A chance constrained techno-economic analysis of using small scale power generation units for providing subways systems: Tabriz Urban Railway System

FARID HAMZEH AGHDAM[1,*] **AND SAEID RAZMJOU**[2]

[1] *Department of Electrical Engineering, Azarbaijan Shahid Madani University, Tabriz, Iran*
[2] *University of Tabriz, Tabriz, Iran*
[*] *Corresponding author: farid.hamzeh@gmail.com*

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The need for diversified energy resources, sustainable development, energy security and improving the reliability of electrical energy systems, have led to serious global attention to the development and expansion of small-scale power plants better known as distributed generation (DG) and increase the share of these resources in the global energy basket. One of the problems for the power supply of subway systems, is that it is difficult to supply the energy they need using the utility grid due to their passage through crowded centers. This requires the construction of power posts by the company in charge of building the metro systems which requires a lot of costs for the company. Therefore, alternative ways of supplying energy for the metro system can be sought. One way is to use small-scale local power plants. The use of these energy sources can achieve benefits such as higher economic productivity, greater reliability and better management of fluctuations. Therefore, in this paper, the issue of using distributed energy sources for the metro system is examined. The proposed framework for effective and efficient resource development, along with long-term planning of the system components, management and intelligent use of these resources to provide the power supply of the subway, in the field of short-term operation also includes. Purchase prices from the upstream network have been considered and the net present value (NPV) and investment costs have been studied using engineering economics methods. The uncertainty of demand levels in traction buses are modeled using chance constrained programming (CCP). By means of CCP approach, better decisions without jeopardizing the security of the system, can be made. Finally, using GAMS and DigSilent softwares, the problem is optimized and the technical parameters are examined for practical Tabriz subway system test system.

keywords: *Distributed generation, Planning, Technical evaluation, Economic analysis, Subway system*

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1. INTRODUCTION

In recent decades, privatization of the electricity industry and its restructuring have been introduced and implemented in some developed countries. Following these changes, different parts of power systems such as production, transmission and distribution have been separated [1, 2]. These changes, on the one hand, and problems such as the construction of new transmission lines, the development and construction of substations and distribution substations, the high cost of construction of new power plants, and the advancement of technology in building of small-scale power generation units, has caused penetration of distributed generation in power systems. These sources will not require transmission lines and large distribution and subtransmission substations to connect to the network and will be connected directly to the distribution network [2]. Small-scale power plants have many pros such as their good performance, good size and scalability and flexibility. In addition, these resources lead to the failure of the monopoly of electricity production by manufacturing companies and deepen the market for buying and selling electricity [3]. The distribution system has seen fewer fundamental changes due to its sensitivity and direct communication with the customers and consumers. Hence, there are problems such as inefficiency of current distribution systems in various dimensions such as technical stability, economic stability, regulatory structures and operation in traditional distribution systems.

With the arrival of the subways systems in the cities, a very large load is placed on the distribution system, which, as mentioned, due to the lack of development of the distribution system, causes the inability of this system to supply metro power. Therefore, the electricity company has left the development of the distribution network to the metro organization, which can increase the amount of investment. Therefore, considering the advantages of distributed generation systems and small-scale power plants, in this study, the technical and economic study of the construction of these power plants to feed the metro power system will be conducted. Few researches have been done in the field of energy network of subway systems. Authors in [4] have proposed a two-stage urban rail transit operation short term scheduling framework comprising running time allocation and regenerative braking energy to be reutilized to save energy consumption. In [5], three schemes of regenerative energy utilization in metro system is introduced, as the energy dissipation type, the energy storage type and the energy feedback type. Yang et al [6] have developed a scheduling approach to coordinate the arrivals and departures of trains in metro system to reduce the trains' energy consumption using the energy regenerated from braking. The problem is formulated using a mixed integer programming model with real-world speed profiles.

By reviewing the sources, it can be seen that such a topic has not been studied so far. Therefore, due to the similarities between the planning of DGs for the subway train system and microgrids (MGs) or active distribution systems, studies that have conducted for planning of DGs in MGs and distribution networks will be reviewed. Examining the available resources and researches, it can be seen that the researches conducted in the field of long-term planning and development of DGs resources is in its infancy. In the reference [7], the authors propose a method for long-term planning and development of DG resources in an MG. This MG with the presence of DG sources and energy storage, has higher security and reliability in the event of accidents leading to faults and outages in the upstream network. Reference [8] provides a framework for the design and use of DGs in the distribution network with the aim of designing and programming robust MGs. In this research, the main purpose of the system optimization is enhancement of reliability and vulnerability as well as economic concepts and operational costs and the mathematical model of the problem is solved using a heuristic method of particle swarm optimization (PSO). Reference [9] also examines the applicability of distributed energy sources in MGs in the expansion of generation and transmission network. In this study, it is shown development of DGs in forms of MGs, can be a good option to assess the benefits of this development for expansion problem of the power system. A bilevel model for determining the optimal locations and capacity of distributed generation resources in the MG is presented in the reference [10]. Yang and Tian [11] have solved the problem of optimal sizing and siting of DGs in an MG. Limitations due to greenhouse gas emissions are considered in the problem modelling and it has been solved using genetic algorithm as a heuristic methodology. Authors in [12], have provided a framework for long-term planning of DGs to determine their optimal location and size in an MG. The optimization is done based on reliability parameters and a heuristic method is used to achieve the results. Likewise, in [13], the authors have presented a long-term planning method for determining the capacity and optimal location of renewable energy sources and fossil fuel based DGs. Constraints on greenhouse gas emissions have also been considered to limit the emissions. The effect of fuel prices on fossil units as well as wind speed on the output of the DGs have been given a sensitivity analysis. In reference [14], a framework for optimum planning of DG units in the power network with the aim of developing MGs and the benefits of this development is studied and evaluated. Hafez and Batacharaya [15] have presented a modeling of long-term planning problem of MG design in the presence of DG sources taking the pollution constraints into account. Also operational costs of using renewable sources has been modelled according to their lifespan. The problem of determining the optimal location and capacity of DGs with the aim of utilizing in MGs has been studied in [16]. Ensuring reliability criteria was one of the objectives of this study and genetic algorithm was used to solve the problem. A two-level optimization framework for optimal design of location and size of combined heat and power (CHP) DGs is presented in [17]. One of the main goals of the study, beside the operating costs, is the cost of greenhouse gas emissions. Najemi et al. [18] have provided a framework for determining the capacity and optimal location of DG units in an MG. In [19], a comprehensive optimization model is proposed for optimal determination of the capacity and location of DG resources such as wind turbines and photovoltaic systems. In this study, batteries and electric vehicles were used to compensate for fluctuations in renewable sources. The proposed framework includes long-term planning for resource development, along with short-term energy management and the use of these resources for supply. Hasanvand et al. [20] have studied the planning of various types of DGs such as fuel cells, wind turbines and solar panels. Development costs, operation and reliability parameters have been considered in the cost function of the system. In addition, the system losses have been investigated. Zhang et al. [21] have proposed a multiobjective optimization and decision-making method for solving the problem of optimal sizing and siting of DGs in distribution networks. A comprehensive analysis of loss sensitivity, voltage profiles and reliability indices has been performed for candidate points of DG installation. NSGA II method is used to solve the multiobjective problem. The objective function is to maximize the profits of the DG owner and distribution companies. Costs in the objective function include not only DG investment costs, but also operating and maintenance costs, as well as revenue from the sale of electricity to the distribution network. Other parameters influencing decision making include loss improvements, voltage profiles and system reliability. In the reference [22], a new strategy for DG planning in distribution system is presented. Reactive power constraints of different generation systems including wind generating units, photovoltaic panels and biomass power plants are included in the planning model. Hemmati et al. [23] have proposed a novel hybrid method to solve the problem of distribution systems development in the presence of DGs. Various parameters such as uncertainty, optimal size and location of DGs, load growth, electricity market, etc. are included in the planning. The proposed planning aims to minimize both investment and operating costs.

In the above reviewed literature, most of the works have employed a scenario-based approach to model the uncertainties. However, in this model, it is required that all the situations of uncertainties to be considered which needs a scenario reduction. In this case, the burden of calculations could be reduced, but, it might jeopardize the security and stability of the system as a result of power which is very undesirable in subway systems where reliability and security parameters are very important.Chance-constrained programming (CCP) is one of the suitable tools for overcoming this issue. In CCP, the probability of violation for some limits including stochastic variables, remains at a desired level. This can lead to increment in system stability and reliability. Thus, in many studies, application of CCP in power system problems has been investigated.

A CCP based scheduling model in MGs energy management has been proposed in [24] to handle the uncertainty of renewable energy generation and loads. Wang et al. [25] have proposed a multi-stage CCP approach for power system planning. In this research, various uncertainties in electric power systems is modlled via CCP to facilitate the procedure of risk management for climate change mitigation. Liu et al. [26] have presented a framework for CCP based short term planning problem for grid-connected MGs. The optimization is motivated by practical MG applications such as peak shaving as in demand response and frequency regulation in presence of renewable resources and random loads. In [27], a CCP based model for network congestion management in the day-ahead power market has been proposed. The problem is modelled through jointly consideration of the uncertainties of wind power and loads, which could help determine the optimal daily dispatch of generators to minimize the hazards of transmission lines congestion. Shi et al. [28] have proposed a CCP based day-ahead scheduling model for an islanded MG in presense of DGs, energy storage units, and renewable generation such as wind turbines. Authors in [29] have proposed a novel method to enhance the performance of a scalable stochastic optimization model for MGs, ensuring utilization of significant portion of the wind power output. The problem is modeled as a two-stage CCP to obtain operation decisions. Daneshvar et al [30] have proposed a distributionally robust CCP model for the optimal scheduling of MGs in coupled electrical and gas networks considering the transactive energy. The aim is defining the optimal scheduling of DGs with goal of maximizing the MGs' profits and minimizing the imbalance costs. The problem is modelled as linear problem to avoid unreliable results. In [31], a model for quantifying the nonlinear impact of the depth of discharge on batteries life cycle is proposed by adopting the CCP. The purpose is to find best schedule of the batteries in day-ahead horizon considering the degradation cost in a multi-objective optimization problem. Likewise authors in [32], have presented a bi-level programming model based on CCP for the planning issues of fast-charging stations in electrified transportation networks. Stochastic mathematical models for MGs energy exchange using a transactive energy structure in a smart grid is presented in [33]. CCP is employed to consider the uncertainties under the transactive energy management. Hemmati et al [34], have proposed a novel strategy for optimal scheduling of reconfigurable MGs. The scheduling problem is formulated as a CCP problem, aiming at minimizing the total operation cost of the MG containing fuel cost, reliability cost, cost of power transactions with utility grid, and switching cost.

Examining the available researches, it can be seen that so far no research has been done on the use of DGs for supplying the subway power system. Therefore, in this research, for the first time, the technical and economic aspects of the utilization of DGs for the metro system will be studied. The case study is line 2 of Tabriz city subway system. The results of this reasearch can be used as a starting point for the use of these resources in subway projects under construction. To sum up, the following items show the objectives of this study:

- Provide a framework for designing and economically exploiting DGs to supply the urban train network power system
- Technical study of using DG resources for use in line 2 of Tabriz city train
- Investigation of economic parameters for the installation of DGs
- Studying the operation of the system in different faulty conditions.

The rest of the paper is organized as follows: Mathematical formulation of the problem is presented in Section 2. Simulations in the test system are presented in Section 3 and the conclusion of the paper is brought in Section 4.

2. MATHEMATICAL FORMULATION OF THE PROBLEM

As mentioned earlier, limitations in the current distribution network have made challenges for the supply of subway system. In addition, the many benefits of using DGs have encouraged investors to use these resources. This chapter will model and formulate the issue of determining the capacity and optimal location of small-scale power plants in the metro power grid. In the proposed framework for the development and optimal planning of resources, in addition to long-term planning, the costs of short-term operation and maintenance of this system will also be considered. The net present value will be used for the economic evaluation of the design and the feasibility of the long-term planning of the system. The proposed modeling and problem formulation will be implemented in the form of a mixed nonlinear optimization problem (MINLP).

A. Objective function

The objective function of the planning of DG resources can be formulated in the form of (1). In this regard, minimizing the net present value of the total investment costs and operation of the project is the goal of optimization.

$$\min O.F. = \min[C_{inst} + C_{main} + C_{op} - InC_{net} + C_{Loss}] \tag{1}$$

In the above relation, C_{inst}, C_{main} and C_{op} are investment, maintenance and operation costs, respectively. In addition, IC_{net} is the revenue generated from the sale of surplus electricity to the global grid via the above distribution post. C_{Loss} is the cost that is paid for compensating the active power loss. Accordingly, the optimization leads to finding places in order to decrease the active power loss. The initial cost of investment and installation of each unit, maintenance costs, operating costs and revenue from the sale of electricity to the network, and finally the cost of active power loss, are obtained from the following relationships:

$$C_{inst} = \sum_{i=1}^{N_{DG}} P_{\max}^{DG} \times C_{fixed} \times U_i \tag{2}$$

$$C_{main} = [\sum_{t=1}^{T} \sum_{n=1}^{N_{DG}} Cost_{main,n})] \times (\frac{1+InfR}{1+IntR})^{t} \tag{3}$$

$$C_{op} = [\sum_{t=1}^{T} \sum_{h=1}^{8760} \sum_{n=1}^{N_{DG}} (P_{n,h,t}^{DG} \times OpCost_{DG})] \times (\frac{1+InfR}{1+IntR})^{t} \tag{4}$$

$$InC_{net} = \sum_{t=1}^{T} \sum_{h=1}^{8760} P_{t,h}^{net} \times \lambda_t \times (\frac{1+InfR}{1+IntR})^{t} \tag{5}$$

$$C_{Loss} = \sum_{t=1}^{T}\sum_{h=1}^{8760} P^{Loss}_{t,h} \times \lambda_t \times (\frac{1+InfR}{1+IntR})^{t} \tag{6}$$

The costs of maintaining and operating the system are expressed in terms of net present value (NPV) using engineering economics techniques and interest rate ($IntR$) and inflation rate ($InfR$). In the above relations, t represents the year of operation, U_i is a binary variable that indicates the presence of DG in bus i. $P^{DG}_{\max}$ and C_{fixed} represent the DG capacity and fixed investment cost per MW of DG, respectively. $P^{net}_{t,h}$, $P^{Loss}_{t,h}$ and $lambda_t$ also indicate the amount of power sold to the utility grid, active power loss of the system, and the price of electricity. The price of electricity can change with the annual increase, and as a result we have the price of electricity in the year t as follows:

$$\lambda_t = \lambda_b \times (1+\alpha_{price})^{t} \tag{7}$$

In the above relation, λ_b is the base price of electricity in the first year, and α_{price} is the rate of growth of electricity prices during the operation period.

B. Problem Constraints

In this subsection, the constraints of the problem are examined. The number of DG system units that have been nominated for network installation is as follows:

$$\sum_{i=1}^{N_b} U_i = N_{DG} \quad U_i \in \{0,1\} \tag{8}$$

Power flow constraints, usually due to nonlinearity, cause severe non-convexity in the problem. Therefore, in this section, convex load flow for distribution networks is used . Limitations related to load flow according to the production capacity of DG systems are defined as follows:

$$P^{inj}_{i,t,h} + U_i \times P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} = P^{Load}_{i,t,h} + \sum_{l} P^{Line}_{ahead_{l,t,h}} \tag{9}$$

$$Q^{inj}_{i,t,h} + Q^{Line}_{back_{l,t,h}} = Q^{Load}_{i,t,h} + \sum_{l} (Q^{Line}_{ahead_{l,t,h}} + Q^{Loss}_{ahead_{l,t,h}}) \tag{10}$$

$$V^2_{i_{se},t,h,s} - V^2_{i_{re},t,h} = 2R_l P^{line}_{l,t,h} + 2X_l Q^{line}_{l,t,h} + R_l P^{loss}_{l,t,h} + X_l Q^{loss}_{l,t,h} \tag{11}$$

$$P^{loss}_{l,t,h} = \frac{(P^{line}_{l,t,h})^2 + (Q^{line}_{l,t,h})^2}{V^2_{i_{re},t,h}} \times R_l \tag{12}$$

$$Q^{loss}_{l,t,h} = \frac{(P^{line}_{l,t,h})^2 + (Q^{line}_{l,t,h})^2}{V^2_{i_{re},t,h}} \times X_l \tag{13}$$

In the above equations, $P^{inj}_{i,t,h}$ and $Q^{inj}_{i,t,h}$, are respective representatives for the active and reactive power injected into the bus i. Also, $P^{loss}_{l,t,h}$ and $Q^{loss}_{l,t,h}$, indicate the active power and reactive power losses of the system, respectively. In addition, the powers passing through the lines are denoted by $P^{line}_{l,t,h}$ and $Q^{line}_{l,t,h}$. The resistance and reactance of each line are shown by R_l and X_l as well as the voltage of each bus with V. Voltage limits are also shown in the following equation.

$$V_i^{\min} \leq V_{i,t,h} \leq V_i^{\max} \tag{14}$$

The exchange of active and reactive power of the system with the upstream network is also limited through the following relations.

$$P^{\min}_{net} \leq P^{net}_{t,h} \leq P^{\max}_{net} \tag{15}$$

$$Q^{\min}_{net} \leq Q^{net}_{t,h} \leq Q^{\max}_{net} \tag{16}$$

The maximum generation capacity of each unit is also determined by (17).

$$0 \leq P^{DG}_{i,t,h} \leq P^{\max}_{DG} \times U_i \tag{17}$$

Also, to ensure the power supply of all loads in islanded mode of operation and to guarantee the reliability parameters, the installed capacity must be more than the total of maximum power of the loads, which is shown in the following relation.

$$\sum_{i=1}^{N_{DG}} P^{\max}_{DG,i} \geq \sum_{i=1}^{N_b} P^{\max}_{Load,i} \tag{18}$$

C. Chance constrained programming

One of the main tools for modeling the uncertainty CCP which is very popular in power system problems. In this approach, in some constraints containing random variables, the probability of its occurrence is of interest and it should stay at an advanced decided level. For subways system, there are two types of power systems known as lightening and power system (LPS) and rectifier system (RS). The RS is reponsible for supplying the electrification system of the trains. The demand level can be considered as a stochastic phenomena which can be modelled as a normal probability distribution function. This can make a better prospective in procedure of planning. The demand power has taken part in (9). Thus, it can be rewritten in the form of a CCP problem as follows:

$$Pr[P^{inj}_{i,t,h} + U_i \times P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_{l} P^{Line}_{ahead_{l,t,h}} = P^{Load}_{i,t,h}] \geq \eta \tag{19}$$

In the above equation, η is confidence level for certainty of the occurrence of the constraint. In order to ensure that the (19) be true for all RS stations, the following relation is needed:

$$\Pr\left[\bigcap_{i=1}^{n_b}\left(P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_{l} P^{Line}_{ahead_{l,t,h}} \geq P^{Load}_{i,t,h}\right)\right] \geq \eta \tag{20}$$

The above formulation is known as joint CCP. The joint CCP is a difficult form to solve and it needs modifications to be converted into a series of separate constraints. Eq. (21) illustrates the complementary of (20):

$$\Pr\left[\bigcup_{i=1}^{n_b}\left(P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_{l} P^{Line}_{ahead_{l,t,h}} \leq P^{Load}_{i,t,h}\right)\right] \leq 1-\eta \tag{21}$$

A sufficient condition for (21) to happen is as follows:

$$\Pr\left(P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_{l} P^{Line}_{ahead_{l,t,h}} \leq P^{Load}_{i,t,h}\right) \leq \frac{1-\eta}{n_b} \tag{22}$$

By writing the complementary of (22), the approximate individual constraint equivalent to joint ccp is achieved as below:

$$\Pr\left(P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_l P^{Line}_{ahead_{l,t,h}} \geq P^{Load}_{i,t,h}\right) \leq 1 - \frac{1-\eta}{n_b} \tag{23}$$

Eq. (23) is a representative for the approximate individual constraint equivalent to joint probabilistic Eq. (20). By knowing the probability distribution function of the stochastic variable, the mentioned equation could be replaced by its deterministic equivalent.

In our planning problem, the random variable is the demand level which is assumed to have a normal distribution function with mean value of μ and standard deviation of σ [35]. Accordingly, we will have:

$$\Pr\left(\frac{P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_l P^{Line}_{ahead_{l,t,h}} - \mu^{Load}_i}{\sigma^{Load}_i} \geq \frac{P^{Load}_{i,t,h} - \mu^{Load}_i}{\sigma^{Load}_i}\right) \leq 1 - \frac{1-\eta}{n_b} \tag{24}$$

The left handside of the (24) is definition of cumulative distribution function for a standard random variable $P^{Load}_{i,t,h}$. Considering F to be the cumulative distribution function, it can be rewritten as follows:

$$F_{P_{Load}}\left(\frac{P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_l P^{Line}_{ahead_{l,t,h}} - \mu^{Load}_i}{\sigma^{Load}_i} \geq \frac{P^{Load}_{i,t,h} - \mu^{Load}_i}{\sigma^{Load}_i}\right) \leq 1 - \frac{1-\eta}{n_b} \tag{25}$$

and for $Z_\eta = F^{-1}(1 - \frac{1-\eta}{n_b})$ the following equations are obtained:

$$\frac{P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_l P^{Line}_{ahead_{l,t,h}} - \mu^{Load}_i}{\sigma^{Load}_i} = Z_\eta \tag{26}$$

$$P^{inj}_{i,t,h} + U_i P^{DG}_{i,t,h} + P^{Line}_{back_{l,t,h}} - \sum_l P^{Line}_{ahead_{l,t,h}} = \sigma^{Load}_i \times Z_\eta + \mu^{Load}_i \tag{27}$$

Eq. (27) is written for every bus with demand and transforms the joint CCP problem into a deterministic equivalent.

D. The Z-update Algorithm

The deterministic approximation is easier to solve than the original CCP problem. Numerical methods are required to update Z [36, 37]. One approach is shown in Fig. 1. The feasibility of the solution is checked through OPF at each iteration.

The update of the Z value means a change in the demand levels and might have a significant effect on the output of the problem. The steps in the algorithm are as follows [36]:

1. The planning problem is initially solved with values Z_h and Z_l which are respected correspondence to probabilities more (ph) and less (pl) than the desired confidence level.

2. The probability values ph and pl are determined by solving OPF for various samples of demand levels with normal PDF. The samples are generated using Mone Carlo simulations. Then, these probabilities are converted to the corresponding Z_1 and Z_2 using the normal PDF of the variable.

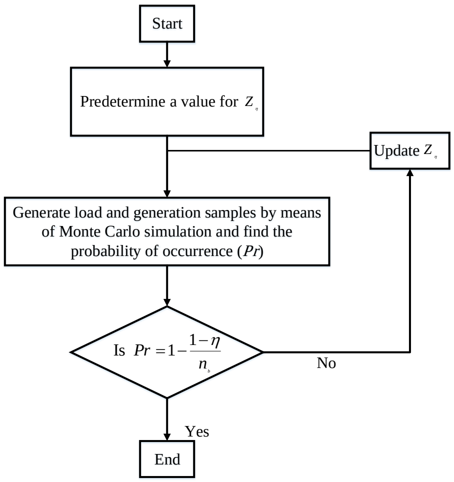

Fig. 1. Flowchart of finding Z_η.

3. Based on these values, Z_η is updated for the next iteration using the following relation:

$$Z^{j+1}_\eta = Z_l + \left(\frac{Z^j_\eta - Z_2}{Z_1 - Z_2}(Z_h - Z_l)\right) \tag{28}$$

in this method it is tried to shrink the interval $[Z_h; Z_l]$.

4. The planning problem is solved with the updated Z^{j+1}_η and then using the OPF and Monte Carlo simulations, the probability of the problem and corresponding Z_{new} is calculated.

5. If calculated Pr is less than ϵ then the algorithm terminates. Else, the following steps are used to choose the new lower and higher values of Z:

   (a) If $Z_{new} \leq Z^j_\eta$ then Z_l and Z_2 are respectively replaced with the Z^{j+1}_η and Z_{new}

   (b) If $Z_{new} \geq Z^j_\eta$ then Z_h and Z_1 are respectively replaced with the Z^{j+1}_η and Z_{new}.

6. Repeat until convergence.

3. SIMULATIONS AND RESULTS

In this section, the problem of optimal sizing and siting DG resources for the Tabriz urban railway system will be addressed. Simulations will be performed in the GAMS software environment to optimize the problem. The technical aspects will also be examined by DigSilent software. The power network of the systems is shown in Fig. 2. This system consists of two parts, RS and LPS. The LPS section is shown in black and full lines, and the RS section for TPS posts is shown in red with a dotted line.

The specifications and size of LPS and TPS cables are shown in Tables 1 and 2. Also, the length of the cables is tabulated in aforementioned Tables. The mean value of power consumption at each station for the LPS and TPS systems is shown in Table 3. Of course, this amount of load is for the working hours, which is considered from 5:30 AM to 24 PM. In other hours, the power consumption of the system is assumed to be zero. Planning data including planning years, interest and inflation rates, cost

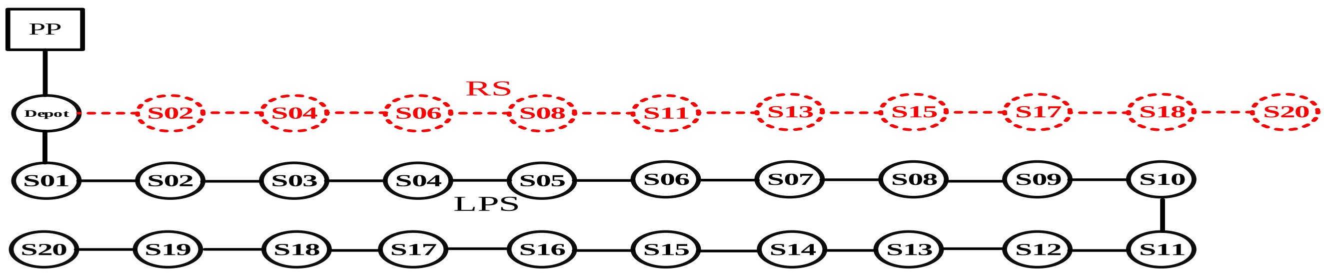

Fig. 2. Diagram of the test system.

Table 1. Line specifications for LPS.

from	to	Length (m)	Cable Type
Depot	S01	2876	3×1×50 mm^2 Cu
S01	S02	1114	3×1×70 mm^2 Cu
S02	S03	1235	3×1×50 mm^2 Cu
S03	S04	1467	3×1×50 mm^2 Cu
S04	S05	850	3×1×50 mm^2 Cu
S05	S06	1604	3×1×50 mm^2 Cu
S06	S07	1059	3×1×50 mm^2 Cu
S07	S08	1023	3×1×50 mm^2 Cu
S08	S09	1230	3×1×95 mm^2 Cu
S09	S10	707	3×1×70 mm^2 Cu
S10	S11	1092	3×1×70 mm^2 Cu
S11	S12	1050	3×1×50 mm^2 Cu
S12	S13	1179	3×1×50 mm^2 Cu
S13	S14	842	3×1×50 mm^2 Cu
S14	S15	1336	3×1×50 mm^2 Cu
S15	S16	1780	3×1×50 mm^2 Cu
S16	S17	1632	3×1×50 mm^2 Cu
S17	S18	1725	3×1×50 mm^2 Cu
S18	S19	938	3×1×50 mm^2 Cu
S19	S20	875	3×1×70 mm^2 Cu

Table 2. Line specifications for RS.

from	to	Length (m)	Cable Type
Depot	S02	3990	3×1×50 mm^2 Cu
S02	S04	2502	3×1×50 mm^2 Cu
S04	S06	2254	3×1×50 mm^2 Cu
S06	S08	1882	3×1×50 mm^2 Cu
S08	S11	2629	3×1×120 mm^2 Cu
S11	S13	2029	3×1×95 mm^2 Cu
S13	S15	1978	3×1×70 mm^2 Cu
S15	S17	3212	3×1×50 mm^2 Cu
S17	S18	1725	3×1×75 mm^2 Cu
S18	S20	1611	3×1×70 mm^2 Cu

Table 3. Mean value of power demand for LPS and RS in the stations.

Station	LPS Power (KW)	TPS Power (KW)
Depot	1922	1592
S01	1223	-
S02	1276	2456
S03	1292	-
S04	1123	2598
S05	1216	-
S06	1278	2643
S07	1655	-
S08	1669	2780
S09	1102	-
S10	1063	-
S11	1384	2870
S12	1177	-
S13	1191	2857
S14	1150	-
S15	1162	3078
S16	1180	-
S17	1118	2962
S18	1023	2665
S19	1106	-
S20	1026	2418

of installation of gas units, maintenance and operation costs, confidence level in CCP, are given in Table 4.

Tables 5 and 6 are the simulation results for DG allocation in Tabriz urban railway power network in line 2. The capacity of the units are assumed to be 10MW or less. These tables show the location and size of DG units at different stations for both RS and LPS systems. The amount of production capacity is considered to be at least 25% higher than the required capacity. The NPV cost is considered for the two scenarios shown in Table 7. In the first scenario, the metro power system is operated in the islanded form and it is impossible to sell power to the utility grid. In the second scenario, by selling electricity to the utility grid, it is possible to make a profit and reduce the NPV cost of the system. For this purpose, station S01 is assumed to be connected to the passage post.

As can be seen, considering the feature of selling electricity to the grid during downtime of the city train system can significantly reduce system costs.

The maximum demanded power of the system in each of the RS and LPS is equal to 30 MW, so with the failure of one of the units, the system can continue to operate.

If we use 5 MW units, the results will be in the form of Tables 8 and 9. In this case, the system reservation capacity will be less than the use of 10 MW units and thus less initial investment will be required for the system. In both designs, if one of the units fails, the system will still be able to power its loads, indicating

Table 4. Planning data.

Parameter	Unit	Value
Investment cost	$\$/MW$	318000
Operation cost	$\$/MWh$	29
R & M cost	$\$/MWh$	7
Interest rate	%	12.5
Inflation rate	%	9
Planning horizon	years	20
CCP confidence level (ζ)	%	95

Table 5. Planning results of RS system using 10MW or less units.

Location	Capacity (MW)
S04	10
S08	10
S13	10
S18	10

Table 6. Planning results of LPS system using 10MW or less units.

Location	Capacity (MW)
S02	10
S04	10
S11	10
S17	10

Table 7. NPV of costs for two scenarios.

Scenario	Cost ($)
first	246,700,000
second	164,750,000

the high reliability of the system. Table 10 also shows the NPV cost of the system for both islanded performance without the sale of power to the overhead grid as well as the sale of power to the overhead grid scenarios.

A. Effect of CCP confidence level on the output of optimization

Applying the CCP to the stochastic problems has many benefits such as increasing the reliability of the system and reducing the calculations. Different reliability levels in the CCP model may lead to different results. Increasing the reliability level, means that nothing is left to chance and turns the problem into a deterministic model which may increase the cost. On the other hand, decreasing the reliability level and taking more risks, may show a decrease in the objective function, but in price of higher risk. In Tables 11 and 12, the results of the optimization for planning of DGs for both 10mw and 5mw units. It can be inferred from the table that by decreasing the reliability level, less capacity is installed and the cost of the system is reduced.

B. Technical evaluation of using DGs in subway system

In this subsection, using DigSilent software, the technical aspects of using DGs in the urban railway system will be examined. Single-line diagram of Tabriz Line 2 urban railway project is created in the software is shown in Fig. 3. The initial specifications and size of 20 kV cables are as given in Tables 1 and 2.

According to the RS system simulation report, the rated power of RS transformers should be large enough to provide 2 MW of DC power as output power in the rectifier. In addition, at the request of the employer, the normal power demand for the S15 station and the traction transformers in the depot post (which is allocated to the depot station's own traction consumption) will increase to 2.5 MW instead of 2 MW. For LPS substations, three types of transformers are used, 20000/400, whose nominal power values are 1600, 2000 and 2500 KVA.

In the initial state, which is the basic state of the simulation, the RS substations are under load and the DGs will be responsible for providing this load. The amount of power obtained from each of the generators in the case of using 10 MW sources is given in Tables 13 and 14. In this situation, each generator is operating normally and there are no errors in the system. In Tables 15 and 16, it is assumed that one of the units has an error and is out of service. It can be seen that the system is still running without any problems.

The load flow and the amount of power obtained from each of the generators in the case of using 5 MW resources are given in Tables 17 and 18. In this situation, each generator is operating normally and there are no faults in the system. In Tables 19 and 20, it is assumed that one of the units has an error and is out of service. It can be seen that the system is still running without any problems. In this case, compared to the case of 10 MW units, more pressure is applied to the system until the failed unit is

Table 8. Planning results of RS system using 5MW or less units.

Location	Capacity (MW)
S02	5
S06	5
S08	5
S13	5
S15	5
S17	5
S20	5

Table 9. Planning results of LPS system using 5MW or less units.

Location	Capacity (MW)
S02	5
S04	2×5
S08	5
S12	5
S16	5
S19	5

Table 10. NPV of costs for two scenarios.

Scenario	Cost ($)
first	245,110,000
second	163,160,000

Table 11. Effect of confidence level of CCP on the output of the problem in 10MW units.

Reliability Level (%)	100	95	90	85	80	75
Total installed capacity (*MW*)	80	80	80	70	70	60
First scenario cost (million $)	247.41	246.73	246.51	243.48	243.12	240.25
Second scenario (million $)	165.21	164.75	164.13	161.95	161.24	159.57

Table 12. Effect of confidence level of CCP on the output of the problem in 5MW units.

Reliability Level (%)	100	95	90	85	80	75
Total installed capacity (*MW*)	80	80	80	70	70	60
First scenario cost (million $)	246.74	245.11	244.78	242.83	241.36	239.57
Second scenario (million $)	164.62	163.16	162.92	161.18	159.94	158.71

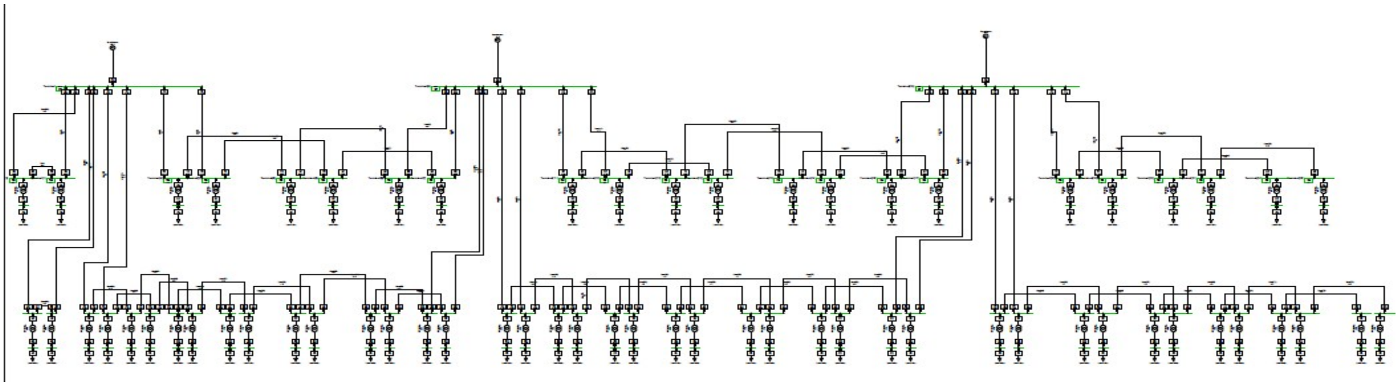

Fig. 3. Digram of system simulation in DigSilent environment.

Table 13. Load flow results for 10MW units of RS.

Location	Output power (MW)
S04	7.1
S08	5.4
S13	5.3
S18	6.8

Table 14. Load flow results for 10MW units of LPS.

Location	Capacity (MW)
S02	3.8
S04	5.3
S11	8.7
S17	6.6

Table 15. Load flow results for 10MW units of RS in case of fault in one of the units.

Location	Capacity (MW)
S08	9.7
S13	8
S18	6.8

Table 16. Load flow results for 10MW units of LPS in case of fault in one of the units.

Location	Capacity (MW)
S02	9.1
S11	8.7
S17	6.6

Table 17. Load flow results for 5MW units of RS.

Location	Output power (MW)
S02	3.4
S06	3.7
S08	4
S13	4
S15	2.7
S17	3.6
S20	3.2

repaired.

4. CONCLUSION

One of the problems in the design and implementation of metro systems is how to provide electrical power to this system due to the size of the project and the amount of power required.

Table 18. Load flow results for 10MW units of LPS.

Location	Capacity (MW)
S02	3.8
S04	5.3
S08	3.8
S12	4.9
S16	3.5
S19	3.2

Table 19. Load flow results for 5MW units of RS in case of fault in one of the units.

Location	Capacity (MW)
S02	4.6
S06	5
S13	4
S15	4
S17	3.6
S20	3.2

Table 20. Load flow results for 5MW units of LPS in case of fault in one of the units.

Location	Capacity (MW)
S02	3.8
S04	8.1
S12	4.8
S16	3.5
S19	4.3

Because these systems often pass through crowded centers, the capacity of upstream network substations is usually insufficient. Therefore, in general, the development of the power system and the construction of the post is the responsibility of the executor of the project, which can create a lot of costs for the executor. One alternative is to use DG resources in the metro system. This paper have examined the technical and economic aspects of using these resources. First, in the form of an optimization problem, the location and capacity of DGs is determined. The purpose of this optimization is to minimize operating costs, maintenance cost and initial investment of the system. Also, the demand of traction systems, is modeled as a stochastic parameter which is handled using CCP approach. The optimization problem is analyzed by GAMS software for the metro power network. Finally, the technical aspects of the problem have been investigated by DigSilent software. Various cases for unit failure have been investigated and the ability of DGs to provide load in the event of an error has been investigated.

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