Improving the Grid Operation and Reliability Cost of Distribution Systems With Dispersed Generation

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***Abstract*—In this work, a mathematical model to analyze the impact of the installation and operation of dispersed generation units in power distribution systems is proposed. The main focus is to determine the trade-off between the reliability and operational costs of distribution networks when the operation of isolated areas is allowed. In order to increase the system operator revenue, an optimal power flow makes use of the different energy prices offered by the dispersed generation connected to the grid. Simultaneously, the type and location of the protective devices initially installed on the protection system are reconfigured in order to minimize the interruption and expenditure of adjusting the protection system to conditions imposed by the operation of dispersed units. The interruption cost regards the unsupplied energy to customers in secure systems but affected by the normal tripping of protective devices. Therefore, the tripping of fuses, reclosers, and overcurrent relays aims to protect the system against both temporary and permanent fault types. Additionally, in order to reduce the average duration of the system interruption experienced by customers, the isolated operation of dispersed generation is allowed by installing directional overcurrent relays with synchronized reclose capabilities. A 135-bus real distribution system is used in order to show the advantages of using the mathematical model proposed.**

***Index Terms*—Distributed power generation, optimization methods, power system protection, power system reliability, smart grids.**

NOMENCLATURE

c	Integer number to define the capacity of one protective device as a function of the continuous current level.
d	Type of protective device: fuses ($d=1$), reclosers ($d=2$), overcurrent relays ($d=3$) and directional overcurrent relay with a synchronized recloser capability ($d=4$).
$\mathrm{AC}_{\mathrm{dc}}, \mathrm{IC}_{\mathrm{dc}}, \mathrm{UC}_{\mathrm{dc}}, \mathrm{MC}_{\mathrm{dc}}$	Acquisition, installing, uninstalling, and annual maintenance costs for the protective device of type d and capacity c.
Fsec	Security factor to ensure stability.
$I\mathrm{device}_{\mathrm{dc}}$	Continuous current level for the protective device of type d and capacity c.
$Imaxsc_{\mathrm{dc}}$	Short-circuit capability for the protective device of type d and capacity c.
I_{rate}	Interest rate.
I_{liy}	Current flow in the line l over the ith period of the load demand curve, and the yth year of the planning horizon.
$I_l^{\max}$	Thermal capability of the line l.
L_l	Length of the line l.
LD_{kiy}	Load demand connected at the receiving bus of line k, during the year y of the planning horizon and the level i of the load demand curve.
ND_d	Available number of continuous current levels for the protective device of type d.
NL	Number of periods in the load demand curve.
$NLin$	Number of lines in the distribution system.
N_{Sub}	Number of substations.
NY	Years in the planning horizon.
$P_{liy}^{DG}, Q_{liy}^{DG}$	Active and reactive power dispatched by the dispersed generation unit connected at the l-line's receiving bus, during the ith period of the load demand curve, and the yth year of the planning horizon.
$P_{siy}^{\mathrm{Sub}}, Q_{siy}^{\mathrm{Sub}}$	Active and reactive power dispatched by the substation s during the ith period of the load demand curve, and the yth year of the planning horizon.
$PC_{siy}^{\mathrm{Sub}}, QC_{siy}^{\mathrm{Sub}}$	Active and reactive costs of power dispatched by the substation s during the ith period of the load demand curve, and the yth year of the planning horizon.

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PC_{liy}^{DG}, QC_{liy}^{DG} Active and reactive costs of power dispatched by the dispersed generation unit connected at the l-line's receiving bus, during the ith period of the load demand curve, and the yth year of the planning horizon.

P_k^{DGmin}, P_k^{DGmax} Active power limits of the DG unit connected at the receiving bus of line k.

$Q_k^{\mathrm{DGmin}}, Q_k^{\mathrm{DGmax}}$ Reactive power limits of the DG unit connected at the receiving bus of line k.

RT_j, ST_j, RST_j Average time to repair, revise, or restore, respectively, the section j.

$S\mathrm{sub}_s^{\max}$ Power capability of substation s.

s_{kiy} Binary variable to define the probability of continuing an operation of the isolated area created downstream of line k.

T_{iy} Duration time of the ith period of the load demand curve of the yth year of the planning horizon.

V_k^{DGnom} Nominal voltage setting for the DG unit k.

V_{kiy} Voltage magnitude at the receiving bus of the line k during the ith period of the load demand and the yth year of the planning horizon.

$V_l^{\min}, V_l^{\max}$ Voltage limits at the receiving bus of line l.

x_{ldc} Binary variable with value 1 when line l is selected to receive the installation of one protective device of type d and capacity c.

x_{ldc}^{base} Binary parameter with value 1 when the line l has initially installed one protective device of type d and capacity c.

y_{jl} Binary parameter with value 1 when line j is used to carry power flow from the substation to the load connected at the receiving bus of line l.

λ_l, γ_l Average index values for permanent and temporal faults at line l.

Γ Planning horizon (hours).

I. Introduction

THE progress of modern society is increasing its dependence on the quality and continuity of the electrical service [1]. Consequently, the health and reliability of its distribution system has gained more attention as an important issue to be improved in order to provide a higher confidence level to customers. Several researchers have made efforts to improve system reliability through the relocation of the protective devices, since their response to unexpected failures defines the duration of the interruptions as well as the number of customers affected. This concept is appropriately exploited in [2] to minimize the cost of the unsupplied energy to customers due to the shortage of power that is caused by the isolation of short-circuit zones. The problem is presented as an optimization model and solved using a binary programming technique. After that, in [3], the model is improved as a mixed-integer nonlinear optimization problem in where there is at least a consideration for fixed costs from the acquisition, installation and maintenance of protective devices. The problem is more comprehensively solved using reactive tabu search algorithms. Moreover, in [4] and [5] particle swarm optimization is employed.

Power system planners must design the necessary methods to ensure long-term power operation and system reliability. Over the last several years, much has been done to assess the impact that the installation of dispersed generation (DG) units have on the grid. This implementation has been seen as an available option to expand the operation of the actual power system and, at the same time, to address the concerns about rising fuel costs and greenhouse gas emissions [6], [7]. At the distribution level, the distributed generation only considers the active power flow production in order to increase the network voltage profile, reduce active power losses, and increase the revenue of the distribution operator while the operation of the protective devices remains unaltered [8], [9]. However, the DG could increase its role in the distribution system if both voltage control and isolated operation features were considered [10].

The isolated operation concept could be used to minimize the system's average duration of the interruption experienced by customers connected to secure systems but affected by the normal tripping of protective devices, (i.e., backup systems). To guarantee the secure operation of isolated DG units, it is necessary to extend a communication network that connects the distribution center and DG sources. This network must be used for metering and controlling the power flow between various power sources and the grid, as well as to verify the power balance and stability of the system. This matter is analyzed in [11]–[14], leading to conclude that the technology necessary to guarantee the secure operation of DG units could be matched in the future.

Normally, the DG operation can focus on improving the quality of service through an appropriate dispatch among the available power sources. Additionally, improving the grid's efficiency and the revenue of the power system owner could be obtained. In this work, the aforementioned approach is presented as a multi-objective mathematical model with mixed-integer nonlinear variables that are further solved by using a multi-objective Taboo Search Technique [15]. The mathematical model that is proposed considers the installation and operation of fuses, reclosers, overcurrent relays and directional overcurrent relays that also have synchronized recloser capabilities (DORSR). The location of DORSR devices should require that directional relay operation creates an isolated area where the functionality of dispersed generators is feasible. Consequently, the directional feature in the DORSR is then focused on the detection of