# A Multi-Objective Stochastic Tri-Level Programming for Highlighting the Role of the Pumped-Storage Power Plant on Electric Grid Defense Budget

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**This paper attempted to highlight the impact of a pumped-storage hydro plant on the electricity grid defense budget, which is spent to increase the power system resilience against terrorist attacks. A stochastic tri-level programming approach known as the defender-attacker-defender technique was applied to detect the defense plan by considering the pumped-storage hydro plant. The stochastic parameter was related to the water volume of the upper reservoir during the disruptive attack. In the stochastic tri-level programming model, the upper level was formulated to identify the components that should be defended for mitigating the system vulnerability against disruptive agent attacks. A terrorist agent seeks to find a set of components for maximizing power system damage. Therefore, the middle level was used to model the disruptive behavior. Finally, the lower level modeled the system operator behavior during the attack. The system operator generally applied flexible sources such as storage to reduce the effects of the attack. Thus, the role of the pump-storage hydro plant was evident at this level. The proposed tri-level problem was solved by transforming it into an equivalent bi-level program, which was solved by using an enumeration algorithm. Simulation results illustrate the effectiveness of the pump-storage hydro plant in reducing the power system defender budget.** 

***keywords:*** *Pumped-storage hydro plant, stochastic tri-level programming, defender-attacker-defender technique.*

## NOMENCLATURE

### Indices:

l transmission line
s Scenario
p Pumped storage unit

### Parameters:

$a_i^d$ Quadratic term of the defended cost function
$b_i^d$ Linear term of the defended cost function
$c_i^d$ Constant term of the defended cost function
$\pi_s$ Scenario probability
$x_{ij}$ Reactance of the transmission line-connected buses $i^{th}$ to $j^{th}$
$P_n^d$ Load demand located in the $i_{th}$ bus in the $s_{th}$ scenario
$P_{ij}^{l,max}$ Maximum power flow of the line
$\sigma_p^T$ Turbine converter factor
$\sigma_p^P$ Pumped converter factors
$Iter_i$ $i^{th}$ iteration

### Variables:

$w_i$ Binary variable for modelling defense plan
$v_i$ Binary variable for modelling attack plan
$P_{ij}^{l,s}$ Power flow of the transmission line-connected buses $i^{th}$ to $j^{th}$
$P_i^{g,s}$ Power of thermal generation
$P_{i,dis}^{p,s}$ Discharging power of the pump-storage hydro power
$P_{i,ch}^{p,s}$ Charging power of the pump-storage hydro power
$V_U^{p,s}$ Water volume of the upper reservoir
$V_L^{p,s}$ Water volume of the lower reservoir
$\varphi_{ij}^s$ Dual variable related to transmission line flow limitation
$\bar{a}_i^s$ Dual variable related to load shedding limitation
$\lambda_i^s$ Dual variable related to power balance limitation
$\gamma_i^s$ Dual variable related to thermal power generation limitation
$\chi_i^s$ Dual variable related to bus angle limitation
$\kappa_i^s, \nu_i^s$ Dual variable related to the water volume of reservoirs limitation

## 1. INTRODUCTION

In recent years, power systems have become an interesting target for disruptive agents. Therefore, the power system planers attempt to increase power system resiliency against disruptive actions by increasing the flexible sources. Today, energy storage units are an important flexible component in the power systems and play a key role in power system scheduling. The primary objective of installing an energy storage system is pick shaving. However, the power system developments have motivated the power system operators to utilize the energy storage system features more. One of these features is covering the intermittent nature of renewable power. The authors of references [1, 2] have highlighted this feature. Another feature pointed out in [3, 4] is the effect of energy storage systems on reducing the operation cost. In addition, the impact of energy storage systems on environmental constraints has been investigated in [5, 6]. These studies have shown that the mentioned energy storage advantages are due to the flexibility of the energy storage. Also, the impact of NaS Battery Storage on the optimal scheduling of virtual power plant was investigated in [7]. In the similar study, the role of energy storage unit on the energy hub scheduling was considered in [8]. In addition, in storage technologies, the flexibility of the pump-storage hydro power is more than that of the other storage technologies. Thus, this type of energy storage system can mitigate power system damages.

The authors of reference [9] argue that the pump-storage unit located in the north of Iran significantly affects load shaving in this country. Also, the impact of this storage on the fuel consumption of the Iranian power system has been evaluated, and it has been concluded that the Iranian power system fuel consumption was reduced during the study horizon. In [10], a robust optimization technique was applied to consider wind uncertainty in a unit commitment problem, which included thermal units, the pump-storage system, and wind farms. A similar study was conducted in [11]. This reference has studied the coordination of the pumped-storage system and wind farm to facilitate their participation in the day-ahead market. Also, the participation of the wind farm co-operated by the pump-storage system on the day-ahead market has been investigated in [12]. In this reference, the uncertainty of wind farms was modeled by the stochastic approach. Moreover, [13] co-operated a wind farm and pumped and battery storages to meet the load and wind farm variations. Another study considered both battery and pump-storage [14] in order to demonstrate the impact of storage units on power system planning based on renewable units. In [15], a multi-objective scheduling system with pump-storage and wind farm was employed to minimize the operational cost and value of load shedding. In [16], an ancillary service based on a pump-storage system and demand response was proposed to meet the challenges related to the stochastic nature of wind farm power. A three-step hybrid approach was applied to schedule a pump-storage system to cover load demands in [17]. In [18], the application of a renewable hybrid power plant including wind, solar generations, and the pump-storage system was investigated to respond to the load curves in a stand-alone island located in the Aegean Sea. Furthermore, in an investigation into the impact of the pump-storage system on scheduling isolated area with a high penetration of renewable generations, the authors of reference [19] highlighted the effect of non-conventional pumped-storage plants, such as variable-speed pumping and hydraulic short-circuit, on reducing the operation cost during wind curtailment periods.

There are different studies to detect a defense plan for increasing power system resiliency against a disruptive agent. In [20], a two level problem known as attacker- defender model was presented to calculate the power system vulnerability against terrorist attacks. This model includes two level. The first level tries to maximize the load shedding value. In contrast with first level, the second level attempts to minimize the load shedding value by considering the power system attacker plan, which is obtained in the first level. Another study related to attacker-defended model was proposed in [21]. This study used a decomposition technique to solve the bi-level attacker-defended model. In addition, authors of reference [22] applied a tri-level optimization model known as defended- attacker-defended model to select critical components of power system and protect them. Other researchers tried to present a suitable approach to solve tri-level optimization model. Such approach can be classified into heuristic approach [23], game theory model [24] and Benders decomposition model [25]. In view of all that has been mentioned so far, one concludes that pump-storage units can reduce the total operation cost, cover the stochastic nature of wind farms, and shave the load curve. However, there are limited studies exploring the role of energy storage systems on power system expansion while considering physical attacks. In this vein, an integrated transmission line and energy storage system expansion planning to decrease the vulnerability against terrorist attacks have been proposed in [26]. A defense plan to specify the components of the connected gas and electric systems from attacks is proposed in [27]. In addition, this reference has taken into account the thermal energy storage. Still, the types of energy storage, which are considered in such references, are not extended to pump-storage plants because installing a pump-storage plant needs to satisfy environmental constraints. Therefore, the optimal locating of this type of storage cannot be considered similar to these references. Nevertheless, the high flexibility of this type of energy storage unit can motivate researchers to consider it for choosing an optimal plan for defending power systems against terrorist attacks. In addition, the storage capacity during the attack has a stochastic nature, which is not considered in the cited references. Thus, herein, the volume of the upper reservoir was considered stochastic to meet this drawback. Finally, the optimal defense is a function of disruptive behavior. Consequently, the mathematical model was formed as a multi-objective optimization. Also, the -constraint technique was derived to solve the multi-objective problem and obtain an optimal Pareto front. The best optimal defense budget and component defended set was found in the Pareto front by fuzzy satisfying model.

This paper proposes a stochastic multi-objective tri-level problem to investigate the impact of pump-storage units on power system resiliency against physical attacks. The remainder of this paper is organized as follows: Section 2 presents the mathematical formulation of the multi-objective defense plan. The solution procedure is presented in Section 3. Section 4 describes case studies. Simulation results are also discussed in this section. Finally, conclusions are drawn in Section 5.

## 2. PROBLEM FORMULATION

The stochastic multi-objective defenses problem is formulated based on the defender-attacker-defender model presented in [28]. A defender-attacker-defender model includes three agents, as illustrated in Fig. 1. According to this figure, such agents act in sequence. The model is started by determining the system planer policy. The system planer identifies the components of the system to be defended for minimizing the effects of the disruptive action. Also, the disruptive action is a reason for the components to be out of service. The effects of the disruptive action are measured by the value of load shedding. Once the policy of the system planer is marked, a disruptive agent attempts to maximize power system damage by performing the terrorist action. Therefore, this agent makes a decision for selecting and damaging the non-defended components. Reference [29] demonstrated that the disruptive agent can only select the actions as non-defended transmission lines and transformers. Finally, the system operator reduces the power system damage during the terrorist attack in order to minimize the load shedding, which is defined as a tool for measuring the effects of the disruptive action.

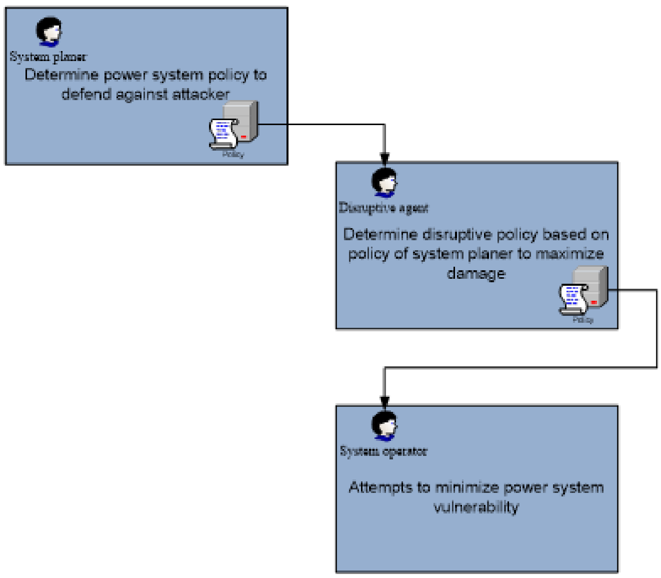


**Fig. 1.** Schematic view of the defender-attacker-defender model

According to the above description, the high-level conflict objective functions are stated in (1), (2). In (1), the power system planner attempts to minimize the effects obtained by the disruptive agent. As mentioned in the above description, such effects are measured by load shedding values in this paper. Therefore, the objective function written in (1) is applied to minimize the load shedding value, and Equation (2) is used to minimize the defenses' action cost.

$$OF_1^{high} = \min_{w} \sum_{n \in N} \Delta P_n^{d*} \tag{1}$$

$$OF_2^{high} = \min_{w} \sum_{n \in N} C_i^d \tag{2}$$

where $w_i$ is a binary variable. If the $i^{th}$ transmission line is selected for defending by the power system planner, this variable is equal to 1; otherwise, it is equal to 0 for non-defended transmission lines. The protection cost of the $i^{th}$ transmission line is illustrated by $C_i^d$, which is calculated by using a quadratic equation shown in (3). In this equation, the length of the $i^{th}$ transmission line is illustrated by li. Also, the quadratic, linear, and constant terms of the defended cost function related to the $i^{th}$ transmission are represented by $a_i^d, b_i^d$ and $c_i^d$, respectively. Finally, the load shedding value at this level is illustrated by $\Delta P_n^{d*}$. This parameter is obtained by considering (4) and the behavior of the disruptive agent.

$$C_i^d = a_i^d l_i^2 + b_i^d l_i + c_i^d \tag{3}$$

$$\sum_{n \in N} \Delta P_n^{d*} = OF_1^{middle} = \max_{v} \sum_{n \in N} \Delta P_n^{d'} \tag{4}$$

where $v_l$ denotes a binary variable. If the $i^{th}$ transmission line is selected for attack by the disruptive agent, this variable is equal to 0; otherwise, it is equal to 1 for non-attacked transmission lines. This equation models the disruptive attack plan. Consequently, it can be classified as the attack objective function of the disruptive agent. The disruptive agent considers another objective function to minimize the attack cost. This objective function is given in (5). In addition, the attack cost of the $i^{th}$ transmission line is formulated based on (6).

$$OF_2^{middle} = \min_{v} \sum_{n \in N} C_i^{at} \tag{5}$$

$$C_i^{at} = a_i^{at} l_i^2 + b_i^{at} l_i + c_i^{at} \tag{6}$$

where $a_i^{at}, b_i^{at}$ and $c_i^{at}$ are the quadratic, linear, and constant terms of the attacker cost related to the ith transmission line, respectively. The disruptive agent should optimize the objective functions and satisfy the constraint illustrated in (7). This constraint is considered to ensure that the disruptive agent does not select a defender component. In the disruptive agent model, the value of $\Delta P_n^{d*}$ is obtained by considering the operator system behavior, which is formulated in (8).

$$v_l \geq w_l \tag{7}$$

$$\sum_{n \in N} \Delta P_n^{d'} = OF_1^{lower} = \min_{P^l, P^g, P^{dis}, \delta, \Delta P_n^d} \sum_{n \in N} \pi_s \Delta P_n^d \tag{8}$$

where the objective function of the operator system is similar to (8). The system operator schedules the thermal generation units and pump-storage hydro power to minimize the load shedding value during a disruptive attack. The system operator objective function should be minimized by satisfying the technical system constraint.

$$P_{ij}^{l,s} = v_l \frac{\delta_i^s - \delta_j^s}{x_{ij}} \tag{9}$$

$$\sum_i P_j^{g,s} + \sum_i P_{ij}^{l,s} + P_{i,dis}^{p,s} + \Delta P_n^d = P_n^d + P_{i,ch}^{p,s} \tag{10}$$

$$P_i^{\min} \leq P_i^{g,s} \leq P_i^{\max} \tag{11}$$

$$-P_{ij}^{l,\max} \leq P_{ij}^{l,s} \leq P_{ij}^{l,\max} \tag{12}$$

$$-\delta_i^{\max} \leq \delta_i \leq \delta_i^{\max} \tag{13}$$

$$P_{dis}^{p,s} = \sigma_p^T q_p^{T,s} \tag{14}$$

$$P_{ch}^{p,s} = \sigma_p^P q_p^{P,s} \tag{15}$$

$$V_U^{p,s} = V_U^{p,s}(t-1) + q_p^{P,s} - q_p^{T,s} \tag{16}$$

$$V_L^{p,s} = V_L^{p,s}(t-1) - q_p^{P,s} + q_p^{T,s} \tag{17}$$

$$V_U^{p,\min} \leq V_U^{p,s} \leq V_U^{p,\max} \tag{18}$$

$$V_L^{p,\min} \leq V_L^{p,s} \leq V_L^{p,\max} \tag{19}$$

$$0 \leq q_p^{p,s} \leq Q_p^{\max} \tag{20}$$

$$0 \leq q_p^{T,s} \leq Q_p^{\max} \tag{21}$$

The transmission line power flow is calculated in (9). In this equation, the power flow and reactance of the transmission line-connected buses $i^{th}$ to $j^{th}$ are shown by $P_{ij}^{l,s}$, and $x_{ij}$, respectively. Also, $\delta_i^s$ represents the $i^{th}$ bus angle. The index of $s$ is used to determine the scenario in stochastic programming. In power flow calculation, the middle decision variable is used to avoid scheduling an attacked transmission line. The power balance is described in (10). In this equation, the power of thermal generation and the load demand located in the $i^{th}$ bus in the $s^{th}$ scenario are illustrated by $P_j^{g,s}$ and $P_n^d$, respectively. Also, the charging and discharging power of the pump-storage hydro power are determined by $P_{i,dis}^{p,s}$ and $P_{i,ch}^{p,s}$, respectively. The power of the thermal unit should be between the minimum ($P_i^{min}$) and maximum ($P_i^{max}$) values. Constraints (11) ensure that this limitation is satisfied. The overload of transmission lines is prevented by (12). In this equation, the maximum power flow of the line connected buses $i^{th}$ to $j^{th}$ is modeled by $P_{ij}^{l,\max}$. The bus angle is set in the correct interval by considering (13). The limitation of the pumped-storage hydro power is modeled by (14)-(22). The discharging and charging power of the pumped-storage unit is calculated in (14) and (15), respectively. In these equations, the turbine and pumped converter factors are denoted by $\sigma_p^T$ and$\sigma_p^p$, in that order. Also, the water volume of the upper and lower reservoirs are updated by using (16) and (17), where the water flow turbine or pumped are represented by $q_p^{t,s}$ or $q_p^{p,s}$. The water volume of upper and lower reservoirs should be lower than the maximum values and higher than the minimum value. Therefore, Constraints (18), (19) are used to model this limitation. Water extraction from the upper reservoir to generate power is limited by Constraint (20), whereas water extraction from the lower reservoir for pumping is limited by Constraint (21).

## 3. SOLUTION PROCEDURE

### A. $\epsilon$-constraint technique

There are different approaches to solving a multi-objective problem such as the $\epsilon$-constraint technique, normal boundary intersection. In this study, the proposed multi-objective problem is solved based on the $\epsilon$-constraint technique in which a multi-objective problem is converted into a single-objective function. Other objective functions are considered by inserting a constraint, whose upper or lower bounds are updated in each iteration. By applying this technique, the proposed multi-objective power system defense plan is transformed into a single-objective function in the upper and middle levels. Therefore, the objective function of the upper and middle level is equal to minimum and maximum load shedding values, in that order. In addition, the objective function related to defense and attack costs is changed into two constraints, which are considered in the high and middle levels of the problem. The upper rates of these constraints are determined by two vectors known as $\epsilon_i^{high}$ and $\epsilon_i^{middle}$. Such vectors are updated based on (22) and (23).

$$\varepsilon_i^{high} = OF_2^{high,\min} + \frac{Iter_i - 1}{M}(OF_2^{high,\max} - OF_2^{high,\min}) \tag{22}$$

$$\varepsilon_i^{middle} = OF_2^{middle,\min} + \frac{Iter_i - 1}{M}(OF_2^{middle,\max} - OF_2^{middle,\min}) \tag{23}$$

where $Iter_i$ and $M$ are the $i^{th}$ iteration and the total iteration number, respectively. Different values of epsilon are used to depict the Pareto front. Herein, the first objective function of the high and middle levels are optimized, whereas the cost constraints illustrated in (24) and (25) are satisfied.

$$OF_2^{high} = \sum_{n \in N} C_i^d \leq \varepsilon_i^{high} \tag{24}$$

$$OF_2^{middle} = \sum_{n \in N} C_i^{at} \leq \varepsilon_i^{middle} \tag{25}$$

### B. Fuzzy satisfying method

The solution from the Pareto front obtained in the previous section is selected based on the fuzzy decision-maker. In this technique, a fuzzy membership is assigned to each solution of the Pareto front. Then, linear fuzzy membership functions are obtained by using (26). Finally, the min-max method is applied to select the best solution. In each iteration, the minimum values of each $\hat{f}_k^*$ are selected. The solution with a higher value of $(f_1^*, f_2^*)$ is the best solution. In this formulation, $*$ indicates the higher and middle levels, and $k$ represents the objective function 1, 2.

$$\hat{f}_k^* = \begin{cases} 1 & f_k^* \leq f_{k,\min}^* \\ \frac{f_{k,\max}^* - f_k^*}{f_{k,\max}^* - f_{k,\min}^*} & f_{k,\min}^* \leq f_k^* \leq f_{k,\max}^* \\ 0 & f_k^* > f_{k,\max}^* \end{cases} \tag{26}$$

### C. Transforming the proposed model into an equivalent bi-level problem

The proposed tri-level optimization problem is converted into an equivalent bi-level problem based on the technique described in [30] whereby the lower level optimization problem is replaced by its dual theory. By applying the dual theory, the max-min problem, illustrated in the middle and lower levels, is converted into a max-max problem, i.e. a single problem. Therefore, the proposed tri-level problem is converted into a bi-level problem, which is formulated as:

$$OF_1^{high} = \min_w \sum_{n \in N} \Delta P_n^{d*} \tag{27}$$

$$\min_w \sum_{n \in N} C_i^d \leq \varepsilon_i^{high} \tag{28}$$

$$C_i^d = a_i^d l_i^2 + b_i^d l_i + c_i^d \tag{29}$$

$$\begin{aligned} \sum_{n \in N} \Delta P_n^{d*} = OF_1^{lower} = \max \sum_{i,j,s} \pi_s(\bar{\phi}_{ij}^s - \underline{\phi}_{ij}^s) P_{ij}^{l,\max} \\ + \sum_{i,s} \pi_s(\bar{\alpha}_i^s + \lambda_i^s) P_i^d + \sum_{i,s} \pi_s \bar{\gamma}_i^s P_i^{g,\max} \\ - \sum_{i,s} \pi_s \underline{\gamma}_i^s P_i^{g,\max} + \sum_{i,s} \pi_s(\bar{\chi}_i^s - \underline{\chi}_i^s)\bar{\delta} \\ + \sum_s \pi_s (V_u^{p,s}(t-1)\kappa_i^s + V_L^{p,s}(t-1)\upsilon_i^s + Q_p^{\max}\beta_i^s \\ - \sigma_p^T \Omega_i^s + \bar{\omega}_i^s P_U^{p,\max} - \underline{\omega}_i^s P_L^{p,\max} + \underline{\omega}_i^s P_L^{p,\max} - \underline{\theta}_i^s P_L^{p,\min}) \end{aligned} \tag{30}$$

$$\sum_{n \in N} C_i^{at} \leq \varepsilon_i^{middle} \tag{31}$$

$$C_i^{at} = a_i^{at} l_i^2 + b_i^{at} l_i + c_i^{at} \tag{32}$$

$$v_l \geq w_l \tag{33}$$

$$-\lambda_{l(in)} + \lambda_{l(o)} + \mu_l + \underline{\phi}_l + \bar{\phi}_l = 0 \quad \textbf{(34)}$$

$$\lambda_i^s + \bar{\gamma}_i^s \leq 0 \quad \textbf{(35)}$$

$$\sum_j \frac{1}{x_{ij}} v_l \mu_{ij}^s + \underline{\chi}_i^s + \bar{\chi}_i^s = 0 \quad \textbf{(36)}$$

$$\lambda_i^s + \bar{a}_i^s \leq \pi_s \quad \textbf{(37)}$$

$$\Omega_i + \mu_{ij}^s \leq 0 \quad \textbf{(38)}$$

$$\Omega^s - \kappa^s + \nu^s + \beta^s \leq 0 \quad \textbf{(39)}$$

$$\bar{\omega}_i^s + \underline{\omega}_i^s + \kappa_i^s \leq 0 \quad \textbf{(40)}$$

$$\bar{\theta}_i^s + \underline{\theta}_i^s + v_i^s \leq 0 \quad \textbf{(41)}$$

$$\begin{aligned} & \bar{\phi}_{ij}^s, \bar{\gamma}_i^s, \bar{\chi}_i^s, \beta_i^s, \bar{\omega}_i^s, \underline{\omega}_i^s \geq 0 \\ & \underline{\phi}_{ij}^s, \bar{a}_i^s, \underline{\gamma}_i^s, \underline{\chi}_i^s, \underline{\omega}_i^s, \underline{\theta}_i^s \leq 0 \\ & \lambda_i^s, \kappa_i^s, v_i^s, \Omega_i^s \in \Re \end{aligned} \quad \textbf{(42)}$$

The pumped-storage hydro power is scheduled in the discharging mode during the attack periods. Therefore, the charging equations are neglected to investigate the role of the pumped-storage hydro power for simplifying the mathematical model. The water volumes of the upper and lower reservoirs have a critical impact on the investigation. As mentioned in the previous section, such parameters can be classified into stochastic data because such values are changed each time, and the attack time is an unknown parameter. Therefore, such parameters should be modeled by stochastic programming.

### D. Solving the equivalent bi-level problem

Due to the binary decision variable of the lower-level of the equivalent problem, a method similar to Section 3-3 cannot be applied to solve the equivalent bi-level problem. Therefore, an enumeration algorithm is derived to solve the equivalent bi-level optimal power system defense plan problem. In the enumeration algorithm, a search tree is examined by considering an assumption related to selecting defended components. In this assumption, an optimal defense set selected by the system planer must have at least one member of the critical set. Also, a critical set is a set of equipment selected by a disruptive agent when the power system defense set is empty.

The enumeration algorithm is started by determining the critical set. Thus, the lower-level problem is solved by considering an empty defense set. The optimal terrorist plan demonstrates the candidate defended component set to be defended corresponded to the root node. According to the assumption mentioned above, at least one of the members of the critical set defined in the root node should be defended by the system planner. A process known as branching is used to create new nodes by considering the new defense plans obtained by solving the lower-level of the equivalent problem in the parent nodes. This process is performed until the limitation related to the defense budget represented in (27) is violated or all the candidate components are defended. At this point, the node has become a leaf. The enumeration algorithm is repeated until all of the nodes became leaves. After stopping the algorithm, the lowest rate of the objective function related to the upper level is chosen as the optimal defense solution. This algorithm is abbreviated in Algorithm 1. According to this algorithm, the first step is initialization in which the set of transmission lines is chosen as a set denoted by $M$. Also, the best response of the load shedding value is set as $z^{best} = \infty$. In addition, the node set ($M$) is formed based on the root node related to the un-defended network. The second step of the enumeration algorithm is node processing in which a node denoted by m is selected and removed from the node set $M$. Then, the lower-level problem is solved by considering the defended vector . The results of solving this problem are $v^m$, $\sum_{i \in N} \Delta P_n^{d(m)}$. Subsequently, the $l^{th}$ transmission line with $v_l^m = 0$ is inserted into the candidate set for the defense denoted by $c^m$. The optimal solution set is updated if $\sum_{i \in N} \Delta P_n^{d(m)} \leq z^{best}$. In this condition, the new value of $z^{best}$ is equal to $\sum_{i \in N} \Delta P_n^{d(m)}$. The third step of the enumeration algorithm is called pruning in which the node $m$ is classified into leaf groups. If the defense budget limitation is violated for expanding the defended component set or the candidate set associated with m node ($c^m$) is empty. Therefore, the algorithm level jumps to Step 5 in this condition. The fourth step of the algorithm is branching in which the new members are added to the node set by using the candidate set of the $m^{th}$ node. The $l^{th}$ member of the candidate component set associated with m node ($c^m$) is selected. Then, two nodes are created while taking into account that the mentioned member is defended (i.e. $w_l^m = 1$) or no-defended (i.e. $w_l^m = 0$). In the fifth step of the algorithm, the algorithm stopping condition is investigated. This condition is measured based on node set members. If the node set is empty, then the algorithm ends; otherwise, the algorithm is repeated by going to Step 2.

**Algorithm 1.** The enumeration algorithm

1: Initialize the node set and candidate sets.
2: Execute the node processing step.
3: Update the candidate set associated with the mth node.
4: **if** $\sum_{i \in N} \Delta P_n^{d(m)} \leq z^{best}$ **then**
5:     Update the best response
6: Execute the pruning step.
7: **if** violating defense budget constraint Or Empty $c^m$ **then**
8:     Classified m into the leaf set.
9:     Go to 12.
10: Execute the branching step.
11: Update the node set.
12: Execute the stopping step.
13: **if** the node set is not empty **then**
14:     Go to 2.

A systematic search is provided by the enumeration algorithm to guarantee that the algorithm can reach an optimal solution with finite iterations.

## 4. CASE STUDIES

The IEEE 24-bus test system illustrated in Fig. 2 is employed to evaluate the efficiency of the tri-level defense model. This test system includes 11 thermal generation units, and its total generation capacity is equal to 2850 MW. The load data of this system are depicted in Fig. 3. More information about this test system is reported in [31]. The performance of the tri-level defense model is assessed in two case studies. In the first case study, the test system vulnerability against the disruptive agent attack is demonstrated. The second case study is written to illustrate the impact of critical transmission line hardness on test system vulnerability. In addition, a pumped hydro power plant is located in the 11th bus to demonstrate its role in increasing power system resiliency against the terrorist attack in the third case study. Characterize of this unit is considered based on study published in [32]. Also, Table 1 reports the pumped hydro power plant parameters.

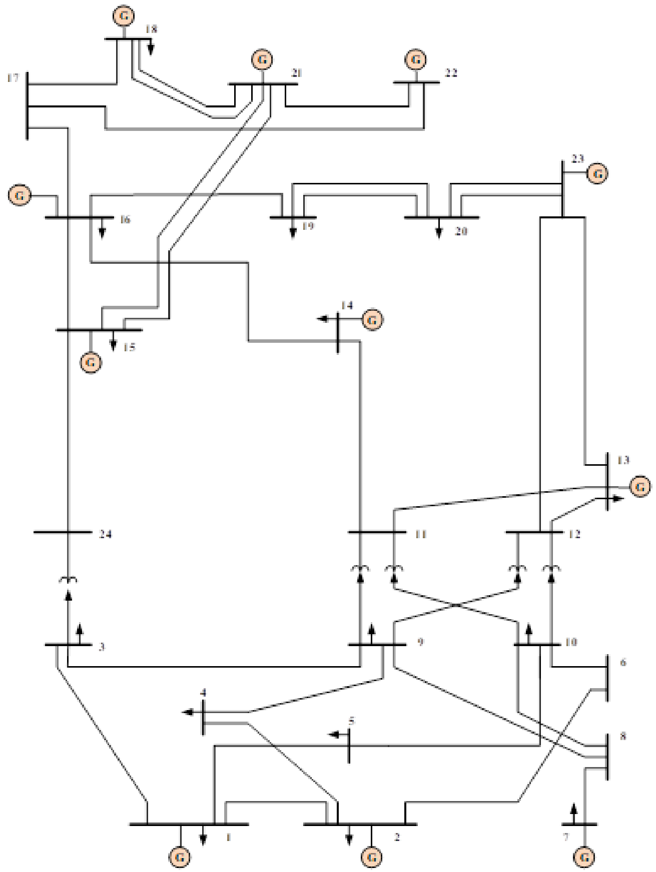

**Fig. 2.** The IEEE 24-bus test system

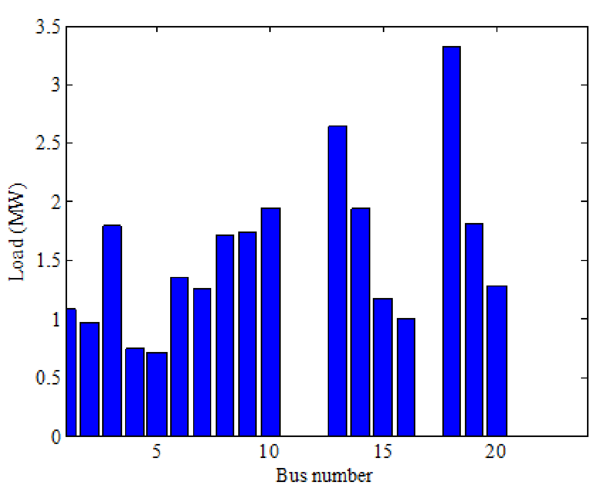


**Fig. 3.** Load data

**Table 1.** Pump storage data

| Parameter | Value |
|---|---|
| Maximum value of pumping/turbining flow ($Hm^3/h$) | 20 |
| Water-flow to power factor ($MW/Hm^3/h$) | 0.8 |
| Power to water-flow factor ($MW/Hm^3/h$) | 1.2 |
| Initial volume of upper reservoir ($Hm^3$) | 40 |
| Maximum value of upper reservoir ($Hm^3$) | 80 |
| Minimum value of upper reservoir ($Hm^3$) | 0 |
| Initial value of lower reservoir ($Hm^3$) | 40 |
| Maximum value of lower reservoir ($Hm^3$) | 80 |
| Minimum value of lower reservoir ($Hm^3$) | 0 |

### A. Testing system vulnerability against the disruptive agent attack

In this case study, the system vulnerability against the terrorist attack is evaluated. Thus, the power system defense budget is considered to be zero to detect the critical component. Also, the impact of the power system operator actions during the disruptive attacks on reducing the load shedding value is illustrated in this case. The selected lines for attacking is mentioned in the table 2. According to this table, the total lines attacked is considered as four transmission lines. Also, the transmission line flow after attack is depicted in Fig. 4. By considering this figure, it can be concluded that the power flow of attacked lines is equal to zero. Therefore, the simulation results are verified. Table 3 reports the value of load shedding obtained during different disruptive agent attacks. According to this table, the increase in the number of transmission lines, which are disrupted by terrorist attacks, can significantly enhance the load shedding value. As mentioned in the descriptions of the defender-attacker-defender model, the power system operator attempts to reduce the load shedding values by re-scheduling the power system during a terrorist attack. This is illustrated in Fig. 5. This figure displays the scheduled thermal generation units before a terrorist attack, which are scheduled to minimize the operation cost, and the output power of such generation units during the terrorist attack, which is scheduled to decrease the load shedding values.

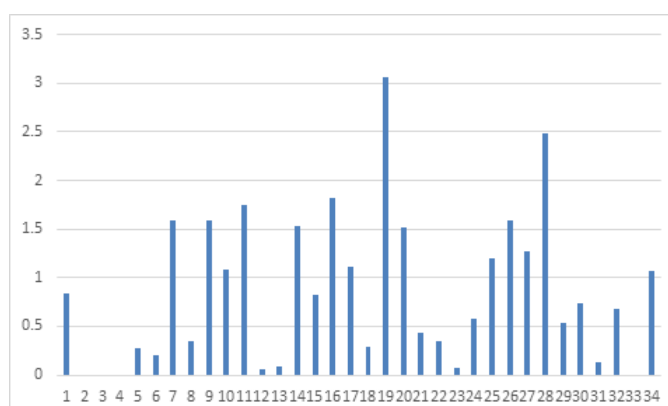


**Fig. 4.** Transmission line flow after attack

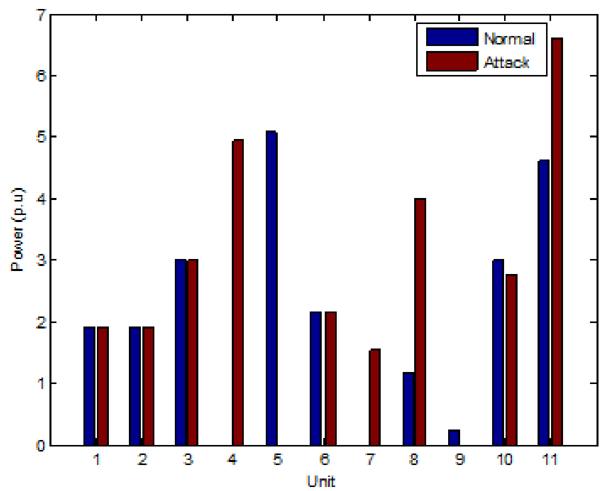


**Fig. 5.** The scheduled thermal generation units

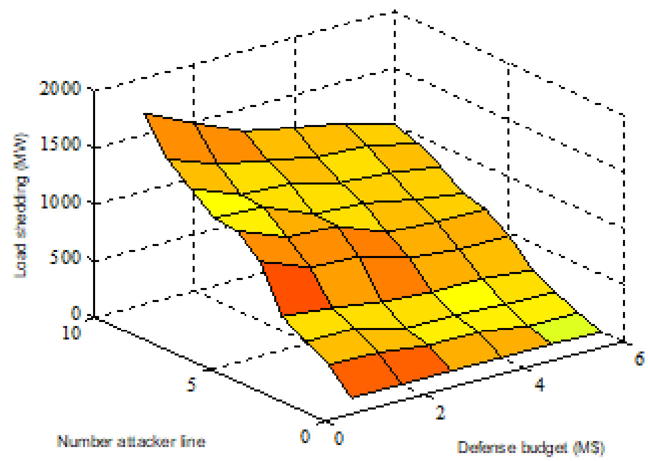


**Fig. 6.** The Pareto front obtained by solving the DAD model without storage

**Table 2.** Attacked lines determined by disruptive agent

| To | From | Line number | To | From | Line number |
|---|---|---|---|---|---|
| 4 | 2 | 4 | 3 | 1 | 2 |
| 23 | 20 | 33 | 5 | 1 | 3 |

**Table 3.** System vulnerability against the terrorist attack

| Load shedding value (p.u) | Number of out-of-service lines | Load shedding value (p.u) | Number of out-of-service lines |
|---|---|---|---|
| 4.42 | 4 | 0 | 1 |
| 8.42 | 5 | 3.09 | 2 |
| 10.17 | 6 | 3.09 | 3 |

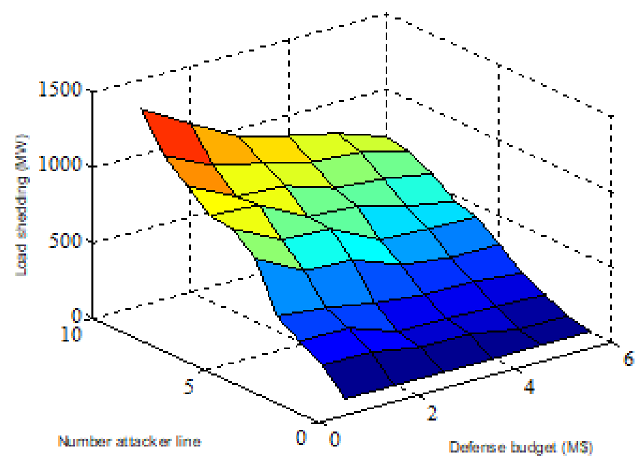


**Fig. 7.** The Pareto front obtained by solving the DAD model with storage

### B. Defense plan without considering the pumped-storage hydro unit

In this case, the proposed multi-objective model is solved without considering the pumped-storage hydro unit. The Pareto front obtained in this problem is depicted in Fig. 6. According to this Fig, the best solution obtained by applying the fuzzy membership method is equal to damaging four transmission lines by the disruptive agent, and the power system planer attempts to protect three transmission lines with a 3.5 M$ defending cost. In this condition, the load shedding value is equal to 308.95 MW.

### C. Defense plan with considering the pumped-storage hydro unit

In this case, the proposed multi-objective model is solved while considering the pumped-storage hydro unit. The Pareto front obtained in this problem is depicted in Fig. 7. According to this figure, the best solution obtained by calculating the fuzzy membership method is equal to damaging three transmission lines by the disruptive agent, and the power system planer attempts to protect three transmission lines with a 2.5 M$ defending cost. In this condition, the load shedding value is equal to 248.809 MW.

## 5. CONCLUSION

A stochastic tri-level defender-attacker-defender problem was formulated to detect an optimal defense plan by considering the pumped-storage hydro plant. In the proposed model, the water volume of the upper reservoir during the disruptive attack was regarded as a stochastic parameter. The detailed and finding of proposed model can be summarized as:

• Stochastic tri-level programming model was transformed into an equivalent bi-level program.

• The equivalent bi-level program was solved by using an enumeration algorithm.

• The simulation results illustrated the effectiveness of the pump-storage hydro plant in reducing the power system defender budget by $\tilde{5}$ M$.

• The installed pumped hydro-power plant reduced the load shedding by $\tilde{6}$0.141 MW.

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