Smart Distribution Grid: Optimal Day-Ahead Scheduling With Reconfigurable Topology

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***Abstract*—This paper proposes an optimal operational scheduling framework to be taken in use in the distribution management system (DMS) as the heart of smart active distribution networks (ADNs). The proposed algorithm targets to optimally control active elements of the network, distributed generations (DGs) and responsive loads (RLs), seeking to minimize the day-ahead total operation costs. The technical constraints of the components and the whole system are accommodated in the ac power flow fashion. As an innovative point, the DMS effectively utilizes the hourly network reconfiguration capabilities being realized by the deployment of remotely controlled switches (RCSs). Accordingly, besides the optimal schedule of active elements, the optimal topology of the network associated with each hour of the scheduling time horizon is determined as well. The effect of hourly reconfiguration on the capacity release of DGs and RLs is highlighted, which could be envisaged as a new trend in the reserve scheduling problem. Considering practical issues, the maximum daily switching actions of RCSs as well as switching costs are judicially included. The optimization procedure is formulated as a mixed-integer nonlinear problem and tackled with the genetic algorithm. To validate the satisfactory performance of the proposed framework, a 33-bus ADN is thoroughly interrogated.**

***Index Terms*—Active distribution network (ADN), distributed generation (DG), reconfiguration, remotely controlled switch (RCS), responsive load (RL).**

NOMENCLATURE

Indices and Sets

t, T	Index and set of time intervals.
i, j, B, N_{bus}	Indices, set, and total number of buses.
f, F, N_{br}	Index, set, and total number of feeders.
s, S	Index and set of substations.
g, G, G_i	Index and set of DGs, and set of DGs at bus i.
l, L	Index and set of RLs.
k	Index of RCSs.

Parameters

ρ^{DA}	Day-ahead wholesale electricity price.
SU, SD	Start-up and shut-down cost of DGs.
C_p^{DG}	Cost function for DGs active power production.
a, b, c	Cost function coefficients of DGs.
ρ^{RL}	Contract price of RLs participation.
${k_q}^{DA}$	Coefficient for day-ahead reactive power price.
${k_q}^{RL}$	Coefficient for RLs reactive power price.
C^{SW}	Cost of each switching action for RCSs.
${k_q}^{DG}$	Coefficient for DGs reactive power cost.
C_q^{DG}	Cost function for DGs reactive power production.
$P^{\mathrm{D}}, Q^{\mathrm{D}}$	Active and reactive power loads in each bus.
Y, θ	Magnitude and phase angle of feeder's admittance.
PF^{RL}	Constant power factor for RLs.
$S_{\max}^{\mathrm{DA}}$	Substation maximum apparent power capacity.
$P_{\max}^{\mathrm{DG}}, P_{\min}^{\mathrm{DG}}$	DGs maximum and minimum active power limits.
$Q_{\max}^{\mathrm{DG}}, Q_{\min}^{\mathrm{DG}}$	DGs maximum and minimum reactive power limits.
$S_{\max}^{\mathrm{DG}}$	DGs maximum apparent power capacity.
$PF_{\max}^{\mathrm{DG}}, PF_{\min}^{\mathrm{DG}}$	DGs maximum and minimum power factors.
$P_{\max}^{\mathrm{RL}}$	Maximum power reduction by RLs.
$S_{\max}^{f}$	Feeder maximum apparent power flow capacity.
$V_{\max}, V_{\min}$	Maximum and minimum limits of bus voltage.
N_{mL}	Number of main loops in the network.
$N_{\max}^{\mathrm{SW}}$	Maximum number of daily switching actions.

Variables

$P^{\mathrm{DA}}, Q^{\mathrm{DA}}$	Day-ahead active and reactive power purchases.
$P^{\mathrm{DG}}, Q^{\mathrm{DG}}$	DG active and reactive power dispatches.
$P^{\mathrm{RL}}, Q^{\mathrm{RL}}$	RL active and reactive power participations.
W, X, Z	Binary variables for DG commitment, start-up, and shut-down status.
I	Binary variable denoting that the power factor of a DG is beyond the mandatory region.
V	Bus voltage.
S^f	Apparent power flow of feeder f.
RCS	Remotely controlled switch status.
N_{RCS}^{SW}	Daily switching actions for each RCS.

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I. INTRODUCTION

WORLDWIDE global warming, ongoing environmental pollutions, and more potent energy crises have motivated all nations to cater the utilization of renewable

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energies instead of fossil fuels [1]. In this way, distributed generations (DGs) and storage devices are recent trends in responding to the electrical energy requirements of distribution companies (discos). These technologies, although are economically/environmentally beneficial, would pose a more complex operational situations for discos. On the other hand, emergence of new mechanisms such as the open access to the electricity markets and demand side programs are other challenging issues in the way of ensuring a sustainable energy future [2].

Although forgotten or maybe underemphasized before, but now, there is a common sense that the sustainable energy development necessitates more intelligent grid with online control capabilities as well as bidirectional interactions with consumers [3]. Thanks to the substantial recent advances in the information and communication technology (ICT) along with the rapid growth of field intelligent electronic devices (IEDs), the notion of Smart Grid has been evolved in power systems specifically at the distribution level. Active distribution networks (ADNs), as the leading sort of smart distribution grids, are characterized with controllable embedded generations such as DGs, demand side management programs such as responsive loads (RLs), and also remotely controlled switches (RCSs) to attain flexible network topologies. Considering the topology changes, modern bidirectional relays should be effectively deployed in all feeders to yield a robust protection scheme in different operational horizons. Distribution management system (DMS) as the heart of economical and technical optimizations is responsible for optimal operational decision makings in ADNs utilizing optimal load flow algorithms [4]. As well, DMS is apt for monitoring the harmonic contents of the network and alleviating the power quality concerns by optimally adjusting the set points of power electronics-based devices. By this way, the DMS optimally assigns the power routings and performs an effective voltage control in the network while keeping all constraints satisfied.

In this context, Algarni and Bhattacharya [5] have proposed a day-ahead operational scheduling framework where DGs are judiciously treated by including their relevant goodness factors. Results revealed remarkable reduction in operation costs due to more decrease in power losses. Niknam *et al.* [6] have proposed a multiobjective strategy minimizing the power losses and operation costs for the day-ahead optimal operation of a distribution network including fuel cell (FC) power plants. Cecati *et al.* [7] have devised an efficient DMS algorithm for day-ahead operation scheduling of smart distribution networks wherein an optimal power flow finely controls the elements such as wind turbines (WTs) and DGs. Meanwhile, some recent studies have proposed a two-stage framework for scheduling of ADNs [8]. The first stage performs a day-ahead scheduling of resources and the effect of real-time data on optimal operation strategies are subsequently explored in the second stage. Although demonstrating noticeable achievements, some of the marvelous merits provided by ADNs such as integration of RLs and RCSs are disregarded in these works. More recently, Khodayar *et al.* [9] have benefited from the application of motorized switches in optimal operation scheduling of microgrid of Illinois Institute of Technology campus to increase the reliability of the system. Wang and Cheng [10] and Rao *et al.* [11]–[12] have tailored the reconfiguration procedure considering the presence of DGs in the network. In these studies, the impact of concurrent reconfiguration and DG sizing problem on the peak load power loss reduction is well-assessed. It is, however, sensible that the possibility of daily reconfiguration could bring further monetary savings in the utility operation cost.

Based on the foregoing discussions, this paper presents an intelligent DMS incorporating supervisory control and data acquisition (SCADA) system to tackle the optimal short-term operational scheduling of ADNs. The proposed DMS undertakes the optimal control of available active elements by minimizing the total operation costs including cost of purchasing electricity from the wholesale market, cost of DG dispatches, cost of RL participations, cost of reactive support, as well as cost of RCSs switching actions. In contrast to constant pricing for reactive power ancillary services, here, a practical pricing model is deployed for DG reactive power participations. Furthermore, the automatic motorized switches namely RCSs and available tie-lines are wisely scheduled to settle the optimal hourly network topologies. In order to establish a more practical technique, the maximum number of RCS switching actions is also limited. The obtained technical and economical improvements are thoroughly explored to assess the effect of applying RCSs in daily scheduling of ADN. The effect of hourly reconfiguration on the capacity release of DGs and RLs is investigated likewise which puts forward new insight to the reserve scheduling problems.

The rest of this paper is organized as follows. Section II addresses the generic description of the envisaged ADN. Section III formulates the proposed operational scheduling framework. Section IV interrogates several test cases and provides numerical results. Eventually, the paper is concluded in Section V.

II. Generic Description of the Envisaged Active Distribution Network

The advent of modern ICT such as wireless communications by general packet radio service (GPRS) are offering excellent online controllability on different engineering applications [13]. Meanwhile, ADNs benefitted from a comprehensive ICT infrastructure are in the way of rapid evolution. ADN refers to a self-organized system capable of controlling and enhancing the operation of all its interconnected ingredients [14]. Fig. 1 demonstrates an ADN wherein, the following information is elaborated.

1) Besides the main grid connection, disco also encompasses DGs, WTs, RLs, and RCSs as active elements.
2) DMS, as a set of hardware/software complements, is entrusted to obtain the optimal operational decisions regarding all network ingredients. To do so, it requires gathering some preliminary system information and henceforth, collaborates with system operator to receive the required data such as market prices one day in advance [15]. Also, DMS may be equipped with market price forecasting mechanism specifically for having effective participation in energy and reserve markets.