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Sustainable generation and transmission expansion planning in competitive power markets

Mohammad Sadegh Javadi[1,2*], Mohsen Saniei[1]

[1*]Department of Electrical Engineering, Shahid Chamran University, Ahvaz,
[2*]Department of Electrical Engineering, Science and Research Branch, Islamic Azad University, Fars, Iran,
[1]Department of Electrical Engineering, Shahid Chamran University, Ahvaz, Iran,
msjavadi@gmail.com*, mohsen.saniei@gmail.com

Abstract

This paper, presents on the coordination of power system expansion planning including sustainable generation expansion planning (GEP) and transmission network expansion planning (TEP). For this purpose, a game theory based model is proposed to determine the dominant strategy of each investor entities in the generation and transmission sectors. In this model, all power producers compete with each other at the same level for maintaining the energy and reserve services. At this stage, after determining the Cournot equilibrium, the suggestions accepted in previous stage are evaluated in the transmission planning stage. Here, according to the existing units and the units proposed in the previous stage, transmission network expansion planning takes place based on cost, social welfare and reliability indices by independent system operator. Thereafter transmission expansion planning results announced, the accepted unit and not accepted units can offer their new strategies to the market. This iterative process continues until the dominant strategy of each entity is satisfied and the final equilibrium is obtained. To solve this game and finding its Nash equilibrium, the mixed integer non-linear programming (MINLP) optimization is used by all decision makers for optimizing their desirable strategies to invest in the power market. A conceptual test system is proposed to show the ability of the model. Simulation results verify the feasibility and capability of the proposed modeling of the long-term expansion planning.

Keywords: Generation Expansion Planning, Transmission Expansion Planning, Game theory.

Introduction

After power system restructuring, preliminary arrangements have been provided in the power industry for making a competitive electricity market in different countries with their specific policies. In most countries, the restructuring was begun with short term competition in weekly and monthly programs in the electricity market. Subsequently, in the mid-term planning including planning for allocation of fuel, pollution, maintenance scheduling, etc, some conditions has been provided to make a competitive environment at this stage. In this level of competitive power market, any of the generation companies, according to their constraints and market conditions, will decide to participate in the electricity market. The next step in the competition liberalization of electricity industry is the preparing conditions for investment in the generation and transmission sectors which due to time horizon are categorized as long-term planning in power systems. Regard to the scheduling of new units entrance and the outage of the retired units and their retirement, in long-term, installation of new generation units or enhancement of the existing units would be considered in the expansion horizon. Determination of type, number, technology and location of nominated units is known as Generation Expansion Planning (GEP). After determination the Location, type, number and technology of the generation units, the requirements of the energy transfer to the load centers should also be considered. For this purpose it is necessary to strengthen existing lines or investment on new transmission lines. Thus in the Transmission Expansion Planning (TEP), candidate lines, links and their capacity are determined. In the transmission expansion planning, the main objective is maintaining the load of subscribers at low cost and the highest reliability.

Numerous articles have been published on generation and transmission expansion planning up to this time. In recent years, the researchers on the generation and transmission expansion planning have been interested on the competition. For example, in reference (Chuang *et al.,* 2001) developed generation planning using game theory is proposed. Similarly (Parsons & Wooldridge, 2000; Simon *et al*., 2006; Simon *et al.*, 2009) have used the concept of Cournot and Stackelberg equilibrium for satisfying the optimal generation expansion planning. In (Dehghan *et al*., 2009) simultaneously generation and transmission expansion planning has been carried out using mixed integer non-linear programming. In (Fischer & Joo, 2008), the generation expansion planning has been presented with regard to the energy market and capacity payment to installed generation units and capacity of transmission lines has been considered too.

This paper is organized as follows: the long-term planning of power systems in traditional and modern systems introduced in section 2. Long-term market design is considered in this section. Section 3 and 4 consider the generation and transmission expansion planning, respectively. Section 5 introduces the problem formulation and mathematically modelling of game structure is also presented there. The validity of the proposed method is examined in a simple case study.

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The simulation results and discussion presents in the section 6.

Long-term market design- conceptual modeling

Imposing the appropriate incentive policies in the electric energy market, in the long term timeframe, to achieve generation and consumption balance, is more complicated than other markets and other commercial goods. Two important factors, is causing this complexity. First reason is the nature and the concentrated nature of the electrical energy generation in generation sectors. Power generation plants, require very high capital costs. However, such units are constructed to supply at local markets. Such local and regional markets can not create desired stability and security that the global and national markets can provide. In such cases, encouraging institutions of the generation investor entities prefer that such global markets to not be created in action. (Moreover, the legislative entity tends to focus on local markets, because, the competition between generation companies is intrinsically possible).

The second case, which causes long-term market complexity, is the reliability of generation units. Because of the reserve requirements, available capacity units should be over the amount of energy can be generated per hour, to provide designated reserve. In such case, the establishment of fair market and full to encourage generation units, which provide operating reserve, and perhaps more important, to determine the required reserve margin to ensure the system(Krause, 2005). So far, no theoretical consensus on the basic structure of a market for long-term horizon has been provided. Other issue and challenges gripped electricity market are the promotion of the transmission network equipments which they should be considered corresponding to the generation expansion. İt also should be noticed that the promotion of the transmission system needs too much expenditure. Financial funding, cost allocation and covering of the system upgrade costs should be considered.

Planning for long-term goals in the electrical energy in a market environment is very similar to the traditional and classic electricity network, although there is also a substantial difference between them. In this case, a series of institutions, which should be determined by the legislative entity or ISO, must approve the project. This is very similar to traditional electricity network.

One of the differences in market environment is the need for comprehensive studies and reviews about the requirements of the transmission system promotion. This important and solemn duty is with ISO which should perform necessary measures in order to maintain the reliability of the system, in addition to the detailed studies. The subject of the covering of the transmission system promotion costs should be finalized after complying with legislative entity and agreed with the contractors company.

In modeling the generation expansion planning, assumed that the generation companies submit their bid to the market after an econometric analysis. Thus, the price proposed by each of the generation companies is based on the utility desirability. Power system planning in such cases, according to the suggestions received, is attempting to run the network expansion planning.

After the output was determined in this level, the planning on the transmission network strengthens or expansion is carried out. Modern Power System Planning is carried out in such an approach that none of the generation enterprises in the power market is not price taker ones. Since the Locationl Marginal Prices (LMP) are function of generation cost, congestion and losses, if the line capacity does not meet the load at one bus, marginal generation unit will determine the final price at this bus.

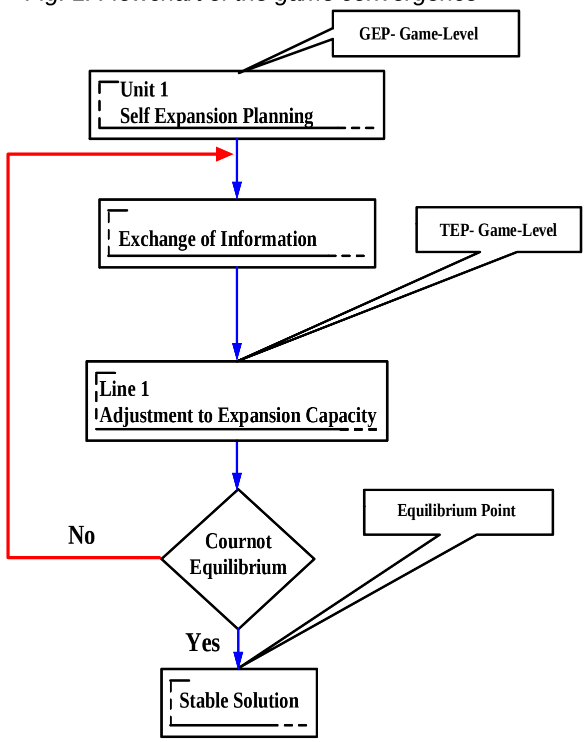
So in this case, unified power system planning performs the network expansion planning, in such an approach, which the ultimate goal is the load maintaining with the lowest cost and the highest level of reliability. In this paper, according to the auction generation expansion model, system planner has this authority to introduce the needed lines to increase social welfare. In such case the costs and reliability are included. In this case the transmission company is required to evaluate the proposal from the stability aspects.

Once the final design is approved by the transmission owner, the expansion plan will be announced to all producers. This allows for generation companies (both those whom their proposals have been accepted in the previous stage and those whom their proposals have not been accepted in the previous stage) to provide their new proposals. Profit from generation companies is calculated from the multiplication of the difference of the offer price and the market price, with the generation amount of the certain units.

For new generation units, the cost of the installation of every kW capacity should be considered. For transmission a company, the profit is obtained from the difference between two sides of bus LMP's product in the amount of transmitted power thorough the total lines. Since the transmission network owner has the operation of all lines, so the total transmission company's profit should be considered.

Again, in this case the cost of the line strengthening or the installation of the new lines, which is also expensive, should be considered. In generation expansion planning, network topology remains constant, but in the transmission network planning, as the admittance network matrix changes, it also affect the power flow thorough lines and network topology. Full generation and transmission expansion model based on game is described in this paper. The comprehensive game flowchart is depicted in Fig.1.

Fig. 1. Flowchart of the game convergence



Generation expansion planning

The aim of generation expansion planning is to determine the number, location, type and year of entrance of new generation units to the grid. In traditional power systems, the administrator generation entity is responsible for the coordination and planning of the new needed units and the investment in the stage of the land purchase and acquisition, obtaining permits needed to build.

In traditional power systems, projects were divided into two categories, projects that would be reviewed by local power companies and projects that would be managed by independent energy entities. Projects that were conducted by regional electricity companies were in the form that the ownership and operation of the power generation units remains in the same company. Before construction, the project must have approval from the relevant state institutions. Licensing was including financial guarantees, loans and providing credits allocated for construction of new units and the review of rates paid to the subscribers with costs allocated for the project.

Another type of projects managed by independent entities were those projects that new units were built by an independent entity, and the ownership and operation would also be given to an independent power producer (IPP). Before a new power plant unit is constructed, power purchasing agreement (PPA) is held between power companies and generation companies. The implementation of the PPA is subject to obtaining a permit from the state institutions. Various structures are presented for the PPA, but the nature of these PPA agreements guarantees that all electricity companies will pay the energy cost to the power generation companies for their energy delivering and installed capacity. In line with these PPA agreements, the state authority will apply a mechanism in order to cover expenses through the payments received from subscribers and energy tariff.

Common point of these two aforementioned mechanisms is the covering of the costs allocated to system planning projects which takes place with determination of the tariff to customers to return the expenses. Moreover, the investment return mechanisms should be appropriate to the useful life of installed units. From point of view of banks, the investments in this sector are very attractive and they often tend to participate in such projects.

In the competitive environments, none of the retailers and generation companies is able to offer specific rates to banks. Large banks have no tend to invest in projects that investment return mechanisms are not clear. In non-traditional markets, the only qualified source to provide guarantees mentioned, is independent system operator (ISO).

This problem is only a small part of the problems that plagued the energy supply entities. This problem is a reason to encourage them to establish free markets. So the regulatory commission should give carte blanche to ISO to conclude needed PPA to ensure investment return. Without such guarantees, investment in construction of new generation units will face with great problems and threat generation resources reliability. However, such powers delegated to the ISO, will lead the market environment to the former traditional environment. In this case, the challenges in the development of free markets and reliability of the network will be created. Long-term planning in such an area will be very difficult and complicated.

Independent power producers, IPPs, will select the projects that will maximize their profits. These companies offer the benefits corresponding to their suggestions, using simulations on the load dispatch scenarios of the generation units based on the predicted desired fuel purchase price and sale of energy in the market for a range of 20-30 years. Simulations on the load economic dispatch for the desired units were presented (Javadi, 2011).

In this case, the prices play the role of λ in the system. In these Simulations, economic size of the investments, unit size, income, fuel prices, requirements corresponding to different fuels and energy generation values are determined. The collection of data with other system costs (maintenance, personnel and investment costs) are total data required in this section. Then, IPPs proceed to studies related to the present value of investment in this sector in which the discounted cash flow will be determined regard to the annual discount rate at the time of investment.

The investor companies' revenue estimation in this case is dependent on fuel and energy prices predicted in the simulator program. Price forecasting for each of the energy resources, which are known as generation unit, takes place in a certain way. This article assumes that results of predictions are available. For energy price forecasting, an acceptable approach explained earlier (Simon *et al*., 2006) and is used here. Price forecasting is dependent on two basic parameters: the energy price forecasts and the level of amount of energy generation.

Component related to the energy price which is the generation marginal cost, of λ system, is calculated using the load dispatch simulation program. Marginal cost by itself does not cover investment costs for construction of new units. An acceptable consumption is considered in the forecasting is that the IPP will be able to cover expenses related to investments and loan instalments. In this case, the number of the units should be so that the generation system reliability indices are fulfilled. Capacity payment should cover the difference between total capacity investment costs and net benefits of generation units and will be paid to all generation units.

In the conclusion, it can be said that after the corresponding price curves were obtained, one can implement the construction project of a new unit based on economic dispatch corresponding to forecasting based on fuel prices and energy for an specific range. Profits corresponding to the energy generation capacity were added to the energy generation costs and so the financial flows of these investments are determined. In the next step, the achieved financial flows must be determined due to the annual discount rate transferred to the investment time and present value of the project is determined accurately (Javadi *et al.*, 2009).

Expansion or enhancement transmission lines

Promotion of energy transmission and transit is very expensive. If the transmission upgrade is required to connect the new power plant unit to the network, should also the network capacity expansion is not too distant future is considered and needed Lines with more capacity should be installed. Promotion of the transmission system to raise transmission capacity is usually uneconomical for low-capacities. In fact, the promotion of the transmission system is carried out for several hundred megawatts.

In traditional power systems, imposed additional costs for expansion and promotion of the transmission systems was received from consumers based on the tariff approved by state legislators, while such a case in a competitive environment is very complex. The fact that generation networks are heavily dependent on the transmission equipments cannot be ignored.

Thus, for any planning scheme, all three institutions must also agree. As noted, the independent power producers tend to accomplish generation expansion planning. The transmission owner should also improve the generation equipments appropriate to the generation expansion. Meanwhile, ISO as a supervisory institution should satisfy various projects in every aspect.

These cases are themselves considered as obstacles to the generation expansion. For this purpose, in any market, Regulatory Commission considers an entity to assess and monitor expansion plans and provide coverage on imposed costs. Desired process, takes place under the supervision of ISO. It means that ISO is correspondence entity for expansion and promotion all plans of the system. In this case, the IPP is also required to coordinate with this body the necessary actions prior to the construction of new units.

So far, no clear and specific methods have been presented for allocation of the system improving costs. In most cases, due to the legal authority, ISO can ask an IPP to make a funding for network expansion. In fact, this institution is a responsible and executive entity to control on how to perform and complete these projects.

Modeling and Formulation

In modelling the generation expansion planning, is assumed that the generation companies submit their bid to the market after an econometric analysis. Thus, the price proposed by each of the generation companies somehow conveys the utility desirability. Power system planning in cases, according to the suggestions received, is attempting to run the network expansion planning.

After the output was determined in this level, the planning on the transmission network strengthens or expansion is carried out. Modern Power System Planning (MPSP) is carried out in such an approach that none of the generation enterprises in the power market are price maker. Since the locationl marginal prices (LMP) are function of generation cost, congestion and losses, if the line capacity does not meet the load at one bus, generation unit will determine the final price at this bus.

So in this case, if the unit offers any cost to the market, it will be accepted. Power system planning performs the network expansion planning, in such an approach that the ultimate goal is the load servicing with the lowest cost and the highest level of reliability. In this paper, according to the auction generation expansion model, planner entity has this authority to introduce the needed lines to increase social welfare. In such case the costs and reliability are included. In this case the transmission company is required to evaluate the proposal from the stability aspects.

Once the final design is approved by the transmission owner, the expansion plan will be announced to all producers. This allows for generation companies (both those whom their proposals have been accepted in the previous stage and those whom their proposals have not been accepted in the previous stage) to provide their new proposals. Profit from generation companies is calculated from the multiplication of the difference of the offer price and the market price, with the generation value of the units.

For new generation units, the cost of the installation of every kWh capacity should be considered. For transmission companies, the profit is obtained from the difference between two sides of bus LMP's product in the amount of transit power of the total lines. Since the transmission network owner has the operation of all lines, so the total transmission company's profit should be considered.

Again, in this case the cost of the line strengthening or the installation of the new lines must be considered. It should be noted that these two approaches are both much expensive. In generation expansion planning, network topology remains constant, but in the transmission network planning, as the admittance network matrix changes, it also affect the power flow thorough lines. Full generation and transmission expansion model based on game is described below.

In the Cournot duopoly model, the Cournot equilibrium is a quantity pair that maximizes the profit of each firm, given other firm's output quantity. In terms of mathematics, the optimal quantity pair (q_1^*, q_2^*) is the Cournot equilibrium if, for firm 1, q_1^*, solves:

$$\underset{q_i}{Max}\ \pi_1 = (q_i, q_i^*) \qquad (1)$$

Where:

π_i : profit for firm "*i*"

q_i : quantities produced by firm "*i*"

q_i^* : optimal quantities produced by firm "*i*"

The profit function for firm 1 can be represented by (2)

$$\pi_1(q_1, q_2) = p(q_1, q_2)q_1 - c_1(q_1) \qquad (2)$$

$p(.)$: market price for aggregate quantity

$c_i(.)$: cost function for firm "*i*"

Profit is the difference between revenues and costs. In our proposed model, the revenue of each line is given by a congestion charge, which is in fact the result of difference in locational marginal prices. In value-based transmission expansion, the total revenue of TransCo is the sum of congestion charge collected by each line in the network. For the sake of simplicity, the total cost is not being considered. Therefore, the total profit collected by TransCo can be expressed as (3):

$$\pi_T = \sum_{i \neq j} (\lambda_i - \lambda_j) P_{ij} - Inv_{ij} \qquad (3)$$

where

π_T : Profit of TransCo in $/h

λ_i : LMP at node "*i*" in $/MWh

λ_j : LMP at node "*j*" in $/MWh

P_{ij} : Active power flow from node "*i*" to node "*j*"

Inv_{ij} : Investment cost of installation line between nodes "*i*" and "*j*"

Assume that the GEP is performed at node "*i*". The objective of GenCo for GEP is simply defined as (4)

$$\pi_G = \lambda_i q_G - c(q_G) - Inv_i(G) \qquad (4)$$

where

π_G : Profit of GenCo in $/h

λ_i : LMP at node in $/MWh

q_G : Active power generation in MW

$c(.)$: Quadratic cost function of active power generation in $/h

$Inv_i(G)$: Investment cost in terms of generation expansion capacity in $/h

Simulation results and discussion

Table. A.1 Available transmission lines data

From	To	Length (km)	X (p.u)	Capacity (MW	Inv.Cost (*1000$)
1	2	3	0.0139	175	30
1	3	55	0.2112	175	550
1	5	22	0.0845	175	220
2	4	33	0.1267	175	330
2	6	50	0.192	175	500
3	9	31	0.119	175	310
3	24	50	0.0839	400	500
4	9	27	0.1037	175	270
5	10	23	0.0883	175	230
6	10	16	0.0605	175	160
7	8	16	0.0614	175	160
8	9	43	0.1651	175	430
8	10	43	0.1651	175	430
9	11	50	0.0839	400	500
9	12	50	0.0839	400	500
10	11	50	0.0839	400	500
10	12	50	0.0839	400	500
11	13	33	0.0476	500	660
11	14	29	0.0418	500	580
12	13	33	0.0476	500	660
12	23	67	0.0966	500	1340
13	23	60	0.0865	500	1200
14	16	27	0.0389	500	540
15	16	12	0.0173	500	240
15	21	34	0.0245	1000	1360
15	24	36	0.0519	500	720
16	17	18	0.0259	500	360
16	19	16	0.0231	500	320
17	18	10	0.0114	500	200
17	22	73	0.1053	500	1460
18	21	18	0.01295	1000	720
19	20	27.5	0.0198	1000	1100
20	23	15	0.0108	1000	600
21	22	47	0.0678	500	940

The proposed algorithm was tested on at 24 bus IEEE reliability test system (RTS) as shown in Fig,A.1 in the appendix. Table A.1 gives the parameters of modified test system and Table A.2 includes the candidate

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transmission lines. Table A.3 provides the data of system generators and Table A.4 shows the candidates' generation unit's data.

Table. A.3 Available generation unit's data

Bus	a	b	c	Pmax
1	0.2917	35.07	3591.39	192
2	0	64.96	306.7	192
7	0.0322	19.18	1940.98	300
13	0.0322	19.18	649.99	591
15	0.0628	27.22	1829.71	215
16	0.0191	14.86	552.8	155
18	0.0191	14.86	1105.6	400
21	0.0086	30	1992.36	400
22	0.0112	14.17	927.15	300
23	0.0017	17.55	1160.23	660

In the modelling and evaluation the state of generation and transmission sector, generation units and transmission candid as presented in table A.1 to A.4 are considered. Because of the strength transmission network, we modify the transmission capacity and reduce the thermal capacity to 62.5 % of original ones. The candidate tables including the capital, capacity and location of installation the mentioned equipments. It also mentioned that the siting and location of expansion planning are not considered in this study.

Table. A.4. Candidate generation unit's data

Type DG	a	b	c	Capacity (MW)	MAR ($)	Max. Inv. (Unit)
1	0.02	15	0.0	50	2500000	4
2	0.03	20	0.0	50	650000	4
3	0.04	25	0.0	50	60000	4

Fig. A.1. IEEE 24 Bus reliabilty test system (RTS)

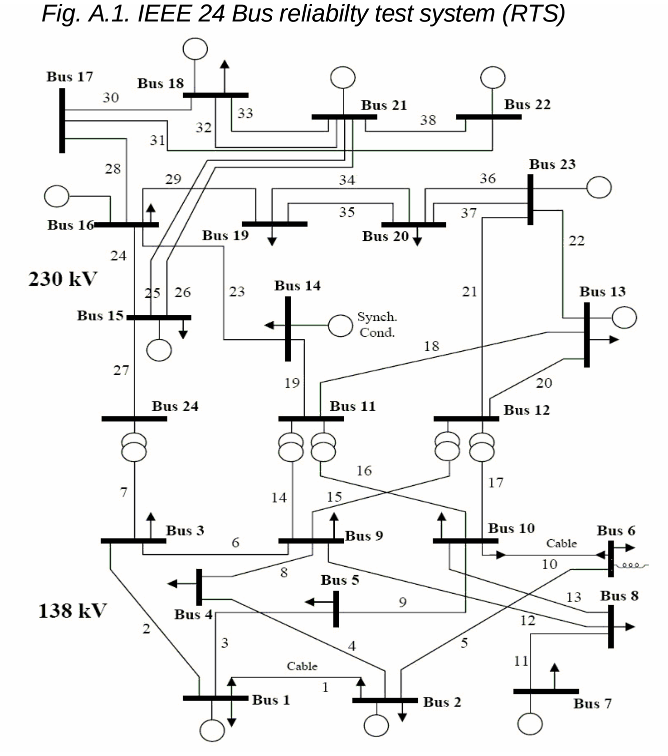
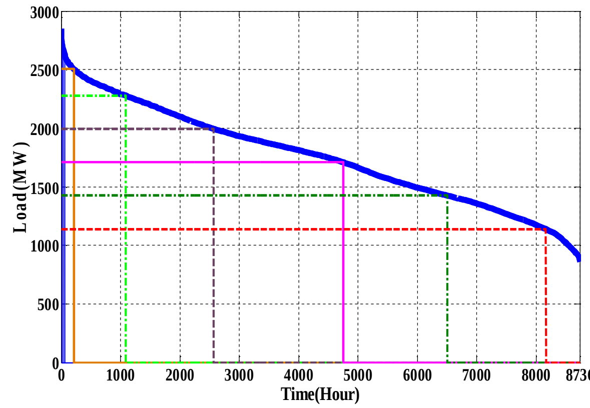
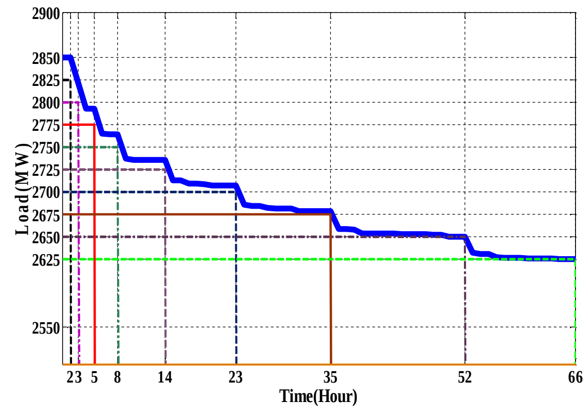


Fig. 2. Annual load duration curve, overall load duration curve (a), peak load duration curve (b)



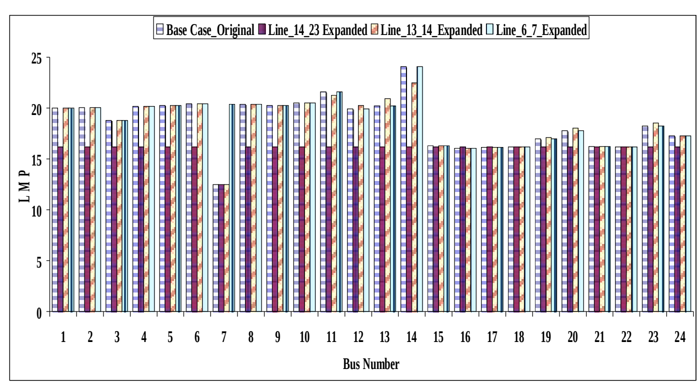
(a)



(b)

One of the important issues that considered in this study is considering the annual load duration curve in modeling and simulation of the proposed algorithm. So, the annual load duration curve, such as Fig.2 is extracted from daily, weekly and monthly coefficients from IEEE 24 Bus RTS. It can be seen that the LMP in peak load hours are very high and not smooth because of transmission lines congestion and reaching the maximum capability of generation units. In this situation two expansion schemes are available, one of them enhancement available transmission lines or construction new transmission lines

Fig.3. Four scenarios simulations LMP



and another one is generation expansion in the high dense buses. Simulation results show that the LMP in bus 7 are low than other bus. This fact is imposed because of the high dense generation units in this bus (3*80 MW units) and the maximum load in peak hour is only 125 MW. The connection of this bus to the network is only through a 110 MW line between this bus and bus 8.This trapped reserve reduces the LMP in this bus and should be considered in expansion studies. From reliability point of view transmission expansion plan are invited. But this plan increases the LMP in bus 11, 13 and 14 and is not preferred. Fig 3

The simulation results show that the 13 to 14 and 14 to 23 transmission expansion are also would be considered. The results confirm that the 14 to 23 line is the best plan. In the generation expansion sector also an economically studies are carried out. In this section minimum acceptable rate of return (MARR) approach is considered. The simulation results show that the best candid is bus 8. The negative injection (Load) to this bus is 6 % of total demand. This bus is connected to the grid through three transmission lines. One of the connections is 8-7 line. As it mentioned above bus 7 have 3*80 MW generation units and its demand is 4.4 % of total demand. In 30% of the time the transmission line between 7 and 8 are fully loaded. The optimal power flow in the network also confirms the generation expansion in this bus. Maintaining load in bus 8 and optimal load dispatch between the generation units required the transmitting 13.48MW from bus 9 to bus 8 and also 17.48 from bus 8 to bus 10. So, this bus is the best case for generation expansion because of the high dense loading and the weakest node from point of reliability indices.

For evaluation of generation expansion planning we consider the distributed generators (DG) because of the lowest size, investment cost and time construction than other conventional energy resources. In this study it is assumed that the generation technologies are same because of maintenance and maintaining the accessories and crew constraints. Table A.3 and A.4 show the generation type and data.

Simulation results show that increasing the generation units rises in line with decreases in disposable income. In this case, implementing the supplementary generation units is not proffered.

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