Presenting new approach for optimal placement of nuclear power plant connected to the grid after the trip

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Abstract

This study presents a combination of optimal placement and power system development with the aim of supplying electricity for Nuclear Power Plant after the trip of power plant. Power supply to the internal loads of power plant by the off-site power system is one of the main fields of research in achieving the safety Nuclear Power Plant. One of the main purposes in this article is to introduce a suitable and safe place for the construction and connection of a Nuclear Power Plant to the power system. These locations are identified by the power plants on-site loads and the average of the lowest number of relay protection after the Nuclear Power Plant trip, based on electricity considerations. Along with the optimal placement in this paper, the power system development, including the generation and transmission development in order to provide electricity with higher reliability to the Nuclear Power Plant after the trip is also presented. Monte Carlo and Latin Hypercube Sampling probabilistic methods are proposed for locating the site of a Nuclear Power Plant and algorithms of Genetic and Particle Swarm Optimization for locating and developing power generation and transmission systems. The simulation results are implemented on the IEEE RTS 24-bus system, and finally suitable locations for the construction of the Nuclear Power Plant and the generation and transmission development with the aim of feeding the power plant from the off-site power system and sufficient assurance that the reactor core does not melt after the trip, are determined.

Keywords Nuclear power plant (NPP) · Monte Carlo Simulation (MCS) · House Load probability (HLP) · Genetic Algorithm (GA) · Particle Swarm Optimization Algorithm (PSO) · Generation and Transmission development (GTD)

Abbreviations

NPP	Nuclear power plant
GTD	Generation and Transmission development
HLP	House Load probability
MCS	Monte Carlo Simulation
GA	Genetic Algorithm
PSO	Particle Swarm Optimization Algorithm
LOOP	Loss of Offsite Power
UPS	Uninterruptable Power Supply
SBO	Station Blackout
OPF	Optimal Power Flow
CV	Coefficient of Variation
AC	Alternating Current
IAEA	International Atomic Energy Agency

List of symbols

P_{Gi}, Q_{Gi}	Active and Reactive power output of generation at bus i
P_{Li}, Q_{Li}	Active and Reactive power load at bus i
V_i, δ_i	Magnitude and angle of voltage at bus i
Y_{ij}, θ_{ij}	Magnitude and angle of ij^{th} element of the admittance matrix Y
$p_{Gi}^{min}, p_{Gi}^{max}$	Minimum and maximum active power output of generator i
$Q_{Gi}^{min}, Q_{Gi}^{max}$	Minimum and maximum reactive power output of generator i
V_i^{min}, V_i^{max}	Minimum and maximum of voltage magnitude at bus i

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S_{i-j}	Apparent power flow in transmission line between bus i and j
$S_{i-j}^{\max}$	Maximum allowed apparent power flow in transmission line between bus i and j
N	The number of repetitions of the algorithm Monte Carlo
x_i	The variable under consideration in the algorithm Monte Carlo
x_{id}	The spatial position corresponding to the d -th of the i -th particle in the Particle Swarm Optimization Algorithm
v_{id}	The spatial position corresponding to the d -th of the i -th particle in the Particle Swarm Optimization Algorithm
w	Inertia Weight in the Particle Swarm Optimization Algorithm
c_1, c_2	Learning factors (acceleration coefficient are also called

1 Introduction

Nuclear power plants (NPP) safety and the reliability of the power system connected to the NPP are the two main factors in the development and operation of each other, because the NPP in case of emergency, start-up and exit need to receive electrical energy from the power system. A normal NPP is one that injects energy into the grid. Therefore, it is important to maintain NPP safety and the stability of the network by increasing the reliability of the power system and reviewing their performance [1].

It is important for the NPP to control the voltage and frequency of the power system connected to it within an acceptable range to provide the internal energy consumption required by the power plant (5–8% of the rated power of the NPP) during operation, shutdown and trip. Several methods have been proposed by the manufacturers, the most important of which are power supply from the main bus of the power plant, power supply from the generator terminal and group power supply.

The NPP internal power grid consists of two general parts, Off-Site and On-Site. The Off-Site section includes the main lines of the power system network that is connected to the power plant through the main post; the main transformer is the connection of the power plant to the power system network, as well as the power system network lines along with the related standby auxiliary (startup) transformer. The On-Site section also includes the main synchronous generator in the power plant along with the unit auxiliary transformer, medium voltage and low voltage lines used in the power plant as well as all transformers and electrical equipment in the power plant

such as motors, batteries, diesel generators. Normally, if the power system is connected to the network through the main lines, the internal power of the power plant is supplied through the main generator and the power system network. In fact, the main generator of the power plant, as part of the power system network, is responsible for providing the internal electrical power of the power plant. If the main network is disconnected, this event is called loss of offsite power (LOOP). The power plant is in House-Load mode and the main generator is responsible for supplying electricity to the power plant. In case of disconnection of the main generator connection breaker, the standby (alternative) power line will provide internal electricity reservation through lines and transformers. With the disconnection of the reserve power grid, diesel generators will come into operation and in case of problems for these diesel generators, batteries and Uninterruptable Power Supply (UPS) will be responsible for providing critical loads. Simultaneous failure in both Off-Site and On-Site leads to Station Blackout (SBO). Various studies have shown that if the SBO event is not controlled in time, it can significantly damage the reactor heart [1, 2].

The availability of AC power is essential for safe operation and accident recovery at NPP. Typically, AC power plants are powered by external sources and through the power grid. Four factors affect the SBO event. One of these factors is the LOOP phenomenon. The LOOP event can have a significant negative impact on the plant's ability to achieve and maintain a return from the accident [3]. Examining the articles, we can see the great importance of the LOOP event. The LOOP event was analyzed in various NRC reports during the years 1988–1988b–1996–2003 and 2010 [3–7].

NUREG/CR-1032 assesses the occurrence of nuclear power plant shutdowns due to the LOOP phenomenon based on USA data during the years 1985–1968 [3]. NUREG/CR-5496 examines the LOOP phenomenon in a NPP based on data from 1980 to 1996 [4]. NUREG/CR-5750 provides a more general account of the initial events at US power plants between 1995 and 1987, including the initial events of the loss of NPP's external power [6]. NUREG-1784 assesses the impact of grid operations on the NPP and the event of the loss of the external power supply from 1985 to 2001 [7]. NUREG-6890 assesses the risk of power plant shutdown due to loss of AC power at NPPs by 2004 [8]. EPRI covers the latest reports on power outages outside the NPP from 2003 to 2012 [9]. According to the statistics provided, the LOOP event has been registered 228 times in the IRSN SAPIDE database, 190 times in the GRS VERA database, 120 times in the LER database and 52 times in the IRS database [10]. These reports contain detailed information on the importance of examining the performance of the power grid connected to NPPs.

The loss of offsite power plant depends on the operating condition of the plant. If the NPP is shut down, this incident will not threaten the power plant. If the power plant is in normal operation and this accident occurs, there will be two situations: in the first case, the power plant will continue to operate without trip, that is, the alternative sources have been put into operation properly. In the second case, the power plant is trip. To prevent this, Taking safe and preventive measures against the threatening dangers of a NPP to increase safety and protect power plants, employees, the environment and the power system is essential and inevitable. One of the important issues that always threaten the nuclear power plant and power grid is the power plant's trip. Power plant unit trip cause power shortages, frequency drops, and power network voltage fluctuations. If for any reason the equipment connected to the power system is unable to return power to the power plant, it will lead to successive blackouts and often the collapse of the power system. But this becomes even more serious when, after the plant's trip, the plant's internal power grid fails to inject the necessary power to cool the reactor, which will greatly help damage the reactor and emit radioactive material. Incidents such as the Fukushima accident in Japan or Chernobyl in Ukraine and the Mile Island 3 in the United States will follow [11]. It is therefore important that the power system connected to the nuclear power plant is a reliable power source with sufficient capacity for all reactor operating modes. This requires monitoring, protection, selection of a suitable location for the construction of a NPP and extensive control of the power system.

For countries that are using nuclear energy and countries that have not yet used this energy and decide to use this energy, always pay attention to the infrastructure of the national electricity grid and make the necessary changes to maintain the stability of the network and the security of the NPP is essential. These changes include the introduction of a suitable location for the construction of the power plant, the addition of transmission lines to connect the power plant to the power grid, as well as considering how the power plant operates and is maintained by the power grid. In order to prevent power grid accidents that lead to challenges to the safety of the NPP, special attention should always be paid to the design and operation of the power grid and their relationship with the nuclear power plant. In its recent publications, The International Atomic Energy Agency (IAEA) has given full details of the communication issues between the electricity grid and the NPP, and the importance of addressing this issue [12–14]. The organization has also been constantly updating recommendations and details on this issue since the 1980s [15–18]. Consequences and events of non-supply of power required by the NPP have been analyzed by the

power grid as the main source of power supply in emergency situations [19]. One of the important issues that has been mentioned before and should be considered is the introduction of a suitable location for the NPP in the electricity network connected to it. In his research, F. Kio-marsi et al. have introduced a suitable construction site for the NPP after the trip of the power plant and in situations where the power plant is not able to return to normal operating conditions and needs to receive power from the national grid to cool the reactor [20].

In addition to the optimal location of NPP, one way to increase the probability of powering NPP after a trip is making the necessary changes in the electricity network infrastructure. Modifications to the power grid infrastructure include adding or subtracting a production unit or transmission line as needed. Creating such changes and developing the workforce network is very important and strategic. Developing a power grid to increase the security of a NPP is a scenario that must be evaluated before nuclear events such as the reactor's heart melt. Developing a power system will cost the planner extra time and will change the network's topology. But in fact, the changes in the topology of the power system and its additional costs in the face of nuclear accidents, which are due to the lack of power supply to the nuclear power plant by the offsite power system, will be very negligible after the power plant unit trip.

Numerous studies in the field of power grid development planning in traditional and restructuring the power system using meta-innovative methods such as Genetic Algorithm [21–23], Simulated Annealing [24], Tabu Search [25], Particle Swarm Optimization Algorithm [26] and a Shuffled Frog Leaping Algorithm [27]. However, no research has been done on the GTD in the presence of the NPP, with the purpose of supplying electricity to auxiliary loads after the power plant trip. So in this article, using the MC probabilistic method and after 2000 repetitions (the reason for choosing this number of repetitions is to achieve convergence in response), first identify the optimal location for the construction of a nuclear power plant and then ensure the introduction of the location. Appropriate, using the super-innovative genetic algorithm to develop the power system (development of transmission lines and production units) taking into account the exit rate for the production unit, transmission lines and protection relays, in order to increase the probability lack of power supply to critical NPP, it is paid for by the offsite power system after the trip.

This paper is organized as follows: In Sect. 2, the problem of power supply to auxiliary loads is formulated by the off-site power system based on voltage, frequency and transient current stability measures. Section 3 describes the probabilistic methods and proposed algorithms for

solving the problem and how to use them in the article. In Sect. 4, the issue of power system development planning is addressed. The proposed flowchart and its solution method in power system development planning are also presented. In Sect. 5, in order to evaluate the efficiency of the proposed methods, the test network is introduced. In Sect. 6, the results of the simulation of the proposed methods on the IEEE 24-bus network are analyzed. Section 7 concludes the article. Section 8 presents future studies.

2 Stability analysis functions

Using Optimal Power Flow (OPF), the House Load probability (HLP) to the NPP by the off-site power system can be evaluated based on the criteria of stability limit, voltage limit, frequency limit and transient current.

The mathematical equations used to solve this problem are as follows [28]:

$$P_{Gi} - P_{Li} - V_i \sum_{j \in N} V_j Y_{ij} \cos(\theta_{ij} + \delta_i - \delta_j) = 0 \quad (1)$$

$$Q_{Gi} - Q_{Li} - V_i \sum_{j \in N} V_j Y_{ij} \sin(\theta_{ij} + \delta_i - \delta_j) = 0 \quad (2)$$

According to Eq. (1), the amount of active power produced is equal to the active power of the load in the network. Active load power in the network is the sum of active power consumption and network losses. After the occurrence and application of the accident in the power system in a transient state, the changes in the speed of the power plant unit as well as the frequency changes of that unit are obtained from the difference between the active power output and the active load power in the power network. In Eq. (2), the amount of reactive power produced is equal to the reactive power of the load in the network. Reactive load power in the network is the sum of reactive power consumption and reactive losses of the network. It is obvious that after the occurrence and application of an accident in the power system in a transient state, the voltage changes of the network buses are obtained as a result of the difference between the reactive power produced and the reactive power of the load in the power network.

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max} \quad (3)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (4)$$

In Eqs. (3) and (4), the constraint indicates the limit of active and reactive power produced by power plant units. Failure to pay attention to the reactive power limit

will cause damage to the excitation coil. Active and reactive power limitations include stator winding limitation, rotor winding limitation, turbine mechanical limitation and torque angle limitation, which must be considered in power grid stability calculations.

$$\frac{Q_{Lj}}{P_{Lj}} = \text{cons} \quad (5)$$

In Eq. (5), the rate of change of reactive power of network load to reactive power of network load is considered and shows that it is always a constant value. If the amount of network loads, which includes load and losses, changes in the power system simulation calculations, the ratio of changes in reactive power to active power of network load is the same.

$$V_i^{min} \leq V_i \leq V_i^{max}, \quad \forall i \in \text{Buses} \quad (6)$$

Equation (6) shows the operating voltage range of each bus. Under normal operating conditions, the bus voltage always has the right to change in the range of from 0.95 to 1.05 per unit (Pu). But in case of emergency, this value can change in the range of from 0.9 to 1.1 Pu.

$$S_{i-j} \leq S_{i-j}^{max}, \quad \forall (i-j) \in \text{Line} \quad (7)$$

Another limitation applied in this paper is the flow limit across transmission lines. In terms of power system stability, the maximum power through the transmission lines should be considered in the operation of the power system. Note, however, that in the simulation provided for the NPP, all restrictions are observed by protection relays, and protection relays will work if they exceed the specified limits.

3 Possible assessment

The House Load Probability (HLP) is a dependent index and cannot be considered a constant value to calculate it. However, it makes sense to use probabilistic methods such as the Monte Carlo (MC) probability method, which always provides a wide range of data.

Due to the approach to the real situation in the simulations performed in this paper, uncertainties such as the correct operation of protection relays, exit of transmission lines and exit of power plants in order to supply HLP of the power plant at the moment of trip, used by the power system And all protection relays such as voltage, current and frequency relays are modeled in this simulation.

3.1 Monte Carlo simulation random sampling (MCS-RS) Method

The steps of implementing the MC algorithm with the aim of supplying electricity to the HLP of the NPP after trip of the power plant are as follows [22]:

Step 1 Specify power plant statuses by producing uniform random variables and compare them with forced outage rates (FOR) of power plant, The FOR for each production unit is shown in Table 1:

$$\mu_i = \begin{cases} 0, & x \leq \text{FOR}_i \\ 1, & x > \text{FOR}_i \end{cases} \quad (8)$$

Step 2 According to Eq. (8), a random number is considered for the transmission line under study and if this random number is less than the FOR of the transmission lines, that transmission line will be out of circuit and if it is higher, it will remain in the circuit. The rate of FOR for transmission lines is 0.02.

Step 3 According to Eq. (8), a random number is considered for the operation of the protection relays under study and if this random number is less than the FOR of the protection relays, that relay will go out of circuit and if it is higher, it will remain in the circuit. The rate of FOR for protective relays is 0.02.

Step 4 Transient studies of the power system after trip of the nuclear power plant are evaluated with the aim of supplying electricity to the auxiliary loads by the off-site power system. The results are then analyzed and after evaluation, the data are stored.

Step 5 If the stop criterion is met, the implementation of the algorithm is completed. Otherwise, to re-run the algorithm, you must go back to the first step and repeat steps 1 to 4 again.

The main criterion in stopping the MC algorithm is to reach a highly reliable answer. Therefore, in this paper, first, the coefficient of variation (CV) is calculated according to Eqs. 9–11 for each stage studied and compared with a

very small value, and if the CV is less than this value, the algorithm will stop. (The smaller the comparable value for the CV, the higher the accuracy of the calculations and the longer the calculation time of the algorithm process.) Another stop criterion in the Monte Carlo algorithm is based on the number of iterations. After 2000 repetitions, based on the scattering coefficient of the Monte Carlo CV method, we obtained the optimal response and the same stop criterion. Therefore, in this paper, in order to facilitate and reduce computational time, the MC method has been selected based on the criterion of stopping the number of repetitions and 2000 repetitions as a computational measure.

$$\bar{X} = \frac{1}{N} \sum_{i=1}^N x_i \quad (9)$$

In Eq. (9), the studied variables x_i are different in each step.

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{X})^2}{n}} \quad (10)$$

Equation (10) shows the standard deviation in which $(x_i - \bar{X})$ is the deviation of the i -th data from the mean of the data. If the standard deviation of the data set is small, it means that the scatter of data around their mean is low and therefore the data is closer to each other, and if the standard deviation of the data set is large, it means that the scatter of data around their mean is high and therefore the data is farther apart.

$$C_v = \frac{\sigma}{\bar{X}} \quad (11)$$

The Eq. (13) shows the coefficient of variation (CV). The CV theory is a criterion for the distribution of data, which is calculated by dividing the standard deviation into the average.

3.2 Genetic algorithm (GA)

The GA is widely used to solve various electrical engineering problems. The basis of the GA is Darwin's law of evolution (best survival). The law states: In the structure of nature, stronger beings will replace weaker beings, and weaker beings are doomed to destruction. The law is based on the premise that the more living beings are able to adapt to their environment, the more alive they are and the more stable their offspring will be. The genetic optimization algorithm has effectively selected a set of possible answers in its computational iterations that search for different areas of possible response spaces. The GA

Table 1 Specifications of production units [30]

Unit size (MW)	Unit Type	Unit FOR
12(5)	Oil	0.02
20(4)	Oil	0.10
50(6)	Hydro	0.01
76(4)	Coal	0.02
100(3)	Oil	0.04
155(4)	Coal	0.04
197(3)	Oil	0.05
350(1)	Coal	0.08
400(2)	Nuclear	0.12

has a simple structure for simulation, and according to the structure of this algorithm, we can easily exit the relative extremes and reach the final optimization answer. This algorithm can be used in discrete and continuous, linear or nonlinear problems, however, depending on the type of optimization problem, proper coding for chromosomes should be considered before starting the program. Obviously, proper coding, in addition to increasing the convergence rate to the answer, increases the accuracy of the calculations.

The important operators of the GA used in this paper are as follows:

In the first step of the GA, the initial population must be created randomly. Creating an early population means creating chromosomes with random genes. In the second step, the crossover and mutation operations must be implemented on the created chromosomes, which will lead to the production of new chromosomes. Obviously, parental chromosomes will be completely stored so that they do not change. In the crossover operator, two random chromosomes will be selected from the parents and cut from a random gene, and after the chromosome genes are moved together, children will be created. In this paper, not all chromosomes are fertilized in accordance with the laws of nature, and with a probability of 90%, which is the same as the crossover rate; fertilization of chromosomes and production of infant chromosomes is performed. The mutation operator in the GA is chosen based on the mutation rate, which is usually a number between 10 and 30%. Genetic mutations are attempted on a random gene from a random parent chromosome. It should be noted that this genetic mutation may improve or worsen the chromosome.

The total population, which includes parents, cross-sectional chromosomes, and mutations, should now be compared in terms of evaluation. For this purpose, we determine and adjust all chromosomes of the total population using the purpose function. The evaluation function, which is the same as the target function, uses the evaluation function to calculate a numerical value for each chromosome. Obviously, using the evaluation function, we optimize the chromosomes for the ultimate goal of optimization and easily separate the superior chromosome and

3.3 Particle swarm optimization algorithm (PSO)

PSO is an optimization technique and is one of the evolutionary algorithms inspired by nature. This algorithm is an optimization technique based on possible rules. PSO is rooted in two main combinations of cognitive styles and is generally tied to the group of birds or fish and collective theory in particular. In this method, by setting the path of a population of particles in the problem space based on information about the best previous performance for each particle and the best previous performance related to the neighbors, each particle performs a search in a chapter of the problem [31, 32].

Using this scenario, PSO uses it to solve optimization problems. In PSO, every answer to a problem is the position of a bird in a search space called a particle. All particles have a certain amount of fitness that is obtained by the fitness function that needs to be optimized, and the bird is closer to the food that has more fitness. Each particle also has a velocity that directs its direction of motion toward the optimal current particle [31, 32].

The PSO starts with a group of random answers (particles), then searches to find the optimal answer in the problem space by increasing the position of the particles. Each particle is defined as multi-dimensional (depending on the nature of the problem) with two values, x_{id} and v_{id} , which represent the spatial position and velocity corresponding to the d -th of the i -th particle, respectively. At each stage of the population movement, each particle gets the best value in two days. The first value is the best response from the population movement, each particle with two values is the best in terms of fitness, which has been achieved separately for each particle so far (the value of fitness must be saved) this value is called v -best. The other best value obtained by PSO is the best value ever obtained by all particles in the population, and this value is the best global and is called g -best (the fitness of the value must be saved). If a particle participates in its own spatial neighborhood as a population, this value is calculated only in the same neighborhood and is the best local called l -best. After finding the two values of v -best and g -best (l -best), each particle updates its new speed and location according to the following equations:

$$v_{id}(t+1) = w \cdot v_{id}(t) + c_1 \cdot \text{rand}(P - \text{best} - \text{xid}) + c_2 \cdot \text{rand}(g - \text{best} - \text{xid}) \quad (14)$$

the undesirable chromosomes. After the chromosomes are sorted, the best chromosome is determined. If the stop criterion is met, the GA ends; otherwise, by creating a new population, we move on to the next iteration.

$$v_{id}(t+1) = \text{xid}(t) + v_{id}(t+1) \quad (15)$$

which in Eqs. (14) and (15), c_1 and c_2 Learning factors (acceleration coefficient are also called) And rand is a random number in the range (1 and 0) [31, 32]. To prevent

algorithm divergence, the final value of each particle velocity is limited by Eq. (16).

$$v_{id} \in [-v_{max}, v_{max}] \quad (16)$$

Equation (14) consists of a sum of three phrases, the first of which is a ratio of the current velocity of the particle and its role is similar to the momentum in the neural network, and the second which is proportional to the difference between the bird's location and the previous one and the third which is the difference, and the third phrase, which is the difference in location with the best answer among the whole population, leads the new particle speed to the optimal answer.

w , c_1 and c_2 are PSO parameters and convergence depends on the value of these parameters. c_1 is usually set to c_2 and numerically between 1.5 and 2. Convergence is highly dependent on the value of w , and should be defined dynamically (in the range of 0.2–0.8) in such a way that it decreases linearly during the process of population evolution. Initially, w must be large in order to find good answers in the early stages, and in the final stages, the smallness of w will lead to better convergence.

4 The problem of GTD

4.1 The purpose function

The purpose function considered in this paper is based on locating and optimizing the expansion of transmission lines and power plant units in the grid. In this article, we have tried to put the conditions of grid expansion using a single line, a power plant unit separately on the agenda. Flowchart 1 shows the procedure.

This paper examines three scenarios. In the first scenario, the base grid was analyzed with 2000 repetition using the MC probabilistic method. In the second scenario, adding 1 transmission line to the grid by using the GA method and observing the effect of its presence on the house load of the NPP in case of the power plant unit trip. In the third scenario, adding 1 power plant unit to the grid by using the GA method and observing the effect of its presence on the house load of the NPP will be analyzed in the case of the power plant unit trip.

As shown in Fig. 1, after making random chromosomes in the GA and applying crossover and mutations on chromosomes, the suitability of chromosomes should be assessed. For this purpose, the desired chromosome must be sent from MATLAB software to DigSILENT software to check the purpose functions and problem constraints in DigSILENT software.

The purpose function of the optimization considered in this paper is to minimize the number of failure to supplies auxiliary loads to the NPP.

Min f

$$f = \text{Sum}(\text{Failure to supply house loads to the NPP}) \quad (17)$$

In this paper, three genes are considered for each chromosome, and the structure of each gene is such that the numbers between 1 and 24 (depending on the system under study) will be included. The coding for this problem is that the first gene is the beginning bus for the new transmission line, the second gene is the end bus for the new transmission line, and the third gene is the bus for the new power plant. Obviously, if the third gene is inactive, this part will not be considered. Because in some scenarios, there is no need to build a power plant at all, and only the construction of the transmission line will be considered.

4.2 Constraints are intended to the GTD

One of the most important problems with GTE is the excessive size is a problem, the complexity, and the difficulty of modeling it. For this reason, the following constraints are considered:

- Add only 1 line to the lines in the grid.
- Add only 1 power plant to the grid units.
- Given that the chromosome defined in the GA identifies the buses on either side of the line, if the voltage of the buses specified by the GA is the same, the transmission line is allowed to be added to the power system. Otherwise, no line will be issued and the suitability of the unsuccessful chromosome will be calculated. For this purpose, penalty coefficients are considered for lines that are incorrectly constrained.
- The inequality constraint of the beginning and end chromosomes is observed. This restriction is also considered for all chromosomes sent from MATLAB software to DigSILENT software, and if the buses on both sides are equal, the evaluation line of this chromosome will not be calculated and will include penalty coefficients.

After examining the constraints by the DigSILENT software and considering the penalty coefficients on the chromosomes, if the initial constraint of the chromosome is observed, it will be directed to the grid development section. In this sub-section, the desired class is first identified and called. For this purpose, according to the defined

Fig. 1 Proposed flowchart of genetic algorithm

scenario, and the code sent from MATLAB software to DlgSILENT software, the transmission line class or power plant class will be called. Then, according to the line voltage level and the nominal voltage level of the power plant, the type of equipment specified also line specifications such as R, X, B line voltage level, nominal apparent power and line length should be considered in the calculations. After fully defining the desired object, according to the location, it should be included in the graphical interface and the element should be connected to the parties. After developing and drawing a new element in the grid, the MC method should be implemented. After completing the number of repetitions and reaching the stop criterion, the program will report the number of cases of Failure to supply house load to the NPP unit and will send it to Matlab software as an evaluation.

5 Numerical studies

In order to evaluate the efficiency of the proposed methods for evaluating the power exchange capacity of the NPP by the power system after trip power plant, IEEE 24-test system has been used, the graphical view of which is shown in Fig. 2.

Voltage, current and frequency relays are adjusted on all system buses under test, and the method of setting each of the above relays in this research is as follows:

Voltage relays: These relays will operate in the range of 0.3 Pu increase or decrease the voltage after a period of 0.2 s from the occurrence of the error. The sampled voltage will be 10 times per second.

Current relays: The above relays will operate if a current of more than 1.8 kA is applied to the power system

Fig. 2 IEEE 24-test bus system [22]

equipment for more than one second. If this overcurrent is not continuous, the relays will be deactivated and will no longer operate. Sampling rate by current transformers is 50 times per second.

Frequency relays: The operating settings of these relays are considered in the range (45 Hz, 55 Hz) and after leaving this range, the frequency relays will operate. The time taken to fix the fault and the operation of the frequency protection relay from the start time of the fault is 0.2 s. The frequency sampling rate of power plant units is equal to 10 per second. In the present study, in order to achieve the real conditions and the best performance of the power system in response to network frequency changes, we equipped two power plants with automatic governor adjustment and frequency control loop.

In the study [20], the best place to build a NPP was estimated using the MC-RS probabilistic survey method and the best place for the construction of Bus NO.3 NPP was estimated. With the construction of a nuclear power plant in this bus, the possibility of Failure to supply house load to the NPP is reduced. As mentioned earlier, this paper tries to study in three scenarios. In the first scenario, the base grid was analyzed with 2000 repetition using the MC probabilistic method. In the second scenario, adding 1 transmission line to the grid and observing the effect of its presence on the house load of the NPP in case of the

Fig. 3 Mean performance of protection relays in MC method after NPP trip

power plant unit trip. In the third scenario, adding 1 power plant unit to the grid and observing the effect of its presence on the house load of the NPP will be analyzed in the case of the power plant unit trip.

6 Results and Discussion

The NPP will generate 400 MW (According to Table 1 and Fig. 2) before the accident and target 18 test systems on the bus [30]. However, in order to carefully examining the grid conditions and analyzing the performance of protection relays at the time of the accident for the NPP unit in the MC method and investigating the conditions of transient state and house load power of the power plant after trip, It is evaluated and after introducing the desired bus to build a nuclear power plant, it is introduced as the base grid.

The base network is based on the fact that the NPP has been built on bus NO. 3 and the analysis of the number of protection relay operating at the time of the accident for the NPP unit has been performed in the MC method. Figure 3 shows the mean performance of protection relays after 2000 repetitions using the MC method on the IEEE 24-bus network. As can be seen, the mean number of protection relays has converged to 3.6595. In other words, this figure shows the mean number of protection relays operating at the time of the accident (power unit trip) for the NPP.

Power supply to house load NPP is very important for network stability. For this reason, Fig. 4 shows the number

Fig. 4 The number of times the NPP auxiliary loads is power failure in the base network

Fig. 5 The mean number of times the NPP auxiliary loads is power failure

of times the NPP auxiliary loads are failure supplied to the base network. As can be seen in Fig. 4, after 2000 repetitions of the MC method, only 7 times in the MC-RS method of power supply failure to NPP has occurred. Figure 5 also shows the mean frequency of power supply failure to the critical auxiliary loads of the NPP. Figure 5 shows that the mean number of times the power supply has failed is 0.0035, which is a very good number. According to the results obtained from the MC method and Figs. 4 and 5, it can be concluded that the selection of bus NO. 3 for the construction of a NPP in case of trip of this power plant unit with the purpose of supplying electricity to the

auxiliary loads of the power plant to cool the reactor and It is very convenient to prevent the heart of the reactor from collapsing. Choosing the right place to build a NPP is a positive step towards the security of the power plant, According to Fig. 4, the lack of power supply to the auxiliary loads of the NPP is 7 times. This amount decreases with the construction and development of the transmission network and power plant unit, and the security of the NPP after the trip and its power supply from the offsite power system network also increases.

To transmission lines development, the optimal location of the transmission line in the network is determined using the GA and PSO algorithms. In this paper for GA algorithm, the initial population is 50 and the number of repetitions is considered to be 100 to ensure that the answer is reached. This article is intended mutation rate of 10% and 90% rates intersection also been considered. Also, for the PSO algorithm, the number of repetitions is considered to be 100. The reason for using this number of repetitions is the possibility of comparing the results of the PSO algorithm and the GA algorithm. The number of primary particles in the PSO algorithm method is 50 and the minimum inertia coefficient is 0.4 and the maximum inertia coefficient is 0.9. For this purpose, the GA and PSO are first implemented in MATLAB software and randomly identify the buses at the beginning and end of the transmission line. After undergoing the initial processes in MATLAB software, the GA sends the lines information to DlgSILENT software to evaluate the fit of the chromosomes and the PSO algorithm to evaluate the fit of the particle information. DlgSILENT software uses a subroutine to build lines and transformers, and then a Monte Carlo probability assessment program to check the suitability of chromosomes and determine the suitability of particles, and sends the result to MATLAB software. In this scenario, the NPP is located on bus NO. 3 and an attempt will be made to build a new line.

After completing the process of the GA and PSO algorithm and the complete convergence of the beam curve to the final answer, the optimal location for the construction of the new transmission line between buses 3 and 24 is estimated. But as shown in Fig. 2, bus 3 has a voltage of 138 kV and bus 24 has a voltage of 230 kV. Therefore, a line between these two voltage levels cannot be constructed. To solve this problem, a sub-program has been written, which, if detected, will use a transformer instead of a line. Table 2 compares several of the best sample states for the purpose grid using the GA and PSO algorithm.

As shown in Table 2 and Fig. 4, before developing the power system in the base network where the NPP is located on bus NO. 3, after 2000 repetitions of the MC method, we have 7 times power supply failure to the auxiliary loads of the NPP. As can be seen in Table 2, the best

Table 2 Number of power supply failure to the NPP with construction of transmission line and transformer

Bus number beginning	Bus number end	Number of power supply failure to the NPP	
		GA	PSO
<i>Basic grid</i>		7	
1	2	1	4
1	10	5	4
1	3	2	2
3	9	1	0
3	24	0	0
15	24	4	3
20	22	3	4
22	16	4	3
4	3	2	1

place to build the transmission line in the GA algorithm is between busses 3 and 24, and for the Paso algorithm between busses 3 and 24, as well as between busses 3 and 9. Therefore, with the construction of a transformer between buses 3 and 24 in both evolutionary algorithms in all possible modes of the MC method, the power supply to the critical loads of the NPP has been successfully completed and no unsuccessful cases have been reported. This means that with the construction of a NPP on bus NO. 3 using the MC method and the results obtained from the GA and the PSO algorithm based on the construction of the transmission line and the transformer between buses 3 and 24, after the power plant trip, the power supply failure to the auxiliary loads of the power plant will be fully charged, that new conditions of the network, due to all the uncertainties, the critical loads of the power plant have

Fig. 6 The mean number of protection relay functions in the MC method with transformer development

always been provided properly. After that, the construction of the transmission line between Bus 3 and 9 with 1 time in the GA method and 0 times in the PSO method of power supply failure to the auxiliary loads of the power plant after trip is in the second place.

Figure 6 shows the mean number of protection relay functions after 2000 repetitions using the MC probabilistic method and after the construction of a transformer between buses 3 and 24 on the IEEE 24-bus network. As can be seen, the average number of protection relays operating in the base network was 3.6595, and in the developed network, using the GA algorithm, this number was reduced to 3.3635 and using the PSO algorithm to 3.5250. In other words, the number of protection relays operating at the time of the accident for the NPP in this scenario has decreased.

In this part of the paper, the goal is to optimize grid development from the perspective of power plant units. The development of power plant units is limited to the addition of only one power plant unit to the network and is done using the GA and PSO. After the complete convergence of the GA and PSO and reaching the stop criterion, Bus No. 3 will be introduced for the construction of a new power plant. The reason for this choice was to optimize, because in this paper the goal was to optimize the addition of grid power plants to reduce the likelihood of power supply failure to auxiliary loads NPP in the event of a NPP accident. Considering the structure of the base network, the NPP was built on bus No. 3, and the addition of a new power plant on bus No. 3 this bus has two power plant units. The following is an analysis of the number of

Fig. 7 The mean number of protection relay functions in the MC method with generation development

performance relays operating at the time of the accident for NPP in the MC method.

Figure 7 shows the average number of protection relay performance after 2000 repetitions using the MC method on the IEEE 24-bus network in two cases where the NPP alone is installed on bus NO. 3 (base network), in the other case that the power plant new one shows the power supply to the power plant after the power plant trip on the bus 3 installed (generation development). As can be seen, the mean number of protection relay functions for the base network is 3.6595 and for the network in developed conditions it is converged with a power unit in the GA to 3.1160 and in the PSO to 3.1420. In other words, this figure shows the mean number of protection relays operating in the event of an accident for a NPP. Figure 7 shows that with the development of the power plant unit, the average performance of the protection relays connected to the power plant has improved after the power plant trip compared to the base network, and this means increasing the safety of the NPP.

As mentioned, power supply to nuclear power plants is of great importance for network stability. For this reason, Fig. 8 shows the number of power supply failure to the auxiliary loads of the NPP in the base network and in the developed network using the addition of a power plant unit in the network. As can be seen in Fig. 8, after 2000 repetitions of the Monte Carlo method, the number of times power supply failure to the auxiliary loads of the NPP after the trip is estimated to be 7 times in the MC-RS method, which is added after this number. The power plant unit network has been reduced to 4 times using the GA and the PSO method has been reduced to 2 times.

Fig. 8 The number of times the NPP auxiliary loads is power failure in the developed network with one power plant unit

Fig. 9 The mean of times the NPP auxiliary loads is power failure

Figure 9 also shows the number of mean power supply failure to auxiliary loads of the NPP. Figure 9 shows that the mean frequency of power failure was 0.0035 for the base network and decreased to 0.002 for the developed network using the GA and 0.001 for the PSO method. Therefore, the development of network power plant units and the optimal location of the new unit can reduce the probability of power supply failure to the auxiliary loads to the NPP to an acceptable percentage.

7 Conclusion

The nuclear power plant is connected to the power grid and transfers its generated power to the grid and receives its required power from the grid. The trip of the power plant unit causes power shortage, frequency drop and fluctuation in the mains voltage and puts the power system under severe stress and pushes it to the brink of collapse. This is especially important when the power system, while maintaining grid stability, provides the power required by the nuclear power plant to cool the reactor. This requires monitoring, protection of the power grid connected to the power plant, selection of the appropriate location for the construction of the nuclear power plant and extensive control and development of the electrical power system.

In this paper, with proper planning in selecting the appropriate location for the construction of a nuclear power plant and the development of the transmission system and power system power plant units after trip power plant, in addition to preventing the collapse of the power system, the power required to power internal loads is managed. First, using the Monte Carlo probabilistic method, considering the output rate for protection relays, production units and lines, a suitable place for the construction

of a nuclear power plant is introduced, and then using the genetic metaheuristic algorithm and particle swarm algorithm which are an effective optimization methods in the Development of transmission and generation system, the optimal location for the development of transmission line and generation unit for the purpose of supplying electricity to auxiliary loads is introduced and the simulation results are implemented on the IEEE RTS 24-bus system.

Finally, the research findings show that the site selected for the construction of the nuclear power plant and also the introduction of a new network with the addition of transmission line and production unit, while preventing the collapse of the power system and controlling the voltage and frequency of the network, the possibility of power supply to internal loads is increased after the trip of the power plant and the reactor heart melts to a large extent.

8 Future study

- Investigating the effect of the presence of distributed generation sources on the recovery of power required by the nuclear power plant from the off-site power system after the trip
- It is suggested that the optimal location and development of the power system for nuclear power plants after the trip of the power plant be considered at the same time as the possibility of failure of part of the power system in the future.

Declarations

Conflict of interest The authors declare that there is no conflict of interests regarding the publication of this paper.

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