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A comprehensive framework for optimal day-ahead operational planning of self-healing smart distribution systems

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ABSTRACT

Providing a cost-efficient and sustainable energy is one of the critical features in modern societies. In response to this demand, this paper proposes a comprehensive framework for optimal day-ahead operational planning of smart distribution systems considering both normal and emergency conditions. The proposed procedure for normal mode minimizes the operation costs and provides sustainability using the seamlessness index. By adjusting this index, the system can be adapted to achieve the desired self-sufficiency level along a specified planning horizon thanks to exploiting the sufficient local generations. The operational planning of emergency mode is integrated into the proposed framework to provide the optimal schemes which can handle the possible abnormal conditions using the available local generations and guarantee the desired resiliency level. In emergency mode, the proposed self-healing strategy will sectionalize the isolated area of the distribution system into island partitions to provide reliable power supply to the critical loads continuously. A set of key operational metrics including power loss, load priority, and system-related constraints are integrated into the proposed island partitioning procedure which promotes the functionality of the method. The proposed framework is implemented on a modified PG&E 69-bus distribution system and is investigated through different case studies. The results of case studies demonstrate significant improvements and benefits which are obtained by applying the proposed framework.

1. Introduction

With the growing dependency on the electricity supplies in the modern societies, the need to achieve a satisfactory level of quality, and reliability at an economic price becomes more important to customers. A number of experts have stated that the reliability of the current supply systems is 0.99% which is close to 8 h of interruption in power supply per a year and this reliability should meet the needs of digital users in the modern societies, 99.9999%, which is close to 32 s outage per year [1,2]. Therefore, a further obligation for the modern electricity supply is reliability. Thus, a priority of modern supply system is that the system should be designed and operated properly under the condition of emergency situations to provide sustainable energy. In order to fulfill such requirements, a new electricity paradigm is demanded. This paradigm introduced based on distributed energy resources, advanced metering, communication and control technologies which provide potentially more controllable and reliable grid, so-called “smart grid” [3]. The American Electric Power Research Institute (EPRI), as an advocator of construction the smart grid, provided this grid a definition which reflects three main requirements on power grid construction; 1. Reliability requirements (self-healing, security, forecasts); 2. Economic and efficiency requirements (optimized, collaborative, interaction); 3. Technology support requirements (integration) [4]. A distribution system as one of the main components of the supplying grid is an arena that is expected to be hosted for many of these functions have been developed. Implementing such functions and related technologies turn the conventional distribution system to the smart one [5]. The smart version of distribution systems, therefore, is distinguished from the conventional distribution systems from their reliability, self-healing and interactive characteristics [6]. Accordingly, the operation of the smart distribution systems in addition to the optimal source scheduling and management should be incorporated with the sustainability as an interest-growing feature.

Optimal source scheduling and management of smart distribution systems can be considered as a downsized version of unit commitment problem which is solved by the ISO for the main grid [7]. In this paper, therefore, this problem dealt with as day-ahead operational planning problem. However, the unique characteristics of the distribution system

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Nomenclature

A. Indices

b	index for energy storage systems
br	index for branches of system
ch	superscript for energy storage system charging mode
d	index for loads
dch	superscript for energy storage system discharging mode
i	index for DGs
j	index for nondispatchable generators
n,m	index for buses
q	superscript for reactive power demand
s	index for scenarios
t	index for time
α	index for controllable loads
μ	index for uncontrollable loads

B. Sets

Br	set of branches
G	set of DGs
Ga	set of online generation units
NG	set of nondispatchable generators
Sb	set of energy storage systems
Sc	set of scenarios
Y	admittance matrix
Δ_{cl}	set of controllable loads
Δ_{ul}	set of uncontrollable loads

C. Parameters

DR	ramp down rate
DT	minimum down time
L	dimension size
MC	minimum charging time
MD	minimum discharging time
SOC	energy storage system state of charge
UR	ramp up rate
UT	minimum up time
vp	per unit value of each load
η_b^{ch},η_b^{dch}	the efficiency of the ESS unit b during charge and discharge process, respectively
γ	minimum power factor of the point of connection
ρ	market price

D. Variables

c_{di}^{TP}	cost of transferring the power from source i to load d
D	load demand
H	knapsack capacity
I	commitment state of the programmable generators
P	active power output of generation units
$P_{loss_{br}}$	power loss of branch br
P_M	main grid active power
$prob_s$	probability of scenario s
Q	reactive power output of generation units
Q_M	main grid reactive power
SD	shut down cost
SI	seamlessness index
SU	startup cost
T^{ch}	number of successive charging hours
T^{dch}	number of successive discharging hours
T^{on}	number of ON hours
T^{off}	number of OFF hours
u	energy storage system discharging state
v	energy storage system charging state
V	magnitude of bus voltage
x^{KP}	binary vector which is define the commitment of loads
x_{di}^{TP}	power amount transferred from source i to load d
δ	angle of bus voltage
θ	angle of admittance

E. Functions

$C(.)$	generation cost of the active power of the DGs
f_c	operating cost objective function
f_{ad}	adjustment objective function
f_{kp}	knapsack problem objective function
f_{tp}	transportation problem objective function
π	profit function
ε	demand-generation balance objective function

with distributed generations (DGs) introduce more constraints to classic optimization processes, which should be taken account [8]. Some of the most important features of a smart distribution system are the intermittent nature of RESs, the proximity of loads and sources, ramp rate limits of DG units if compared with larger power units and sustainability of smart distribution system. This depicts that it is necessary to implement a distinctive modeling structure to reflect these differences [8].

The optimal scheduling and management of distribution systems with DGs are vastly investigated in the literature. In [9], a multi-agent system (MAS)-based strategy is proposed for the optimal dispatch of DGs considering voltage profile improvement of a distribution system. The study in [10] developed a MAS-based energy management system architecture in which non-cooperative game theory used for the multi-agent coordination. In [11], a management scheme provided to enhance the islanded microgrid security in a cost-effective manner by using a centralized control model. The study in [12] proposed a strategy based on model predictive control (MPC) to adjust the active and reactive power of DGs to improve the voltage and frequency profiles in a distribution system. In addition to above mentioned studies, there are other researches which deal with the control and power management of resources [13–16], however, they are only designed for the normal operation condition without considering the sustainability and self-healing capability of a DG-integrated distribution system.

There exist a number of studies such as [17–19] in which the management models consider the resilient operation (i.e., when the main grid power is not available and the system would switch to the isolated mode to restore the supply) along with the normal operation of the system. This feature increases the sustainability of power supply and assures a successful transition to the self-recover mode after missing the main grid. However, by using the proposed model of mentioned studies, the scheduling and management of distribution systems with DGs are always addressed so that the system has the capacity to be able to self-recover seamlessly to a new normal state after the main grid disconnection. However, this idealization from the safety standpoint imposes the system a considerable amount of cost which was confirmed in [8]. Thus, under the conditions of incorporating complementary emergency strategies such as self-healing control actions proposed in [20,6], it could be economical if the self-sufficiency level of the distribution system would be adjustable from the point of duration and rate of independence.

Self-healing function as one of the key functions of smart grid brought out as consequence of automation of a smart distribution system [1]. This function defined as the fast-responding capability to