Original Research

A hierarchical heuristic method to analysis of economics and safety of a pressurized water reactor in a power market

Ghafour Ahmad Khanbeigi [1]. Naser Mansour Shariflou [1*]. Gholamreza Jahanfarnia [1]. Mohamad Kazem Sheikh-el-Eslami [2]. Kaveh Karimi [3]

Received: 16 Oct 2022/ Accepted: 23 Oct 2023/ Published online: 23 Oct 2023

* Corresponding Author, naser.sharifloo@gmail.com

1- Department of Nuclear Engineering, Science and Researches Branch, Islamic Azad University, Tehran, Iran
2- Power system Lab, Tarbiat Modares University, Tehran, Iran
3- East Tehran Branch, Islamic Azad University, Tehran, Iran

Abstract
In this paper, according to the discussion of improving the safety of nuclear power plants (NPPs) according to reports and findings of Fukushima accident, a model for the economic analysis of a NPP with a higher level of safety in an electricity power market is provided. Therefore, a solution to determine the balance between safety and economy to deal with station black-out (SBO) accident in a pressurized water reactor (PWR) nuclear power plant is presented. A supply function equilibrium (SFE) that takes into account carbon tax in the power market is used to calculate the profit of each power generation firm. A hierarchical innovative approach is used to make decisions about improving the safety of NPP. In this method, breakeven point (BEP) is used as the decision criterion to compare the safety improvement costs and profit of NPP in the power market. This method is used to add an emergency diesel generator (EDG) and a mobile heat exchanger to a NPP that examines the impact of investment costs and profits. The result shows that with the addition of an EDG to the NPP, the BEP of investment costs and net profit of the NPP is one month later. Finally, it can be suggested to the investor of the NPP to add EDG to improve safety, so that the implementation of this proposal leads to a slight increase in payback period, but greatly reduces core damage frequency (CDF) of NPP reactor in SBO accident.

Keywords - Safety; Electricity market; Payback period; Economics; Optimization

INTRODUCTION

The Fukushima Daiichi NPP accident was a beyond design basis accident (BDBA) known as SBO, resulting in complete failure of both on-site and off-site alternating current (AC) electricity sources. All but one of the EDGs were destroyed by the tsunami and subsequent floods [1], [2].

Regarding nuclear power plant spent fuel pool (SFP) cooling strategies in emergency situations, mobile heat exchanger is an alternate cooling of SFP. A trailer with a pump and a heat exchanger that can be quick connected to the SFP. This mobile heat exchanger can use several means of cooling water (including river water) and can thus ensure long-term cooling of the spent fuel elements as shown in Fig. 1 [3], [4].

FIGURE 1
SFP MOBILE HEAT EXCHANGER

All PWR power plants in Japan use diesel (DG) generators for uninterruptible power supplies. These types of engines require cooling water to work, meaning that the Ultra Heat Sink (UHS) for diesel engine operation must maintain its performance. Therefore, if any natural access to UHS (LUHS) occurs as a result of external event, all emergency power supplies will be out of order. So, in addition to uninterruptible power supplies, installation of non-UHS based power supplies (e.g. DG air cooling) is essential. The use of this type of power supply for alternative AC creates variation between alternative AC and uninterruptible power supply, increasing reliability of the electricity sources [5].Plan and construction options were investigated to tackle with station blackout event to reduce both the frequency of event initiator and probability of incident reduction [6].

The experiences and reports mentioned above indicate a great need to increase the safety of NPP to cope with SBOs. In this study the safety enhancement is proposed with an extra EDG (type of air cooling) and a mobile heat exchanger.In order to implement any of the mentioned options, extra investment cost is needed for NPP. The net present value (NPV) method is used in this paper [7], [8]. After the construction of the power plant is completed, the amount of NPV reaches to largest negative amount with the capital cost incurred. Over time, the negative NPV value decreases due to the end of the investment. Thus, the NPV curve crosses zero when the income from the sale of electricity in the electricity market begins. This is point of breakeven and started pay-back of project [9]. Therefore, the total costs of power generating plants and the annual income in the power grid is required. In unregulated electricity markets, the power generating plants offer their offers in the electricity market the next day with offers to sell or buy. The competition and auction mechanism, determines the final price and balance for each hour. The competition and auction mechanism determines the equilibrium price and the quantity for each hour [10].

To calculate revenue, it is necessary to predict the electricity price in the electricity market during the studied period. Therefore, this paper considers a complementary approach to investigate the market interactions between the electricity power generation companies (GENCOs). The ability of complementary models to model the simultaneous optimization of several competing companies in the market is their strength [11–15]. In this project, a model for the economic analysis of the NPP for IEEE 30-bus electricity power grid has been developed, taking into account the carbon tax. Therefore, the price offer of electricity generating companies is predicted. For this purpose, the system was modeled using game theory. Power generation companies participate in a game to maximize their profit through competition and play a game with the proposed strategies of their generation quantities in the market. One of the most important specifications of power generators that limits the number of their bidding strategies is their ramp rate, which limits the increase or decrease of output within its range [15]. This model consists of an optimization for the independent system operator (ISO) and an optimization for each electricity generation company (GENCO), whose equations are implemented in the coupled MATLAB and GAMS software, and by solving this two-level optimization the market equilibrium point is calculated. To calculate income and NPV profit, the price at the equilibrium point is used.

CALCULATION OF MARKET PRICE

In this research the supply function equilibrium (SFE) model is used to calculate the electricity market clearing price (MCP). The most realistic method can be obtained by using this model to calculate some criteria such as quantitative curves of the price to the Genco sales price, independent system operator (ISO), GENCO income, GENCO profit, consumer purchase price and GENCO cost. In a constrained power market, there is constraint for demand, generation and ramp rate. There is a sell/ buy price for entire network per hour in a uniform power market. The problems of all power generation companies must be solved together to calculate the supply function equilibrium (SFE).

Suppose that the utility of consuming $P_{D_j}^{(t)}$ by consumer D_j at time t is equal to $f\left(P_{D_j}^{(t)}\right) = c_j^{(t)} P_{D_j}^{(t)} - 0.5 d_j^{(t)} P_{D_j}^{(t)^2}$ and the cost of production of $P_{S_i}^{(t)}$ by electricity supplier S_i at time t is $g\left(P_{S_i}^{(t)}\right) = a_i P_{S_i}^{(t)} + 0.5 b_i P_{S_i}^{(t)^2}$. Note that because the times of the day change significantly during the day, the coefficients of useful performance of consumers vary over time [12], [14], [15], [16]. The position of nuclear power in the energy mix needs to be reassessed, as the world moves towards carbon neutrality, because nuclear power does not generate any direct carbon dioxide emissions [17], [18]. Thermal power plants have to pay carbon tax, but nuclear power plants do not, and this affects the profitability of nuclear power plant compared to other power plants, so the carbon tax is important in the power grid despite the presence of NPPs. The carbon tax is a quadratic function of production as $CT\left(P_{S_i}^{(t)}\right) = (\gamma^0 \rho_i) P_{S_i}^{(t)} + 0.5(\beta \rho_i^2) P_{S_i}^{(t)^2}$ where γ^0 is the first-order parameter of carbon tax in $\$/ton$ and ρ_i is the emission intensity of electricity supplier i in ton/MWh and β is the carbon tax second-order parameter in $(\$/ton)/(ton/h)$ [19]. So, the carbon tax is applied as a quadratic function to the cost function in this paper. Therefore, the cost of production of $P_{S_i}^{(t)}$ by electricity supplier i at time t is equal to $g\left(P_{S_i}^{(t)}\right) = (a_i + \gamma^0 \rho_i) P_{S_i}^{(t)} + 0.5(b_i + \beta \rho_i^2) P_{S_i}^{(t)^2}$. The marginal cost function of $P_{S_i}^{(t)}$ by electricity supplier i at time t or its true bid function is equal to $MC_i^{(t)} = Bid_i^{true(t)} = (a_i + \gamma^0 \rho_i) P_{S_i}^{(t)} + (b_i + \beta \rho_i^2) P_{S_i}^{(t)}$. Each electricity supplier offers a power supply function for each hour in the following day. Firms are assumed to manipulate only their actual bid function, i.e., the bid function $Bid_i^{(t)} = \alpha_i^{(t)} + (b_i + \beta \rho_i^2) P_{S_i}^{(t)}$ for time t to ISO where $\alpha_i^{(t)}$ is bid of electricity supplier i at hour t in $\$/MWh$. So, the proposition of electricity supplier t is denoted time t is denoted by $[\alpha_1^{*(t)} \alpha_2^{*(t)} \dots \alpha_{ng}^{*(t)}]^T$, which ng is the number of electricity suppliers.

To calculate market equilibrium using SFE model, a set of two-level optimization problems must be solved together [12], [14]. The benefit maximization problem of the fth firm is fth upper-level problem. The ISO optimization problem is lower-level problem of each upper-level problem. Maximizing social welfare is the goal of ISO to meet constraints of demand and production. Therefore, the problem of optimizing ISO social welfare is written: $MaxJ_{ISO} = \sum_{t \in T} \left(\sum_{i \in D} f\left(P_{D_i}^{(t)}\right) - \sum_{i \in S} g\left(P_{S_i}^{(t)}\right) \right)$. Where J_{ISO} is social welfare, ISO objective function in \$.

Following the aforementioned definitions, ISO optimization is modeled as follows:

$$\mathrm{Max} J_{ISO} = \sum_{t \in T} \left(\sum_{i \in D} \left(c_i^{(t)} P_{D_i}^{(t)} - \frac{1}{2} d_i^{(t)} P_{D_i}^{(t)^2} \right) - \sum_{i \in S} \left(\alpha_i^{(t)} P_{S_i}^{(t)} + \frac{1}{2} (b_i + \beta \rho_i^2) P_{S_i}^{(t)^2} \right) \right) \quad (1)$$

s.t.:

$$\sum_{i \in S} P_{S_i}^{(t)} - \sum_{i \in D} P_{D_i}^{(t)} = 0 \qquad \forall t \in T \qquad (2)$$

$$P_{S_i}^{min} \le P_{S_i}^{(t)} \le P_{S_i}^{max} \qquad \forall i \in S, \forall t \in T \qquad (3)$$

$$-D_{rr_i}. P_{S_i}^{max} \le P_{S_i}^{(t)} - P_{S_i}^{(t-1)} \le U_{rr_i}. P_{S_i}^{max} \quad \forall i \in S, \forall t \in T \quad (4)$$

Where $P_{S_i}^{min}$ and $P_{S_i}^{max}$ are the lower and upper active power generation limits of firm i, S set of generation units, D set of consumers, T set of hours in understudy period, D_{rr_i} and U_{rr_i} are the ramp-down and ramp-up rate limits of firm i in $perunit/h$. The last constraint (Eq. 4) in NPP analysis is important, because most NPPs have low ramp rates. Market equilibrium may be significantly affected by ramp rate limits [15]. The optimization problem of the firm (GENCO) f , $\forall f \in F$ is modeled as follows:

$$\mathrm{Max}. \pi_f = \sum_{t \in T} (\sum_{i \in S_f} \lambda^{(t)} P_{S_i}^{(t)} - (a_i + \gamma^0 \rho_i) P_{S_i}^{(t)} - \frac{1}{2} (b_i + \beta \rho_i^2) P_{S_i}^{(t)^2}) \qquad (5)$$

s.t.:

$$ISO's\ optimization\ problem\ (1)-(4) \qquad (6)$$

Where π_f is the profit of firm (GENCO) f in \$, $\lambda^{(t)}$ is the electricity market clearing price at hour t in $\$/MW^2h$, S_f is set of generating units of firm f. In equation (5), the first term is income of the firm f, second and third terms are its electricity generation cost.

MARKET BALANCE

Definition of equilibrium in constrained market in detail has been given in [15]. Overall, however, the constrained market equilibrium point is defined as:

$$\left\{\alpha_i^{(t)} \middle| \, d\pi_f/d\alpha_i^{(t)} = 0\ \forall f \in F\ and\ \forall i \in U_f^{(t)}\ and\ \forall t \in T\right\} \cup \{\alpha_j^{(t)} | P_{S_j}^{(t)} = P_{S_j}^{min}\ or\ P_{S_j}^{(t)} = P_{S_j}^{max}\ or\ P_{S_j}^{(t)} = P_{S_j}^{(t-1)} - D_{rr\,j}.P_{S_j}^{max}\ or\ P_{S_j}^{(t)} = P_{S_j}^{(t-1)} + U_{rr\,j}.P_{S_j}^{max}\ \ \forall j \in C_f^{(t)}\ and\ \forall t \in T\} \qquad (7)$$

Where $C_f^{(t)}$ is set of finite units of GENCO f at time t and $U_f^{(t)}$ is set of unlimited units of GENCO f at time t. In order to calculate the SFE using the innovative algorithm discussed above, active production constraints and ramp rate constraints are required at equilibrium.

AN INNOVATIVE HIERARCHICAL METHOD FOR DETERMINING THE BALANCE BETWEEN SAFETY AND NPP COST

To reduce the risk of nuclear accidents such as SBO, the safety of nuclear power plants should be increased. On the other hand, additional safety systems and equipment can impose additional costs on NPP. So, one solution is to find a trade-off for additional cost and increased safety. In this paper, safety evaluation of Westinghouse (PWR type) NPP for station black-out incident was carried out. Fig. 2 shows a Westinghouse PWR type NPPs. The original design of this nuclear power plant includes 4 trains of the emergency diesel generator set in standby mode, which will maintain the required electricity in case of emergency, if there is no access to off-site electricity. There is also a seawater-cooled EDG to initiate an SBO event. In this paper, the addition of another type of diesel generator for a variety of AC electricity sources is considered to tackle with station black-out accident.

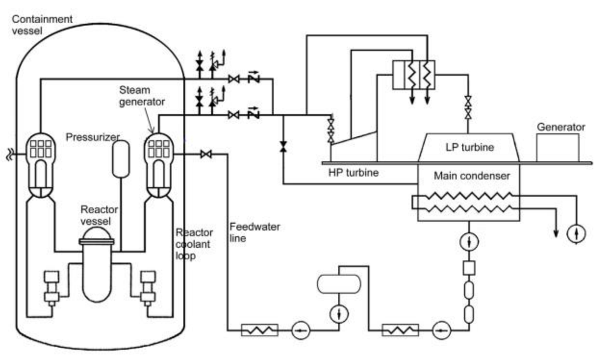

FIGURE 2
ERROR! NO TEXT OF SPECIFIED STYLE IN DOCUMENT.1NPP [20]

In recent years, many NPPs have conducted probabilistic safety assessments (PSAs) to identify and understand key plant vulnerabilities. PSA is a consistent technique for quantifying risk in nuclear power plants. It determines what adverse events can happen, with what probabilities and what the results they can have. Moreover, it could generate indirectly information such as the importance of participants in individual risks. In traditional PSA framework for commercial NPPs, PSA has three levels and, in this research, only first level is used. The PSA first level is described as follows:

Assessing plant failures determines the frequency of core damage accident. Provides insights into design weakness and way to prevent NPP core damage, that in many cases is a precursor of incidents leading to major radioactive releases with the potential health and the environmental outcomes. In this research, using the first level of PSA by Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE), the probabilistic risk of station black-out accident for a NPP is analyzed. SAPHIRE software is also used to analyze and calculate CDF_{SBO}. The resulting flowchart for determining the balance between safety and cost is shown in Fig. 3.

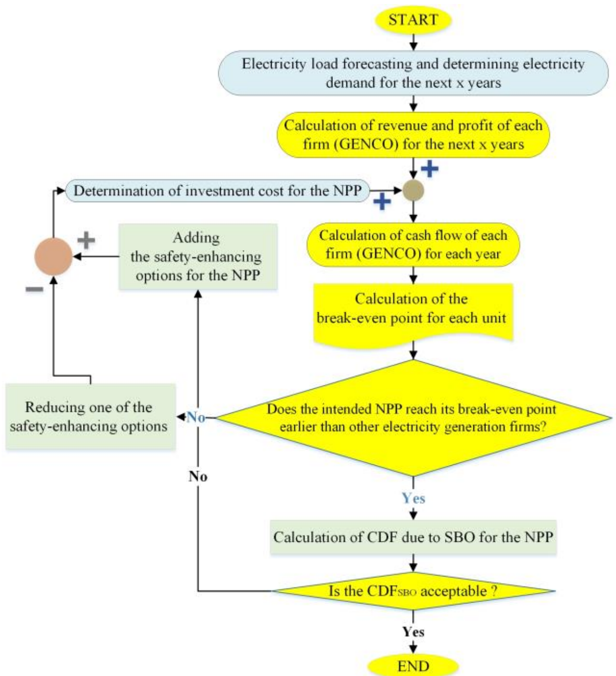

FIGURE 3
SUGGESTED FLOW DIAGRAM FOR DESIGNATION TRADE-OFF BETWEEN SAFETY AND COST

The offered flowchart can be classified as follows:

1- According to the electricity consumption history of the studied electricity network and the growth trend of electricity consumption in that network, the power system load and electricity demand are predicted for next x years.
2- The heuristic algorithm [15] is used and the parameters related to the equations are adjusted and then the income and profit of each firm (GENCO) is calculated for the next x years.
3- Safety enhancement options for NPP are added and related costs are calculated. Then, the total investment cost of NPP is determined based on the calculated safety costs and investment costs.
4- Using the results of the previous items, the cash flow per firm for the next x years is calculated. The NPV equation is presented as follows [9]:

$$NPV(m,Z) = \sum_{z=0}^{Z} R_z/(1+m)^z \qquad (8)$$

Where m is discount rate, Z is total number of periods, z is time of cash flow, R_z is the net profit during year z. The net profit of each GENCO in year zero is calculated using NPV and cash flow.
5- The breakeven point of the net profit and the investment cost of each GENCO is calculated.
6- Whether the breakeven point of the nuclear power plant occurs earlier than other electricity generation firms is investigated. It means, is the payback period of the NPP still competitive with other firms? If the answer is positive (yes), it goes to the next article. If the answer is negative (no), one of the safety-enhancing options is reduced and then goes to

the item 2.

7- Calculation of CDF for SBO after NPP safety improvement.

8- It is checked whether the calculated CDF_{SBO} is acceptable. If the answer is no, a safety-enhancing option will be added to the nuclear power plant. If the answer is yes, the algorithm is finished.

SIMULATION AND RESULT

The algorithm proposed in the previous section is applied to IEEE 30 bus test system (shown in Fig. 3) to evaluate the performance of this algorithm. In this electricity power system, there are one nuclear power plant and five fossil fuel power plants as follows:

- Power plant 1 and power plant 3 as combined cycle gas turbine (CCGT)
- Power plant 2 and power plant 4 as open cycle gas turbine (OCGT)
- Power plant 5 as an integrated gasification combined-cycle (IGCC) coal fired
- Power plant 6 as a nuclear power plant (NPP).

In Table 1, generation information and supply function parameters of these power plants are given. In the calculations performed in this research, carbon tax parameters γ^0 is assumed to be 30 $\$/ton$, β is 0.05 $(\$/ton)/(ton/h)$ and discount rate m is 0.05.

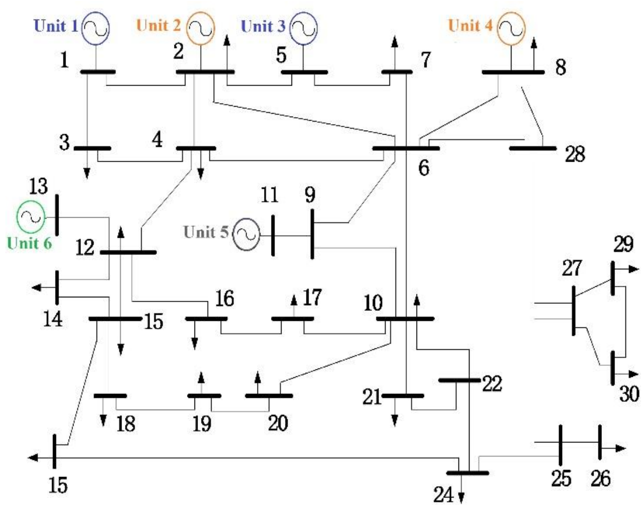

FIGURE 4
IEEE 30 BUS ELECTRIC SYSTEM

TABLE I
GENERATION INFORMATION FOR THE 30 BUS ELECTRIC POWER SYSTEM

Parameter / Firm	a	b	ρ	$P_{S_i}^{min}$	$P_{S_i}^{max}$	U_{rr_i}	D_{rr_i}
1	20	0.2	0.167	0	80	23/80	25/80
2	30	0.25	0.133	0	40	8/40	16/40
3	17.5	0.175	0.2	0	80	12/80	17/80
4	30	0.25	0.15	0	30	5/30	9/30
5	10	0.625	0.23	0	50	12/50	15/50
6	5.754	0.00066	0	70	80	2.4/80	2.4/80

a in $(\$/MWh)$, b in $(\$/MW^2h)$, ρ in (ton/MWh), $\mathbf{P}_S^{min}$ and $\mathbf{P}_S^{max}$ in (MW), U_{rr} and D_{rr} in $perunit/hr$

From the Alberta Electric System Operator (AESO), hourly electricity consumption data was obtained from year 2005 to 2016 [21]. The data is normalized based on the IEEE 30-bus electricity power system load data. Due to the growth of annual electricity consumption in the electricity grid and the subsequent expansion of electricity generation, 10 megawatts are added annually to one of the firms ($GENCO_S$) except the NPP, which can be seen in Table 2. The interface between MATLAB software and GAMS software was used to solve equilibrium problem with equilibrium constraints so by using results of these problems and replacing it in the equation (7), the profit of each firm is calculated [22].

TABLE 2
GENERATION EXPANSION DATA ($\boldsymbol{P_{S_i}^{max}}$ (MW))

Year	firm 1	firm 2	firm 3	firm 4	firm 5	firm 6
2005	80.0	40.0	80.0	30.0	50.0	80.0
2006	90.0	40.0	80.0	30.0	50.0	80.0
2007	90.0	50.0	80.0	30.0	50.0	80.0
2008	90.0	50.0	90.0	30.0	50.0	80.0
2009	90.0	50.0	90.0	40.0	50.0	80.0
2010	90.0	50.0	90.0	40.0	60.0	80.0
2011	100.0	50.0	90.0	40.0	60.0	80.0
2012	100.0	60.0	90.0	40.0	60.0	80.0
2013	100.0	60.0	90.0	40.0	60.0	80.0
2014	100.0	60.0	100.0	50.0	60.0	80.0
2015	100.0	60.0	100.0	50.0	70.0	80.0
2016	100.0	60.0	100.0	50.0	70.0	80.0

The investment cost [23-25] and the summary of the results obtained regarding the profit of 6 firms ($GENCO_s$) is listed in Table 3. According to the information in Table 3, the firm 3 will recover its investment cost after 12 years of selling electricity to the electricity power grid. The profit of firms 1, 2, 4 and 5 listed in Table 3 shows that BEP of investment and profit of these firms has not been achieved after 144 months. The results in Table 3 show that the NPV profit of the firm 6 (NPP) after 111 months has exceeded its investment cost. Therefore, the payback period of the firm 6 (NPP) is 111 months, which is achieved 33 months earlier compared to firm 3 (CCGT).

TABLE 3
NPV PROFIT AND INVESTMENT COST OF 6 FIRMS (ALL AMOUNTS IN $)

	firm 1	firm 2	firm 3	firm 4	firm 5	firm 6
Investment cost	60,018,654	25,151,786	48,351,574	23,472,496	98,620,362	166,320,000
Profit 144 months	35,686,759	4,103,460	48,793,309	3,407,870	29,771,251	**206,029,874**
Profit 111 months	27,774,202	2,906,145	38,184,508	2,378,088	23,625,872	**167,065,708**
Profit 112 months	28,006,858	2,937,660	38,498,461	2,404,737	23,811,027	**168,274,671**

In the main design of the NPP considered in this paper, it has 1 diesel generator with water cooling system to activate in SBO conditions. Adding a new 2 MW air-cooled diesel generator to the nuclear plant's safety system adds $1,604,000 to NPP investment cost, so the total investment cost for firm 6 after safety enhancements is $167,924,000. Considering the 112-month NPV profit of firm 6 (listed in Table 3) and comparing it with the total investment cost of NPP with improved safety, it is concluded that the payback period of the NPP with the addition of EDG is one month later. SFP mobile heat exchanger costs include a trailer-mounted, diesel driven centrifugal pump and a heat exchanger. Adding mobile heat exchanger adds $35,000 to the NPP investment cost [3], [4]. So, total investment costs of this NPP is calculated to be $ 166,355,000. Considering the 111-month NPV profit of firm 6 (shown in Table 3) and comparing it to the total investment cost of the safety improved NPP, it can be concluded that the addition of the SFP mobile heat exchanger has little effect on the payback period of this NPP.

TABLE 4
RESULTS OF THE FREQUENCY (PROBABILITY) OF CORE DAMAGE IN SBO

Event	CDF
SBO	1.701E-08
SBO (with additional EDG)	1.610E-08

In order to increase the safety of the NPP studied in this paper in the event of SBO, the options of adding different safety emergency systems were proposed and for the option of adding an additional EDG, the CDF_{SBO} was calculated. To validate the results listed in Table 4, the calculation of CDF of the NPP is also modeled by Risk Spectrum software and the result is 1.67E-08, which is very close to the result obtained by Saphire software and the difference is less than two percent. According to the validation of Saphire software, Saphire software is used to model the SBO accident after applying safety equipment to improve the safety of the NPP. The safety of this NPP has been increased by adding an air-cooled EDG to the safety system under SBO accident. Using fault tree analysis in SAPHIRE, the EDG failure probability is 2.26E-02. According to the results of the NPP safety calculations in Table 4, the reduction in the CDF_{SBO} is evident by adding the EDG. It should be noted that for the presented model and algorithm, it is recommended to investigate the issue of uncertainty for future studies.

CONCLUSION

A hierarchical heuristic search technique to determine the balance between safety and economy to deal with SBO incident in a NPP (PWR type) is presented in this paper. The Fukushima accident experiences demonstrated the urgent necessity to increase the safety of NPPs in response to SBO accident as a BDBA. The effects of SBO accident on the reactor core damage frequency of a NPP are very serious. The criterion for evaluating the investment cost needed for the additional safety-enhancing options, is breakeven point of NPV profit and the investment cost of NPP. For each firm, in order to find the breakeven point of NPV profit and investment cost, the expense and annual income of GENCOs are obtained. In order to find the income of the power plants from selling electricity and the costs of generating electricity in the deregulated electricity market, SFE model is used to predict how the competitive price of electricity will be discovered per hour.

According to the flowchart presented in this paper, the profit and income of each firm is calculated by taking into account the carbon tax in the power market. A safety enhancement option such as air-cooled EDG is then added to the NPP. By using this modeling, the case safety level of the NPP can be increased to the extent that its electricity sales price is still justified and the payback period of the mentioned NPP is competitive. One of the options to increase the safety of the NPP in event of SBO was to add an air-cooled EDG. The results of this paper show that the breakeven point of the NPP is reached one month later with the addition of EDG than with the addition of the SFP mobile heat exchanger. By installing additional EDG in PWR, the CDF_{SBO} results of PSA models show a great effect on safety enhancement. The results obtained in this paper show that the cost of the additional safety enhancement systems to improve the safety of the NPP in SBO accident has a small impact on the total investment costs, so with a small investment, the safety of the NPP is greatly increased.

REFERENCES

[1] *The Fukushima Daiichi Accident*. (2015). INTERNATIONAL ATOMIC ENERGY AGENCY. Retrieved from https://www.iaea.org/publications/10962/the-fukushima-daiichi-accident

[2] ENSREG, E. U. (2011). Stress Test. *Specifications, Annex I to the Declaration of ENSREG*. Retrieved from http://www.ensreg.eu/sites/default/files/EU Stress tests specifications_1.pdf

[3] Update of the Slovenian post-Fukushima action plan, *Slovenian Nuclear Safety Administration*, URSJV/RP-119/2021, Slovenia, December 2021

[4] Florida Power & Light/St. Lucie Site Revised FLEX Final Integrated Plan, *U.S. Nuclear Regulatory Commission*, L-2016- 057, 10 CFR2.202, 2016

[5] Nomoto, T. (2015). *Electrical systems design applications on Japanese PWR plants in light of the Fukushima Daiichi Accident*. Retrieved from https://inis.iaea.org/collection/NCLCollectionStore/_Public/46/066/46066617.pdf

[6] Al Shehhi AS, Chang SH, Kim SH, Kang HG (2013). Analysis of economics and safety to cope with station blackout in PWR. Ann Nucl Energy 59:63–71

[7] Teegala, S. K., & Singal, S. K. (2015). Economic analysis of power transmission lines using interval mathematics. *Journal of Electrical Engineering & Technology*, *10*(4), 1471–1479.

[8] Hulio, Z. H., & Jiang, W. (2018). Assessment of the apparent performance characterization along with levelized cost of energy of wind power plants considering real data. *Energy Exploration & Exploitation*, *36*(6), 1708–1728.

[9] Kharitonov, V. V, & Kosterin, N. N. (2017). Criteria of return on investment in nuclear energy. *Nuclear Energy and Technology*, *3*(3), 176–182.

[10] Yucekaya, A. (2013). Bidding of price taker power generators in the deregulated Turkish power market. *Renewable and Sustainable Energy Reviews*, *22*, 506–514. https://doi.org/https://doi.org/10.1016/j.rser.2013.01.038

[11] Ruiz, C., Conejo, A. J., Fuller, J. D., Gabriel, S. A., & Hobbs, B. F. (2014). A tutorial review of complementarity models for decision-making in energy markets. *EURO Journal on Decision Processes*, *2*(1–2), 91–120.

[12] Buygi, M. O., Zareipour, H., & Rosehart, W. D. (2012). Impacts of large-scale integration of intermittent resources on electricity markets: A supply function equilibrium approach. *IEEE Systems Journal*, *6*(2), 220–232.

[13] Hobbs, B. E. (2001). Linear complementarity models of Nash-Cournot competition in bilateral and POOLCO power markets. *IEEE Transactions on power systems*, *16*(2), 194–202.

[14] Hobbs, B. F., Metzler, C. B., & Pang, J.-S. (2000). Strategic gaming analysis for electric power systems: An MPEC approach. *IEEE transactions on power systems*, *15*(2), 638–645.

[15] Yaghooti, A., Buygi, M. O., & Zareipour, H. (2014). Impacts of ramp rate limits on oligopolistic opportunities in electricity markets. *IEEE Systems Journal*, *10*(1), 127–135.

[16] Gharib, M., Yaghooti, A., & Buygi, M. O. (2011). Efficiency upgrade in PWRs. *Energy and Power Engineering*, *3*(04), 533.

[17] Fang, Zh. (2021). Economic Factors Analysis and Optimization Strategy of Third-generation Nuclear Power. *International Conference on New Energy Technology and Industrial Development (NETID).* Retrieved from https://doi.org/10.1051/e3sconf/202129202024

[18] Yang, X., Cai, B., Xue, Y (2022). Review, Optimization of Nuclear Power Development: A Cyber-Physical-Social System in Energy Perspective. *JOURNAL OF MODERN POWER SYSTEMS AND CLEAN ENERGY, VOL. 10, NO. 3* (547-561). IEEE. Retrieved from https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=9673695

[19] El Khatib, S. T. (2011). Oligopolistic Electricity Markets Under Cap-and-trade and Carbon Tax. McGill University Library.

[20] Tominaga, J. (2017). Steam turbine cycles and cycle design optimization: Advanced ultra-supercritical thermal power plants and nuclear power plants. In *Advances in Steam Turbines for Modern Power Plants* (pp. 41–56). Elsevier.

[21] AESO. (2016). Hourly Alberta Internal Load Data. Retrieved March 10, 2017, from https://www.aeso.ca/assets/Uploads/Hourly-load-data-for-2016.xlsx

[22] Ahmad Khanbeigi, G., Jahanfarnia, G., Sharifloo, N.M. *et al.* Trade-off Between Cost and Safety To Cope with Station Blackout in A PWR in A Deregulated Electricity Market. *J. Electr. Eng. Technol.* 15, 2045–2056 (2020). https://doi.org/10.1007/s42835-020-00488-5

[23] NEA, I. E. A. and. (1998). Projected Costs of Generating Electricity: Update 1998. OECD Paris, France. Retrieved from https://www.oecd-nea.org/ndd/pubs/1998/768-projected-costs.pdf

[24] International Energy Agency, & N. E. A. (2005). *Projected Costs of Generating Electricity: 2005 Update*. OECD/IEA. Retrieved from https://www.oecd-nea.org/ndd/pubs/2005/5968-projected-costs.pdf

[25] IEA, N. E. A. (2010). *OECD. Projected Costs of Generating Electricity: 2010 Edition*. ISBN 978-92-64-08430-8, OECD PUBLICATIONS, 2 rue Andr-Pascal, 75775 Paris . Retrieved from https://www.oecd-nea.org/ndd/pubs/2010/6819-projected-costs.pdf