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Capacity Evaluating of Accommodating Renewable Energy Considering Adjustable Characteristic of Nuclear Units and External Transport Power Constraints

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Abstract. Along with renewable resource dominating the evolutionary trend of the further electrical structure, the uncertainty characteristics of renewable energy have made a profound influence on electrical dispatch, operation, and planning in modern renewable energy resource. As a result, the issue of quantitative capacity evaluating of accommodating renewable energy has drawn widespread concern across the home and abroad. In this paper, we fully consider the impact of both of the adjustable characteristic of nuclear plants and the external transmission power constraints caused by multi-area interconnection on the operation mode of power system with proportion of renewable energy, on this basis, a novel modified model based on unit commitment (UC) to evaluated the capacity of accommodating renewable energy of power system is proposed. Furthermore, an actual example is used to demonstrate the feasibility of the proposed method.

1. Introduction

Nowadays, building a new generation of power system with the productional and operational theme of “Clean, Low-carbon, Safe and efficient” is the curial point to cope with the global fossil energy crisis and a series of climate and environment problems. Under this background, nuclear power plants and renewable energy have been promoted in many countries and areas in order to reduce the dependence on conventional fossil energy sources. However, because of the characters of randomness uncertainty and difficult dispatching of the output of renewable energy, the economic operation of renewable energy resource needs to consider the impact of different uncertainty characters that come from the renewable source and load forecasting.

Surrounding with the issue that is just mentioned, a lot of research on the quantitative assessment of the capacity of accommodating renewable energy has been put forward. *Ref*[1] presented a method for predicting the accommodation of renewable energy with considering peak-load shaving and transmission regualtion. *Ref*[2] analysis the several kernel factors of accommodating renewable energy considering the multi-area interconnection. And *Ref*[3] uses probabilistic production simulation based



on available capacity distribution to analysis the reliability of power supply and the capacity of accommodating renewable energy in the environment of multi-area interconnection. *Ref* [4] - [6] take the joint operation of several different types of units (such as thermal unit, hydropower units, pumped storages, compressed air storages) into account, and then construct different solution method for evaluating the capacity of accommodating renewable energy. It can be easily seen that existing literature which is about the capacity evaluating of accommodation renewable energy can be divided into two categories, one focuses on analyzing the impact of the multi-area interconnection on renewable energy consumption, whereas another one studies the impact of the coordinated operation of different types of conventional units and renewable energy on the problem of accommodating renewable energy. However, in some countries and area (like United States, France, Japanese, Germany and some areas in China, etc.) with the electric structure dominated by thermal units, nuclear units, and renewable energy, because of the lags behind of investment and construction and the limit of resource endowment, the hydropower units and different types of energy storage in this area account for a small proportion^{[7]-[18]}. Therefore, the ability to promote the absorption of renewable energy is limited by simply using the regulating characteristic of thermal power, In this condition, the role of giving rein to an adjustable characteristic of nuclear units has seemed to become the most important and unique method to solve the problem of peak-load shaving brought by integration of renewable energy. In this paper, we fully consider the impact of both the adjustable characteristics of unclear units and multi-area interconnection on accommodating renewable energy, and analysis the capacity of accommodation renewable energy based on the method of units commitment (UC).

Based on the above, the arrangement of the context is as follows. Section II describes the solution method of the output of renewable energy by using stochastic simulation technique. Section III describes a model of nuclear plants considering the adjustable characters of power output, and a simulation method of electric power input from eternal regions considering the multi-area interconnection. section IV presents the evaluation method of the available capacity of accommodating renewable energy based on section III. section V give the result of an actual province power grid in China by using the proposed models. section VI outlines the conclusion of the research.

2. Simulation technique of renewable energy

Simulation techniques of renewable energy can be mainly divided into two categories. one is about the simulation of wind farms, and another is about the simulation of photovoltaic units. Here list the corresponding simulation themes of different kinds of renewable energy.

1) Simulation of wind farms

The uncertainty of power output of wind farms can be divided into randomness uncertainty and sequential uncertainty. Taking different uncertainty characteristics of the output of wind farms into account, a suitable simulation scheme is established as follows. Firstly, according to the historical data of wind speed by energy management system (EMS), statistical laws of correlation and randomness of wind farms is then analyzed by calculating corresponding evaluation indexes of randomness uncertainty and sequential uncertainty of power output of wind farms. Furthermore, the stochastic difference equation is used to simulation the correlation and randomness of the time series of the power output of wind speed. Besides, by using sequential Monte Carlo (SMC) technique, the sample of times series of wind speed is generated. Based on this, the sample of the power output of wind farms can be simulated though characteristic curve of wind farms which represents the relationship of wind speed and power output of wind farms.

The stochastic difference equation of wind speed can be described as follows:

$$v_{i,t} = v_{i,t-1} - \theta(v_{i,t-1} - \mu) + \sqrt{w(v_{i,t-1})}(W_{i,t} - W_{i,t-1}) \quad \text{SEQ}$$

Where $v_{i,t}$ and $v_{i,t-1}$ are the sample value of wind speed at the time t and the time $t - 1$, respectively; $t = \{1, 2, 3, \dots, T\}$, T is the amount of simulation period; μ is the mean of wind speed; $W_{i,t}$ and $W_{i,t-1}$ are the random variables of wind farms i at the time t and the time $t - 1$ that satisfied the probability

distribution of Brownian motion. $\sqrt{w(v_{i,t-1})}$ is determined by the characteristic parameter of the Weibull distribution function of wind speed.

After obtaining the sequential sample of wind speed, the simulation series of the power output of wind farms can be easily obtained by the following formula:

$$p_{i,t} = n_{i,t}(1 - \eta_i)C_i(v_{i,t}k_{i,h}k_{i,m})_{\text{SEQ}}$$

Where $p_{i,t}$ is the power output of wind farm i at time t ; $n_{i,t}$ is the number of available units, whose operational state is normal, of wind farm i at time t ; $\eta_{i,t}$ is the wake factor of wind farm i ; C_i is the characteristic curve of wind farms; $k_{i,h}$ and $k_{i,m}$ are the correction factor of wind farms in order to describe the impact of the daily characteristic and the seasonal characteristic on the power output of wind farms.

2) Simulation of photovoltaic units

The power output of photovoltaic units is closely depended on the irradiance that is received on the photovoltaic panel and the site where the solar panels are installed, as a result, the simulation of power output of photovoltaic units can be included the model of solar irradiance and the model of solar panels. Firstly, the extra atmospheric irradiance of geographical location where the photovoltaic power plants installed needs to be calculated by using the mathematical model of global solar irradiance. Based on this, according to the top-to-down and layer-by-layer decomposition method, the sequential series of power output of photovoltaic units is then obtained, and at this time, the HDRK model is used to simulate the light of receiving condition of the ground photovoltaic panels. Furthermore, combining with the conversion function of photovoltaic to electric power output, the sequential output of photovoltaic units can be obtained. Among them, the equation 2 give the process of gives output of photovoltaic units.

$$p_{i,t} = n_{i,t}K_t p^e (I_T / I_s)_{\text{SEQ}}$$

Where $n_{i,t}$ is the number of the available terrestrial photovoltaic modules for photovoltaic plant i at time t ; I_T are the ambient irradiance of the atmosphere irradiance of the photovoltaic units, and I_s is the benchmark of atmosphere irradiance; K_t is the attenuation factor that is used the impact of extern environment factor (such as obscured, and weakened by meteorological, temperature difference, shadow by cloud, etc.) on the irradiance of photovoltaic units. p^e is the standard power output of photovoltaic irradiance at the reference irradiance I_s (usually, $I_s = 1000 \text{ W} / \text{m}^2$).

3. Models of nuclear plants considering adjustable dispatch of power output

1) Metamaterial model of nuclear units considering adjustable characteristic of power output

Generally, the conventional operation mode of nuclear units is to run with a basic system load. However, with the increasing permeability rate of renewable energy year by year, research on a characteristic of peak load shaving of nuclear units has drowned public attention all over the world. Since the 1970s, different types of nuclear loads, such as pressurized water reactors (PWR), boiling water reactors (BWR), improved thermal neutron reactors (TNW), track tests and actual operations, have been implemented in United States, Germany, France, Japan, and other countries. It has been shown that the operation of daily or weekly load tracking does not adversely affect the fuel performance over 40 years of experience in PWR. Even though by use of the adjustable characteristic of unclear units, the radioactivity concentration of the primary coolant does not obviously increase, which better confirms the reliability of the pressurized water reactor. Feasibility of daily load tracking operations.

In this paper, we take the adjustable characteristic of PWR that is widely used for example, due to the design structure and actual operation mode of PWR, PWR power stations can track daily load with the rate of an output change of $(\pm 5\%P_n) / \text{min}$. based on which, the constraints of output and load-tracking of PWR units are listed as follow:

$$P_{\min}^N \leq P_t^N \leq P_{\max}^N_{\text{SEQ}}$$

Where P_t^N is the output of nuclear units at time t , P_{min}^N and P_{max}^N are the minimum and maximum electrical power output of nuclear units (generally speaking, $P_{min}^N \in [0.4 \times P_{max}^N, 0.4 \times P_{max}^N]$).

Load-tracking constraint:

$$\begin{cases} P_t^N - P_{t-1}^N \leq 5\%P_n \\ P_{t-1}^N - P_t^N \leq 5\%P_n \end{cases} \quad \text{SEQ}$$

Where P_n is the rated output of PWR unit. This constraint means that PWR units is allowed to change its power output with a maximum rate of $5\%P_n$ per minute.

Actually, considering the depth and speed limits of peak shaving, in most cases (especially in Guangzhou in China), PWR nuclear power plants use "12-3-6-3" daily load tracking mode to shave peak load, in other words, full-power operation for 12 hours, 3 hours for power reduction, 6 hours of continuous operation at low power level, and 3 hours of power up to full power operation. The adjustable characteristic curve of the power output of nuclear units is described in Fig.1. in this mode of the condition, because the characteristic curve of system load is similar as the output regulation of nuclear units, therefore, this kind of operation mode has become the main method to improve the available capacity of accommodating of renewable energy which especially in proposed areas.

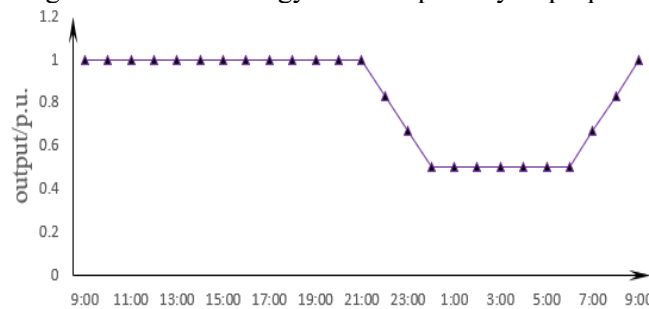


Fig.1 Daily output curve of PWR units

2) Equivalent generator model of transmission power from extern areas

Because of the large demand of the electric power load and the uneven distribution of energy resources, load center, and environmental protection, the mutual supply of multi-areas electric power has become an inevitable trend of the power system under the circumstance of integration of renewable energy. in this circumstance, it becomes another effective measure to realize the trans-regional absorption of renewable energy by tracking the fluctuation rules of renewable energy and power supply of interregional areas. In order to simplify the analysis of the capacity evaluating of accommodating renewable energy, it can be taken the transmission power from the extern areas as a corresponding equivalent generator or virtual system load. Fig 2 shows the equivalent process of transmission power from extern areas.

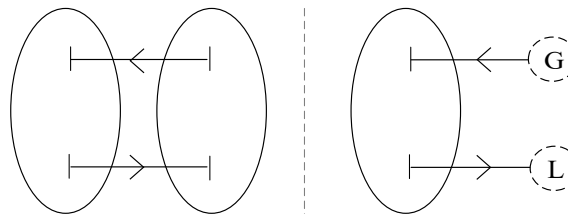


Fig 2 The equivalent model of transmission electric power from extern areas

It can be seen from Fig.2 that the equivalent model of the transmission power is depended on the direction of power flow among the multi-areas. In other words, when the direction of electric power is from the outer areas to the inner areas, the simplification of the external power supply can be considered as an equivalent power supply, on the contrary, when the direction of electric power is from the inner areas to the outer areas, the corresponding work of simplification of the external power supply can be

treated as an equivalent virtual load, based on this, considering the limit of transmission power among multi-areas, the equivalent electric output of external areas can be modeled as the constraints listed as following.

$$p_{i,j}^{\min} \leq |p_{i,j,t}| \leq p_{i,j}^{\max} \quad \text{SEQ}$$

Where $P_{ij}^{\min}, P_{ij}^{\max}$ are the upper and lower of external transport power between the area i and the area j , $p_{i,j,t}$ is the real-time transmission power at time t .

4. Available capacity evaluation of accommodating renewable energy

In order to receive the available capacity evaluating of accommodating renewable energy considering the adjustable characteristic of unclear units and external transport power of multi-areas. We built an improved security constraint unit commitment (SCUC) with additional constraints include the operational constraints, ramping constraints of nuclear units and the upper and lower constraints of external transport power. in the proposed model of available capacity evaluation of renewable energy, the minimum operating cost of the renewable energy resource is taken as the objective function that is listed as follows.

$$\min C = \sum_{t=1}^T \left(\sum_{i=1}^{N_C} (f(P_{i,t}^C) + Q_i^{on} u_{i,t}) + \sum_{i=1}^{N_N} Y(P_{i,t}^N) + \rho_L \sum_{i=1}^{N_L} P_{i,t}^L + \rho_W \sum_{i=1}^{N_W} (P_{i,t}^{W(0)} - P_{i,t}^W) + \rho_S \sum_{i=1}^{N_S} (P_{i,t}^{S(0)} - P_{i,t}^S) \right) \quad \text{SEQ}$$

Where the N_C, N_N, N_L, N_W and N_S are respectively the number of thermal generators, nuclear units, system load, wind farms and photovoltaic units. $P_{i,t}^C$ is the output of thermal generators i at time t , and $f(P_{i,t}^C)$ is the operating cost of conventional thermal units, Q_i^{on} is the startup cost and the shutdown cost of the conventional thermal units, $u_{i,t}$ is the operating state of thermal units i at time t , when the units i is run, $u_{i,t} = 1$; otherwise, $u_{i,t} = 0$. $P_{i,t}^N$ is the power output of nuclear power unit i at time t and $Y(P_{i,t}^N)$ is the fuel cost and maintenance charge of it. $(P_{i,t}^{W(0)}, P_{i,t}^W)$ and $(P_{i,t}^{S(0)}, P_{i,t}^S)$ are the available installed capacity and actual electric output of wind farms and photovoltaic units. ρ_L, ρ_W, ρ_S are corresponding penalty factors of the curtailment of the system load, the wind units or the photovoltaic units.

The mathematical expression of the specific constraint is as follows. Among the constraints of equations (8) - (15), the equations (8) - (11) are the constraints of the upper and lower of the power output, the ramping rate, the minimum time of startup and shutdown for conventional thermal units, the equations (12) is the abandon of renewable energy that includes wind farms or photovoltaic units, the equations (13) is the real-time power balance between the electric output of different types of generators and the amount of the system load, the equations (14) - (15) the constraint of upper and lower system spinning reserve and the constraint of power balance.

$$P_{\min}^C \leq P_i^C \leq P_{\max}^C \quad \text{SEQ}$$

$$-P_D \leq P_t^C - P_{t-1}^C \leq P_U \quad \text{SEQ}$$

$$\begin{cases} 0 \leq P_{i,t}^W \leq P_{i,t}^{W(0)} \\ 0 \leq P_{i,t}^S \leq P_{i,t}^{S(0)} \end{cases} \quad \text{SEQ}$$

$$\begin{aligned}
& \sum_{i=1}^{N_N} P_{i,t}^N + \sum_{i=1}^{N_C} P_{i,t}^C + \sum_{i=1}^{N_W} P_{i,t}^W + \sum_{i=1}^{N_S} P_{i,t}^S = \sum_{i=1}^{N_D} P_{i,t}^D \\
& \quad \text{SEQ} \\
& -d_t^C \leq x_t^C - x_{t-1}^C \leq u_t^C \\
& \quad \text{SEQ} \\
& \sum_{i=1}^{N_C} p_{i,t}^C + \sum_{i=1}^{N_N} p_{i,t}^N + \sum_{i=1}^{N_S} p_{i,t}^S + \sum_{i=1}^{N_W} p_{i,t}^W = \sum_{i=1}^{N_L} p_{i,t}^L \\
& \quad \text{SEQ} \\
& \sum_{i=1}^{N_C} (p_{i,t}^{C,\max} - p_{i,t}^C) + \sum_{i=1}^{N_N} (p_{i,t}^{C,\max} - p_{i,t}^C) + \sum_{i=1}^{N_E} (p_{i,t}^{E,\max} - p_{i,t}^E) \geq \sum_{i=1}^{N_L} p_{i,t}^L + \alpha^{up} \left(\sum_{i=1}^{N_W} p_{i,t}^W + \sum_{i=1}^{N_S} p_{i,t}^S \right) \\
& \quad \text{SEQ} \\
& \sum_{i=1}^{N_C} (p_{i,t}^C - p_{i,t}^{C,\min}) + \sum_{i=1}^{N_N} (p_{i,t}^C - p_{i,t}^{C,\min}) + \sum_{i=1}^{N_E} (p_{i,t}^E - p_{i,t}^{E,\min}) \geq \sum_{i=1}^{N_L} p_{i,t}^L + \alpha^{down} \left(\sum_{i=1}^{N_W} p_{i,t}^W + \sum_{i=1}^{N_S} p_{i,t}^S \right) \\
& \quad \text{SEQ}
\end{aligned}$$

Where P_{\min}^C, P_{\max}^C are the minimum and maximum power output of conventional thermal unit i , P_U, P_D is the upper and down ramping rate of thermal units. d_t^C, u_t^C are two exclusive characteristic variables that reflects the change of the system status, when the unit runs, d_t^C equals to 0, u_t^C equals to 1, oppositely, when it is out of service, d_t^C equals to 1 and u_t^C equals to 0. $P_{i,t}^N, P_{i,t}^C, P_{i,t}^R, P_{i,t}^W, P_{i,t}^S$ are respectively the power output of unclear units, conventional thermal units, wind units and photovoltaic units. $P_{i,t}^D$ is the possible amount of load shedding in some extremely circumstance.

5. Case Studies and Simulation

In order to illustrate the feasibility of the proposed method of capacity evaluating of renewable energy, an actual power grid in China is tested, in this chapter, two different situations are compared to analysis the improved effect of the renewable consumption capacity, in this actual power grid, the total amount of installed capacity of the conventional thermal units is 71058MW, and the installed capacity of nuclear units and renewable energy is respectively about 1320MW and 1200MW. based on the proposed method with the optimization function of (7) and a series of conventional constraints (8) - (12), the constraints (1) - (3) of renewable energy, and the constraints (4) - (5) of nuclear units, and the constraints (6) of external transport by multi-areas interconnection. Simulation is carried out in 40 hyper-threaded PC server, and hardware simulation environment is Intel 2.5GHz 10 core \times 2 CPU, 256G RAM, the software is Visual Studio 2017 and CPLEX 12.80. the precision is set at 0.5%. Table.1 lists the result of the proposed cases whether considering the adjustable characteristic of nuclear units and multi-area interconnection or not. Of which, the plan.2 considers the adjustable characteristic of nuclear units and plan.1 is not.

Table.1 evaluating result of the index in different Plans.

Method	I_w/GWh	I_s/GWh	I_c/CNY
Plan 1	880.4	248.9	45.03
Plan 2	679.2	97.2	44.33

Appendix: I_w is the amount of electrical power curtailment of wind farms, I_s is the amount of electrical power curtailment of photovoltaic unit, I_c is the operational cost of renewable energy resource. The corresponding solution algorithm can be found in *ref*[2].

We can see from table.1 that the capacity of accommodating renewable energy in plan 1 is better than that in plan 2, which demonstrated the feasibility of the adjustable characteristic of nuclear units and multi-area interconnection. Fig.3 shows the result of the electric power of renewable energy by hour under different schemes.

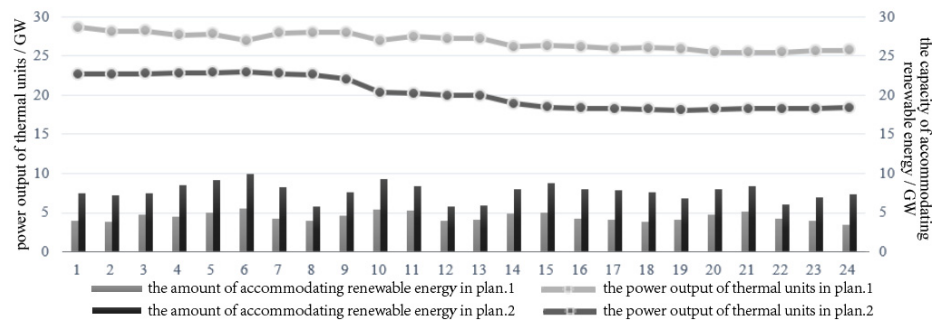


Fig.3 result of accommodating renewable energy and power output of conventional thermal units

After considering the adjustable characteristic of renewable energy and external transport power of multi-interconnection, the capacity of renewable energy has increased 2487MW on the average, besides, the operation cost dominated by thermal units has gone down.

6. Conclusion

This paper builds an improved security constraint unit commitment (SCUC) to evaluate the available capacity of renewable energy considering the adjustable characteristic of nuclear units and multi-areas interconnection, and based on this, an actual power grid is tested to demonstrate the validity and correctness of the proposed method. From the results, we can see that the adjustable characteristic of nuclear units and multi-area has an obvious effect on the more absorption of renewable energy. Besides, these factors also have an obvious positive significance to reduce the operating cost of the power system.

References

- [1] Zhou, Wei; Hu, Shubo; Sun, Hui. Joint generation dispatch of power system with nuclear power units participating in peak load regulation. *International Conference on Smart Grid and Clean Energy Technologies*: 324-327, 2016.
- [2] Attya, Aymanakryaha T.; Hartkopf, Thomas. Utilizing stored wind energy by hydro-pumped storage to provide frequency support at high levels of wind energy penetration. *IET Generation, Transmission & Distribution*, 9(12): 1485-1497, 2015.
- [3] Cheng, Hongliang. Long-term power system operation simulation including large-scale renewable energy. Xi'an:Xi'an Jiaotong University, 2015.
- [4] Amjady N, Ansari M R. Hydrothermal unit commitment with AC constraints by a new solution method based on benders decomposition[J]. *Energy Conversion and Management*, 2013, 65: 57-65.
- [5] Chen C L. Optimal wind - thermal generating unit commitment[J]. *IEEE Transactions on Energy Conversion*, 2008, 23(1): 273-280
- [6] Ye, Qizhen. China's nuclear power development after Fukushima nuclear power plant accident. *Proceedings of the CSEE*, 32(11): 1-8, 2012.
- [7] Zhang, Yao; Wang, Jianxue. GEFCom2014 probabilistic solar power forecasting based on k-nearest neighbor and kernel density estimator. *IEEE Power & Energy Society General Meeting*, 2015.
- [8] Wang, Jianxue; Ahmed Faheem Zobaa; Huang, Chengcheng. Day-ahead allocation of operation reserve in composite power systems with large-scale centralized wind farms. *Journal of Modern Power Systems & Clean Energy*, 4(2): 238-247, 2016.
- [9] Wang, Jun; Zhao, Jie; Ye, Xiaoli. Safety constraints and optimal operation of large-scale nuclear power plant participating in peak load regulation of power system. *IET Generation, Transmission & Distribution*, 11(13): 3332-3340, 2017.
- [10] Akin, H.Levent; Altin, Vural. Rule-based fuzzy logic controller for a PWR-type nuclear power plant. *IEEE Transactions on Nuclear Science*, 38(2): 883-890, 1991.

- [11] Yim, Man-Sung; Christenson, John M. Application of optimal control theory to a load-following pressurized water reactor. *Nuclear Technology*, 100(3): 361-377, 1992.
- [12] Khajavi, Mehrdad N.; Menhaj, Mohammad B.; Suratgar, Amir A. A neural network controller for load following operation of nuclear reactors. *Annals Nuclear Energy*, 29(6): 751-760, 2002.
- [13] Kirby, Brendan; Kueck, John; Leake, Harvey. Nuclear generating stations and transmission grid reliability. 39th North America Power Symposium: 279–287, 2007.
- [14] Khorramabadi, Sima Seidi; Boroushaki, Mehrdad; Lucas, Caro. Emotional learning-based intelligent controller for a PWR nuclear reactor core during load-following operation. *Annals Nuclear Energy*, 35: 2051-2058, 2008.
- [15] Saif, Mehrdad. A novel approach for optimal control of a pressured water reactor. *IEEE Transactions on Nuclear Science*, 36(1): 1317-1325, 1992.
- [16] Forsberg, Charles W. Economics of Meeting Peak Electricity Demand Using Hydrogen and Oxygen from Base-Load Nuclear or Off-Peak Electricity. *Nuclear Technology*, 166(1):18-26, 2009.
- [17] Berkovich, V.M.; Gorokhov, V.F; Tatarnikov, V.P. Possibility of regulating the capacity of a power system by means of nuclear power plants. *Teploenergetika*, 6:16-19, 1974.
- [18] Ebert, David D. Practicality of and benefits from the application of optimal control of pressured water reactor maneuvers. *Nucl Technol*, 58(2): 218-232, 1982.