AC-OPF Based Static Transmission Expansion Planning: A Multi-objective Approach

Tohid Akbari*, Mohammad Tavakoli Bina **, and Ali Abedini ***
* K.N. Toosi University of Technology, Tehran, Iran, tohidakbari@ee.kntu.ac.ir
** K.N. Toosi University of Technology, Tehran, Iran, tavakoli@kntu.ac.ir
*** K.N. Toosi University of Technology, Tehran, Iran, abedini@eetd.kntu.ac.ir

Abstract: *This paper presents a methodology for transmission expansion planning using AC optimal power flow. A multi-objective framework has been considered in which three objectives are represented. The objectives are to minimize the investment cost (IC), minimize the operation cost (OC) and also to minimize the power losses (PL). The augmented ε-constraint method was used so as to solve the proposed multi-objective mathematical programming (MMP) problem using lexicographic optimization for every objective function in order to construct the payoff table. The method used can create all Pareto optimal solutions in which the decision maker can select the best optimal solution based on his/her preferences. The proposed model has been applied to Garver's six bus test system and also to a real system of north-eastern part of the Iranian national 400-kV transmission grid. The detailed results of the case study are presented and analyzed.*

Keywords: AC optimal power flow, Augmented ε-constraint method, Lexicographic optimization, Multi-objective mathematical programming, Transmission expansion planning.

NOMENCLATURE:

This section provides a quick reference for the notation used throughout this paper.

Indices:

g	Index of generators.
i, j	Indices of buses.
l	Index of lines.

Sets:

B	Set of all buses.
CL	Set of all candidate lines.
EL	Set of all existing lines.
G	Set of all generators.

Constants:

$AP_{L,l}^{\max}$	Maximum apparent power flow of line *l*.
C_{1g}, C_{0g}	Bid coefficients of generator *g*.
IC_l	Investment cost of candidate line *l*.
nc	Number of candidate lines.
ng	Number of generators.
$P_{D,i}$	Active power demand at bus *i*.
$P_{G,g}^{\min}$	Minimum active power of generator *g*.
$P_{G,g}^{\max}$	Maximum active power of generator *g*.
$Q_{D,i}$	Reactive power demand at bus *i*.
$Q_{G,g}^{\min}$	Minimum reactive power of generator *g*.
$Q_{G,g}^{\max}$	Maximum reactive power of generator *g*.
$\lvert V_i^{\min}\rvert$	Minimum voltage magnitude at bus *i*.
$\lvert V_i^{\max}\rvert$	Maximum voltage magnitude at bus *i*.
$G_{ij}^{\bullet}, B_{ij}^{\bullet}$ G_{ij}, B_{ij}	Conductance and Susceptance of line *ij* for existing and candidate lines, respectively.
θ_{ref}	Voltage phase for the slack bus ($\theta_{ref} = 0$).

Variables:

IC	Investment cost.
OC	Operation cost.
PL	Power losses.
$P_{G,g}$	Active power of generator *g*.
$P_{L_{i\to j},l}^{0}$	Active power flow of existing line *l* from bus *i* to bus *j*.
$P_{L_{i\to j},l}$	Active power flow of candidate line *l* from bus *i* to bus *j*.
$P_{Loss,l}^{0}$	Active power loss in existing line *l*.
$P_{Loss,l}$	Active power loss in candidate line *l*.
$Q_{G,g}$	Reactive power of generator *g*.
$Q_{L_{i\to j},l}^{0}$	Reactive power flow of existing line *l* from bus *i* to bus *j*.
$Q_{L_{i\to j},l}$	Reactive power flow of candidate line *l* from bus *i* to bus *j*.
u_l	Binary variable related to the candidate lines: equals 1 if candidate line *l* is constructed, 0 otherwise.
$\lvert V_i\rvert$	Voltage magnitude at bus *i*.
θ_i	Voltage angle at bus *i*.

1. Introduction

Transmission Expansion Planning (TEP) addresses the problem of augmenting an existing transmission network to optimally serve a growing electric load while satisfying a set of economical, technical and reliability constraints [1]. In general, TEP is a stochastic decision making problem that consists of determining the time, the location, and the type of the transmission lines to be built [2].

TEP can be classified from various points of view. Based on the solution methods there are three types of algorithms to solve the planning problem: 1) mathematical optimization methods, 2) heuristic methods and, 3) combinatorial methods called meta-heuristic methods. Transmission expansion planning can be also categorized to static and dynamic planning. In the dynamic expansion planning the constructing time of lines will be determined in the optimization process, while in the static one there is only a "target year" that the selected optimal lines should be built within that.

The planners of the power system will face many uncertainties during the planning. So far many published papers have been considered uncertainties during the planning process [3-5].

A mixed integer linear programming that considers losses is used in reference [2] for TEP problem. [4] presented a stochastic coordination of generation and transmission expansion planning model. The authors of reference [3] presented a bi-level optimization model for transmission expansion planning. Torre et al. [6] employed a mixed-integer linear programming (LP) formulation for the long-term transmission expansion planning problem. References [7,8] have analyzed the TEP and Generation Expansion Planning (GEP) problem together. The authors in [9] have modeled a multistage stochastic TEP problem including available transfer capability (ATC). Ref. [10] studied TEP considering the load uncertainty using benders decomposition.

The papers reviewed in the literature survey use a DC approach in order to solve the TEP problem which is not completely suitable due to ignoring the reactive power. This paper proposes an approach for transmission planning based on AC optimal power flow (AC-OPF). Using AC-OPF could provide us a more precise picture of the active and reactive power flows in the expanded power network. Although the new model is more complicated than previous models, however it certainly leads to more precise and optimal plan in the future. A multi-objective optimization framework in order to handle the various objectives has been presented. The augmented ε-constraint method is used in order to solve the formulated multi-objective decision making problem using lexicographic optimization for every objective function. In general, the lexicographic optimization of a series of objective functions is to optimize the first objective function and then among the possible alternative optima optimize for the second objective function and so on [11]. Our novel contributions to this paper are: 1) Using AC-OPF based optimization. 2) A new revisited formulation based on multi-objective mathematical programming considering active power losses.

The remaining parts of the paper are outlined as follows: Section 2 presents the proposed problem formulation. The numerical example and its results on the Garver six bus test system and also on a real power system are presented and discussed in section 3, and finally concluding remarks and contributions are drawn in section 4.

2. Formulation

This section is arranged as follows: subsection 2.1. describes the augmented ε-constraint method which has been used in this paper so as to solve the formulated multi-objective problem. The problem formulation is then given in subsection 2.2.

2.1 Augmented ε-constraint Method (AUGMECON)

In the ε-constraint method, one of the objective functions is selected to be optimized using the other objective functions as constraints [12]:

$$\begin{aligned} &\text{Min } F_1(x) \\ &\textit{subject to}: F_2(x) \le \varepsilon_2 \;,\; F_3(x) \le \varepsilon_3 \;, \\ &\qquad F_4(x) \le \varepsilon_4 \;,\; \dots \;,\; F_p(x) \le \varepsilon_p \end{aligned} \tag{1}$$

In order to avoid the weakly Pareto optimal solution we use the method proposed in [11]. Thus the new optimization problem will be as follows:

$$\begin{aligned} &\text{Min } F_1(x) - \delta \times (s_2 + s_3 + \dots + s_p) \\ &\textit{subject to}: F_2(x) + s_2 = \varepsilon_2 \;, \\ &\qquad F_3(x) + s_3 = \varepsilon_3 \;,\; \dots \;, \\ &\qquad F_p(x) + s_p = \varepsilon_p \end{aligned} \tag{2}$$

where δ is a small number (between 10^{-3} and 10^{-6}).

In order to avoid any scaling problems it is recommended to replace the s_i in the second term of the objective function by s_i / r_i, where $r_i = z_i^{nadir} - z_i^{ideal}$. z_i^{nadir} is the upper bounds of $F_i(x)$ in the feasible region of the problem or "nadir value" of ith objective function and z_i^{ideal} is the lower bounds of $F_i(x)$ or "ideal value" of ith objective function. Thus, the objective function of the ε-constraint method becomes:

$$\text{Min } F_1(x) - \delta \times \left(\frac{s_2}{r_2} + \frac{s_3}{r_3} + \dots + \frac{s_p}{r_p} \right) \tag{3}$$

This type of ε-constraint method is called augmented ε-constraint method or AUGMECON method [11].

The lower bounds of the Pareto optimal set are obtained by minimizing each of the objective functions individually subject to the feasible region. Obtaining the upper bounds of the Pareto optimal set is not a trivial task. The nadir and ideal values can be calculated from the "payoff table" that has been demonstrated in reference [13].

Since F_1 is the main objective function in our MMP problem, only the ranges of objective functions F_2 and F_3 should be calculated. These ranges for F_2 and F_3 are divided by q_2 and q_3. Considering the minimum and maximum values of the ranges, we have the total of (q_2+1) and (q_3+1) grid points for F_2 and F_3, respectively. Thus, we should solve $(q_2+1) \times (q_3+1)$ optimization sub-problems where sub-problem *(i, j)* has the following form:

$$\text{Min} \quad F_1(x) - \delta \times \left(\frac{s_2}{r_2} + \frac{s_3}{r_3}\right)$$
$$\textit{subject to}: \quad F_2(x) + s_2 = \varepsilon_{2i} \qquad F_3(x) + s_3 = \varepsilon_{3j} \tag{4}$$

$$\varepsilon_{2i} = Max(F_2) - \left(\frac{Max(F_2) - Min(F_2)}{q_2}\right) \times i \quad i = 0,1,\ldots,q_2$$
$$\varepsilon_{3j} = Max(F_3) - \left(\frac{Max(F_3) - Min(F_3)}{q_3}\right) \times j \quad j = 0,1,\ldots,q_3$$

2.2 Problem Formulation

Three objective functions are considered for the proposed problem: 1) Investment Cost (IC), 2) Operation Cost (OC) and Power Losses (PL).

Using an AC power flow, the expansion planning problem can be formulated as follows:

$$Min \begin{cases} F_1 = IC = \underbrace{\sum_{l=1}^{nc} u_l IC_l}_{Investment\ \text{Cost (IC)}} \\ F_2 = OC = \underbrace{\left(8760 \times \sum_{g=1}^{ng} C_{1g} P_{G,g} + C_{0g}\right)}_{\text{Operation Cost (OC)}} \\ F_3 = PL = \underbrace{\left(\sum_{l \in EL} P^0_{Loss,l} + \sum_{l \in CL} P_{Loss,l}\right)}_{\text{Power Loss}} \end{cases} \tag{5}$$

Subject to the following equality and inequality constraints:

Equality constraints are as below:

$$P_{G,i} - P_{D,i} = \sum_{l \in EL_i} P^0_{L_{i\to j},li} + \sum_{l \in CL_i} P_{L_{i\to j},li} \quad \forall i \in B \tag{6}$$

$$Q_{G,i} - Q_{D,i} = \sum_{l \in EL_i} Q^0_{L_{i\to j},li} + \sum_{l \in CL_i} Q_{L_{i\to j},li} \quad \forall i \in B \tag{7}$$

$$\begin{aligned} P^0_{L_{i\to j},l} &= |V_i|^2 G^0_{ij} - |V_i||V_j| \times \\ &\left(G^0_{ij}\cos(\theta_i - \theta_j) + B^0_{ij}\sin(\theta_i - \theta_j)\right) \quad \forall l \in EL, \forall i,j \in B \end{aligned} \tag{8}$$

$$\begin{aligned} P_{L_{i\to j},l} &= u_l \Big(|V_i|^2 G_{ij} - |V_i||V_j| \times \\ &\left(G_{ij}\cos(\theta_i - \theta_j) + B_{ij}\sin(\theta_i - \theta_j)\right)\Big) \quad \forall l \in CL, \forall i,j \in B \end{aligned} \tag{9}$$

$$\begin{aligned} Q^0_{L_{i\to j},l} &= -|V_{is}|^2 B_{ij} - |V_i||V_j| \times \\ &\left(G^0_{ij}\sin(\theta_i - \theta_j) - B^0_{ij}\cos(\theta_i - \theta_j)\right) \quad \forall l \in EL, \forall i,j \in B \end{aligned} \tag{10}$$

$$\begin{aligned} Q_{L_{i\to j},l} &= u_l \Big(-|V_i|^2 B_{ij} - |V_i||V_j| \times \\ &\left(G_{ij}\sin(\theta_i - \theta_j) - B_{ij}\cos(\theta_i - \theta_j)\right)\Big) \quad \forall l \in CL, \forall i,j \in B \end{aligned} \tag{11}$$

$$\begin{aligned} P^0_{Loss,l} &= G_{ij} \times \\ &\left(V_i^2 + V_j^2 - 2 \times V_i V_j \cos(\theta_i - \theta_j)\right) \quad \forall l \in EL, \forall i,j \in B \end{aligned} \tag{12}$$

$$\begin{aligned} P_{Loss,l} &= u_l \times G_{ij} \times \\ &\left(V_i^2 + V_j^2 - 2 \times V_i V_j \cos(\theta_i - \theta_j)\right) \quad \forall l \in CL, \forall i,j \in B \end{aligned} \tag{13}$$

Inequality constraints are as below:

$$P^{\min}_{G,g} \le P_{G,g} \le P^{\max}_{G,g} \quad \forall \text{g} \in \text{G} \tag{14}$$

$$Q^{\min}_{G,g} \le Q_{G,g} \le Q^{\max}_{G,g} \quad \forall \text{g} \in \text{G} \tag{15}$$

$$\left(P^0_{L_{i\to j},l}\right)^2 + \left(Q^0_{L_{i\to j},l}\right)^2 \le \left(AP^{\max}_{L,l}\right)^2 \quad \forall l \in EL \tag{16}$$

$$\left(P_{L_{i\to j},l}\right)^2 + \left(Q_{L_{i\to j},l}\right)^2 \le u_l \left(AP^{\max}_{L,l}\right)^2 \quad \forall l \in CL \tag{17}$$

$$\left|V_i^{\min}\right| \le |V_i| \le \left|V_i^{\max}\right| \quad \forall i \in B \tag{18}$$

Equation (5) shows the objective functions (i.e. Investment Cost (IC), Operating Cost (OC) and Power Losses (PL), respectively). Equations (6) represent the active power balance for both existing and candidate buses. Equations (7) represent the reactive power balance for both existing and candidate buses. Constraints (8) and (9) indicate the active power flows from existing and candidate lines, respectively. Constraints (10) and (11) indicate the reactive power flows from existing and candidate lines, respectively. Superscript index 0 is used to denote the existing lines. Eqs. (12) and (13) are used in order to calculate the active power losses in line *ij* for existing and candidate lines, respectively. Active and reactive power generation limits of the generators are represented by Eqs. (14) and (15). Transmission flow limits are shown by Eqs. (16) and (17) for the existing and candidate lines, respectively. The voltage constraints are shown by Eq. (18).

Fig.1 shows the flowchart of the proposed method.

3. Numerical Example

The proposed model has been successfully applied to the Garver six bus test system and also to an actual system as illustrated in case A and case B, respectively.

This problem was solved on a PC running the windows operating system with Core 2 Duo CPU clocking at 2.00 GHz and 1 GB of RAM memory. The software used to solve the problem is DICOPT under GAMS (General Algebraic Modelling System) [14].

3.1 Case A: Garver System

The Garver test system is depicted in Fig. 2. It has six buses, 15 candidate branches, and a total demand equal to 760 MW. Generators and loads data have been shown in TABLE I. Reactive power demand in each bus is assumed to be 10% of the active power demand in that bus. We assume every generator submits its supply offer in the form of a linear function $C_g P_g$. TABLE II shows the existing and candidate lines data.

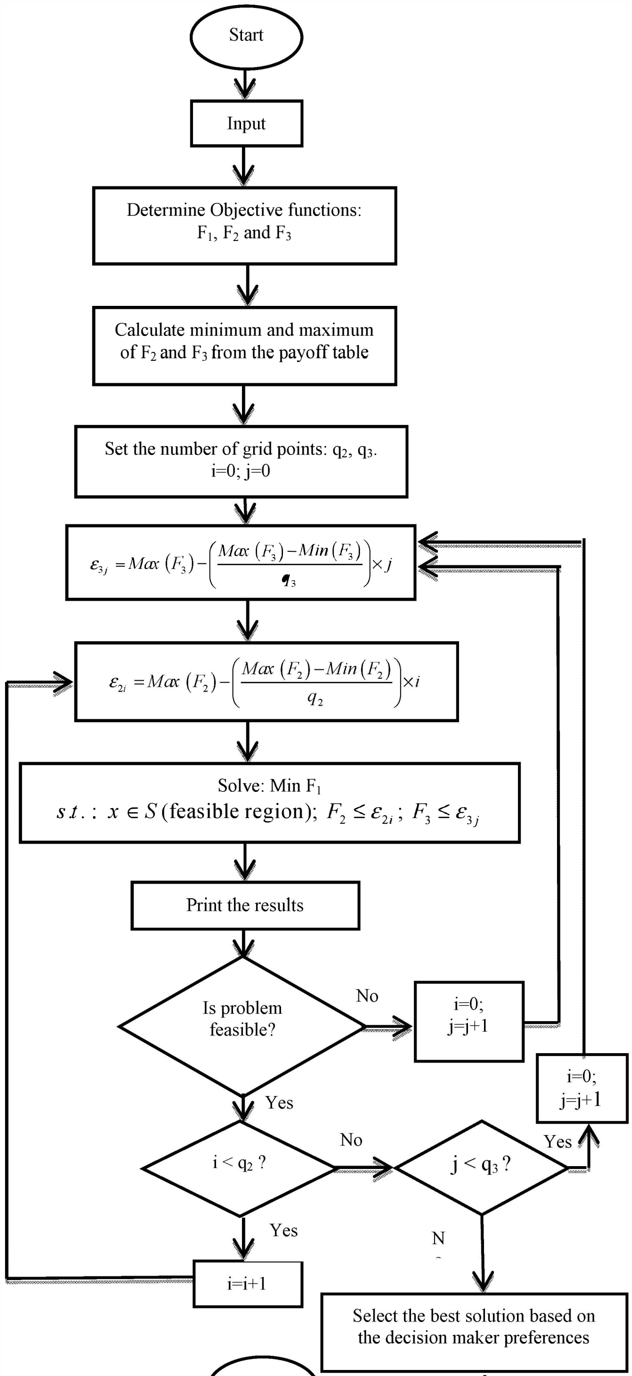

Fig. 1: Flowchart of the proposed method

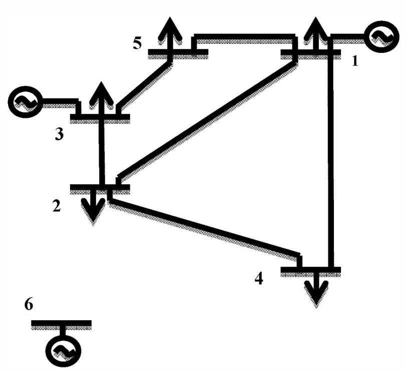

Fig. 2: Garver's 6-bus test system

TABLE I: Generators and Loads Data

Bus	Generators		Demand	
	Offer coefficients	-		
	c_g	P_G^{max}	P_D [MW]	Q_D [MVar]
1	10	150	80	8
2	-	-	240	24
3	20	360	40	4
4	-	-	160	16
5	-	-	240	24
6	30	600	-	-

TABLE II: Lines Data

Lines (L)	From	To	Capacity (MW)	Length	Resistance (p.u.)	Reactance (p.u.)	Investment Cost ($\$10^6$US)
EL_1	1	2	100	40	0.10	0.40	-
EL_2	1	4	80	60	0.15	0.60	-
EL_3	1	5	100	20	0.05	0.20	-
EL_4	2	3	100	20	0.05	0.20	-
EL_5	2	4	100	40	0.10	0.40	-
EL_6	3	5	100	20	0.05	0.20	-
CL_1	1	2	100	40	0.10	0.40	40
CL_2	1	3	100	38	0.09	0.38	38
CL_3	1	4	80	60	0.15	0.60	60
CL_4	1	5	100	20	0.05	0.20	20
CL_5	1	6	70	68	0.17	0.68	68
CL_6	2	3	100	20	0.05	0.20	20
CL_7	2	4	100	40	0.10	0.40	40
CL_8	2	5	100	31	0.08	0.31	31
CL_9	2	6	100	30	0.08	0.30	30
CL_{10}	3	4	82	59	0.15	0.59	59
CL_{11}	3	5	100	20	0.05	0.20	20
CL_{12}	3	6	100	48	0.12	0.48	48
CL_{13}	4	5	75	63	0.16	0.63	63
CL_{14}	4	6	100	30	0.08	0.30	30
CL_{15}	5	6	78	61	0.15	0.61	61

Table III: "Payoff table" for case A

	IC [\$]	OC [\$]	PL [MW]
IC [\$]	3.96×10^8	1.508663×10^8	34.073
OC [\$]	6.28×10^8	1.503352×10^8	32.052
PL [MW]	6.28×10^8	1.503352×10^8	32.052

Table IV: Objective functions values in each sub-problem for case A

	IC [\$]	OC [\$]	PL [MW]
1	3.96×10^8	1.5087×10^8	34.073
2	4.54×10^8	1.5050×10^8	32.683
3	5.34×10^8	1.5036×10^8	32.138
4	6.28×10^8	1.5034×10^8	32.052

For IC equals 3.96×10^8 the candidate lines 3, 5, 6, 9, 10, 11, 12, 14 and 15 should be built. For IC equals 4.54×10^8 all candidate lines but candidate lines 1, 7, 8 and 13 should be built. Also for IC equals 5.34×10^8 all candidate lines except candidate lines 8 and 13 should be built. For IC equals 6.28×10^8 all candidate lines should be built.

3.2 Case B: north-eastern part of Iranian national 400-kV transmission grid

Fig. 3 shows the simplified actual power system of north eastern part of Iranian national 400-kV transmission grid. The connection of the system to the Iranian main grid at Aliabad bus is considered as a positive load i.e. 300 MW and the connection to the neighbouring country, Turkmenistan grid, is considered as a negative load i.e. -300 MW. As it can be seen a new power plant at bus Shirvan and a new load at bus Kashmar will be added to the network in the planning horizon. The candidate lines are represented in Fig. 3 by dashed lines.

Table V shows the lines data.

TABLE VI shows the generators data (coefficient of GENCO's bid and maximum active power) and loads data (active and reactive power) for the end of the planning horizon. A linear offer function for GENCOs in the form of $C_{1g}P_{G,g}+C_{0g}$ has been considered. Upper and lower reactive power generation limit of power plant is assumed to be 50% and -40% of the upper active power generation limit. Tous bus is selected to be reference bus.

Table V: Lines (Existing and Candidate) Data

	Capacity (MVA)	Length (km)	Investment Cost ($/MVA-km)
L_1	800	183	N.A.
L_2	800	180	200
L_3	800	175	200
L_4	1100	110	N.A.
L_5	800	240	N.A.
L_6	1100	44	N.A.
L_7	800	181	N.A.
L_8	1200	132	N.A.
L_9	1100	80	200
L_{10}	1100	110	N.A.
L_{11}	800	170	N.A.
L_{12}	1200	90	N.A.
L_{13}	1100	120	200
L_{14}	1200	60	200
L_{15}	800	198	200
L_{16}	1100	105	200
L_{17}	800	230	200
$L_{18,19}$	800	350	N.A.
$L_{20,21}$	800	265	N.A.

The problem has 3960 single equations, 2638 single variables and 8 discrete variables. We have considered q_2=q_3=6, therefore the total 49 sub-problems must be solved in which the execution time to solve each sub-problem by DICOPT varies from 0.1 to 1.1 seconds. Among all these sub-problems, 10 sub-problems are infeasible.

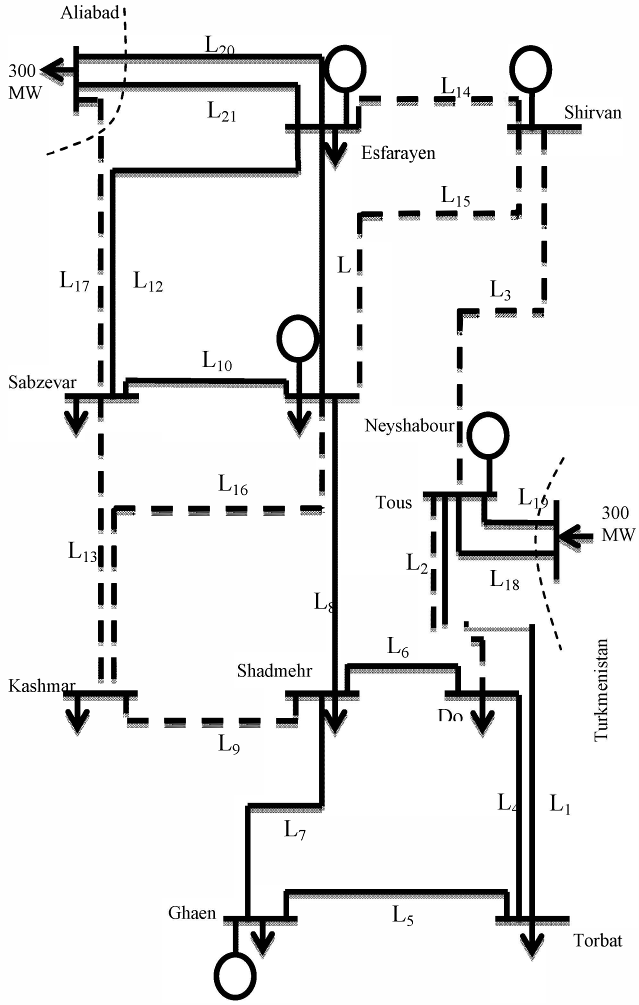

Fig. 3: Northeastern part of Iranian national 400-kV transmission network

Table VII is the obtained payoff table. Payoff table clearly shows the conflicts among the considered objectives and demonstrates that a multi-objective approach is essential in the power system planning. Multiplying the objectives by a number will multiply its values in payoff table in the same number meaning that the weighting factors for objectives have no impact in the results and therefore we will face no scaling problem in the optimization process.

TABLE VI: Generators and Loads Data

Bus	Generators			Demand	
	Offer coefficients		-		
	c_{1g}	c_{0g}	$P_G^{\max}$	P_D [MW]	Q_D [MVar]
Tous	0.0113	12.14	1650	506	100

Torbat	-	-	-	810	162
Dolat	-	-	-	823	165
Ghaen	0.0113	15.14	800	434	87
Shadmehr	-	-	-	1250	250
Neyshabour	0.0222	17.92	1000	531	106
Sabzevar	-	-	-	530	106
Esfarayen	0.03	20.02	1200	362	72
Shirvan	0.01	12.44	1500	-	-
Kashmar	-	-	-	520	104
Aliabad	-	-	-	300	60
Turkmenistan	-	-	-	-300	-60

Table VIII shows only the obtained unique solutions for the remaining sub-problems that have integer solutions.

Table VII: "Payoff table" for case B

	IC [\$]	OC [\$]	PL [MW]
IC [\$]	9.7980×10^8	1503810.04	154.76
OC [\$]	1.7878×10^8	1498384.44	134.12
PL [MW]	1.7878×10^8	1541666.41	128.43

Table VIII: Objective functions values in each sub-problem for case B

	IC [\$]	OC [\$]	PL [MW]
1	9.7980×10^8	1.5038×10^8	154.760
2	1.7878×10^8	1.4984×10^8	134.115
3	9.7980×10^8	1.5417×10^8	150.114
4	1.1558×10^8	1.5015×10^8	146.093
5	1.1558×10^8	1.5272×10^8	142.806
6	1.1558×10^8	1.5128×10^8	144.587
7	1.1558×10^8	1.5056×10^8	145.539
8	1.1558×10^8	1.5417×10^8	141.192
9	1.1558×10^8	1.5023×10^8	145.984
10	1.1558×10^8	1.5200×10^8	143.675
11	1.1558×10^8	1.5056×10^8	145.539
12	1.4198×10^8	1.4986×10^8	134.840
13	1.4198×10^8	1.5345×10^8	130.090
14	1.4198×10^8	1.5128×10^8	132.836
15	1.4198×10^8	1.5056×10^8	133.832
16	1.4198×10^8	1.5129×10^8	132.820
17	1.7878×10^8	1.5128×10^8	132.060
18	1.7878×10^8	1.5417×10^8	128.432

For IC equals 9.7980×10^8 the candidate lines 2, 14, 15 and 16 should be built. For IC equals 1.7878×10^8 all candidate lines but candidate line 3 should be built. Also for IC equals 1.1558×10^8 candidate lines 2, 14, 9, 15 and 16 should be built while for IC equals 1.4198×10^8 candidate lines 2, 9, 13, 14, 15 and 16 should be built. Also as it can be seen from the payoff table the power loss when OC is the main objective, is less than when IC is the main objective. This can be justified as follow: the more losses in the system means the more power should be produced by generators in order to meet the demand that will lead to more production cost.

4 Conclusion

In this paper a new expansion planning model for transmission based on AC-OPF was provided and applied to the Garver's six bus test system and to an actual power system of Iranian national 400-kV transmission grid. A new revisited formulation based on multi-objective optimization was presented and the augmented ε-constraint method was used in order to solve the formulated mathematical multi-objective programming (MMP). Creating only Pareto optimal solutions and capability of producing all of the Pareto solutions are some of the advantages of the augmented ε-constraint method. Therefore the proposed method provides more flexibility for the planner of the transmission in order to select the best solution among the non-dominated solutions obtained by AUGMECON method. The results of the case study were shown and analyzed.

References

[1] J. Choi, T.D. Mount, R.J. Thomas, Transmission Expansion Planning Using Contingency Criteria, *IEEE Trans. Power Syst. vol. 22 n. 4*, 2008, pp. 2249 – 2261.

[2] N. Alguacil, A.L. Motto, A.J. Conejo, Transmission Expansion Planning: a Mixed-Integer LP Approach, *IEEE Trans. Power Syst. vol. 18 n. 3*, 2003, pp. 1070 – 1077.

[3] L.P. Garces, et al., A Bi-level Approach to Transmission Expansion Planning Within a Market Environment, *IEEE Trans. Power Syst. vol. 24 n. 3*, 2009, pp. 1513 – 1522.

[4] J.H. Roh, M. Shahidehpour, L. Wu, Market-Based Generation and Transmission Planning With Uncertainties, *IEEE Trans. Power Syst. vol. 24 n. 3*, 2009, pp. 1587 – 1598.

[5] P. Wu, and H.C.J. Xing, The Interval Minimum Load Cutting Problem in the Process of Transmission Network Expansion Planning Considering Uncertainty in Demand. *IEEE Trans Power Syst, vol. 23 n. 3*, 2008. pp. 1497-1506.

[6] S.D.L. Torre, A.J. Conejo, J. Contreras, Transmission Expansion Planning in Electricity Markets. *IEEE Trans. Power Syst, vol. 23 n. 1*, 2008. pp. 238-248.

[7] B. Graeber, Generation and transmission expansion planning in southern Africa. *IEEE Trans. Power Syst, vol 14.* 1999. pp. 983–988.

[8] M. Kandil, S. El-Debeiky, N. Hasanien, Rule-based system for determining unit locations of a developed generation expansion plan for transmission planning. *IEE Proc Gener Transm Distrib, vol. 147. n. 1,* 2000. pp. 62–68.

[9] T. Akbari, A. Rahimikian, A. kazemi, A multi-stage stochastic transmission expansion planning method. *Energy Convers Manage, vol. 52,* 2011. pp. 2844–2853.

[10] T. Akbari, S. Zolfaghari, A. Kazemi., Multi-Stage Stochastic Transmission Expansion Planning under Load Uncertainty Using Benders Decomposition. *International Review of Electrical Engineering-IREE vol 4 n. 5,* 2009. pp. 976-984.

[11] G. Mavrotas, Generation of efficient solutions in Multiobjective Mathematical Programming problems using GAMS. Effective implementation of the ε-constraint method. Available from: www.gams.com/modlib/adddocs/epscm.pdf.

[12] K.M. Miettinen, Nonlinear Multiobjective Optimization. 1999, *Kluwer Academic.*

[13] J. Cohon, Multiobjective programming and planning. 1978: *Academic Press.*

[14] Generalized Algebraic Modeling Systems (GAMS). 2011; Available from: http://www.gams.com.