Advances in Science and Technology Research Journal
Volume 10, No. 32, Dec. 2016, pages 198–205
DOI: 10.12913/22998624/65109

Research Article

RELIABILITY EVALUATION OF RENEWABLE ENERGY-BASED POWER SYSTEM CONTAINING ENERGY STORAGE

Amir Ghaeedi[1], Erfaneh Noroozi[1]

[1] Islamic Azad University of Dariun Branch, Dariun, Islamic Republic of Iran, e-mail: erfanehnoroozi@iaudariun.ac.ir

Received: 2016.08.31
Accepted: 2016.10.18
Published: 2016.12.01

ABSTRACT

In recent years, renewable energy based power plants, especially wind and solar farms are increasingly installed and operated for electric power generation. Uncertainty nature associated to the generated power of these power plants, arisen from variability of wind speed or solar radiation, effects on different aspects of power system such as reliability, operation, dynamic and so on. Energy storages in connection with renewable power plants can reduce the variability and uncertainty nature of these renewable resources. In recent years the flow batteries such as vanadium redox (VR) with large capacities are developed and so in this paper effect of this large-capacity energy storages on the reliability performance of power system containing large-scale wind and photovoltaic (PV) farms are investigated. The renewable energy-based power plants and also energy storages are different from conventional units, so, for study of power system containing these resources new methods and techniques must be developed. To this end in this paper for reliability evaluation of renewable-energy based power system containing energy storage, an analytical approach is proposed. This approach can be employed both in planning and also operation studies of the power system when large scale wind and photovoltaic farms with energy storages exist. Data associated to wind speed of Manjil and solar radiation of Jask regions both in Iran are utilized for studying the reliability evaluation of RBTS and also IEEERTS in planning phase.

Keywords: reliability evaluation, renewable resources, vanadium redox batteries, fuzzy clustering method.

INTRODUCTION

Renewable energies specially wind and solar, are increasingly used in the power system because of the availability, clean and no pollutant nature and free operation cost of them. The output power of wind and photovoltaic (PV) farms is dependent on the wind speed and solar radiation. Since the wind speed and also the solar radiation continuously change and are not accurately predictable, the output powers of these renewable resources are variable. To overcome this challenge and for reducing the intermittency of the output power of these resources, energy storages such as batteries [1-8], pumped storage [9], a system containing water electrolyze, hydrogen tank and fuel cell [10-15], ultra-capacitor [16], superconducting magnetic energy storage [17], compressed air energy storage [18] and flywheel [19] can be used in connection with these power plants. Amongst these storages, flow batteries such as vanadium redox type are made in large capacities and can be used in large-scale power system [8].

The intermittent nature associated to the output power of renewable resources, effect on the different aspects of power system such as reliability, power quality and so on that can be investigated. To this purpose, new methods and techniques must be developed. Power system reliability is one of the important aspect that used in planning and operation studies of the power system. In this paper an analytical approach for reliability evaluation of renewable-energy based power system containing battery storage is suggested. For reliability evaluation of power system containing renewable resources and energy storages many efforts have been done, but more of these works are related to the reliability evaluation of the renewable energy-based power system containing battery storage in the isolated, hybrid or distributed generation systems [1–7]. Besides in these papers, Monte Carlo simulation method is used for load, wind and solar generation modelling. In [8], reliability evaluation of power system containing wind farms and vanadium battery storages in HLI is investigated. In this paper, Monte Carlo method is used for simulation of wind output power, load and the state of battery. However the long time consumption and the large required volume of memory are the main drawback of this technique. In this regard this paper proposes an analytical approach which does not have these difficulties.

The main idea of this paper is developing a multi-state reliability model for renewable resources connected to the energy storage. Since, the operation of the energy storage is dependent on the operation of renewable units, the reliability model is not independently developed to renewable units. Based on this model, simultaneously, the system composed of the renewable units and battery storages in one block, is modeled. The proposed reliability model would be similar to the conventional units, but with derated states. For determining the suitable number of states and also the capacity of them, it is utilized from the robust fuzzy c-means clustering method. The resulted multi-state reliability model associated to the system including renewable resources and battery storages can be used for reliability evaluation of power system in HLI in planning or operation phases.

STRUCTURE OF VANADIUM REDOX BATTERIES

The power range kW-MW, energy storage capacity kWh-10 MWh, high efficiency more than 75 percent, long life time 10-20 years, deep discharge ability, fast response, environmental friendly nature, full charging and de-charging capacity in very short time, charging and de-charging cycle more than 10000 times, lead to the growth of vanadium redox batteries application in recent years [20–23]. Due to the good performance and high storage capacity of these batteries resulted from 30 years researches, in the future, the frequent use lead acid batteries may be replaced by these VR batteries. The structure of a VR battery is shown in Figure 1. As can be seen in this figure, the VR battery electrochemically store or release electrical power by the valence change of the species in the electrolyte that circulate through the cathode and the anode, which are separated by an ion exchange membrane. The total reaction is occurred in the two main tanks and the stored electrolytes are reserved in the two large tank. The electrolytes are circulated between small and large tanks by a pump [20–23].

The total VR, anode and cathode reactions are given in (1), (2) and (3), respectively. The VR batteries are composed of several cell modules and each module is composed of several single cells that is shown in Figure 2.

$$\begin{aligned}&\textit{Total reaction}:\\&\varnothing^{2+} + V^{3+} + H_2O \leftrightarrow \varnothing_2^{+} + V^{2+} + 2H^{+}\end{aligned} \tag{1}$$

$$\begin{aligned}&\textit{Cathode}:\\&V^{3+} + e \leftrightarrow V^{2+}\end{aligned} \tag{2}$$

$$\begin{aligned}&\textit{Total reaction}:\\&\varnothing^{2+} + V^{3+} + H_2O \leftrightarrow \varnothing_2^{+} + V^{2+} + 2H^{+}\end{aligned} \tag{3}$$

The output power of the VR battery is DC and for transferring the electrical power between VR battery and the AC grid, an inverter and also a control unit for determining the charge or decharge states are required.

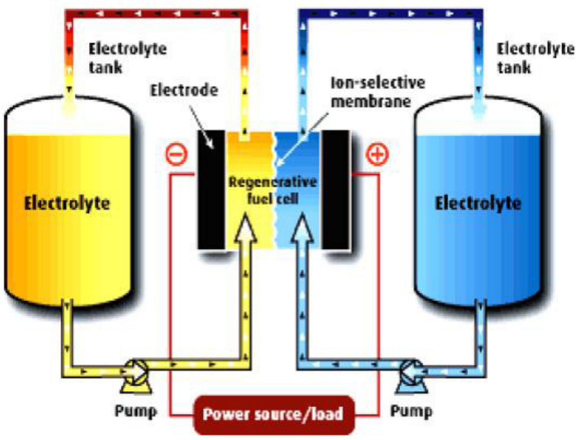

Fig. 1. The structure of a VR battery

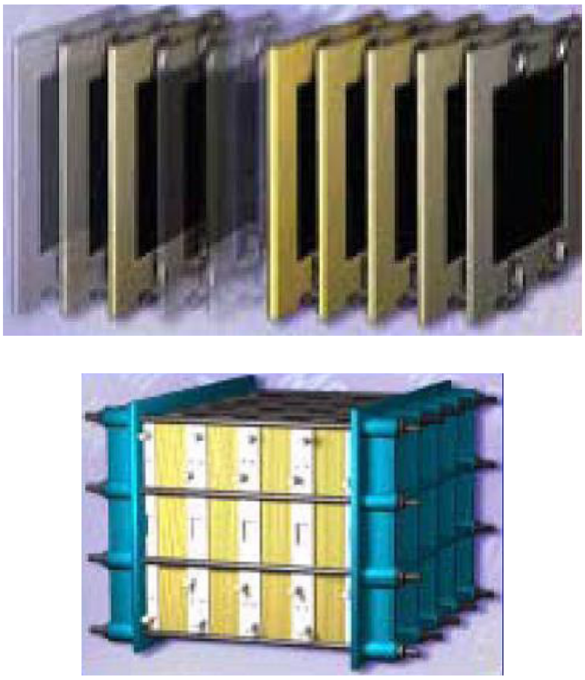

Fig. 2. The structure of module and cells of a VR battery

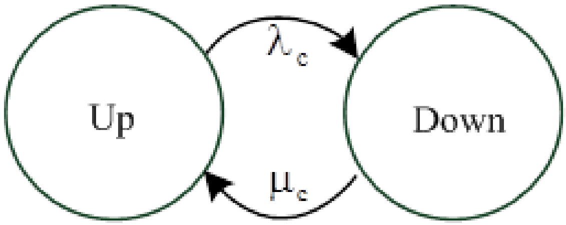

Fig. 3. Two-state Marco model

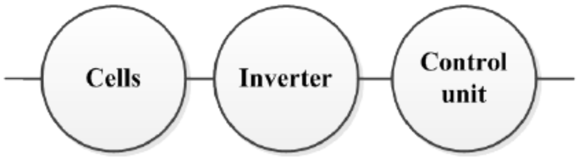

Fig. 4. The reliability model of VR battery

THE RELIABILITY MODEL OF VR BATTERIES

The Marco model of an element with up and down states is shown in Figure 3. In this model the element is failed (transferred from up state to the down state) with failure rate λc and is repaired (transferred from down state to the up state) with repair rate μc [24]. In this paper this two-state reliability model is considered for different components of a VR battery including cells, inverter and control unit. The failure of each three components results in the failure of system and so from reliability point of view, these components are in series with each other (as shown in Figure 4) and the reliability parameters of the equivalent model are determined by (4) [24].

$$\lambda_{eq} = \sum \lambda_i , U = \sum U_i , r = \frac{\sum \lambda_i r_i}{\sum \lambda_i} \tag{4}$$

THE RELIABILITY MODEL OF THE SYSTEM COMPOSED OF THE RENEWABLE-BASED FARM CONNECTING TO THE VR BATTERY

The efficiency of storing electrical energy in the VR battery and transferring the power to the grid in the de-charging state is less than 100 percent and storing the generated power of conventional units with high operation costs is not economic. However with growth of penetration level of renewable resources such as wind and solar farms with free operation cost, it is economic that stores the electrical energy of wind and photovoltaic (PV) farms in the VR batteries when the power generation of these renewable energy-based units is more than the required loads. In this circumstance the extra power of wind and PV farms is stored in the VR battery and when the generated power of renewable energy-based units with free operation costs is less than the required loads, these batteries are de-charged and supplied the existing loads. Thus, the operation of the VR battery is dependent on the operation of renewable energy-based farms and in this paper the reliability model of a system containing the wind or PV farms connecting to the battery storages is developed.

For reliability modelling of the system containing renewable resources connected to the energy storage, the hourly output power of the system in one or more years must be available. When the reliability model of the system, based on the historical output power of the system, is determined, the limitation of the system including failures of the components of renewable units and storage system, efficiency of the storage system, maximum and minimum capacity of the battery, charging and de-charging speed of the battery are simultaneously considered.

The historical data of the output power of the system has numerous different values resulted in a reliability model with numerous states that is not suitable for reliability evaluation of the power system. For decreasing the number of the states and capacity determination of these states, a robust clustering method must be employed. In this paper, fuzzy C-means clustering method is used and the optimum number of states and the capacity of these states are determined by optimization of the objective function given in (5) [25].

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

In (5), n output powers are clustered into the C clusters, where x_k is the output power of the system in hour k, v_i is the center of ith cluster, uik is Fuzzy degree to which x_k belongs to the ith cluster.

For adequacy studies of a power system containing the renewable resources connected to the VR battery energy storage, capacity outage probability table (COPT) of the generation system composed of the two-state reliability model of conventional units and multi-state reliability model of the system containing wind or solar unit connected to the VR battery as shown in Figures 5 and 6 is achieved. Convolving the resulted COPT of the system (generation model) and the load model, the adequacy indices of the system can be determined. The calculated adequacy induces can be used for generation expansion planning of the power system containing the renewable resources connected to the large-capacity VR batteries.

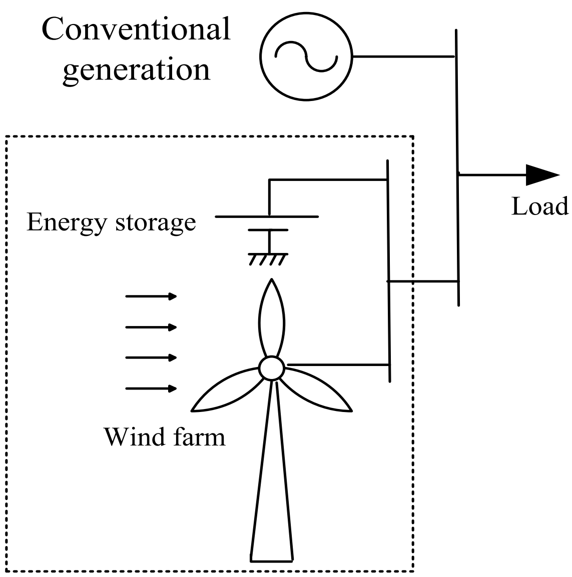

Fig. 5. Adequacy studies of a power system containing wind farms connected to the VR batteries

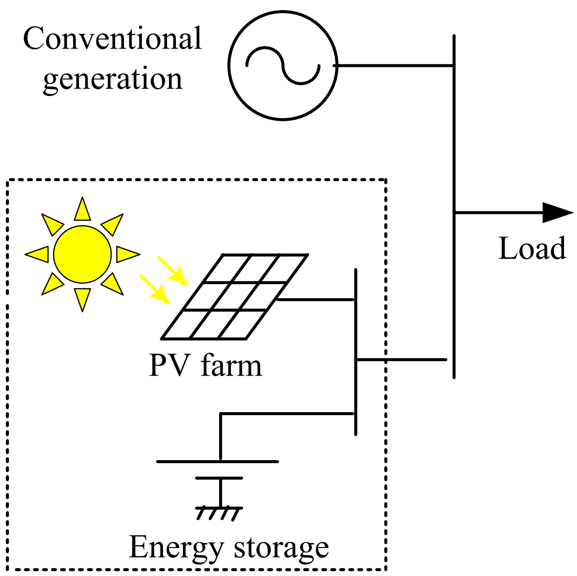

Fig. 6. Adequacy studies of a power system containing PV farms connected to the VR batteries

NUMERICAL RESULTS

In this section the adequacy studies of two well-known test systems i.e. RBTS and IEEE-RTS when wind and PV farms connected to the VR batteries are added to these systems are performed. The specification of the renewable farms is considered as below:

- **Wind farm**: a 30 MW wind farm with failure and repair rates 5 and 87.6 occ./yr, composed of the 6 turbines V90, is considered to be installed in Manjil region of Iran. The historical wind speed data of the Manjil region in 2014 is presented in Figure 7. The output power of the farm can be determined based on the power curve of the turbine Vestas90.
- **PV farm**: a 100% reliable 30 MW PV farm is considered to be installed in Jask region of Iran and generated the nominal power in solar radiation 900 W/m^2. The historical solar radiation data of Jask region in 2014 is presented in Figure 8.
- **VR batteries**: two 5 MW VR batteries with capability of 10 MWh stored energy and efficiency 75%, composed of 500 batteries with 10 kW capacity are connected to the wind and PV farms. The failure and repair rates are considered to be 0.5 and 87.6 occ./yr. and the up and low capacities of the battery are not limited.

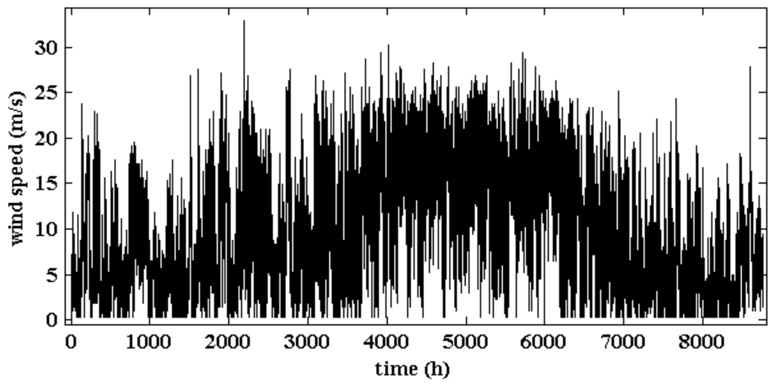

Fig. 7. The historical wind speed data of Manjil region in 2014

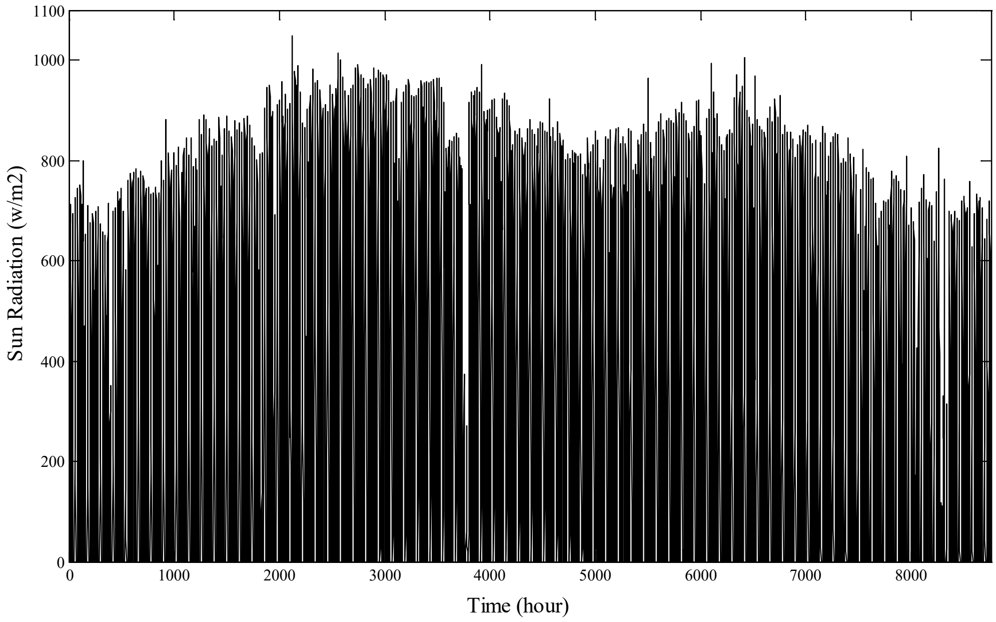

Fig. 8. The historical solar radiation data of Jask region in 2014

Since the historical data of the system containing wind farm connected to the VR battery and also the PV farm connected to the VR battery are not available, in this paper, generation of output power of the system is done by Monte Carlo simulation with 100 years' time span. In this simulation the IEEE-RTS load pattern as shown in Figure 9 is used.

The resulted data from the Monte Carlo simulation is used as input data of the FCM technique and the reliability models of system containing wind farm connected to the VR battery and also PV farm connected to the VR battery are extracted and shown in Table 1. This reliability model can be used for adequacy studies of two test systems.

RBTS CASE STUDY

The RBTS is composed of 11 generation units with total capacity 240 MW. The specification of generated units and reliability parameters of them is given in [26]. The load duration curve is considered to be a straight line from 100 to 60 percent of the maximum peak load. For adequacy evaluation of the system three cases are considered as below: case 1 is the original RBTS and in cases 2 and 3, respectively a 30 MW wind farm connected to the 5 MW VR battery and a 30 MW PV farm connected to the 5 MW VR battery are added to the RBTS. Two important indices i.e. loss of load expectation (LOLE) and expected energy not supplied (EENS) considering different peak loads, are calculated and shown in Tables 2 and 3. As can be seen in these tables, addition of the re-

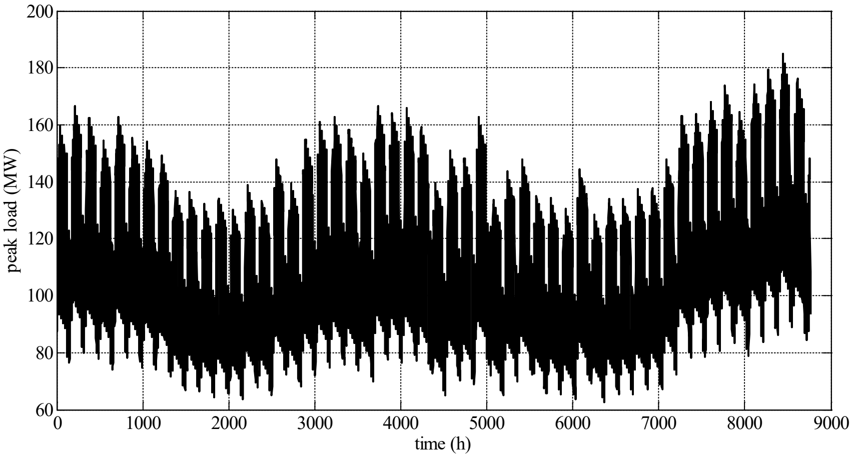

Fig. 9. IEEE-RTS load pattern

Table 1. The reliability model of renewable energy-based systems connecting to the VR battery

	Wind farm + VR battery		PV farm + VR battery	
Cluster number	**Cluster center (MW)**	**Probability**	**Cluster center (MW)**	**Probability**
1	33.6	0.3357	32.9	0.1280
2	28.7	0.0597	28.5	0.1551
3	22.6	0.0558	23.5	0.0881
4	16	0.0528	16.6	0.0603
5	9.7	0.0806	10.5	0.0567
6	5.7	0.1159	3.8	0.4667
7	3.6	0.2995	0.2	0.0451

newable energy-based generation units connected to the VR batteries can significantly improve the reliability performance of the power system.

IEEE-RTS CASE STUDY

The IEEE-RTS is a large power system and can be modeled as a real power system in compare to the RBTS. In this part adequacy studies of this system with addition of the renewable energy-based farms connected to the VR batteries is performed. The specification of the IEEE-RTS generation units is given in [27]. In this stage three cases as below are considered: case 1 is the original IEEE-RTS and in cases 2 and 3, respectively a 30 MW wind farm connected to the 5 MW VR battery and a 30 MW PV farm connected to the 5 MW VR battery are added to the IEEE-RTS. The LOLE and EENS of three cases are calculated and presented in Figures 10 and 11. As can be seen from these figures, the reliability of power systems is improved with addition of the renewable energy-based generation units connected to the large capacity VR batteries.

Table 2. LOLE (h/yr)

Peak load (MW)	LOLE (h/yr)		
	Case 1	**Case 2**	**Case 3**
170	3.5714	1.0958	1.4113
175	4.9676	1.8158	2.2320
180	6.3579	2.6020	3.1120
185	11.1228	3.7126	4.5694
190	15.6532	5.9110	7.2873
195	20.7491	8.5359	10.3527
200	26.3562	11.7494	13.9025

Table 3. EENS (MWh/yr)

Peak load (MW)	EENS (MWh/yr)		
	Case 1	**Case 2**	**Case 3**
170	28.5296	7.9550	10.2451
175	48.8088	14.8990	18.9180
180	75.4248	25.3624	31.5394
185	116.6625	39.7186	48.8729
190	179.8059	62.2933	76.8274
195	265.2044	96.1215	118.1851
200	375.0485	143.6777	174.9459

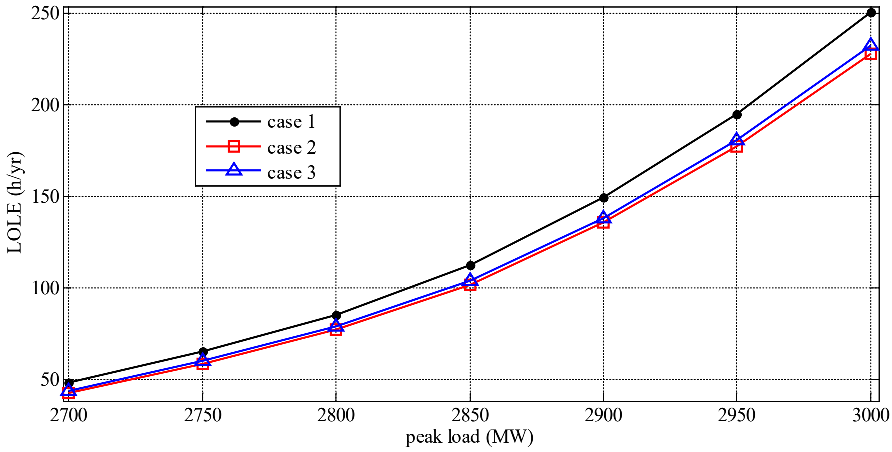

Fig. 10. LOLE (h/yr)

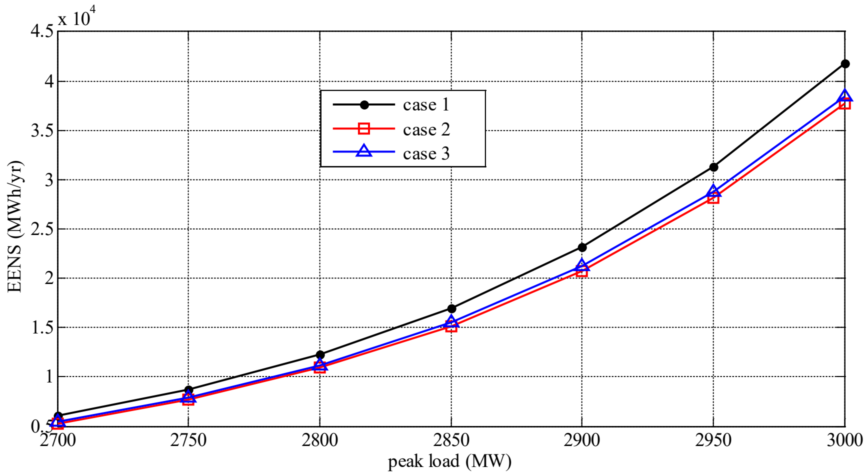

Fig. 11. EENS (MWh/yr)

CONCLUSIONS

In this paper an analytical method is introduced for adequacy analysis of a power system containing the large-scale renewable energy-based farms connected to the large capacity VR batteries. Due to the uncertainty nature of wind speed and solar radiation, the output power of wind and PV farms are variable in times and so for decreasing the intermittency of these farms, energy storages can be connected to these plants. In this paper VR batteries with high capacity connected to the wind and PV farms, are considered; and a multi-state reliability model based on the output power historical data is developed for them. This model is used for adequacy studies of RBTS and IEEE-RTS when wind and PV farms connected to the VR batteries are added to them. The COPT of the system is constructed from the two-state reliability model of conventional units and multi-state reliability model of system composed of wind or PV farms connected to the VR batteries. For reducing the number of the states in the reliability model of renewable energy-based farms, fuzzy C-means clustering method is employed and the number of clusters as well as the capacity of the states is determined.

It is deduced from the numerical results that addition of the large-scale renewable energy-based power plants can improve the reliability indices of the power system when the VR batteries are connected to them.

REFERENCES

1. Liu X. and S. Islam. Reliability evaluation of a wind-diesel hybrid power system with battery bank using discrete wind speed frame analysis. IEEE International Conference on Probabilistic Methods Applied to Power Systems, 2006.

2. Liu Xu, et al. Reliability evaluation of a wind-diesel-battery hybrid power system. IEEE Technical Conference on Industrial and Commercial Power Systems, 2008.
3. Khadkikar V., Rajiv K. Varma and Ravi Seethapathy. Grid voltage regulation utilizing storage batteries in PV solar—Wind plant based distributed generation system. IEEE Electrical Power & Energy Conference, 2009.
4. Giraud F. and Zyiad M. Salameh. Steady-state performance of a grid-connected rooftop hybrid wind-photovoltaic power system with battery storage. IEEE Transactions on Energy Conversion, 16(1), 2001, 1–7.
5. Lu, Ming-Shun, et al. Combining the wind power generation system with energy storage equipment. IEEE Industry Applications Society Annual Meeting, 2008.
6. Völler S., Al-Awaad A-R. and Verstege J.F. Wind farms with energy storages integrated at the control power market. CIGRE/IEEE PES Joint Symposium on Integration of Wide-Scale Renewable Resources Into the Power Delivery System, 2009.
7. Barote L., Georgescu M. and Marinescu C. Smart storage solution for wind systems. Power-Tech IEEE conference, Bucharest, 2009.
8. Hu P., Karki R. and Billinton R. Reliability evaluation of generating systems containing wind power and energy storage. IET Gener- Transm- Distrib, 3(8), 2009, 783–791.
9. Gao Feng, Arne Hallam and Chien-Ning Yu. Wind generation scheduling with pump storage unit by collocation method. IEEE Power and Energy Society General Meeting, 2009.
10. Zahedi A. Technical analysis of an electric power system consisting of solar PV energy, wind power, and hydrogen fuel cell. IEEE Power Engineering Conference, Australasian Universities, 2007.
11. Dehghan S., et al. Optimal sizing of a hydrogen-based wind/PV plant considering reliability indices. IEEE International Conference on Electric Power and Energy Conversion Systems, 2009.
12. He Aishan, Zhuoyong Yan and Weidong Gu. Research on non-grid-connected wind power systems used for hydrogen production from water-electrolytic. IEEE World Non-Grid-Connected Wind Power and Energy Conference, 2009.
13. Miller A.I. and Duffey R.B. Integrating large-scale cogeneration of hydrogen and electricity from wind and nuclear sources (NUWIND TM). Proceedings of the 2008 International Congress on Advances in Nuclear Power Plants, 2008.
14. Thakur T. et al. Optimization of imbalance cost for wind power marketability using hydrogen storage. Power System Technology and IEEE Power India Conference, POWERCON, 2008.
15. Wang C. and Hashem Nehrir M. Power management of a stand-alone wind/photovoltaic/fuel cell energy system. IEEE transactions on Energy conversion, 23(3), 2008, 957–967.
16. Chen S.X. and Gooi H.B. Capacitor planning of power systems with wind generators and PV arrays. TENCON IEEE Region 10 Conference, 2009.
17. Jung Hee-Yeol, et al. A study on the operating characteristics of SMES for the dispersed power generation system. IEEE Transactions on Applied Superconductivity, 19(3), 2009, 2028–2031.
18. Lerch E. Storage of fluctuating wind energy. IEEE European Conference on Power Electronics and Applications, 2007.
19. Mansour Mohamed, Mansouri M.N. and Mimouni M.F. Performance Evaluation of a Flywheel Energy-Storage System Associated to a Variable-Speed Wind Generator. Sustainability in Energy and Buildings, Springer Berlin Heidelberg, 2012, 201–211.
20. Miyake S. and Nobuyuki T. Vanadium redox-flow battery for a variety of applications. IEEE Power Engineering Society Summer Meeting, 1, 2001.
21. Shibata A. and Kanji S. Development of vanadium redox flow battery for electricity storage. Power Engineering Journal 13(3), 1999, 130–135.
22. Skyllas-Kazacos M. et al. Recent advances with UNSW vanadium-based redox flow batteries. International Journal of Energy Research, 34(2), 2010, 182–189.
23. Shibata A., Sato K. and Masato N. Development of vanadium redox flow battery for photovoltaic generation system. IEEE Photovoltaic Energy Conversion, 1994.
24. Billinton R. and Ronald N.A. Reliability Evaluation of Power Systems. 2nd Edition, Plenum Press, New York and London, 1994.
25. Ghaedi A. et al. Toward a comprehensive model of large-scale DFIG-based wind farms in adequacy assessment of power systems. IEEE Transactions on Sustainable Energy, 5(1), 2014, 55–63.
26. Billinton R., et al. A reliability test system for educational purposes-basic data. IEEE Transactions on Power Systems, 4(3), 1989, 1238–1244.
27. Subcommittee, Power Market. IEEE reliability test system. IEEE Transactions on Power Apparatus and Systems, 6, 1979, 2047–2054.