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Considering cost and reliability in electrical and thermal distribution networks reinforcement planning

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ABSTRACT

The concurrent expansion of both electrical and thermal energy distribution systems has been addressed in this paper. The EEP (energy expansion planning) is formulated as a multi-objective optimization problem which is subjected to reduced I&O (investment and operation) costs as well as to improve the system reliability. As a result, apart from the total costs, the reliability measures of SAIFI (system average interruption frequency index), SAIDI (system average interruption duration index), and AENS (average energy not supplied) have been included in the objective function. Moreover the ability of the system reconfiguration in enhancing the system reliability has also been employed as a failure rate reduction strategy. The proposed EEP problem tries to minimize the objective function with respect to system constraints by means of rewiring, network reconfiguration, installation of new lines and also new electrical/thermal generating units. Such complex large-scale optimization problem mandates the utilization of an effective optimization tool to find the global optimum solution. The well-known TLO (Teaching Learning Optimization) is the core of exploited optimization method, ITLO (Improved TLO), in solving the proposed static EEP problem. In order to evaluate the proposed algorithm, two modified test systems are used as case studies.

1. Introduction

The increasing rate of energy demand has presented many technical and economic challenges to energy distribution grids. The close direct connection and interaction of the energy distribution system to the end users and customers has imposed special concern and high investment costs to the utility. Consequently, appropriate considerations should be undertaken in the energy expansion planning to pledge the satisfactoriness of the installed system. The development of the energy distribution system should then be scrutinized thoroughly to guarantee a secure, economical and reliable operation of the system. As a result, the system operator must be equipped with effective planning tools to assess different aspects of proposed decision alternatives. EEP can be solved in only one single stage of time period or in segregated multiple stages of the planning horizon based on the technical considerations. The first planning method is categorized as static EEP and the second one is grouped in dynamic or multistage EEP category.

In the previous papers, efforts have been focused on the expansion optimization of systems employing only one form of energy, in particular for electricity, natural gas, and district heating networks [1–6] and also objectives such as minimizing cost and loss as well as voltage profile enhancement and other functions [7–9]. The techniques used are diverse but may be classified as classic optimization [10–13], heuristic methods [14,15], and intelligent systems [16–19]. The joint modeling of EEP has recently been a subject of interest, so that several researches have been conducted in order to investigate the concurrent planning of systems with various energy systems such as natural gas and electricity [20–23].

Despite the great variety of methods for traditional energy system expansion planning, the main deficiencies with all of the aforementioned and previous works are as follow:

Abbreviations: EEP, Energy Expansion Planning; TLO, Teaching Learning Optimization; CHP, Combined Heat and Power; DFR, Distribution Feeder Reconfiguration; MOP, Multi-objective Optimization Problem; SAIFI, System Average Interruption Frequency Index; SAIDI, System Average Interruption Duration Index; AENS, Average Energy Not Supplied.

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Nomenclature

Symbol and description

$C_{Investment}$	Investment Cost (IC)
$C_{Operation}$	Operation Cost (OC)
N_P	Number of power units
N_C	Number of CHP units
N_h	Number of heat units
N_L	Number of lines
N_{Cus}	Total number of customers served
λ_i	Average failure rate of the ith component
ρ_i	Current compensation coefficient
$\lvert I_i \rvert$	Absolute current amplitude of the ith feeder
$\lvert I^i_{new} \rvert$	Current magnitude of ith branch after reconfiguration
$\lvert I^i_{old} \rvert$	Current magnitude of ith branch before reconfiguration
U_i	Annual outage time of the ith component
δ_i	Angle of the voltage at the ith bus
Y_{ij}	Amplitude of admittance between the ith and jth buses
θ_{ij}	Angle of branch between the ith and jth buses
$C_i^{Elec.}$	Cost of a power unit that can be added at the ith bus
C_i^{CHP}	Cost of a CHP unit that can be added at the ith bus
$C_i^{Ther.}$	Cost of a heat unit that can be added at the ith bus
C^{line}	Cost of a circuit that can be added or upgraded between ith and jth bus
N_{FL}	The number of the main loops
N_{br}	The number of branches
N_{buses}	The number of buses
T	Planning horizon time
$P^{Line}_{ij,min}$	Minimum active power between ith and jth bus
P^{Line}_{ij}	Expected value of active power between ith and jth bus
$P^{Line}_{ij,max}$	Maximum active power between ith and jth bus
P^h_j	Electric power equivalent thermal power at the jth bus
P_i^P	Net injected active power of the power unit at the ith bus
P_j^C	Net injected active power of the CHP unit at the jth bus
P_d	Electric power demand of system
H_j^C	Injected heat of the CHP unit at the ith bus
H_k^h	Injected heat of the heat unit at the kth bus
H_d	Thermal demand of the system
H_k^{hmin}	Minimum thermal outputs of the kth unit
H_k^{hmax}	Maximum thermal outputs of the kth unit
$P_j^{Cmin}(H_j^C)$	Minimum power limit of CHP unit j which are functions of generated heat (H_j^C)
$P_j^{Cmax}(H_j^C)$	Maximum power limit of CHP unit j which are functions of generated heat (H_j^C)
$H_j^{Cmin}(P_j^C)$	Minimum heat generation which are functions of generated power (P_j^C)
$H_j^{Cmax}(P_j^C)$	Maximum heat generation which are functions of generated power (P_j^C)
V_{max}	Maximum voltage magnitude
V_{min}	Minimum voltage magnitude
$f_i(X)$	The ith objective function
$g_i(X)$	ith inequality constraint of MOP
$h_i(X)$	ith equality constraint of MOP
N_{eq}, N_{ueq}	Number of equality and inequality constraints
f_i^{min}/f_i^{max}	Lowest/Highest limit of ith objective function
M_D	Mean value of the population column-wise
m_i	Mean value of the ith element column-wise
$\gamma_1,\ldots,\gamma_4$	Random numbers in the range (0, 1)
N_{pop}	The student population size in TLO algorithm
P_i^{pmin}	Minimum injected active power of the power unit at the ith bus
P_i^{pmax}	Maximum injected active power of the power unit at the ith bus
K_F	Random integer which equals 1 or 2
Tie_i	The ith tie switch
Swi	The ith sectionalizing switch

(i) the lack of a comprehensive model for concurrent expansion planning of energy networks with both forms of thermal and electrical energy systems is recognized.

(ii) Moreover, up to the authors' knowledge, the previous research does not report the reconfiguration and reliability effects in their models.

Such a comprehensive model is addressed extensively in this study. The proposed deterministic EEP employs a model based on static planning horizon. The decision maker has a variety of choices such as determination of the capacity, installation and/or reinforcement of power units, heat units and/or the CHP (combined heat and power) units, and also the addition or rewiring of distribution feeders to provide energy to the future energy demand in an optimum manner.

Distribution system is the source of numerous unavailability of supply to the customers since it is the linking segment of the utility system which interacts with the end users directly. The many influences of considering the reliability of distribution systems offered to the planner and system operator are counted in the failure statistics mentioned in Refs. [24]; the influences which are achieved by utilizing the most out of existing power sources and improving reliability indices. Upgrading the system from the viewpoint of reliability concerns can be implemented by various means such as improving system protection by installing devices, reclosing and switching as well as automation and system reconfiguration. Rapid reaction to faults and decreasing the repair process time may be accomplished by fast fault prediction techniques to prevent contingencies and fast experienced crew to expedite the repair progression [25–27].

Automation can also be implemented through various strategies such as DFR (Distribution Feeder Reconfiguration) to enhance system reliability [28]. Despite the many benefits that DFR suggests to increase reliability at no cost, it has to some extent been ignored recently. Through DFR the existing tie switches and sectionalizing switches in the system will be closed and opened respectively in contrast to their normal condition. The core idea behind DFR is to change the topology of the network so that the desired objectives are achieved with respect to the constraints and limitations. One may account the preservation of the radial topology in the system as the most important constraint in DFR due to simple inexpensive design it provide the network, as well as better protection [29].

Altogether, there are four objectives considered in the present study which pledge the minimized simultaneous expansion cost of