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Optimal capacity planning of substation transformers by demand response combined with network automation

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ABSTRACT

The inclusion of smart grid features such as demand response (DR) and network automation for capacity planning of substation transformers may provide substantial monetary savings. This paper proposes an optimization model for quantification of the savings in capacity management of substation transformers over long-run. The proposed model incorporates the DR as a resource to decrease the outage cost during contingencies while considering existing switching types for load transfer between substations. The model provides optimal selection and scheduling of multistage transformer installations and their refurbishments by considering all the costs associated with them including investment, losses, maintenance, reliability, and the salvage value. For a realistic study, numerical value of the savings in transformers' cost is calculated for a typical Finnish two-transformer primary distribution substation planning over a period of forty years. Case studies are performed based on situations encountered by utilities and type of load transfer switching (manual and remote) between substations. A sensitivity analysis based on DR penetration and load curtailment (LC) cost is also performed. The results indicate that substantial monetary benefits can be obtained in substation transformers' cost by utilities through employing DR. The benefit of DR is superior for cases where it is used in combination with remote switching of load transfer between neighbouring substations (NSS).

1. Introduction

Smart grid features offer new opportunities for improving practices of the asset management in the future power systems. Demand response (DR) and network automation are the most critical features among others as they have impact on the load profile at feeders and transformers. Substation transformers, the most costly components in a distribution system, can gain substantial increase in their utilization efficiency by using these techniques [1–7]. These utilization gains may be obtained by activating DR and/or transferring load to neighbouring substations (NSS) following a contingency, thus releasing the reserve capacity for normal operation usage [2–7]. This reserve capacity is kept, due to conventional design requirements (e.g., $N-1$), to provide support during contingencies which are rare events.

The best time to consider DR for substation transformer capacity management is at the planning phase as extra investments in the assets may be avoided resulting into higher utilization efficiency over their entire lifetime. This can be confirmed by the European Directive 2009/72/EC [8] emphasizing that the DR should be considered during planning stage of the distribution system capacity. The existing load transferring switch types (e.g., manual and remote) can have a significant impact on DR based planning solution [5–7]. This is because the DR cannot provide load reduction for longer time as flexible appliances cannot be turned off for many hours [9] and after certain time DR payback/rebound load also appears in the load profile. Therefore, activating DR potentials and the existing switching type for load transfer to NSS should be considered in parallel in the planning.

In the literature of substation transformer capacity planning, the possible impact of employing DR in the planning process of distribution networks has not been well examined. The research in this field has almost been limited to the effect of DR in operational planning of distribution system and transformer capacity [1–4], [10–12]. The authors evaluated the utilization efficiency improvement of substation transformers using DR in [1–4]. The impact of electric vehicle load on the secondary distribution transformers and their integration using DR was evaluated in [13–15]. The

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Nomenclature

Sets and indices

h, z, z', z''	indices of hour in a year
i	index for choices of transformer sizes
j, j'	indices for transformer locations in a substation
t, t'	indices of year
LL	index for load level of demand
LLm	number of load levels
M	number of transformer locations
N	number of transformer size choices
T	number of years of planning

Parameters

c_{DR}	unit incentive paid to customers for using their DR flexibility
c_{LC}	unit load curtailment cost
d	discount rate (based on inflation and interest rates)
h_{sw}	switch time, its value depends upon the type of load transfer (i.e., manual or remote) between substations
r_j^t	loss equivalent resistance of transformer on location j at year t
y	decrease in equivalent age of a transformer due to a maintenance action
C_i	procurement cost of transformer size i
D_{LL}	duration of load level LL
ER	emergency rating multiplier of a transformer
NL_j^t	no-load loss of transformer on location j at year t
NSS^t	neighbouring substation capacity at year t
$P_{\mathrm{C}}^{t,z}$	available critical load at year t, hour z
$P_{\mathrm{DR}}^{t,z}$	available flexible load at year t, hour z
$P_{\mathrm{DR}}^{t,z,z'}$	peak bound of variable for load deferred from hour z to later hour z'
$P_{\mathrm{Eng,LL}}^t$	energy price at load level LL and year t
PW^t	present worth factor of costs at year t
$T_{\mathrm{DR}}^{\max}$	maximum time for which a load can be deferred
T_r	repair time of a transformer
η_i	general symbol for parameters (of capacity, cost, resistance, and no-load of loss of transformer) of size i

Binary variables

$b_{i,j}^t$	decision for selection of a transformer size as a replacement
$\mathrm{fb}_{i,j}$	decision for selection of a particular transformer i as initial transformer at location j
$\beta_{i,j}^t$	dependent variables
$\beta_j^t, \beta_{j'}^t$	dependent variables; unity value indicates that replacement transformer are in service
$\gamma_{i,j}^t$	dependent variables
$\gamma_j^t, \gamma_{j'}^t$	dependent variables; unity value indicates that initial transformer are in service
ϕ_j^t	decision for refurbishment of transformer at location j and year t

Continuous variables

mc_j^t	maintenance cost of transformer at location j and year t
A_j^t	age of transformer at location j and year t
$C_{\mathrm{Inv}}^{\mathrm{ini}}$	investment cost of initial transformer
$C_{\mathrm{Inv}}^{\mathrm{rep}}$	investment cost of replacement transformer
C_j	investment cost of the transformer at j
$C_{j,\mathrm{ini}}$	investment cost of initially selected transformer at location j
$\mathrm{Cap}_{j',\mathrm{ini}}$	capacity of initial transformer at location j''
$\mathrm{Cap}_{j',\mathrm{rep}}$	capacity of replacement transformer at location j'
$\mathrm{DR}_{j,t,h}^z$	demand deferred under demand response
$\mathrm{DR}_{j,t,h}^{z,z'}$	load deferred from hour z to later hour z'
$\mathrm{DR}_{j,t,h}^{z'',z}$	load deferred to z in prior hours z''
$I_{j,\mathrm{LL}}^t$	current flowing through transformer at location j, load level LL, and year t
$\mathrm{LC}_{j,t,h}^z$	amount of critical load curtailed
$\mathrm{LOL}_{j,\mathrm{ini}}^t$	loss-of-life of initial transformer at location j and year t
$\mathrm{LOL}_{j,\mathrm{rep}}^t$	loss-of-life of replacement transformer at location j and year t
NL_j^t	no-load loss of transformer on location j at year t
$P_{j,t,h}^z$	modified load profile after overload relieving actions
PWC	total present value of costs of transformers in a substation
$\mathrm{PWC}_{\mathrm{Int}}^t$	present value of interruption/reliability cost at year t
$\mathrm{PWC}_{\mathrm{Inv}}^t$	present worth of the investment cost at year t
$\mathrm{PWC}_{\mathrm{Loss}}^t$	present worth of losses cost at year t
$\mathrm{PWC}_{\mathrm{Mai}}^t$	present worth of maintenance cost at year t.
$\mathrm{PWC}_{\mathrm{Sal}}$	present worth of salvage value of investments
TEC_j^t	emergency capacity of healthy transformers during contingency of transformer at location j and year t
TLOL_j	total accumulated loss-of-life of transformer existing at j by the end of the study period
$\mathrm{TLOL}_{j,\mathrm{ini}}$	total accumulated loss-of-life of initial transformer at location j
$\mathrm{TLOL}_{j,\mathrm{rep}}$	total accumulated loss-of-life of replacement transformer at location j
$\eta_{j,\mathrm{ini}}$	parametric values (capacity, cost, resistance, and no-load of loss) for initial transformers at location j
$\eta_{j,\mathrm{rep}}$	parametric values (capacity, cost, resistance, and no-load of loss) for replacement transformers at location j
λ_j^t	failure rate of transformer at location j and year t

benefit of DR for reliability improvement of distribution systems was assessed in [11,12], [16,17]. The impact of DR and automation on distribution system reliability cost was discussed in [18]. Studies [19,20] reported that overinvestments in transmission network capacity can be avoided using DR at the planning stage. In [21], the substation capacity planning was in conjunction with distribution system reinforcement in presence of DR, however, transformer maintenance scheduling, increasing failure rate with aging, salvage value based on insulation loss-of-life (LOL), and load transfer to neighbouring substation (NSS) during contingencies were not incorporated. The authors also presented an optimization model [22] for substation capacity planning, but NSS support and DR features were not considered. Therefore, an appropriate tool for quantification of DR benefits considering load transferring switch types in substation capacity planning is needed.

In this article, the influence of DR along with type of switches for load transferring to NSS is investigated on the optimal capacity planning of transformers for a primary substation. The impacts of DR and load transferring time to NSS are appropriately included in outage cost calculation of the proposed optimization model for