

Expansion Planning of Automated Sub-transmission and Distribution Networks integrated by Distributed Generations

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Abstract: This paper presents sub-transmission and distribution network expansion planning (S&DEP) including distributed generation (DG) and distribution automation (DA) considering reliability indexes. The objective function is to minimize investment, operation, maintenance and reliability costs subjected to AC power flow, system operation and generation unit and DG limits, reliability, and distribution automation constraints (including the constraints of protection devices and volt/VAr control mechanism). The proposed model is a mixed integer non-linear programming (MINLP) model which is hard to solve. For this reason a MINLP problem is transformed to mixed integer linear programming (MILP) model. The validity of the proposed method is investigated in the two synthetic test networks.

Keywords: Sub-transmission and distribution network expansion planning, Distributed generation, Distribution automation, Reliability indexes, and mixed integer linear programming.

Nomenclature

1) *Indices and Sets*

$(n, j), t, l, (h, p), k$ Indices of bus, time, load level, circuits in a connection, linearization segments of circular

	constraint
$\Omega_n^A, \Omega_n^S, \Omega_n^0, \Omega_n$	Sets of circuit or equipment candidates to be added and replaced, Existing circuits or equipments, bus
$\Omega_l, \Omega_g, \Omega_t$	Sets of load level, generation, time
2) Variables	
inv, op, mi, re	Investment, operation, maintenance and reliability costs
x^A, x^S, x^0	Binary variable of circuit or equipment candidates to be added and replaced, and existent circuits or equipment
dg, f	Binary variable of DG and capacitor candidates to be added
$SAIFI, SAIDI, CIF,$	Reliability indexes
CID	
PL, PG, PDG	Active power of line, generation and distributed generation
QL, QG, QDG, QF	Reactive power of line, generation, distributed generation and capacitor
$V, \Delta V, \theta$	Voltage amplitude, voltage deviation, voltage angle
λ, u, z	Failure rate, equivalent interruption duration time, parallel circuits number
3) Constants	
C^A, C^S	Investment and replacement costs of line
C^{DG}, C^F	Investment cost of DG and capacitor
C^{Am}, C^{Sm}, C^{Om}	Maintenance cost of circuit or equipment candidates to be added and replaced, Existing circuits or equipment
C^{DGm}, C^{Fm}	Maintenance cost of DG and capacitor
C^{op}	Operation price
K	Reliability indexes price
g, b	Line conductance and susceptance
$SG^{max}, SL^{max},$	Maximum capacity of generation, line, DG and capacitor
SDG^{max}, SF^{max}	

η	Efficiency of capacitor
V^{max}, V^{min}	Maximum and minimum voltage
n^{max}	Maximum number of line
ND	Number bus of distribution network
$\Delta\lambda, \Delta u$	Deviation of failure rate and equivalent interruption duration time
$SAIFI^{max}, SAIDI^{max},$ CIF^{max}, CID^{max}	Maximum value of reliability indexes such as SAIFI, SAIDI, CIF and CID, respectively
PD, QD	Active and reactive load

1. Introduction

In recent years the distribution network demand is increasing due to the population growth and also the presence of new technologies. In distribution network. hence, the distribution network cannot meet the increasing of load the system; resulting in voltage drop and power losses and over loading of distribution lines as well (Gao et. al and Heidari et al) [1, 2]. This matter causes to reduce the reliability and power quality of the distribution network (Moradi et. al, Mazhari et. al) [3, 4]. Therefore, the distribution network expansion planning (DNEP) is required to consider the load increment, and improvement of system power quality and reliability (Koutsoukis et. al, Ahmadigorji and Amjady) [5, 6]. The DNEP challenges are to install new post, distribution line, distributed generations (DGs) and other alternative elements for distribution network. Accordingly, in DNEP all the related cost should be minimized while improving power quality, and reliability of the system.

The problem of DNEP is studied in different research works. Naderi and Seifi [7] the optimal power flow model of dynamic DNEP is presented, in the presence of DGs, minimizing investment, operation and maintenance costs, and which is solved by genetic algorithm (GA). Zou and Prakash [8], the DNEP with DGs is modeled as a stochastic programming solved by particle swarm optimization (PSO) algorithm. The uncertainty of loads and DGs, is included in DNEP, considering reliability indexes and system operation limits (Bagheri and Monsef) [9]. The DNEP is formulated as a multi stage framework from the viewpoint of energy generation company, in the form of MINLP problem, solved by PSO algorithm (Saboori, Hemmati, and Abbasi) [10].

Heidari, Fotuhi-Firuzabad and Kazemi [11], a multi stage of DNEP with distribution automation devices is proposed; indicating that, distribution automation devices are helpful in improvement of smart grid structure.

.Moreover, this paper estimates reliability indexes such as SAIDI and SAIFI, and finally, the problem is as MINLP problem, solved by genetic algorithm. Munoz-Delgado, Contreras and Arroyo [12], the optimal placement of DGs is considered in DENP problem, minimizing, the energy loss, investment and operation cost, in which the non-linear equation of energy loss cost is converted to a linear equation using conventional piecewise linearization. AIKaabi, Zeineldin and Khadkikar [13], the active distribution network planning with considering multi-DG configurations is presented. Also, short-term expansion planning of radial electrical distribution systems is presented by Gonecalves, Franco and Rider [14], that its base model is expressed as a mixed-integer linear programming (MILP) problem. Also the sub-transmission expansion planning is presented by Karimi and Haghifam in [15]. In [15], the reliability, environmental and higher power quality is considered in multi-objective problem. Moreover, the active distribution network expansion planning with considering of storage systems is expressed by Shen et. al and Xing et. al [16-17]. Also, the reliability index considered by Munoz-Delgado et. al and Shivaie et. al in [18-19] with problem of distribution network expansion planning. Finally, Table 1 shows taxonomy of proposed methodologies for problem of sub-transmission and distribution networks expansion planning.

Based on Table 1, the main research gaps is as follows:

- The more researches are not considered the impacts of DNEP on sub-transmission network. It is possible that the changing of distribution network structure causes changing of the sub-transmission network [20].
- The more researches are not considered equations of reliability indexes in proposed problem. In other words, they solve the proposed problem firstly, and thus, they investigate the reliability index.
- The more researches use evolutionary algorithms for solving of proposed problem. But, it is noted that this methods are based on rule of random phenomena, also, since these methods are based iteration method, hence, the calculation time of these methods is generally high. In addition, the evolutionary algorithms are based on stochastic search, the global optimality of the solutions cannot be guaranteed.

To cope with above issues, in this paper, the sub-transmission and distribution networks expansion planning presents that it considers DGs and distribution automation (DA) from distribution companies' viewpoint. It is noted that the DA includes protection and volt/VAr control devices such as switches and capacitor bank and other power elements. Hence, the distribution network is as active network. Moreover, the reliability indexes such as CID, CIF, SAIDI and SAIFI is considered as constraints in the proposed problem model. The objective function is minimizing of investment, operation, maintenance and reliability costs. Also, the AC power flow equations, reliability constraints,

system operation and generation unit limits, DG equations, distribution automation (DA) constraints and radial structure equations for distribution network are as constraints of base problem. This problem is as MINLP that has been high calculation time and locally optimal solution. Hence, this paper used equivalent MILP model. It is noted that the reactive power term is not removed in the MILP model. The main contributions of this paper can be summarized as follows:

- Sub-transmission and distribution networks expansion planning simultaneously
- Considering reliability indexes as problem constraints
- Considering optimal placement of DGs and DA devices
- Presenting MILP model
- Contribution related to DA inclusion in DNEP

The rest of the paper is organized as follows: Section 2 describes the problem model, and Section 3 expresses numerical simulations. Sections 4 demonstrate conclusions.

2. Problem Model

In this section, the proposed problem model is presented. In this optimization problem, the investment, operation and reliability costs are minimized. Also, the constraints of proposed problem are AC power flow equations, planning constraints, operation limits and reliability constraints. The main problem can be written as follows from distribution companies' viewpoint:

2.1 The main problem model

1) *Objective function*: The investment, operation, maintenance and reliability costs are included in the as objective function as follows:

$$\text{Minimize } Cost = \sum_{t \in \Omega_t} inv_t + op_t + mi_t + re_t \quad (1)$$

where:

$$inv_t = \frac{1}{(1+r)^{t-1}} \left\{ \overbrace{\sum_{(n,j) \in \Omega_n^A} x_{(n,j),t}^A C_{(n,j),t}^A + \sum_{(n,j) \in \Omega_n^S} x_{(n,j),t}^S C_{(n,j),t}^S}^{\text{Between two buses}} + \overbrace{\sum_{n \in \Omega_n} dg_{n,t} C_{n,t}^{DG} + \sum_{n \in \Omega_n} f_{n,t} C_{n,t}^F}_{\text{Connected to bus}} \right\} \quad (2)$$

$$op_t = \frac{8760}{(1+r)^{t-1}} \left\{ \sum_{l \in \Omega_l} \left(\sum_{i \in \Omega_g} C_{i,l,t}^{op} PG_{i,l,t} + \sum_{n \in \Omega_n} C_{n,l,t}^{op} PDG_{n,l,t} \right) \right\} \quad (3)$$

$$mi_t = \frac{1}{(1+r)^{t-1}} \left\{ \overbrace{\sum_{(n,j) \in \Omega_n^0} x_{(n,j),t}^0 C_{(n,j),t}^{0m} + \sum_{(n,j) \in \Omega_n^A} x_{(n,j),t}^A C_{(n,j),t}^{Am} + \sum_{(n,j) \in \Omega_n^S} x_{(n,j),t}^S C_{(n,j),t}^{Sm}}^{\text{Between two buses}} + \overbrace{\sum_{n \in \Omega_n} dg_{n,t} C_{n,t}^{DGm} + \sum_{n \in \Omega_n} f_{n,t} C_{n,t}^{Fm}}^{\text{Connected to bus}} \right\} \quad (4)$$

$$re_t = \frac{1}{(1+r)^{t-1}} \left\{ K_{SAIDI} (SAIDI^{\max} - SAIDI_t) x_{t,SAIDI} + K_{SAIFI} (SAIFI^{\max} - SAIFI_t) x_{t,SAIFI} \right. \\ \left. + \sum_{n \in \Omega_n} \left(K_{CID} (CID^{\max} - CID_{n,t}) x_{n,t,CID} + K_{CIF} (CIF^{\max} - CIF_{n,t}) x_{n,t,CIF} \right) \right\} \quad (5)$$

- *Investment cost (IC)*: This term is presented in (2), including two parts. The first part refers to investment cost of elements connected two buses such as line, station transformer and protection device such as switches that is connected to line as series. The second part is related to the investment cost of elements connected to bus such as DG and custom power device (capacitor, D-STTCOM).
- *Operation cost (OC)*: In this paper, the conventional power plant and DG meet the demand energy of loads. Hence, the operation cost that refers to fuel cost of these elements written in (3).
- *Maintenance cost (MC)*: This term in (4) includes two parts. The first part refers to maintenance cost of elements that are between two buses, while the second part related to those connected to bus.
- *Reliability cost (RC)*: This term is presented in (5) that consists of four reliability indexes costs. Costs of SAIDI and SAIFI, are defined to power system, while costs of CID and CIF are defined to each bus of network.

2) The constraints of elements connected between two buses

In this paper, the lines, station transformer and protection device that is connected to line as series belong to this group. Hence, the terms of $C^{A,S}$ and $C^{0m,Am,Sm}$ are considered for line with protection device or station transformer costs. Finally, these constraints are written as follows:

$$PL_{(n,j),l,t}^m = g_{(n,j)}^m (V_{n,l,t})^2 - V_{n,l,t} V_{j,l,t} \left\{ g_{(n,j)}^m \cos(\theta_{n,l,t} - \theta_{j,l,t}) + b_{(n,j)}^m \sin(\theta_{n,l,t} - \theta_{j,l,t}) \right\} x_{(n,j),t}^m \quad \forall (n,j), l, t, m = 0, A, S \quad (6)$$

$$QL_{(n,j),l,t}^m = -b_{(n,j)}^m (V_{n,l,t})^2 + V_{n,l,t} V_{j,l,t} \{b_{(n,j)}^m \cos(\theta_{n,l,t} - \theta_{j,l,t}) - g_{(n,j)}^m \sin(\theta_{n,l,t} - \theta_{j,l,t})\} x_{(n,j),t}^m \quad \forall (n,j), l, t, m = 0, A, S \quad (7)$$

$$(PL_{(n,j),l,t}^m)^2 + (QL_{(n,j),l,t}^m)^2 \leq (SL_{(n,j)}^{m,\max})^2 \quad \forall (n,j), l, t, m = 0, A, S \quad (8)$$

$$x_{(n,j),t}^0 + x_{(n,j),t}^S \leq 1 \quad \forall (n,j), t \quad (9)$$

$$x_{(n,j),t}^m \geq x_{(n,j),t-1}^m \quad \forall (n,j), t, m = A, S \quad (10)$$

The active and reactive power flow of lines or station transformer are formulated in (6) and (7). The limit of apparent power of lines or station transformer is shown in (8). It is indicated in (9) that it is not possible to simultaneously have both existent and replacement element at the same time. It is noted that if $x = 1$ at the year of t , then it should be one at the future years. This statement is presented in (10) that repeated for A and S indices.

3) *DG constraints*: In this paper it is assumed that each bus can include on DG. Also, it is noted that the selecting of DG, depends on investment, operation and maintenance costs and reliability indexes. Hence, the different variables of DGs should be considered in investment, operation and maintenance costs equations and power balance equations. Another constraint of DG is as equation (11) (Kermanshahi and Kamel) [21]:

$$(PDG_{n,l,t})^2 + (QDG_{n,l,t})^2 \leq dg_{n,t} (SDG_n^{\max})^2 \quad \forall n, l, t \quad (11)$$

This equation presents the limit of apparent power of DG. It is noted that the binary variable of dg determines whether or not the interested DG is selected. In other words, the DG is selected if $dg = 1$; otherwise, the DG is not selected.

4) *Distribution automation (DA) constraints*: The distribution automation system includes protection element and custom power device. The protection elements are on lines or station transformer, and its constraints are in (6)-(10). The selection of custom power device depends on investment and maintenance costs and network and reliability indexes. Hence, the different variables of custom power device should be presented in investment and maintenance costs and power balance equations. Other constraint of customer power device is as equation (12) (Memarzadeh and Esmaeili) [22]:

$$QF_{n,l,t} (\leq or =) f_{n,t} \sqrt{(SF_n^{\max})^2 - ((1 - \eta_n) SF_n^{\max})^2} \quad \forall n, l, t \quad (12)$$

This equation indicates the reactive power limit of custom power device. It is noted that the binary variable of f determines the selection of custom power device. In other words, the custom power device will be select if $f = 1$; otherwise, the custom power device will not be select. Also, the term $(1-\eta_n)SF_n^{\max}$ is considered as active power loss of custom power device.

5) *Generating Units limit*: The limit of generation units, is as equation (13):

$$(PG_{i,l,t})^2 + (QG_{i,l,t})^2 \leq (SG_i^{\max})^2 \quad \forall i,l,t \quad (13)$$

6) *Voltage limit*: The voltage limit is as equation (14):

$$V_n^{\min} \leq V_{n,l,t} \leq V_n^{\max} \quad \forall n,l,t \quad (14)$$

The maximum value of voltage is considered 1.05 per unit, and the minimum value of voltage is 0.95 and 0.9 for transmission and distribution networks, respectively.

7) *Radial distribution network constraints*: In general, the distribution network are considered as radial. In radial distribution network, the number of buses is equal to the number of lines + one. This statement presents as follows:

$$\sum_{m=0,A,S} x_{(n,j),t}^m = N_{(n,j),t}^{line} \quad \forall (n,j),t \quad (15)$$

$$y_{(n,j),t} \leq N_{(n,j),t}^{line} \leq n_{(n,j),t}^{\max} y_{(n,j),t} \quad \forall (n,j),t \quad (16)$$

$$\sum_{(n,j) \in \Omega_n} AD_{(n,j)} y_{(n,j),t} = ND - 1 \quad \forall (n,j),t \quad (17)$$

In (15), the number of elements between buses n and j is calculated. The number of elements is between one and n^{\max} , hence, $y = 1$. But, if the number of elements is equal to zero, thus, $y = 0$. Finally, the radial distribution network constraint is presented in (17). It is noted that AD is equal to one if element of between (n,j) belongs to distribution network, and is equal to zero if element of between (n,j) belongs to transmission network.

It is noted that the proposed model can be considered the model of meshed sub-transmission/distribution network with remove the radial distribution network constraints, i.e., equations (15) to (17).

8) *Reliability constraints*: The reliability constraints are as follows (Billinton and Grover) [23]:

$$\lambda_{(n,j),t} = \lambda_{(n,j),h=1,t} z_{(n,j),h=1,t} - \sum_{h=2}^{n_{(n,j),t}^{\max}} \Delta \lambda_{(n,j),h,t} (z_{(n,j),h,t} - z_{(n,j),h-1,t}) \quad \forall (n,j),h,t \quad (18)$$

$$u_{(n,j),t} = u_{(n,j),h=1,t} z_{(n,j),h=1,t} - \sum_{h=2}^{n_{(n,j),t}^{\max}} \Delta u_{(n,j),h,t} (z_{(n,j),h,t} - z_{(n,j),h-1,t}) \quad \forall (n,j),h,t \quad (19)$$

$$z_{(n,j),h,t} = \sum_{p=1}^h y_{(n,j),p,t}^A \quad \forall (n,j),h,t \quad (20)$$

$$y_{(n,j),p+1,t}^A \leq y_{(n,j),p,t}^A \quad \forall (n,j),p,t \quad (21)$$

$$y_{(n,j),p,t}^A \leq \sum_{\tau=1}^t x_{(n,j),l,\tau}^A \quad \forall (n,j),p,t \quad (22)$$

$$CIF_{n,t} = S_{\lambda} \lambda_{(n,j),t} \quad \forall n,t \quad (23)$$

$$CID_{n,t} = S_{\lambda} u_{(n,j),t} \quad \forall n,t \quad (24)$$

$$SAIFI_t = \frac{\sum_{n \in \phi_n} CIF_{n,t}}{\text{total load number}} \quad \forall t \quad (25)$$

$$SAIDI_t = \frac{\sum_{n \in \phi_n} CID_{n,t}}{\text{total load number}} \quad \forall t \quad (26)$$

$$\begin{cases} CID_{n,t} \leq CID^{\max} (1 - x_{n,t,CID}) \\ CID_{n,t} \geq CID^{\max} x_{n,t,CID} \end{cases} \quad \forall n,t \quad (27)$$

$$\begin{cases} CIF_{n,t} \leq CIF^{\max} (1 - x_{n,t,CIF}) \\ CIF_{n,t} \geq CIF^{\max} x_{n,t,CIF} \end{cases} \quad \forall n,t \quad (28)$$

$$\begin{cases} SAIDI_t \leq SAIDI^{\max} (1 - x_{t,SAIDI}) \\ SAIDI_t \geq SAIDI^{\max} x_{t,SAIDI} \end{cases} \quad \forall t \quad (29)$$

$$\begin{cases} SAIFI_t \leq SAIFI^{\max} (1 - x_{t,SAIFI}) \\ SAIFI_t \geq SAIFI^{\max} x_{t,SAIFI} \end{cases} \quad \forall t \quad (30)$$

Equations (18) and (19) calculate the failure rate and equivalent interruption duration time, and (20) is for parallel circuits' number. Finally, the reliability indexes obtained based on (23)-(26), and the limitation of reliability indexes expressed in (27)-(30). It is noted that the binary variable of x is one if the reliability index is greater than its maximum. For example, if CID is less (more) than CID^{\max} , thus, the cost of CID is (is not) zero. So that the binary variable of x_{CID} based on equation (27) is zero (one), therefore, the CID cost is (is not) removed in equation (5) based on value of x_{CID} . Finally, equations (27)-(30) uses in this paper for obtaining of different x value. Moreover, the elements of matrix S_{λ} is equal to one if line (n,j) impacts on load bus n .

9) *Power balance constraints*: These constraints for active and reactive power balance are presented in (31) and (32). Also, the voltage angle of reference bus is expressed in (33).

$$PDG_{n,l,t} + \sum_{i \in \Omega_g} AG_{i,n} PG_{i,l,t} + \sum_{m=0,A,S} \sum_{(n,j) \in \Omega_n^m} AL_{(n,j)}^m PL_{(n,j),l,t}^m = PD_{n,l,t} \quad \forall n,l,t \quad (31)$$

$$QDG_{n,l,t} + QF_{n,l,t} + \sum_{i \in \Omega_g} AG_{i,n} QG_{i,l,t} + \sum_{m=0,A,S} \sum_{(n,j) \in \Omega_n^m} AL_{(n,j)}^m QL_{(n,j),l,t}^m = QD_{n,l,t} \quad \forall n,l,t \quad (32)$$

$$\theta_{n,l,t} = 0 \quad \forall n = ref, l, t \quad (33)$$

2.2 The MILP model

The optimization problem is mixed integer non-linear programming (MINLP) model. Also, this model is non-convex due to (6) and (7). Hence, it is predicted that the problem traps in locally optimal point, and also, the calculation speed of this model is very low. Finally, it is possible that this problem becomes infeasible for large network with high number of elements, because, the proposed problem is a special instance of a knapsack problem, which is NP-hard formulation (Garey and Johnson, Pirouzi et. al)[24-25]. Therefore, this paper presents mixed integer linear programming (MILP) model that is equivalent by main problem model negligible error.

In the main problem model, (6)-(8), (5), (11), (13), (18) and (19) are mixed integer non-linear. For linearization of (6) and (7), it is considered that the voltage can be closed 1 per unit, and the voltage angle difference between two bus or across a line is lower than 6 degrees. Hence, the voltage expresses as $1+\Delta V$ that ΔV is much lower than 1, and terms of ΔV^2 and $\Delta V \times (\theta_i - \theta_j)$ close to zero, thus, negligible. Finally, the linear equations of (6) and (7) are as (Pirouzi et. al) [26-27]:

$$PL_{(n,j),l,t}^m = \left\{ g_{(n,j)}^m (\Delta V_{n,l,t} - \Delta V_{j,l,t}) - b_{(n,j)}^m (\theta_{n,l,t} - \theta_{j,l,t}) \right\} x_{(n,j),t}^m \quad \forall (n,j), l, t, m = 0, A, S \quad (34)$$

$$QL_{(n,j),l,t}^m = - \left\{ b_{(n,j)}^m (\Delta V_{n,l,t} - \Delta V_{j,l,t}) + g_{(n,j)}^m (\theta_{n,l,t} - \theta_{j,l,t}) \right\} x_{(n,j),t}^m \quad \forall (n,j), l, t, m = 0, A, S \quad (35)$$

It is noted that the Eqs. (34) and (35) still is as mixed integer non-linear due to multiplication between x and right hand of Eqs. (34) and (35). Based on these equations, $PL, QL \neq 0$ if $x = 1$, and $PL, QL = 0$ if $x = 0$. This statement can be written as follows:

$$-M(1 - x_{(n,j),t}^m) \leq PL_{(n,j),l,t}^m - \left\{ g_{(n,j)}^m (\Delta V_{n,l,t} - \Delta V_{j,l,t}) - b_{(n,j)}^m (\theta_{n,l,t} - \theta_{j,l,t}) \right\} \leq M(1 - x_{(n,j),t}^m) \quad \forall (n,j), l, t, m = 0, A, S \quad (36)$$

$$-M(1-x_{(n,j),t}^m) \leq QL_{(n,j),l,t}^m + \left\{ b_{(n,j)}^m (\Delta V_{n,l,t} - \Delta V_{j,l,t}) + g_{(n,j)}^m (\theta_{n,l,t} - \theta_{j,l,t}) \right\} \leq M(1-x_{(n,j),t}^m) \quad \forall (n,j),l,t,m=0,A,S \quad (37)$$

$$\left(PL_{(n,j),l,t}^m \right)^2 + \left(QL_{(n,j),l,t}^m \right)^2 \leq x_{(n,j),t}^m \left(SL_{(n,j)}^{m,\max} \right)^2 \quad \forall (n,j),l,t,m=0,A,S \quad (38)$$

Based on Eqs. (36)-(38), $x = 1$, thus, $PL, QL \neq 0$. But, $PL, QL = 0$ if $x = 0$. Eqs. (11), (13) and (38) are circular inequalities, that the linear equations of these constraints based on [28] are as Eqs (39)-(41):

$$PL_{(n,j),l,t}^m \cos(k\Delta\alpha) + QL_{(n,j),l,t}^m \sin(k\Delta\alpha) \leq x_{(n,j),t}^m SL_{(n,j)}^{m,\max} \quad \forall (n,j),l,t,k,m=0,A,S \quad (39)$$

$$PDG_{n,l,t} \cos(k\Delta\alpha) + QDG_{n,l,t} \sin(k\Delta\alpha) \leq dg_{n,t} SDG_n^{\max} \quad \forall n,l,t,k \quad (40)$$

$$PG_{i,l,t} \cos(k\Delta\alpha) + QG_{i,l,t} \sin(k\Delta\alpha) \leq SG_i^{\max} \quad \forall i,l,t,k \quad (41)$$

In this equations, $\Delta\alpha$ is angle deviation and k is indices of linearization segments of circular equation. It is noted that $\Delta\alpha$ is equal to $360/n_k$ that n_k is number of linearization segments of circular equation, thus, $k = \{1, 2, \dots, n_k\}$. In addition, Eqs (5), (18) and (19) include the multiplication cautious variable and binary variable. Linearization of this equation used from Equation (42):

$$a \times b = c \quad \forall a_{\min} \leq a \leq a_{\max}, b = 1, 2, 3, \dots, n \quad (42)$$

$$\Leftrightarrow \begin{cases} b = \sum_{i=1}^n i \times x_i \quad \forall x_i \in \{0,1\} \\ c = \sum_{i=1}^n i \times z_i \quad \forall z_i = a \times x_i \\ a_{\min}(1-x_i) \leq z_i - a \leq a_{\max}(1-x_i) \\ a_{\min}x \leq z_i \leq a_{\max}x \end{cases}$$

Finally, the MILP model is show by Eqs (43) and (44):

$$\min \quad Cost = \sum_{t \in \Omega_t} inv_t + op_t + mi_t + re_t \quad (43)$$

Subject to:

$$(2)-(4), (9), (10), (12), (14)-(17), (20)-(33), (36), (37), (39)-(42) \quad (44)$$

3. Numerical Results and Discussion

3.1 Case study

The proposed problem model is studied based on 6-bus transmission and sub-transmission network (as depicted in Figure 1) and 10-bus or two feeder radial distribution network (as depicted in Figure 2). The data of transmission, sub-transmission and distribution networks is expressed in tables 2 to 5. In these tables, n^0 is equal to the number of

equipment in the starting time of planning. There is a transmission substation with 230/138 kV transformer that is between rb1 and st3 buses. Also, the distribution network connects to transmission network with 138/13.8 kV transformer that is between st2-d17 buses.

The energy price for generation unit and DGs is considered 4.2 and 2.5 \$/MW year, respectively. Moreover, the generation units are connected to rb1, st1 and st6 with capacity 120, 5 and 60 MVA, respectively. In addition, this paper considers that DG can be connected to d8 and d4 buses with capacity of 2.4 and 4.8 MVA, and investment cost of 0.04 and 0.08 M\$, respectively. Also, this paper considers that there are two fixed capacitor banks that can be connected to d8 and d4 buses with capacity of 1.2 and 2.4 MVar, and investment cost of 0.02 and 0.04 M\$, respectively. The maximum voltage is equal to 1.05 per unit, and minimum voltage for transmission and distribution networks consider 0.95 and 0.9 per unit, respectively.

The value of active load is presented in table 6. Also, this paper considers that the power factor is equal to 0.85 that is same for all loads. Moreover, there are three level for load in one year that are called low, medium and high level. The load coefficients for three levels are equal to 0.5, 0.75 and 1, respectively. Moreover, the reliability factors such as CID^{max} , CIF^{max} , $SAIDI^{max}$ and $SAIFI^{max}$ is equal to 4 hours/year, 4 interruptions/year, 2 hours/year and 4 interruptions/year (Pirouzi et. al) [28].

3.2 Results

In this paper, the proposed problem is applied to case study test network with GAMS. 24 software, and CPLEX and BONMIN solvers for MILP and MINLP models, respectively (Pirouzi et. al) [29].

- 1) *Comparison of MINLP and MILP models:* Table 7 expresses the results of comparison between MINLP and MILP models. Based on this table, the calculation error between two models for active and reactive powers is equal to about 3%, and it is equal to about 0.5% for angle and amplitude of voltage. Therefore, the calculation error of different variables between two models almost is very low. Also, the calculation time of MINLP model is very long, because, the number of binary variables is high and the equations are non-linear and non-convex. Hence, it is predicted that this model does not reach to a feasible solution in the large network. But, the calculation time is low for MILP model. Therefore, the MILP model is suitable, because, it has low calculation time and error.

2) *Investigating economic results:* The results of this section are expressed in tables 8-10. Table, 8 shows the investment characterizes such as investment cost and number of investment circuit. Based on the this table, 1 high voltage post (rb1-st3), 1 medium voltage post (st2-d17), 6 transmission line, 6 distribution line, 2 DG and 2 capacitor added to test network at the first year. It is noted that the investment cost of each circuit is low at first year based on tables 2-5. Hence, the new circuits add into test network at first year. Moreover, the total investment cost is equal to 23.396 M\$ that 22 M\$ is for transmission network and 1.396 M\$ is for distribution network.

Table 9 presents replacement characterizes such as replacement cost and replacement option. Based on this table, 1 transmission line with option 2, 2 distribution line with option 1 and 2 replaced in the test network. It is noted that the replacement cost for distribution and transmission networks are equal to 0.072 M\$ and 1 M\$, respectively. In addition, maintenance and operation costs present in table 10. It should be noted that maintenance cost is equal to:

$$\text{Maintenance cost of each circuit} = (\text{Number} \times \text{Capacity} \times \text{Maintenance rate}) \text{ of circuit}$$

Finally, the total maintenance cost is equal to 3.095 M\$ that high percentage of this cost is for transmission network and low percentage of this cost is for distribution network. Also, the operation cost of proposed problem is equal to 11.2 M\$ that 10.71 M\$ and 0.49 M\$ is for transmission and distribution networks.

3) *Investigating technical results:* the results of this section are expressed in tables 11. Based on this table, the mean voltage of transmission network is equal to 1.01 per unit, and the low voltage of this network is 0.98 per unit. It is noted that this paper considers that there is not voltage controlled (PV) bus in the proposed problem. Hence, the voltage in the each bus can be increased to 1.05 per unit. In addition, the mean and low voltage in the distribution network is equal to 0.926 and 0.906 per unit. Based on this statement, the reason of the selecting of double lines in the d6-7 and d7-8 determines. In other words, the double lines selected in d6-7 or d7-8 for improvement of voltage in the distribution network.

According to table 11, the active power loss in transmission network is less than reactive power loss in the distribution network, because, the reactance of transmission lines is more than resistance of transmission lines. Also, the reactive power loss of distribution network is less than active power loss in the distribution network. Because, the distribution line resistance is more than distribution line reactance. Hence, the active

power loss of the distribution network is less than active power loss of the transmission network. This statement is vice versa for reactive power loss.

4) *Investigating reliability results:* the reliability characterizes of the test network presents in table 12. Based on this table, the reliability indexes such as CID and CIF in transmission network is less than distribution network. Hence, the reliability of transmission network is more than distribution network. Because, the number of generation unit in the transmission network is more than distribution network, and transmission network is not as radial. Moreover, the reliability indexes are less than its maximum value. Therefore, the reliability cost is equal to zero.

5) *Investigating impacts of the reducing of maximum reliability indexes:* in this section, this paper considers that the maximum reliability indexes such as CID^{max} , CIF^{max} , $SAIDI^{max}$ and $SAIFI^{max}$ increase from zero to 100% with step 10% (0.4, 0.4, 0.2 and 0.2 for CID^{max} , CIF^{max} , $SAIDI^{max}$ and $SAIFI^{max}$, respectively). The results of this section present in Figures 3 and 4. Figure 3 shows the relationship between reliability cost and index. Based on this figure, the reliability cost will be reduced if the reliability index increases. Also, the reliability cost is equal to zero in the period of (62%, 100%) reliability index, i.e., CID^{max} , CIF^{max} , $SAIDI^{max}$ and $SAIFI^{max}$ are equal to (2.48, 4), (2.48, 4), (1.24, 2) and (1.24, 2), respectively.

Figure 4 shows the relationship between total cost and reliability index. Based on this figure, the total cost will be reduced if the reliability index increases. Also, the total cost is equal to 38.764 M\$ in the period of (62%, 100%) reliability index.

6) *Investigating impacts of the DA:* in this section, the results of impacts of DA in the power network express. Hence, this paper considers two cases of with and without of DA in the power network. Also, the CID^{max} , CIF^{max} , $SAIDI^{max}$ and $SAIFI^{max}$ considered to 0.8, 0.8, 0.4 and 0.4, respectively. The results of this section presents in table 13. Based on this table, the DA causes that reliability and network index improve. Because, the custom power devices are used to improvement of network indexes, and switches are used for improvement of reliability indexes.

4. Conclusions

This paper presents sub-transmission and distribution network expansion planning with considering DG and distribution automation (DA), and reliability indexes. The objective function is to minimize the investment, operation, maintenance and reliability costs. Also, the constraints of proposed problem includes AC power flow

equations, reliability constraints, system operation and generation unit limits, DG equations, distribution automation (DA) constraints and radial structure equations for distribution network. The base proposed problem model is as mixed integer non-linear programming (MINLP) which is hard to solve. Hence, the equivalent mixed integer linear programming (MILP or MIP) model is used that reaches to optimal solution with lower computation burden. Based on the numerical results, the change in the distribution network needs to change the transmission network. Also, the investment, operation and maintenance costs are low in distribution and high in transmission network. Also, the DA causes improvement of network and reliability indexes. Moreover, the total and reliability costs are decreased by increasing the reliability index.

In addition, some of parameters in the proposed problem such as load are as uncertainty, hence, the robust model of proposed problem present in future works. Also, the operation of DA systems for fault management and network index management considers in future works. Moreover, the MILP formulation is solved as hard for a large scale of real networks, and it has a high calculation time for this network. Hence, the MILP model with innovative methods such as candidacy proposed for real network in future works.

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Figure Captions

Figure 1. Transmission and sub-transmission network

Figure 2. Distribution network

Figure 3. Relationship between reliability cost and index

Figure 4. Relationship between total cost and reliability index

Table Captions

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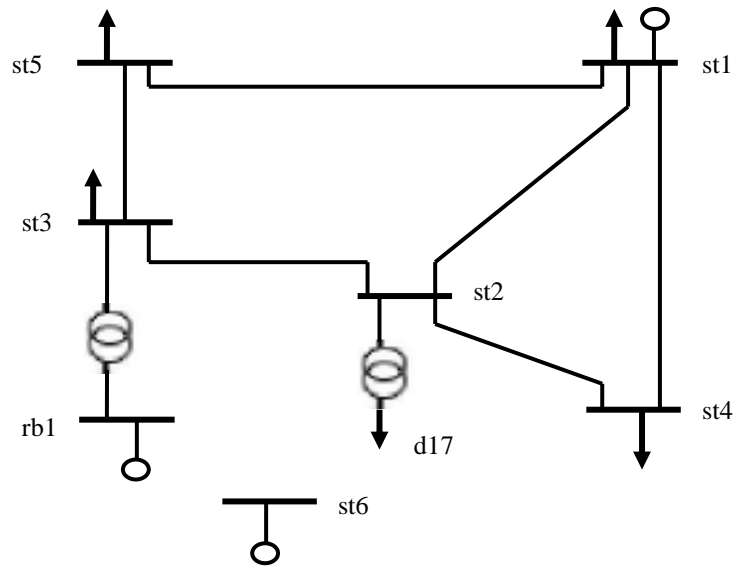


Figure 1. Transmission and sub-transmission network

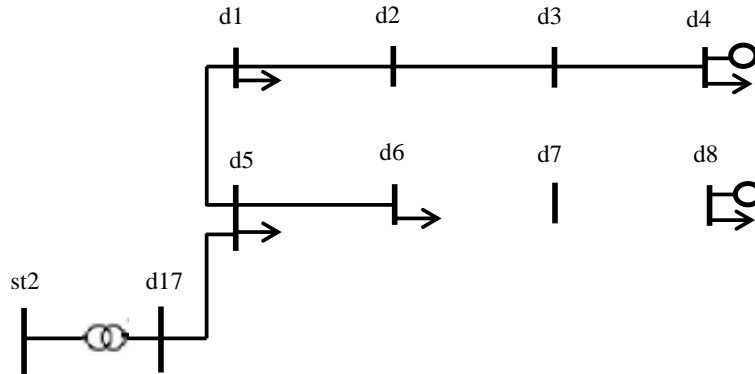


Figure 2. Distribution network

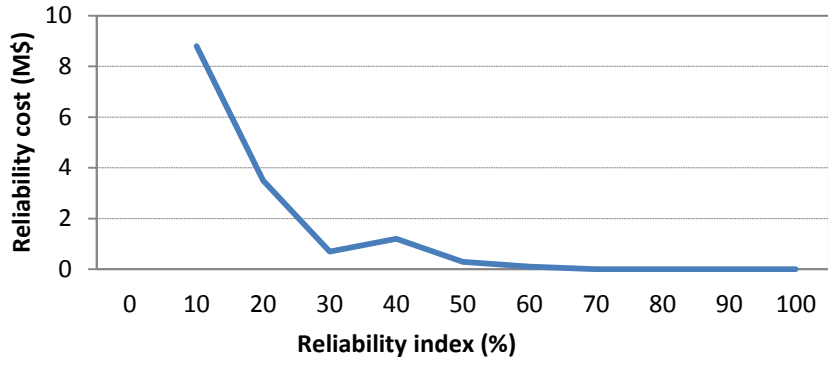


Figure 3. Relationship between reliability cost and index

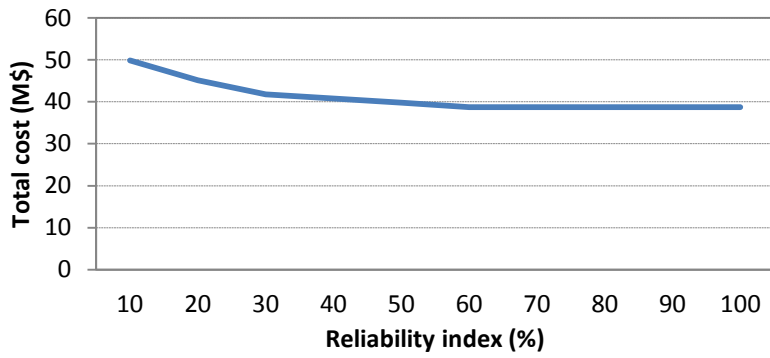


Figure 4. Relationship between total cost and reliability index

Table 1. Taxonomy of recent works

Ref	Expansion planning of		Problem based on		Considering of			Solving method
	Sub-transmission network	Distribution network	Power flow	Current flow	Re	DG	DA	
[7]		√	√			√		GA
[8]		√	√			√		PSO
[9]		√	√		√	√		PSO
[10]		√	√			√		PSO
[11]		√	√		√	√	√	GA
[12]		√		√		√		MT-based MILP
[13]		√	√			√		MT-based MINLP
[14]		√		√				MT-based MILP
[15]	√		√		√			MT-based MILP
[16]		√	√			√		TLBO
[17]		√	√			√		GA
[18]		√	√		√			MT-based MILP
[19]		√	√		√	√		MT-based MILP
Proposed Method	√	√	√		√	√	√	MT-based MILP

Re: reliability; DG: distributed generation; DA: Distribution automation; GA: Genetic algorithm; PSO: Particle swarm optimization algorithm; MT: Mathematic technical; TLBO: Teaching learning based optimization algorithm; MILP: Mixed integer linear programming; MINLP: Mixed integer non-linear programming

Table 2. Transmission equipment's data

From-to	n^0	$R^0(\text{pu})$	$X^0(\text{pu})$	$S^{max}(\text{MVA})$	n^{max}			$C^A(\text{M\$})$		
					$t=1$	$t=2$	$t=3$	$t=1$	$t=2$	$t=3$
rb1-st3	1	0	0.1	35	2	2	3	6	6.3	6.62

Table 3. Sub-transmission network data

From-to	n^0	R^0 (pu)	X^0 (pu)	S^{max} (MVA)	n^{max}			C^A (M\$)			Replacement option S=1		Replacement option S=2	
					$t=1$	$t=2$	$t=3$	$t=1$	$t=2$	$t=3$	S^{max} (MVA)	C^S (M\$)	S^{max} (MVA)	C^S (M\$)
st1-2	1	0.04	0.4	10	2	2	3	4	4.2	4.41				
st1-4	1	0.06	0.6	8	2	2	3	6	6.3	6.62				
st1-5	1	0.02	0.2	10	2	2	3	2	2.1	2.21				
st2-3	1	0.01	0.1	10							16	0.6	20	1
st2-4	1	0.04	0.4	10	2	2	3	4	4.2	4.41				
st2-6	0	0.01	0.1	10	4	4	5	3	3.15	3.31				
st3-5	1	0.05	0.5	10	2	2	3	2	2.1	2.21				
st4-6	0	0.01	0.1	10	2	2	3	3	3.15	3.31				

Table 4. Sub-transmission/distribution substation equipment's data

From-to	n^0	R^0 (pu)	X^0 (pu)	S^{max} (MVA)	n^{max}			C^A (M\$)		
					$t=1$	$t=2$	$t=3$	$t=1$	$t=2$	$t=3$
st2-d17	1	0	0.2	16	2	2	3	0.6	0.63	0.662

Table 5. Distribution network data

From	To	n^0	$R^0(10^{-4}$ pu)	$X^0(10^{-4}$ pu)	S^{max} (MV A)	n^{max}			C^A (M\$)			Replacement option S=1		Replacement option S=2	
						$t=1$	$t=2$	$t=3$	$t=1$	$t=2$	$t=3$	S^{max} (MVA)	C^S (M\$)	S^{max} (MVA)	C^S (M\$)
d17	d5	1	21	15	12	2	2	3	0.13	0.137	0.144				
d5	d1	1	42	32	6							9.6	0.027	12	0.045
d1	d2	1	42	32	6	2	2	3	0.09	0.095	0.1				
d2	d3	1	42	32	6	2	2	3	0.09	0.095	0.1				
d3	d4	1	42	32	6	2	2	3	0.09	0.095	0.1				
d4	d8	0	42	32	6	2	2	3	0.09	0.095	0.1				
d6	d6	1	42	32	6							9.6	0.027	12	0.045
d6	d7	0	42	32	6	2	2	3	0.094	0.099	0.104				
d7	d8	0	42	32	6	2	2	3	0.096	0.101	0.106				

Table 6. the value of active load in high level load

Bus	Active load (MW)			Bus	Active load (MW)		
	$t = 1$	$t = 2$	$t = 3$		$t = 1$	$t = 2$	$t = 3$
rb1				d1	4.8	5.3	5.8
st1	8	8.8	9.7	d2			
st2				d3			
st3	4	4.4	4.8	d4	4.8	5.3	5.8
st4	16	17.6	19.4	d5	4.8	5.3	5.8
st5	24	26.4	29.1	d6	4.8	5.3	5.8
st6				d7			
d17				d8	4.8	5.3	5.8

Table 7. Comparison of MINLP and MILP models

Cases	MINLP	MILP	Deviation (%)
Total active power generation (MW)	78.1	75.9	2.81
Total reactive power generation (MVar)	50.76	49.34	2.79
Mean of voltage amplitude (pu)	0.963	0.959	0.415
Mean of voltage angle (pu)	-0.092	0.09206	-0.652
Calculation time (s)	3842	971	74.72

Table 8. Investment characterizes

Elements	Investment number			Elements	Investment number		
	$t = 1$	$t = 2$	$t = 3$		$t = 1$	$t = 2$	$t = 3$
rb1-st3	1	0	0	d2-3	0	0	0
st1-2	0	0	0	d3-4	0	0	0
st1-4	0	0	0	d4-8	0	0	0
st1-5	0	0	0	d6-7	2	0	0
st2-4	0	0	0	d7-8	2	0	0
st2-6	2	0	0	DG4	1	0	0
st3-5	2	0	0	DG8	1	0	0
st4-6	2	0	0	Cap4	1	0	0
st2-d17	1	0	0	Cap8	1	0	0
d17-5	2	0	0	Total	18	0	0
d1-2	0	0	0	Investment cost (M\$)	23.396	0	0

Table 9. Replacement characterizes

Elements	Replacement option	
	$S = 1$	$S = 2$
st2-3	0	1
d5-1	1	0
d5-6	0	1
Replacement cost (M\$)	0.027	1.045

Table 10. Maintenance and operation costs

Elements	Number	Capacity (MVA)	Maintenance rate (\$/MVA)	MC (M\$)	OC (M\$)	Elements	Number	Capacity (MVA)	Maintenance rate (\$/MVA)	MC (M\$)	OC (M\$)
rb1-st3	2	35	8000	0.56	0	d17-5	3	12	2000	0.072	0
st1-2	1	10	5000	0.05	0	d5-1	1	9.6	2000	0.0192	0
st1-4	1	8	5000	0.04	0	d1-2	1	6	2000	0.012	0
st1-5	1	10	5000	0.05	0	d2-3	1	6	2000	0.012	0
st2-3	1	20	5000	0.10	0	d3-4	1	6	2000	0.012	0
st2-4	1	10	5000	0.05	0	d4-8	0	0	2000	0	0
st2-6	2	10	5000	0.10	0	d5-6	1	12	2000	0.024	0
st3-5	3	10	5000	0.15	0	d6-7	2	6	2000	0.024	0
st4-6	2	10	5000	0.10	0	d7-8	2	6	2000	0.024	0
grb1	1	120	9000	1.08	6.07	DG4	1	4.8	2500	0.012	0.31
g1	1	5	4000	0.02	0.33	DG8	1	2.4	1200	0.0028	0.16
g6	1	60	7000	0.42	4.41	Cap4	1	2.4	300	0.00072	0
st2-d17	2	16	5000	0.16	0	Cap8	1	1.2	200	0.00024	0
Total							35	-	-	3.095	11.2

Table 11. Technical characterizes of network

Index	$t = 3$	
	Transmission network	Distribution network
Mean of voltage amplitude (pu)	1.01	0.926
Low of voltage amplitude (pu)	0.98	0.906
Active power loss (MW)	0.16	1.92
Reactive power loss (MVar)	1.53	1.21

Table 12. Reliability characterizes of network

Index	Years						Reliability cost (M\$)
	$t = 1$		$t = 2$		$t = 3$		
	TN	DN	TN	DN	TN	DN	
Mean of CID (h)	0.72	1.65	0.72	1.65	0.72	1.65	
Mean of CIF (h)	0.36	1.3	0.36	1.3	0.36	1.3	0
SAIDI (hour/year)	1.25		1.25		1.25		
SAIFI (interr/year)	0.89		0.89		0.89		

TN: Transmission network; DN: Distribution network

Table 13. Technical and reliability characterizes of network

Case	Index	$t = 3$	
		TN	DN
Without DA	Mean of voltage amplitude (pu)	1.011	0.921
	Low of voltage amplitude (pu)	0.981	0.901
	Active power loss (MW)	0.165	2.03
	Reactive power loss (MVar)	1.58	1.29
	Mean of CID (h)	0.72	1.65
	Mean of CIF (h)	0.36	1.3
	SAIDI (hour/year)	1.25	
	SAIFI (interr/year)	0.89	
	Reliability cost (M\$)	0	
With DA	Mean of voltage amplitude (pu)	1.01	0.926
	Low of voltage amplitude (pu)	0.98	0.906
	Active power loss (MW)	0.16	1.92
	Reactive power loss (MVar)	1.53	1.21
	Mean of CID (h)	0.72	0.8
	Mean of CIF (h)	0.36	0.8
	SAIDI (hour/year)	0.4	
	SAIFI (interr/year)	0.4	
	Reliability cost (M\$)	3.5	