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# Coordinated transmission substations and sub-transmission networks expansion planning incorporating distributed generation

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#### ABSTRACT

Transmission and distribution systems are linked to each other through the sub-transmission network, where it receives the electric energy from the transmission network at extra high-voltage levels, and delivers it to the distribution network at low-voltage level. Hence, if the sub-transmission network is designed in an optimal manner, it will supply the loads of distribution system adequately on one hand, and this leads to an efficient design of transmission network on the other hand. As the design optimality of transmission, sub-transmission, and distribution systems are dependent on each other, the best result for the network expansion is achieved when these three networks are considered coordinately. Since implementing the coordinated design of transmission, sub-transmission, and distribution has been developed for the coordinated expansion planning of transmission substations, sub-transmission network, and distribution system. In addition, to obtain more efficient results for the network expansion (DG) units are considered in the problem. The proposed approach is implemented on a real network of Zanjan Regional Electrical Company, and the results are discussed. The obtained results demonstrate the effectiveness of the conducted planning method.

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#### 1. Introduction

Power system expansion planning, as a major part of the power system studies, determines the characteristics of network equipment to be installed or upgraded in order to reliably supply the loads in an economical manner. The expansion planning study is performed in three levels of generation, transmission, and distribution systems. Sub-transmission system is an intermediate system between the transmission and distribution networks that receives the electric energy from the transmission system at extra highvoltage (EHV) levels, and delivers it to the distribution network at low-voltage (LV) levels [1]. In this regard, the adequate design and operation of sub-transmission system will lead to an efficient design of transmission network on one hand and the adequacy of power delivery to the distribution loads on the other hand [1,2]. Different models have been presented in the literature for the optimal design of HV/MV sub-transmission substations [3-7]. In Ref. [4], a constructive heuristic algorithm (CHA) has been used to

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http://dx.doi.org/10.1016/j.energy.2016.12.010 0360-5442/© 2016 Published by Elsevier Ltd. solve the power distribution system expansion planning problem. By employing a local improvement phase and a branching technique in CHA, the algorithm seeks for the optimal location and capacity of MV feeders and HV/MV substations. The objective function to be minimized includes the system operating costs and cost of constructing feeders and substations by taking into account the power flow, voltage drop, and radial configuration as the problem constraints. Authors in Ref. [5] proposed a model for solving the multistage planning problem of a distribution system. The objective function is the net present value of the investment cost to add, reinforce, or replace the feeders and substations, and also, the losses cost, and operation and maintenance costs. The nonlinear objective function of the problem is approximated by a piecewise linear function, resulting in a mixed integer linear model that is solved using standard mathematical programming. Moreover, the reliability indices and the related costs are computed for each solution based on the regulation model of Brazil. An approach is proposed in Ref. [6] for the planning of low-voltage distribution systems where the location, number, and capacity of distribution transformers are optimally determined for the sake of improving the system reliability and minimizing the power and energy losses under energy demand growth. The considered objective function is

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$\begin{array}{lll} \lambda_i^{tr} & \mbox{Failure rate of transformer located on sub-transmission} \\ substation i (fail/year) \\ r_i^{tr} & \mbox{Repair time of transformer located on sub-transmission substation i (hr) \\ \lambda_i^{sl} & \mbox{Failure rate of ith sub-transmission line (fail/(km.year r_i^{sl} & \mbox{Repair time of ith sub-transmission line (hr) } \\ \Delta V^{max} & \mbox{Maximum permitted voltage drop (p.u.) } \\ Variables \\ n_i^{tr} & \mbox{Number of transformers installed on ith sub-transmission substation } \\ n_i^{DG} & \mbox{Number of installed DG units on ith sub-transmission substation } \\ LNS_i^{tr} & \mbox{Load not supplied due to the outage of transformer located on sub-transmission substation i (kW) } \\ LNS_i^{sl} & \mbox{Load not supplied due to the outage of ith sub-transmission line (kW) } \\ p_{ij}^{f} & \mbox{Current flowing through the feeder in } ij \mbox{path (A) } \\ p_{ij}^{f} & \mbox{Thermal canacity of feeder } ii (A) \\ \end{array}$	Loss cost (\$/kW)				
substation <i>i</i> (fail/year) $r_i^{tr}$ Repair time of transformer located on sub- transmission substation <i>i</i> (hr) $\lambda_i^{sl}$ Failure rate of <i>i</i> th sub-transmission line (fail/(km.year $r_i^{sl}$ Repair time of <i>i</i> th sub-transmission line (hr) $\Delta V^{max}$ Maximum permitted voltage drop (p.u.) <i>Variables</i> $n_i^{tr}$ Number of transformers installed on <i>i</i> th sub- transmission substation $n_i^{DG}$ Number of installed DG units on <i>i</i> th sub-transmission substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation <i>i</i> (kW) $LNS_i^{sl}$ Load not supplied due to the outage of <i>i</i> th sub- transmission line (kW) $p_{ij}^{f}$ Current flowing through the feeder in <i>ij</i> path (A) $r_{ij}^{sl}$ Chermal capacity of feeder <i>ii</i> (A)	Failure rate of transformer located on sub-transmission				
$r_i^{fr}$ Repair time of transformer located on sub- transmission substation $i$ (hr) $\lambda_i^{sl}$ Failure rate of $i$ th sub-transmission line (fail/(km.year $r_i^{sl}$ $r_i^{sl}$ Repair time of $i$ th sub-transmission line (hr) $\Delta V^{max}$ Maximum permitted voltage drop (p.u.)Variables $n_i^{tr}$ $n_i^{tr}$ Number of transformers installed on $i$ th sub- transmission substation $n_i^{DG}$ Number of installed DG units on $i$ th sub-transmission substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation $i$ (kW) $LNS_i^{sl}$ Load not supplied due to the outage of $i$ th sub- transmission line (kW) $l_{ij}^{sl}$ Current flowing through the feeder in $ij$ path (A) $l_{ij}^{sl}$ Thermal capacity of feeder $ii$ (A)	substation <i>i</i> (fail/year)				
transmission substation i (hr) $\lambda_i^{sl}$ Failure rate of ith sub-transmission line (fail/(km.year $r_i^{sl}$ Repair time of ith sub-transmission line (hr) $\Delta V^{max}$ Maximum permitted voltage drop (p.u.)Variables $n_i^{tr}$ $n_i^{tr}$ Number of transformers installed on ith sub- transmission substation $n_i^{DG}$ Number of installed DG units on ith sub-transmission substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation i (kW) $LNS_i^{sl}$ Load not supplied due to the outage of ith sub- transmission line (kW) $p_{ij}^{sl}$ Current flowing through the feeder in $ij$ path (A) $l_{ij}^{sl}$ Thermal capacity of feeder $ii$ (A)	Repair time of transformer located on sub-				
$\lambda_i^{a^*}$ Failure rate of <i>i</i> th sub-transmission line (fail/(km.year $r_i^{sl}$ Repair time of <i>i</i> th sub-transmission line (hr) $\Delta V^{max}$ Maximum permitted voltage drop (p.u.)Variables $n_i^{tr}$ Number of transformers installed on <i>i</i> th sub-transmission substation $n_i^{DG}$ Number of installed DG units on <i>i</i> th sub-transmission substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation <i>i</i> (kW) $LNS_i^{sl}$ Load not supplied due to the outage of <i>i</i> th sub- transmission line (kW) $INS_i^{sl}$ Current flowing through the feeder in <i>ij</i> path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A)	transmission substation <i>i</i> (hr)				
$r_i^{ii}$ Repair time of ith sub-transmission line (hr) $\Delta V^{max}$ Maximum permitted voltage drop (p.u.)Variables $n_i^{tr}$ $n_i^{tr}$ Number of transformers installed on ith sub- transmission substation $n_i^{DG}$ Number of installed DG units on ith sub-transmissio substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation i (kW) $LNS_i^{sl}$ Load not supplied due to the outage of ith sub- transmission line (kW) $P_{ij}^{sl}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $P_{ij}^{f}$ Thermal capacity of feeder $ii$ (A)	Failure rate of <i>i</i> th sub-transmission line (fail/(km.year))				
$\Delta V^{max}$ Maximum permitted voltage drop (p.u.)Variables $n_i^{tr}$ Number of transformers installed on ith sub- transmission substation $n_i^{DG}$ Number of installed DG units on ith sub-transmissio substationLoad not supplied due to the outage of transformer located on sub-transmission substation i (kW) $LNS_i^{tr}$ Load not supplied due to the outage of ith sub- transmission line (kW) $LNS_i^{sl}$ Load not supplied due to the outage of ith sub- transmission line (kW) $I_{ij}^{sl}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{sl}$ Thermal capacity of feeder $ii$ (A)	Repair time of <i>i</i> th sub-transmission line (hr)				
Variables $n_i^{tr}$ Number of transformers installed on ith sub- transmission substation $n_i^{DG}$ Number of installed DG units on ith sub-transmissio substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation i (kW) $LNS_i^{sl}$ Load not supplied due to the outage of ith sub- transmission line (kW) $P_{ij}^{l}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Thermal capacity of feeder $ii$ (A)	Maximum permitted voltage drop (p.u.)				
$n_i^{tr}$ Number of transformers installed on <i>i</i> th sub- transmission substation $n_i^{DG}$ Number of installed DG units on <i>i</i> th sub-transmission substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation <i>i</i> (kW) $LNS_i^{sl}$ Load not supplied due to the outage of <i>i</i> th sub- transmission line (kW) $LNS_i^{sl}$ Courrent flowing through the feeder in <i>ij</i> path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{sl}$ Thermal capacity of feeder <i>ii</i> (A)	Variables				
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$n_i^{DG}$ Number of installed DG units on ith sub-transmissio substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation i (kW) $LNS_i^{sl}$ Load not supplied due to the outage of ith sub- transmission line (kW) $INS_i^{sl}$ Current flowing through the feeder in ij path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{f}$ Thermal capacity of feeder ii (A)	transmission substation				
substation $LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation $i$ (kW) $LNS_i^{sl}$ Load not supplied due to the outage of $i$ th sub- transmission line (kW) $I_{ij}^{sl}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{sl}$ Thermal capacity of feeder $ii$ (A)	Number of installed DG units on <i>i</i> th sub-transmission				
$LNS_i^{tr}$ Load not supplied due to the outage of transformer located on sub-transmission substation $i$ (kW) $LNS_i^{sl}$ Load not supplied due to the outage of $i$ th sub- transmission line (kW) $I_{ij}^{f}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{f}$ Thermal capacity of feeder $ii$ (A)	substation				
located on sub-transmission substation $i$ (kW) $LNS_i^{sl}$ Load not supplied due to the outage of $i$ th sub- transmission line (kW) $I_{ij}^{f}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{f}$ Thermal capacity of feeder $ii$ (A)	Load not supplied due to the outage of transformer				
$LNS_i^{sl}$ Load not supplied due to the outage of <i>i</i> th sub- transmission line (kW) $I_{ij}^{f}$ Current flowing through the feeder in <i>ij</i> path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $I_{ij}^{f}$ Thermal capacity of feeder <i>ii</i> (A)	located on sub-transmission substation $i$ (kW)				
Image: transmission line (kW)      Image: transmission line (kW) </th <th>Load not supplied due to the outage of <i>i</i>th sub-</th>	Load not supplied due to the outage of <i>i</i> th sub-				
$P_{ij}$ Current flowing through the feeder in $ij$ path (A) $I_{ij}^{sl}$ Current flowing through the sub-transmission line in path (A) $P_{ij}^{f}$ Thermal capacity of feeder <i>ii</i> (A)	transmission line (kW)				
<i>I</i> <sup>si</sup> Current flowing through the sub-transmission line in path (A) <i>I</i> <sup>f</sup> . Thermal capacity of feeder <i>ii</i> (A)	Current flowing through the feeder in <i>y</i> path (A)				
patn (A) I <sup>f</sup> . Thermal capacity of feeder <i>ii</i> (A)	Current flowing through the sub-transmission line in ij				
$k_{i}$ Thermal capacity of feeder <i>ii</i> (A)	path (A)				
ij,max	Thermal capacity of feeder <i>ij</i> (A)				
<i>ij</i> ,max					

composed of investment, maintenance, losses, and reliability cost. It was shown that the appropriate placement of distribution substations leads to considerable reduction of interruption cost. Ref. [7] has proposed a multi-objective mixed-integer non-linear programming (MINLP) model for the planning problem of primary distribution networks in order to minimize the expansion and operation costs of the network as well as the system's reliability cost in contingency events. This study has considered the expansion and operation costs of transformers, lines, and sectionalizing switches, as well as reliability cost as the objective functions to be optimized by a Multi-objective Reactive Tabu Search (MORTS) algorithm. A novel mixed-integer second-order cone programming model is developed in Ref. [8] for the robust multi-stage expansion planning of sub-transmission substations considering the stochastic nature of demand. To take into account the total expected

I <sup>sl</sup>	Thermal capacity of sub-transmission line $ij$ (A)
Piron	No-load power loss of <i>i</i> th sub-transmission substation
1055,1	(kW)
$P_{loss,i}^{cu}$	Load power loss of <i>i</i> th sub-transmission substation
1000,1	(kW)
$S_i^r$	Rated capacity of the transformer located on <i>i</i> th sub-
	transmission substation (kVA)
$S_i$	The power flowing through the transformer located on
ts may	ith sub-transmission substation (kVA)
Sisimux	Thermal capacity of <i>i</i> th transmission substation (kVA)
$\theta_{ij}$	Power factor of load flowing through the feeder if
Function	c.
	S ( Chew) Control for the second in the second interaction of its second in the second interaction of the second interact
$EC_{ts,i}(S_{ts,i})$	$(s_{ts,i}^{i,tw})$ Cost of expanding the capacity of ith existing
	transmission substation from $S_{ts,i}^{old}$ to $S_{ts,i}^{new}$ (\$)
$IC_{ts,i}(S_{ts,i}^{nev})$	<i>v</i> ) Cost of installing new transmission substation <i>i</i> with
,.	the capacity of $S_{ts,i}^{new}$ (\$)
$EC_{ss,i}(S_{ss,i}^{old})$	$I_i^d$ , $S_{ss,i}^{new}$ ) Cost of expanding the capacity of <i>i</i> th existing
	sub-transmission substation from Sold to Snew (\$)
IC : (Snev	(N) Cost of installing new sub-transmission substation i
icss, i css, i	with the capacity of $S^{new}(\$)$
FC-1::(Sole	$\frac{d}{ds} S^{new}$ Cost of expanding the capacity of existing sub-
$2 \circ s_{l,l} \circ s_{l,l}$	$(j, S_{sl}, ij)$ cost of expanding the capacity of ellipsing sub-
	transmission line in ij path from $S_{sl,i}^{out}$ (\$)
$IC_{sl,ij}(S_{sl,ij}^{nev})$	$(j_{j})$ Cost of installing new sub-transmission line $i$ with
	the capacity of <i>S</i> <sup>new</sup> (\$)
$FUC_{ij}(S_{f,i}^{old})$	$(j_i^d, S_{f,ij}^{new})$ Cost of upgrading the capacity of MV feeder
	from $S_{f,ij}^{old}$ to $S_{f,ij}^{new}(\$)$
$FIC_{ij}(S_{f,ij}^{new})$	) Installation cost of new MV feeder in <i>ij</i> path with the
	capacity of $S_{f,ij}^{hew}(\$)$
$IC_{dg,i}(S_{dg})$	(i) Installation cost of DG unit with the capacity of $S_{dg,i}$
	OII III SUD-UTAIISIIIISSIOII SUDSLALIOII (\$)
$EC_{ts,i}(S_{ts,i})$	$(s_{ts,i}^{i,cu})$ Cost of expanding the capacity of ith existing
	transmission substation from $S_{ts,i}^{old}$ to $S_{ts,i}^{new}$ (\$)
$IC_{ts,i}(S_{ts,i}^{nev})$	<i>v</i> ) Cost of installing new transmission substation <i>i</i> with
,	the capacity of $S_{ts,i}^{new}(\$)$
$EC_{ss,i}(S_{ss,i}^{old})$	$(i_i^d, S_{ss,i}^{new})$ Cost of expanding the capacity of <i>i</i> th existing
	sub-transmission substation from <i>S</i> <sup>old</sup> <sub>ss i</sub> (\$)
$IC_{ssi}(S^{nev})$	<i>v</i> ) Cost of installing new sub-transmission substation <i>i</i>
55,1 \ SS,1	with the capacity of $S_{cs}^{new}(\$)$
	<b>x y</b> 33, <i>l</i> <b>x y</b>

expansion planning cost and the robustness probability, a multiobjective formulation has been proposed, and the classical optimization techniques have been used to optimally solve the problem. The solution gives the construction of new substations, reinforcement of existing substations, and service area of each substation. In addition, the Monte Carlo (MC) simulation is carried out in order to evaluate the extent of the problem constraints satisfaction.

Recently, the integration of distributed generation (DG) resources into distribution networks has affected the planning and operation problems of the power system [9]. These small-scale power generating units bring various benefits to power system such as peak cutting, losses reduction, voltage profile improvement, reliability enhancement, and deferring the capacity reinforcement of network equipment [10-13]. Due to potential

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