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Objective functions of distribution network expansion planning - a comprehensive and exhaustive review

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Abstract. Utmost of elucidation about the research accomplished in an article is cleared from the objective function of the planning problem. An objective function is a mathematical expression which describe the existing condition of a system with numerous variables, in which alteration of these variables result in optimized value largest or smallest, depending on problem or desired value. That value may be obtained by minimizing or maximizing the objective function. In this paper, a review has been carried out on objective functions of distribution network expansion planning (DNEP). These objective functions have been classified into five main categories: financial, income related, technical, optimal size & location and social & economic. The selection of objective function clearly shows increasing penetration of distributed generation (DG), distributed energy storing systems (DESS) and fuel cells with renewable technologies. Most of the reviewed articles highlight these objectives in details, however; not all fields have been covered in any single work on DNEP. This review article aims to address this gap so that widespread DNEP can be achieved with flawlessness. Substantial information has been offered of research work done in the field of DNEP through this review article which will mitigate the impending researchers from the difficulties of getting apposite supervision.

1. Introduction

The classic objective of the distribution network expansion planning (DNEP) was to fulfil technical necessities (improvement of voltage profile, reliability, reduction of losses etc.). Later on, to ensure an economic and consistent energy supply, foremost aim of DNEP turn into determining an effective and least investment schedule [1]. Decision making progression becomes more complex task when one deals simultaneously to cover maximum aspects of the problem. Another characteristic features of distribution network operation and scheduling is that the judgement making problem is to be encountered with substantial level of ambiguous information. With more penetration of DG, the normal distribution networks becomes active distribution network. Depending upon the objectives functions considered for the expansion planning of distribution network, DNEP problem can be categorize into mono-objective problem and multi-objective problem [2]. The review of various articles reflects the shifting of DNEP from few objectives to multi-objective fulfillment. This paper provides a review on various objective functions utilized by various eminent researchers in the field of DNEP. These objective functions have been classified into five main categories: financial, income related, technical, optimal size & location and social & economic objectives. For original articles on various DNEP [1-80], literature survey has been summarized in tables 1-5.

Financial objectives are the most utilized objective function [1, 2, 4-19, 20-23, 25-33, 35-50, 52-61, 63-76, 78-80] which are categorize into two types: minimization of total expansion cost and maximization of distribution companies (DISCO's) net profit. Income related objectives functions have been separated out from the financial one [14, 49, 75] as these are essentially earnings of DISCO's that can be obtained by selling energy, getting subsidies in lieu of green technologies or by salvage cost.



Concrete DNEP starts with technical objectives, which are the most affected part while doing expansion. These are classified into five types: energy losses minimization [3, 8, 15, 20, 33, 35, 45, 51, 53, 62, 67, 69, 70, 80], voltage stability & profile improvement [3, 13, 34, 45, 47, 51, 62, 67, 70, 80], reliability improvement [2, 6, 7, 21, 36, 69], line loading minimization [24, 77] and optimal power flow (OPF) solution [51]. While doing DNEP, it is obvious that new devices, equipment, switches [76], substations [2, 14] as well as DG and DESS [76] are needed to be installed. Among these, optimal sitting and sizing of DG is second most prominent objective function among all type of classifications. Few researchers have also given concerns of customer's profit and reducing planers workload while doing DNEP. These two concerns have been taken as maximization of social welfare function objective [77] and load forecasting [14].

The rest of the survey is organized into seven sections. These sections are divided mainly on basis of objective function classification. Section two is dedicated to classification of objective functions. A brief review on objective functions related to financial matter is mentioned in section three. Income related objectives are introduced and discussed in section four. Objective functions related to technical matter are outlines and classifies in section five. Optimal size and location objectives functions for DG, DESS, substation etc. are summarized in section six. A few researchers have also given attention to social and economic objectives which is presented in section seven. Finally section eight concludes the article along with short comings and future prospects.

2. Classification of objective functions

Depending upon aim of DNEP, objective functions are decided. The DNEP can be framed as a single-objective or a multi-objective expansion planning problem. Various objective functions considered by numerous renowned researchers have been taken in analogical order which depicts changing trends in selection of objective function. From the analysis of various objective functions, their classification and hierarchical distribution is performed and is summarized in Table 1.

According to review performed on various articles, it has been deduced that most prominent objective is to minimize total expansion cost. Rests are in total equivalent to this single objective alone. If a researcher has considered the problem as mono-objective, a single most optimal solution can be obtained but in case of multi objective problem, the objective become conflicting in it selves which have normally set of solutions rather than a unique and single solution [76]. Customarily multi-objective DNEP optimization technical hitches require minimizing or maximizing objective function ($f(x)$) as

$$f_{min}(x) = (f_1(x), f_2(x), \dots, f_n(x)) \quad (1)$$

$$f'_{max}(x) = (f'_1(x), f'_2(x), \dots, f'_m(x)) \quad (2)$$

s.t. various technical, economic, geographical etc. constraints. Discussion on constraints is not included in this review article.

Table 1. Objective functions classification of DNEP

S. No.	Objective functions	Reviewed articles	No. of research work reviewed*	%age of research work reviewed
Financial objectives				
1	Minimization of total expansion cost	[1,2,4-19,21-23,25-33,35-50,52-61,63-76,78-80]	73	91.25%
2	Maximization of net profit of DISCO's	[20,75]	2	02.50%
Income related objectives				
3	Selling energy	[14,49,75]	3	03.75%
4	Award subsidies	[49]	1	01.25%
5	Salvage cost	[49,52]	2	02.50%
Technical objectives				
6	Minimization of energy losses	[3,8,15,20,33,35,45,51,53,62,67,69,70,80]	14	17.50%
7	Voltage stability & profile improvement	[3,13,34,45,47,51,62,67,70,80]	10	12.50%
8	Reliability improvement	[2,6,7,21,36,69]	6	07.50%
9	Optimal power flow (OPF) solution	[24,77]	2	02.50%
10	Minimize line loading	[51]	1	01.25%
Optimal size and location (OSL) objectives				
11	OSL of DG	[10,11,16,22-24,26,27,32,33,36,37,39,40,42,45,46,53,62,65-68,71,74,75,77,78,80]	29	36.25%
12	OSL of substation	[2,14,21]	3	03.75%
13	OSL of DESS	[76]	1	01.25%
14	OSL of switching devices	[76]	1	01.25%
Social and economic objectives				
15	Maximization of social welfare function	[77]	1	01.25%
16	Load forecasting	[14]	1	01.25%

* The numeric values of number of papers and the percentage calculated on the basis of total papers reviewed in the references

**is done by cost reduction method also.

3. Financial objective functions

Objective functions related to finance are mainly of two types: primarily related to expenditure for expansion and secondly concerning profit for distribution companies (DISCO's).

3.1 Total expansion cost

DNEP models aims for finding the most cost-effective solution through minimizing investment cost in various equipment's, in their operation and maintenance and can be mentioned as exhaustive objective. Total expansion cost is highest taken objective function (with 91.3% reviewed work) (from Table 1). Besides equipment's concern, there are expenditure in energy losses, poor reliability, power imported, punishment for pollution and many more miscellaneous objective functions related to investment such as reinforcement costs, interest rate, cost of violating bus voltage limits and line loading limits, load curtailment cost, start-up costs (from either a cold stop or a hot stop), DSM incentive cost etc (Table 2).

Table 2. Various objective functions of DNEP related to expansion cost

S. No.	Objective function related to expansion cost	Reviewed articles	No. of research work reviewed	%age of research work reviewed
1	Installation	[1,2,4-19,21-23,25-33,35-49,52-61,63-76,78-80]	72	90.00%
2	Operation	[4,5,9-11,14-16,18,21,22,25,27,33,36-41,43-45,47-49,52,54, 56,58,60,61,63,66-68,71,74,75,78-80]	42	52.50%
3	Energy losses	[8,9,12,15,17,18,21,23,26-33,35,37-41,43,44,46, 48,49,52-58,61,64-66,68,69,73]	41	51.30%
4	Maintenance	[8-11,16,18,21,27,31-33,37-40,49,52,54,60,61,64,66,68,69, 71,72,75,80]	28	35.00%
5	Reliability index	[6,7,10,11,17,22,23,26-28,30-32,38-40,43,45,49,52,54,56,61, 63,64,68,72,73]	28	35.00%
6	Power imported	[16,23,25-27,33,43,49,50,56,59-61,66-68,71,72, 74,75,78, 79]	22	27.50%
7	Carbon punishment	[25,27,33,35,56,71]	06	07.50%
8	Miscellaneous	[6-11,17,23,26,28,30-32,35,38-40,43,48,52,58,61, 64,66,69, 72,73]	27	33.80%

Table 3. Various objective functions of DNEP related to installation cost

S. No.	Objective function related to inst. cost	Reviewed articles	No. of research work reviewed	%age of research work reviewed
1.	DG	[13,16,22,23,25-27,32,33,36,39,40,42,45,47,49,53,54,56, 58-61, 65-68,70,71,73-75,78,80]	34	42.50%
2.	Substations	[2,6,7,13-15,17,18,21,22,30,31,36-38,41,42,44-46,48,52,54-56, 58,59,61,65,66,67,69,70,74]	34	42.50%
3.	Distribution cable	[1,2,4-9,12,14,16-19,23,29,35,37,38,41,44,45,48,55,58,65,66,69, 72,78]	30	37.50%
4.	Feeders	[2,6,7,13,15,21,22,28,30,37,38,42,46,54,56, 59,61,64,67,68,70,74]	22	27.50%
5.	Transformers	[1,6,7,12,17,29,54,61,64,67]	10	12.50%
6.	Sectionalizing switches	[21,23,28,30,37,64,76]	07	08.75%
7.	DESS	[63,66,72,75,76,78,79]	07	08.75%
8.	Capacitors bank	[48,57,65,73]	04	05.00%
9.	New load points	[43,52]	02	02.50%
10.	Voltage regulators	[57,65]	02	02.50%
11.	Circuit breakers	[28]	01	01.25%
12.	Fuel cells	[73]	01	01.25%

- 3.1.1** *Installation cost.* This objective function is supreme prominent one among all expansion cost objective functions. The survey results are shown in Table 3 from which it can be concluded that 90% literature reviewed uses installation cost as one of the objective functions. Installation mainly includes those equipments which are back bone of distribution system and comprises of feeders, substations, transformers, reactive power sources (capacitor banks, inductors etc.), sectionalizing switches, protective devices (voltage regulators, circuit breakers etc.), fuel cells, distribution cable/line/conductors/branch, DG, DESS, new load points.
- 3.1.2** *Operation cost.* After installation of various devices, most of them also required financial assistance for their smooth operation and long life. The operation cost of electrical equipment's and devices have been considered in various articles which are summarize in Table 4. From Table 2 it can be concluded that 52.5% literature reviewed uses operation cost as objective function. These equipment and devices are: DG, substations, feeders, new branches, DESS, transformers and fuel cells.
- 3.1.3** *Maintenance cost.* All new and old equipment require maintenance whose cost is to be included in main objective function of DNEP and 35% literature reviewed uses maintenance cost as objective function.
- 3.1.4** *Energy losses cost.* In most of the cases, the losses cost is considered as energy losses and 51.3% literature reviewed uses energy loss cost as objective function.
- 3.1.5** *Reliability index.* 35% literature reviewed uses poor reliability cost as objective function. This function has also been termed as: costs of interruptions [17], reliability cost [22], non-distributed energy costs [23], cost for system reliability [27], customer interruption cost [28], energy not delivered cost [31], interruption cost [38], energy not served penalty cost [39,40], cost of energy not distributed (END) [45], energy not supplied cost [49], unserved energy cost [54], penalties cost for undelivered services [64], cost of load not served [72], expected customer outage cost (ECOST) [73] in various articles.
- 3.1.6** *Cost of power imported.* Power has been imported from big producers in case: the distribution network is operated by private players or there is increase in power demand and DISCOs are not interested in setting up DG or DESS options. 27.5% literature reviewed uses cost of power purchased as objective function. Depending upon the requirement, DISCOs can purchase active and reactive powers separately.
- 3.1.7** *Carbon punishment.* Pollution or carbon punishment is also termed as carbon emission cost or environmental compensation costs [33] or CO₂ emission tax [71]. 7.5% literature reviewed (which has considered non-renewable resources-based DG) uses carbon punishment cost as objective function.
- 3.1.8** *Miscellaneous.* A few eminent researchers have considered some investment cost other than described above. Its summarized literature is given in Table 2 from which it can be concluded that 33.8% literature reviewed uses miscellaneous costs as objective function. Summarize in Table 5, these costs are reinforcement costs [10-12, 23, 25, 42, 43, 48, 49, 52, 57, 60, 64, 68, 71, 72] or re-conductoring or reinstallation cost, which is mainly done to strengthen the existing structure and is utilized in 20% of surveyed literature. The cost incurred in paying interest rate against the loan amount taken for expansion have been considered by [8, 9, 28, 48, 69] and is utilized in 6.25% of surveyed literature. Cost of violating limits (violating the bus voltage and line loading limits) [39, 40, 43] and is utilized in 3.75 % of surveyed literature, load (or DG) curtailment cost [35, 58] and is utilized in 2.5% of surveyed literature, start-up costs (from either a cold stop or a hot stop) [43] and is utilized in 1.25% of surveyed literature and demand side management (DSM) incentive cost [66] and is utilized in 1.25% of surveyed literature.

Table 4. Various objective functions of DNEP related to operation cost

S. No.	Objective function related to operation cost	Reviewed articles	No. of research work reviewed*	%age of research work reviewed
1.	DG	[16,22,25,27,33,36,39,40,43,45,47, 49,54,56,58, 60,61, 66-68,71,74,75, 78,80]	25	31.25%
2.	Substations	[17,18,21,22,36-38,41,44,45,48,52, 61,64,65]	15	18.75%
3.	Feeders	[15,21,22,37,38, 54,61,64]	8	10.00%
4.	New branches	[9,17,37,38,41,45,69]	7	08.75%
5.	DESS	[63,66,72,75]	4	05.00%
6.	Transformers	[15,17,61]	3	03.75%
7.	Fuel Cells	[73]	1	01.25%

Table 5. Various objective functions of DNEP related to miscellaneous cost

S. No.	Miscellaneous objective function	Reviewed articles	No. of research work reviewed*	%age of research work reviewed
1.	Reinforcement costs	[10-12,23,25,42,43, 48,49,52,57, 60,64,68,71,72]	16	20.00%
2.	Interest rate	[8,9,28,48,69]	5	06.25%
3.	Cost of violating limits	[39,40,43]	3	03.75%
4.	Load/DG curtailment cost	[35,58]	2	02.50%
5.	Start-up costs	[43]	1	01.25%
6.	DSM incentive cost	[66]	1	01.25%

3.2 DISCO's net profit maximization

It has been observed at some occasions that DISCOs are considered as sole owner of DG units whereas sometimes DG units are the investment made by external investors. For both these cases the objective function for maximizing net profit of DISCO's are different. In case DISCO does not expand the distribution system and purchase power from private investors, the objective function will be described as DISCO's profit index function ($DNP_{max,1}$) in which all terms are considered per year. In second case, DISCOs are considered as sole owner of DG units [75]. Both active and reactive powers are included in DNEP and DGs & DESSs are optimally scheduled to escalate profit of DISCO.

4. Income related objectives

The earnings and savings of DISCO's are considered in income related objectives. They are mainly of three types: selling energy, award of subsidies, salvage cost.

4.1 Selling energy

This objective is related to income from electricity sales, which in turn depends upon the tariffs according to type of customers. [14] has managed this objective with the help of geographic information system (GIS) based production management system (PMS) software. [49, 75] more precisely explain this objective by separating out active (P_r) and reactive (Q_r) power sale.

4.2 Award subsidies

DISCO's can be encouraged to use cleaner technologies, and to reduce carbon emission. In lieu of green technologies utilization for power production, DISCO's can be awarded subsidies [49] which will add to their income.

4.3 Salvage cost

[49] has also introduced salvage cost of DG units obtained at the end of planning period. This cost function can also be considered for other equipment.

5. Technical objectives

While doing DNEP, the study reveals that investment part has become more prominent than technical issues. Still without fulfilling technical objectives, DNEP can't be achieved. These are mainly energy losses minimization, voltage stability & profile improvement, reliability improvement, minimization of line loading and optimal power flow (OPF) solution.

5.1 Energy losses minimization

Energy losses minimization is the most utilized technical function (17.5%). Minimization of energy losses is also done by cost reduction method in some reviewed articles.

5.2 Voltage stability & profile improvement

Most of the researchers have maintained voltage stability by taking this objective as constraint. A few have taken it as objective function. The second most considered technical objective (12.5%), voltage stability & profile improvement is evaluated mainly by determining voltage stability index (VSI_{WN}) of whole distribution network [80].

5.3 Reliability improvement

Just like energy losses minimization objective, reliability improvement is also done by considering it as financial objective by many researchers. Reliability improvement (7.5%) is measured with the help of reliability index factor which is acknowledged by many names in available text [2, 6, 7, 21, 36, 69]. Most of the researchers have considered reliability as one of the main objective terms but, in few reviewed articles, reliability has been considered as a constraint instead of objective function. Lowest RI factor shows better system reliability.

5.4 Minimize line loading

While doing DNEP with placement of reactive power sources and DG, overloading of few lines in network system occurs due to their incongruous engagement [51]. To determine intensity of line loading, indexing of line loading (LLI_{min}) is formulated w.r.t. its maximum power carrying capacity.

5.5 Optimal power flow (OPF) solution

Many articles encountered which are dedicated to advance and hybrid OPF methods for distribution networks. They are omitted because they are not dedicated to DNEP. Only few (2.5%) are found to be engaged in DNEP with also providing OPF solution [24, 77].

6. Optimal size and location (OSL) objectives

While doing DNEP, it is obvious that new devices, equipment, substations as well as DG and DESS are needed to be installed. Their optimal size and location determination is also important objectives which are taken by many researchers and are described below.

6.1 OSL of DG

After total expansion cost minimization objective function, OSL of DG objective is found to be second most employed objective function (37.5%) which is decided with the help of penetration capacity of DG.

6.2 OSL of substation

This objective function has been detected in few reviewed articles [2, 14, 21] and has been fulfilled with the help of software, product management system (PMS) which operates and provides results on the basis of practical geographical information system (GIS). The size has been decided by present demand and future uncertainty whereas location can be determined mathematically. To distinguish physical

distance and electrical distance between load center and substation locations, a correction factor with statistical sampling of prevailing low voltage feeders is obtained. This correction factor is termed as K.

6.3 OSL of DESS

[76] has decided OSL of DESS on the basis of reliability improvement factor. The reliability indexes are associated with momentary interruptions in case of determining OSL of battery banks. Momentary interruptions have been defined and evaluated with the help of MAIFI (Momentary Average Interruption Frequency Index).

6.4 OSL of switching devices

Similar to determination of OSL of DESS, [76] has determine the OSL of switching devices on the basis of long interruptions of power supply. Long interruptions have been defined and evaluated with the help of SAIDI (System Average Interruption Duration Index).

7. Social and economic objectives

While undertaking DNEP, a few researchers have also consider concerns of customer's profit and reducing planers workload. These two concerns have been taken as maximization of social welfare function objective and load forecasting.

7.1 Maximization of social welfare function

The social welfare function is a real-valued and differentiable term belongs to welfare economics. When applied to power systems, it can be defined as difference of end consumer's benefit and total cost of power produced [77] (both active and reactive power production) of DISCOs.

7.2 Load forecasting

[14] has utilize a decision-making support system software named as geographic information system (GIS) based production management system (PMS) which has been implemented on a practical system. Along with other objective fulfillment, this software also reduces the planner workload by doing load forecasting.

8. Conclusion

The sequence of this review study has considered a wide-ranging review of objective functions to be fulfilled while doing DNEP and found the changing trend of DNEP initially with reinforcement, then with new substations, conductoring, and then with penetration of DG in distribution network converting them into micro grids, then came utilization of DESS and last but not least utilization of fuel cells. Each article has utilized various and limited objectives to solve DNEP problems. The reviewed work shows that for achieving similar intentions of DNEP, different objective functions have been considered by various eminent researchers. A few objectives are there such as reliability improvement, energy losses etc. which have been considered by a few researchers as financial objective functions whereas by few as non-financial objective functions. This confusion should be removed and there inclusion must be done in single type of objective function. With increased penetration of green and proficient supply sources, the objectives of DNEP have moved from low cost solutions to somewhat expansive solutions. This review article aims to address this gap so that complete DNEP can be achieved with perfection. The suggested objective functions need to be enriched and articulated for application to a DNEP with multiple types of objective functions. It is also found that due to different regulations of each country, a few objectives have been taken by very less researchers such as carbon penalty, DCM incentive cost etc. these objective functions are prominent one and must be included by various DISCOs in general practice. It is anticipated that this review will be beneficial to the operators, engineers, manufacturers, scholars involved with DNEP for developing new strategies.

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