SIMULTANEOUS OPTIMIZATION OF TIE SWITCHES PLACEMENT AND RESERVE CAPACITY MARGIN OF SUB-TRANSMISSION SUBSTATIONS CONSIDERING THE CONFLICT BETWEEN SHORT-TERM AND LONG-TERM PLANNING

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ABSTRACT

Outage management has a crucial role in improving reliability level of distribution networks, and it is profoundly dependent on the reserve capacity margin of Sub-Transmission (ST) Substations and load transferring capability between them. These factors enable DSOs to restore interrupted load points in out of service areas. In this paper, the connection of reserve capacity in ST substations and load transferring capability, made by tie switches, is studied. The mentioned correlation is addressed via Costumer Interruption Cost (CIC) derived from outage management in primary distribution networks. Then, a mathematical model is developed in which optimal reserve capacity of ST substations and optimal placement of tie switches are determined simultaneously. The resulted optimization model is formulated as a mixed-integer non-linear problem (MINLP), and the genetic algorithm (GA) is used to solve the problem. Finally the effectiveness of the proposed model is evaluated in a test distribution network.

Keywords: *substation planning, reserve capacity, outage management, load transferring capability, tie switch,*

NOMENCLATURE

1) Indices:

i	Index of ST substations.
j	Index of candidate tie points.
b	Index of network branches.
σ	Index of interrupted load points.
n	Index of network nodes.
S	Index of feeder sections.

2) Sets:

Ω	Set of ST substations.
Λ	Set of network branches.
N	Set of network nodes.
κ	Set of control variables.
$Ndlp, b$	Set of interrupted load points due to fault in branch b.

3) Parameters:

n_{ST}	Number of ST substations.
N_T	Number of candidate tie points.
N_b	Number of network branches.
ICT	Installation cost of a tie switch [$/switch].
TCC	Tie line creation cost [$/Km].
l_j	Length of the tie line in candidate tie point j [Km].
λ_b	Failure rate of branch b [fail/year].
r_b	Repair time of branch b [hour].
$\Gamma_{\sigma,b}$	Interruption cost in load point σ during fault in branch b [$/kW].
t	Study period [year].
int_{rt}	Interest rate.
$d_{\sigma,b}$	Demand of load point σ which could not be restored due to failure in branch b [kW].
d_i	Load demand of main transformer in ST substation i [MVA].

4) Variables:

γ_i	Utilization factor of ST substation i.
ψ_j	Presence or absence of tie switch in candidate location j.
$C_{ST,i}$	Total capacity of ST substation i [MVA].
ν^i_{cap}	Capacity of virtual transformer in ST substation i [MVA].
ν^i_{IC}	Installation cost of virtual transformer in ST substation i [$].
MCC	Maneuver creation cost [$].
CIC_b	Customer interruption cost because of failure in branch b [$].
$\tau^i_{L,b}$	Transferred load to ST substation i because of failure in branch b [kW].

INTRODUCTION

Today distribution companies (discos) are in a time of changes and challenges. The main changes come with distribution networks liberalization, modernization, automation, and more efficient utilization of network assets. On the other side, the most important challenge is the increasingly demand of customers for reliability regard to increasingly growth of critical loads such as digital loads. So discos should adapt for the changes in such a way that is in line with challenges and manage their assets inclined to their objective, in top of them network reliability. But there is a conflict between improving the service reliability and controlling of costs. In this emerging environment of changes and challenges, asset management plays a key role. Asset management signifies strategic planning, maintenance, utilization, and operation of a physical resource. In addition, possible time scopes of it contains real time, short term, midterm and long term. From a practical prospective, there are interactions between aforementioned time scopes. Furthermore, it has known that the coordination of asset management strategies in different time scopes has a significant impact in decision making process of a disco. A overall view into the prominent interactions in asset management strategies of distribution networks is given in Fig1.

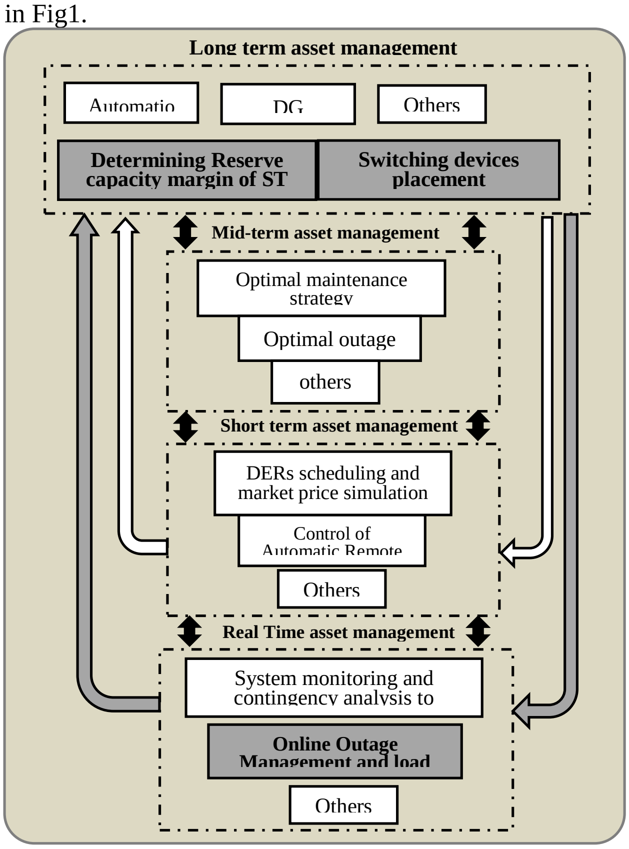

Fig1. The prominent interactions in asset management strategies of the distribution networks

High proportion of customer's interruptions are caused by failures in primary distribution networks [1]. Therefore, it's rational that special attention is paid to improve the reliability of distribution networks in asset management strategies [2]. One of the efficient methods for relieving customer's interruption duration, and also improving reliability, is to provide reserve capacity in ST substations and feeders [3, 4]. With this additional capacity in ST substations and by using the capability of the normally closed and opened switches in primary distribution networks, the DSO can restore out of service areas from other routes [5].

The capability of tie switches for transferring interrupted load points to adjacent ST substations is highly dependent on available reserve capacity. However, in the literatures high share of works concern about placement of tie switches and switching devices in reliability optimization problems regardless of the correlation of tie switches and the reserve capacity of ST substations. In [6], to improve the system reliability with distributed generation under fault conditions, tie-lines placement schemes through graph-based algorithms have been proposed. A micro genetic algorithm, in conjunction with the fuzzy logic, for modelling expert knowledge has been proposed as a solution for optimal placement of sectionalizers and tie switches in [7]. An ant colony optimization method for placement of sectionalizing switches in presence of distributed generation sources by using a fuzzy multi objective approach has been illustrated in [8]. Particle swarm optimization algorithm was developed to determine optimum number and locations of sectionalizers and breakers [9]. In addition, optimum number of switches in a distribution network was obtained by cost analysis on a system, and optimum locations of switches were found by simulated annealing algorithm [10]. As mentioned earlier, studies which relates to reserve capacity margin of ST substations are rare regardless of vast studies in switching devices and load transferring capability. For example, the capacity of a ST substation was empirically analysed based on Single-Contingency Policy (SCP), which assumes that adjacent ST substations should support one another when one of them is unavailable [11-13]. In addition to SCP for the determination of reserve capacity in ST substations, the capacity/load ratio is a popular and useful index in ST substations capacity planning [14-15]. Despite low efficiency and lack of accurate mathematical validation, this approach is practical and has been widely used by engineers. The aforementioned studies do not give the optimal solution because the supply capability of distribution networks could not be efficiently utilized. With regard to growing tendency and satisfying consequences derived from implementation of asset management activities in discos, researchers implement more efficient and accurate approaches for using the supply capabilities of distribution networks in which multiple ST substations are interconnected with normally open switches [16]. Plus, in the previous studies, real time, short-term, midterm, and long-term asset management activities were performed independently whereas coordinated planning in distribution networks reduces overall cost of discos [3]. In this regard, highlighted boxes in **Error! Reference source not found.** indicate the interactions that are considered in the present study. Due to these highlighted boxes, the main contribution of this study is the coordination between long-term decisions, which are the determination of ST substations reserve capacity and tie switches placement, and real-time decisions, which is outage management using tie switches.

The rest of this paper is organized as follows: Section 2 presents the proposed model of the problem. Section 3 discusses formulations and outage management process. Section 4 provides the codification of the problem. Section 5 investigates the results of simulation. Finally in section 6, the conclusion of this study is presented.

DESCRIPTION OF THE PROPOSED MODEL

As mentioned earlier, we propose a model that considers the interaction between real-time and long-term asset management strategies of a disco. In this work, the reserve capacity is modelled as a small individual virtual transformer in a ST substation apart from the capacity of the main transformer which was obtained from the forecasted demand. As discussed in the previous section, the reserve capacity of ST substations depends on the number and location of tie switches. The correlation between the reserve capacity and tie switches is investigated in fault condition through outage management strategies, and finally the optimal decisions about the reserve capacity and tie switches placement are made. The conceptual framework of the proposed model is illustrated for a distribution network with two feeders and m candidate tie switches in Fig 2.

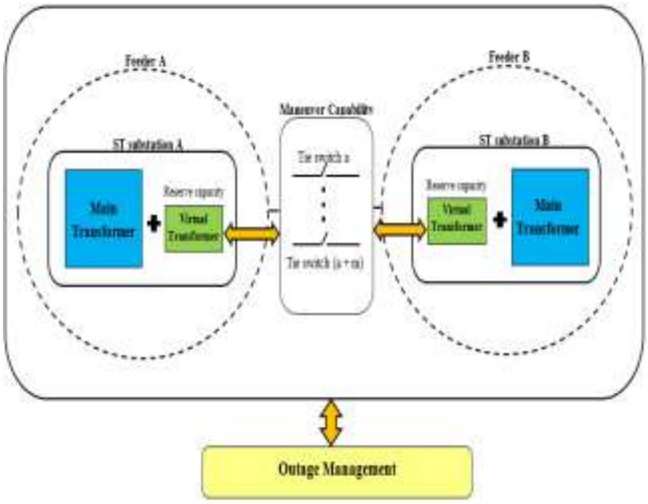

Fig 2. Conceptual framework of the proposed model

PROBLEM FORMULATION

The decision making variables in this paper are considered as an $\kappa : 1\times(n_{ST}+N)$ array, which n_{ST} and N_T represent the number of the ST substations and candidates for tie switches placement respectively. The set of decision making variables of this paper includes continuous variables $\gamma_i : \kappa_i, 1 \le i \le n_{ST}$ and binary variables $\psi_j : \kappa_j, (n_{ST}+1) \le j \le (n_{ST}+N)$. ψ_j denotes the presence or absence (1: presence and 0: absence) of tie switch in candidate location j . Also γ_i represents the utilization factor of ST substation i . With respect to the utilization factor, the total capacity of ST substation i , which consists of the forecasted load demand of ST substation i and the capacity of virtual transformer in it, can be derived as below:

$$C_{ST,i} = \frac{d_i}{\gamma_i}, \quad 1 \le i \le n_{ST} \tag{1}$$

Hence the reserve capacity or the capacity of virtual transformer can be computed based upon Equations (2):

$$v^i_{cap} = d_i \frac{1-\gamma_i}{\gamma_i}, \quad 1 \le i \le n_{ST} \tag{2}$$

The mathematical model resulted from these assumptions makes a Mixed Integer Nonlinear Programming (MINLP) problem. In what presented in following, formulations are described in detail.

Investment cost

The investment cost consist of two parts, the first part relates to the installation cost of the virtual transformer with capacity of v^i_{cap} and can be formulated as:

$$v^i_{IC} = \begin{cases} v_{IC,1} & if, v_{cap,1} \le v^i_{cap} < v_{cap,2} \\ v_{IC,2} & if, v_{cap,2} \le v^i_{cap} < v_{cap,3} \\ \cdot & \cdot \\ \cdot & \cdot \\ v_{IC,m-1} & if, v_{cap,m-1} \le v^i_{cap} \le v_{cap,m} \end{cases} \tag{3}$$

The second part of the investment cost relates to Maneuver Creation Cost (MCC) which can be formulated as:

$$MCC = \sum_{j=1}^{N} \psi_j (ICT + l_j TCC) \tag{4}$$

Reliability cost

For computing Customer Interruption Cost (CIC) after fault creation in each branch, interrupted load points are founded, then load restoration is done. In load restoration with considering interrupted load points and the set of available tie points all network configurations which can restore these load points are examined. If sum of the interrupted load points connected to ST substation i is higher than v^i_{cap} , a load point is disconnected from end of the interrupted feeder. This procedure is repeated until non-delivered power is equal or lower than the capacity of virtual transformer and then forward-backward sweep load flow is implemented to check the voltage and current constraints in the new topology. If there is no constraints violation in the new topology, the loads are restored, otherwise a load point is disconnected from end of interrupted feeder and added to CIC. Customer Interruption Cost during fault in branch b of the network can be obtained from (5) [3].It should be noted that the switching time is negligible.

$$CIC_b = (\lambda_b \sum_{\sigma=1}^{Ndlp,b} d_{\sigma,b}\Gamma_{\sigma,b})(1-\text{int}_{rt})^{t-1} \quad (5)$$

Objective function

The objective function of the proposed MINLP problem is to minimize the total cost from the viewpoint of a distribution company, therefore the resulting optimization problem is

$$\min_{\kappa} \left\{ \sum_{i=1}^{n_{ST}} \nu^i{}_{IC} + \sum_{b=1}^{N_b} CIC_b + \sum_{j=1}^{N} \psi_j (ICT + 1_j TCC) \right\} \quad (6)$$

subject to

A. Utilization factor

$$0 \le \gamma_i \le 1, \forall i \in \Omega \quad (7)$$

B. Load transferring constraint during load restoration because of fault in branch b :

$$\tau^i{}_{L,b} \le \nu^i{}_{cap}, \forall i \in \Omega \quad (8)$$

C. Voltage and current constraints after load restoration:

$$V_{\min} \le V_n \le V_{\max}, \forall n \in N \quad (9)$$

$$|I_b| \le I_{\max}, \forall b \in \Lambda \quad (10)$$

CODIFICATION

The proposed optimization problem is a MINLP problem which is solved through GA. The coding strategy of this paper is shown in **Error! Reference source not found.**, in which the proposed chromosome is composed of two strings. The first and second strings represent the utilization factor of each ST substation and tie points allocation, respectively. In the string which represents the utilization factors of ST substations, each gene contains a value between 0 and 1, and in the string representing tie points allocation each gene contains a binary value. This binary coding characterizes the candidate locations for tie switches installation in the network. The values 1 and 0 in gene N represent “existing” and “not existing” of a tie point in the candidate location N .

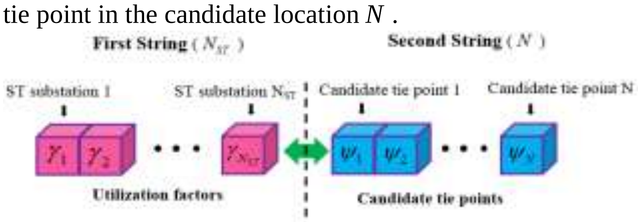

Fig 3. Implemented codification scheme

NUMERICAL ANALYSIS

In this section, the proposed model for coordinate determining of the optimal reserve capacity of ST substations and the placement of tie switches is investigated. The proposed model is applied to a typical 20-kV urban distribution network (Fig 4). There are five 63/20 kV ST substations and 82 MV/LV distribution substations in the network. Service area of each ST substation is separated by automatic normally open switches. In addition, there are automatic normally close switches in each section between two distribution substations, and in order to avoid complication of the network diagram, these switches are not depicted in Fig 4. In this test case, the designer engineer considers 6 candidate tie points. Also, the input parameters are shown in Table 1, and the interruption cost for all load points including residential, commercial, and industrial are calculated based on Customer Damage Function (CDF) in [17].

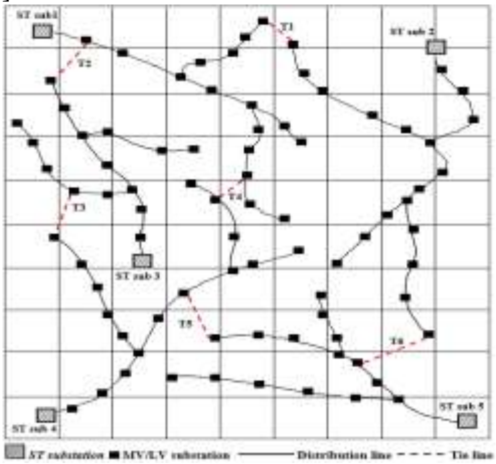

Fig 4. Test case

Table 1. Input parameters

TECHNICAL AND ECONOMICAL INFORMATION		
Parameter	Unit	Value
t	*year*	10
ν_{IC}	$\$/MVA$	20000
ICT	\$/switch	5000
TCC	$\$/km$	19000

Case 1 is a base case for assessing the overall network reliability status and how it is crucial to establish tie points in the network. As mentioned, in Case 1 no tie point is available in the network for load restoration. So, as we expected, the utilization factors of the ST substations derived from the model is equally 1. It means that there would be no reserve capacity in the network to restore the interrupted load points in emergency conditions.

Case2 is dedicated to the main idea of this paper which is about coordinated optimization of tie points placement and the reserve margin of ST substations. In Table 2 the optimal tie points for the proposed network, with regard to the interaction of the reserve margin and tie points, are found, which are T1, T3, T4, and T5. Among the ST substations, ST substation 4 has the maximum number of tie points and the maximum reserve capacity interpreting the significant CIC of feeders connected to the ST substation 4 through the tie points. As shown in **Error! Reference source not found.**, no reserve capacity is allocated to ST substation 2, however this ST substation is connected through T1 to the ST substation 1. This observation shows that if any fault occurs in feeder 1, the interrupted load points could not transfer to ST substation 2, and the interrupted load points are restored through T4 from the ST substation 4. Then, the motivation of the existence of T1 is only for restoration of the interrupted load points in feeder 2 under fault condition; in other word, ST substation 1 is a backup for ST substation 2, while the ST substation 2 is not a backup for it.

Table 2. Results of case 2

ST sub.	Demand (MVA)	Utilization factor(opt.)	Total capacity(MVA)	Reserve (MVA)	Linked Tie points
1	3.25	0.62	5.24	1.99	T1,T4
2	3.57	1	3.57	0	T1
3	2.95	0.81	3.64	0.69	T3
4	3.35	0.62	5.4	2.05	T3,T4,T5
5	3.85	0.86	4.47	0.62	T5

A comparison is made between the case 2 and case1 (Fig 5), which is assumed there is no tie point in the network. In case 2 leading to optimal solution, a remarkable plunge is observed in CIC and therefore in the total cost, because of the tie points which are placed with regarding to the connection of load transferring capability and the reserve capacity margin of ST substation.

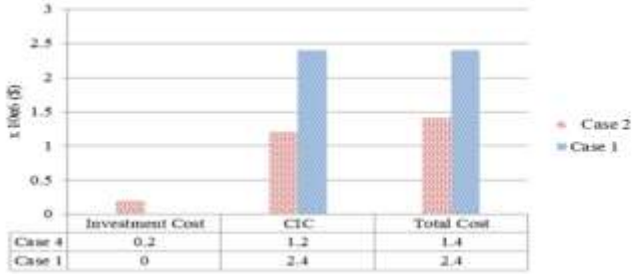

Fig 5. Comparison between case 1 and 2

CONCLUSION

This paper focuses on the correlation of the reserve capacity margin of ST substations and tie points placement, and based on this correlation it proposes a model for coordinated optimization of the reserve capacity in ST substations and network tie points. The high value of CIC in the first case reveals the adverse consequence of the lack of tie points in the network. It is shown that a small investment in tie points creation and the reserve capacity makes a decisive plunge in CIC, and the optimal solution is obtained by trade-off between CIC and investment cost.

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