Thus, in this research, to consider the impact of pumped-storage generation unit on reliability of power system, load duration curve is modified as presented in Fig. 7. At low load

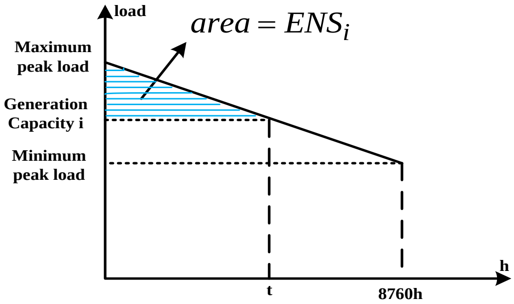


Fig. 6: System load duration curve.

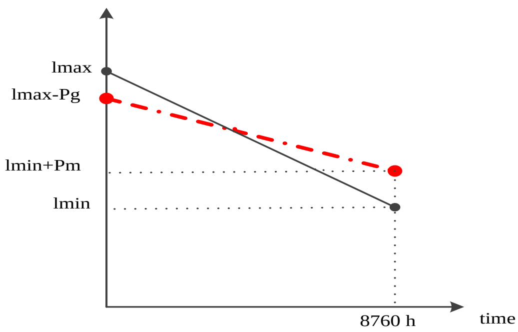


Fig. 7: System load duration curve affected by pumped-storage generation unit in optimal case.

level, pumped storage generation unit acts as a load (the machine acts as a motor and the pump-turbine acts as a pump) that consumes the electric power (*Pm*) for pumping water from lower reservoir to upper basin. When, load is high, water of upper basin is released and plant acts as a power plant (the machine acts as a generator and the pump-turbine acts as a turbine) that generates the electric power (*Pg*). In optimal operation of pumped-storage generation unit, plant acts as a load when the load is minimum, and the plant acts as a power plant when the load is maximum. In the current research, optimal operating plan related to pumped-storage generation unit is performed and according to this operation, system load duration curve is modified. Thus, consumed power of pumped-storage generation unit (*Pm*) is added to minimum load (*lmin*) and the maximum load (*lmax*) is reduced by the amount of generated power of unit (*Pg*). Efficiency of pumped-storage generation unit is less than 100% and so, value of generated power is less than consumed power of pumped-storage power plant.

Thus, for adequacy analysis of power system containing maximum impact of pumped storage generation plant in HLI, the following procedures should be tracked:

Step. 1. Equivalent failure rate and repair rate of pumped storage generation plant are calculated as equations (2) and (3).

Step. 2. Capacity outage probability table of all conventional generation units is obtained.

Step. 3. Total capacity outage probability table is obtained by combining all capacity outage probability tables.

Step. 4. Reliability indices of power system without pumped storage generation unit is calculated.

Step. 5. Load duration curve of the system by considering impact of pumped storage generation plant is modified as Fig. 7.

Step. 6. Reliability indices of power system with modified load duration curve is calculated.

Step. 7. To calculate reliability indices of power system containing pumped storage generation plant, the following equation is used:

$$s = s_0 U + s_1 A \tag{7}$$

In (7), s, s_0 and s_1 are reliability index considering impact of pumped storage generation plant, reliability index without pumped storage generation unit and reliability index considering modified load duration curve, U and A are unavailability and availability of pumped storage generation unit. The flowchart related to adequacy analysis of power system containing pumped storage generation unit is presented in Fig. 8.

4.2. Adequacy Assessment of Composite Power System Containing Pumped-Storage Power Plant

To study adequacy of composite power system containing generation and transmission parts, integrated with pumped-storage generation units, contingency analysis approach is proposed. In the current research, power system components such as power plants and transmission lines are modeled by two-state reliability model (with down and up states). Based on this model, composite power systems with n power plants and m transmission lines have 2^{m+n} contingencies. To reduce contingencies associated with large-scale power system, state selection technique is proposed. According to the state selection approach, high-probability contingencies are considered and low-probability contingencies are neglected. In this paper, to analyze different contingencies of the composite power system, DC-type load flow considers transmission lines capacity is implemented. Thus, based on DC-type load flow, each contingency is evaluated. If the contingency makes interruption of load at load points, load shedding program is run for minimizing cost of curtailed loads as equation (8).

$$\text{interrupted load cost} = \sum_{i=1}^{n} L_i VOLL_i \tag{8}$$

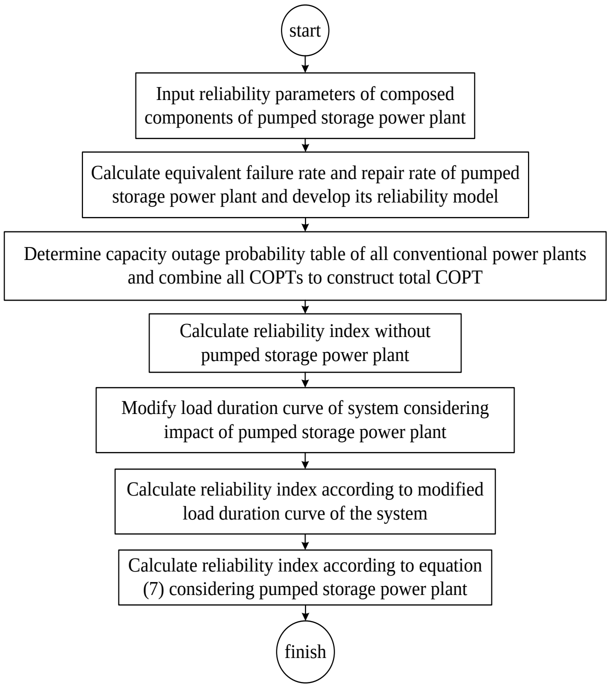


Fig. 8: Flowchart of adequacy analysis of power systems containing pumped-storage generation units in HLI.

In (8), L_i and $VOLL_i$ are interrupted load and value of lost load in $/kWh for bus i. For minimizing interrupted loads cost, linear programming approach with interior point method is implemented. Problem constrains includes:

- Balance between generated power and required load minus interrupted load must be established.
- Generated power of all power plants must be within the allowable range.
- The curtailed load must be less than total load of each bus.
- The power transferring by transmission lines must be less than capacity of corresponding line.

According to the proposed approach, adequacy assessment of composite power system containing pumped-storage generation units can be performed. In adequacy evaluation of power system in HLII, load is considered to be constant and equal to maximum value. Thus, to consider the impact of pumped-storage generation plant on the adequacy indices of composite power system, capacity of these units is considered as the generated power of them. In the current research, important reliability indices of composite power system such as probability of interrupted load (Q_S), average time of interrupted load or loss of load expectation ($LOLE$) and average energy not provided or expected energy not supplied ($EENS$) corresponding to load points are determined as:

$$Q_s = \sum_{i=1}^{n} P_i B_i \tag{9}$$

$$LOLE = \sum_{i=1}^{n} P_i B_i \times 8760 \tag{10}$$

$$EENS = \sum_{i=1}^{n} L_i P_i \times 8760 \tag{11}$$

In (10), P_i presents probability related to state i, B_i with 0 and 1 values (0 for events without curtailment and 1 for events lead to load interruption at desired bus). n presents number of contingencies and L_i presents interrupted load at desired load point corresponding to contingency i. Fig. 9 illustrates flowchart for reliability analysis of composite power system containing pumped-storage generation unit.

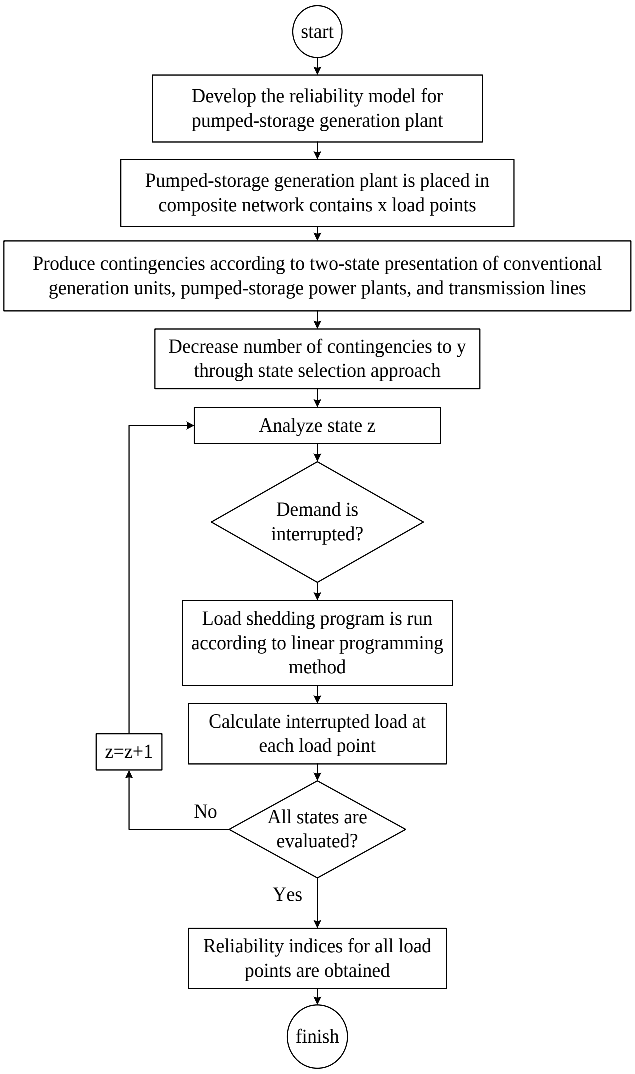


Fig. 9: Flowchart for adequacy analysis of composite power system containing pumped-storage generation units.

Table 1: Failure rate and repair time of composed components of pumped-storage generation unit.

Components	Failure rate (occ./yr)	Repair time (hour)
Upper reservoir	0.25	50
Lower reservoir	0.25	50
Penstock	0.25	50
Turbine house	0.25	50
Pump - turbine	2	100
Generator - motor	1	100
Control, protection and measurement system	0.9	50
Transformer	1	100

5. Numerical Results

In this section, numerical outcomes related to adequacy assessment of two power systems including pumped-storage generation units at HLI and HLII are given. To this end, according to the proposed technique, reliability model of understudied pumped-storage generation plant is achieved and used in adequacy analysis of test systems.

5.1. Reliability Modelling of Understudied Pumped-Storage Generation Unit

In this part, a 30MW pumped storage generation unit that generates 120MWh electric energy, and efficiency of 80% is considered. Table 1 illustrates failure and repair rates of plant components. Thus, equivalent failure rate and repair time of reliability model of pumped-storage power plant would be 5 failures per year and 80 hours, respectively. Based on equation (1), availability of pumped-storage power plant would be 0.96.

The efficiency of the plant is 80% and so, the consumed power of the plant when water is transferred from lower basin to upper basin by pumping would be 37.5MW.

5.2. Adequacy Analysis of RBTS

In this part, adequacy analysis of RBTS including mentioned pumped-storage generation unit in HLI and HLII is performed. This test system is shown in Fig. 10. The characteristics of RBTS are given in [22]. Load duration curve is a line continues from 100% to 60% of maximum load.

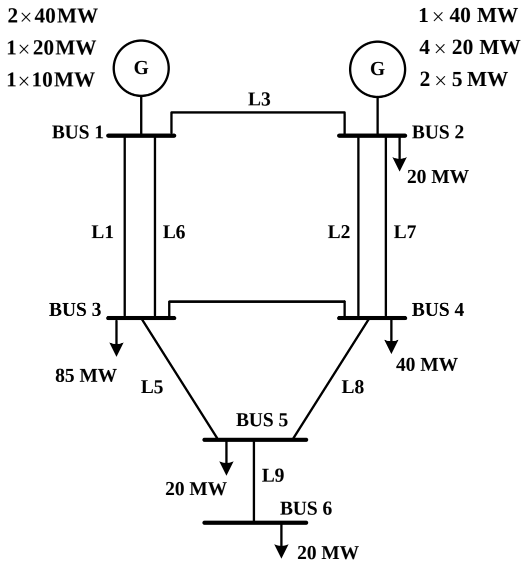


Fig. 10: Roy Billinton Test System (RBTS) [22].

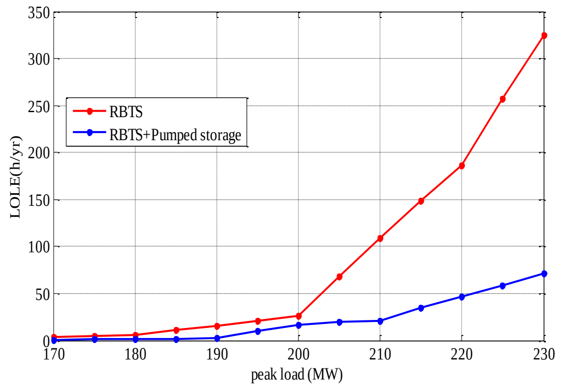


Fig. 11: LOLE for different peak loads.

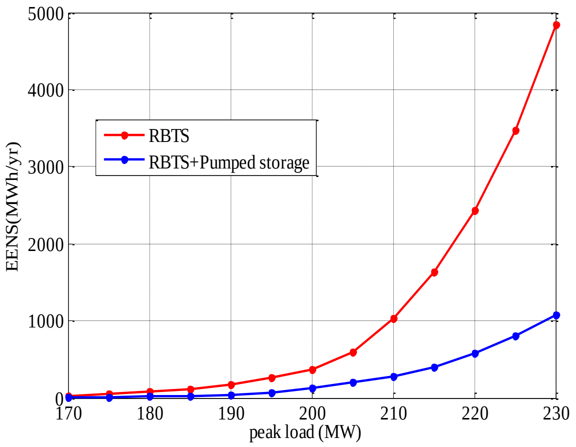


Fig. 12: EENS for different peak loads.

In this stage, RBTS as case I and RBTS integrated with understudied pumped-storage generation unit as case II are studied to calculate adequacy indices including *LOLE* and *EENS* of them at HLI for different peak load. The results are illustrated in Figs. 11 and 12, respectively.

PLCC of case I and case II provided that expected energy not supplied of system remains less than allowable value is obtained and illustrated in table 2. IPLCC of system by addition of understudied pumped-storage power plant is obtained and illustrated in table 3. Numerical results present that pumped-storage generation unit significantly improves reliability indices of power system.

Table 2: PLCC.

Cases / Permissible EENS	100 MWh/yr	200 MWh/yr	300 MWh/yr	400 MWh/yr
Case I	180MW	190MW	195MW	200MW
Case II	195MW	205MW	210MW	210MW

Table 3: IPLCC.

Cases/Permissible EENS	100 MWh/yr	200 MWh/yr	300 MWh/yr	400 MWh/yr
Case II	15MW	15MW	15MW	10MW

At this stage, adequacy assessment of composite RBTS including pumped-storage generation unit is performed. For reducing number of contingencies, contingencies related to 4 or less power plants failure, 3 or less transmission lines failure and 3 or less power plants or transmission lines failure are investigated. According to the proposed approach, *LOLE* and *EENS* related to different load points for initial RBTS are obtained and illustrated in table 4. As can be seen in the table, the reliability of load point 5 is weak and so, the pumped-storage generation plant should be connected to this load point. According to the proposed method, reliability indices of modified system are obtained and illustrated in table 5. This table presents that reliability indices of composite power system at bus 5 is improved by addition of the pumped-storage generation unit to this bus.

5.3. Adequacy Analysis of IEEE-RTS

In this part, adequacy assessment of large-scale IEEE-RTS as shown in Fig. 13, including understudied pumped-storage power plant in HLI and HLII is performed. Paper [23] presents characteristics of power plants, transmission lines and load points of IEEE-RTS. Load duration curve is a line continues 100% and 60% of peak load that is 2850MW. According to the proposed approach, adequacy assessment of

Table 4: Reliability indices of composite RBTS.

Bus	Probability of lost load	LOLE (hrs/yr)	EENS (MWh/yr)
2	0	0	0
3	0.0086	75.34	6403.9
4	0	0	0
5	1.2733e-06	0.01115	0.223
6	0.00113913	9.9787788	199.575576

Table 5: Reliability indices of composite RBTS including the understudied pumped-storage generation unit.

Bus	Probability of lost load	LOLE (hrs/yr)	EENS (MWh/yr)
2	0	0	0
3	0.000363	3.182225	270.5
4	0	0	0
5	1.26E-06	0.011063	0.221
6	0.00113911	9.9786036	199.572072

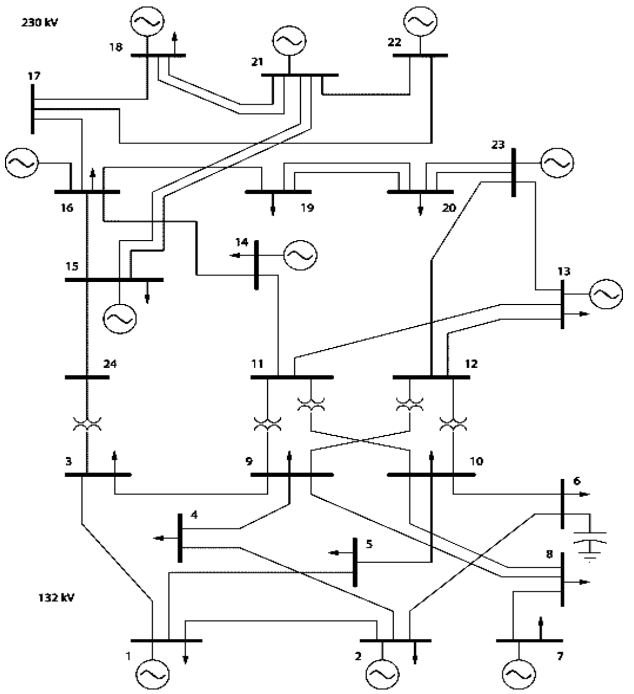


Fig. 13: IEEE Reliability Test System (IEEE-RTS) [23].

IEEE-RTS when different numbers (from 0 to 5) of the understudied pumped-storage power plants are added to it is performed, and different reliability indices including LOLE, EENS, PLCC and IPLCC are calculated and illustrated in table 6. PLCC and IPLCC of system are obtained when EENS<16985MWh/yr. It is concluded from table 6 that by addition of pumped-storage power plants, reliability indices of IEEE-RTS improve, significantly.

In this stage, adequacy analysis of composite IEEE-RTS containing pumped-storage generation plant is performed. For reducing number of contingencies, contingencies related to simultaneous failures of up to 2 generation power plants, up to 2 transmission lines and up to 2 generation power plants and transmission lines are taken into account. According to the proposed approach, loss of load probability, loss of load expectation and expected energy not supplied at different load points for initial IEEE-RTS are calculated and illustrated in table 7. It is deduced from this table that reliability of load point 19 is weak and so, pumped-storage generation plant should be connected to this load point. According to the proposed approach, reliability indices of the modified system are calculated and presented in table 8. This table presents that reliability indices of the composite power system at load point 19 is improved by addition of pumped-storage generation unit to this load point.

Table 6: Reliability indices of IEEE-RTS in HLI.

Number of added plants	LOLE (h/yr)	EENS (MWh/yr)	PLCC (MW)	IPLCC (MW)
0	112.9085	16984	2850	0
1	100.3366	14755	2872	22
2	89.8462	12806	2893	43
3	81.4793	11065	2914	64
4	73.3801	9509	2935	85
5	65.1861	8139	2955	105

Table 7: Reliability indices of composite IEEE-RTS.

Bus	Probability of lost load	LOLE (hrs/yr)	EENS (MWh/yr)
1	0	0	0
2	0	0	0
3	2.35e-7	0.0020586	0.370548
4	4.70e-8	0.0004117	0.030466
5	3.80e-8	0.0003329	0.023636
6	1.86e-7	0.0016294	0.221598
7	0	0	0
8	0	0	0
9	0.0108849	95.3517244	16686.551770
10	0	0	0
13	0	0	0
14	6.01e-8	0.0005265	0.102141
15	0	0	0
16	0	0	0
18	0	0	0
19	0.02198609	192.5981484	34860.264860
20	0	0	0

Table 8: Reliability indices of composite IEEE-RTS including understudied pumped-storage power plant.

Bus	Probability of lost load	LOLE (hrs/yr)	EENS (MWh/yr)
1	0	0	0
2	0	0	0
3	2.25E-07	0.001968	0.35424
4	4.50E-08	0.000395	0.02923
5	3.60E-08	0.000315	0.022365
6	1.78E-07	0.001558	0.211888
7	0	0	0
8	0	0	0
9	0.004573	40.05832	7010.206
10	0	0	0
13	0	0	0
14	5.75E-08	0.000504	0.097776
15	0	0	0
16	0	0	0
18	0	0	0
19	0.021003	183.9865	33301.5565
20	0	0	0

6. Conclusion

In the current research, adequacy studies of power system including pumped-storage power units in generation and composite levels of power system are performed. According to the authors' knowledge, reliability of these power plants has not been investigated in any reference. To this end, an equivalent two-state reliability model is developed for pumped-storage generation units. This model considers failure of composed components including upper basin, lower reservoirs, penstock, turbine house, motor-generator, pump-turbine, transformer and control, protection and measurement devices. It is concluded from reliability analysis of pumped-storage generation unit that mentioned components makes the plant fails. Thus, in reliability modeling of plant, all components are series. To determine the impact of pumped-storage generation unit on reliability of power system, load duration curve of system is modified. The minimum load is increased by the amount of consumed power of pumped-storage generation unit and maximum load is reduced by the amount of generated power of the plant. Adequacy studies of generation system is performed through the analytical method based on the COPT of the generation plants and load duration curve of the demand. To perform adequacy analysis of composite power system, contingency analysis methodology is proposed. Besides, for reducing number of contingencies of large-scale composite power system, state selection method is proposed. Numerical outcomes related to the reliability analysis of RBTS and IEEEE-RTS conclude that by integration of pumped-storage generation plants into the power system the reliability of power system in both levels, i.e. HLI and HLII, is improved. The reliability of RBTS in load point 5, and IEEE-RTS in load point 19 is weak. By integration the understudied pumped storage power plant into RBTS and IEEE-RTS in these load points, reliability of modified RBTS and IEEE-RTS is improved.

Credit Authorship Contribution Statement

Amir Ghaedi: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Software, Validation, Roles/Writing - original draft. **Mehrdad Mahmoudian**: Methodology, Project administration, Supervision, Visualization, Writing - review & editing.

Declaration Of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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