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Controlled islanding using transmission switching and load shedding for enhancing power grid resilience

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ABSTRACT

A controlled splitting strategy is proposed as the last resort to determine the splitting points of an interconnected power system before occurring a critical transition. The proposed strategy is expressed as a mixed-integer formulation with considering the slow coherency of synchronous generators. In the proposed integer programming formulation, each coherent group of generators is located in an individual island. This grouping constraint may assure the synchronism of generators after islanding. Each island contains a coherent group of generators and its boundary is determined with the aim of achieving minimum load shedding. Two artificial DC load flow algorithms are proposed to model grouping and connectivity constraints. In addition to operational limits, a switching constraint and a frequency stability constraint are proposed to limit the number of line switchings and assure the stability of resulted islands, respectively. The proposed mixed integer model is solved using Benders Decomposition (BD) technique. Using BD technique, the CPU time of computation is reduced significantly. The proposed splitting strategy is simulated over the IEEE 30-Bus and IEEE 118-Bus test grids. Transient stability simulations are done to validate the accuracy of the proposed method.

1. Introduction

1.1. Background and literature review

An important element of each self-healing scheme in power systems is the network reconfiguration to minimize the system vulnerability and to facilitate the restoration process to stop the spread of cascading failures [1,2].

Enhancing the resilience of power system to rare events such as uncontrolled islanding is an important requirement in power system operation and control. Self healing schemes have been recently developed in large scale power systems [1]. One of major phenomena, during a partial or wide-spread cascading failure is the formation of unplanned electric islands. Many blackouts would have been mitigated if the suitable controlled splitting strategy had been executed in time [3,4]. Controlled islanding refers to the intentional splitting of an interconnected power system into stable isolated islands before experiencing a critical transition or blackout [5]. Two major issues must be considered in each controlled islanding strategy: (a) the time of islanding and (b) the splitting points. Many approaches have been proposed to determine the number and locations of islands such as slow coherency concept [6–9], optimization-based approaches [10–14] and fuzzy-based algorithms [15]. In [6,7], a singular perturbation technique is developed to divide the state variables of system into slow and fast states. The slow states represent groups with the slow coherency. In [8,9], an integrated algorithm has been utilized to identify a cutset for large scale power system. The large scale power system is presented as a graph and a simplification technique is developed to reduce the complexity of system. In [10], the combination of spectral clustering and distributed optimization technique has been utilized for power system partitioning. In [11–13], evolutionary algorithms including particle swarm optimization, genetic algorithm, and tabu search have been utilized to solve the MINLP model of controlled islanding. In [14], a MILP stochastic programming model has been proposed to optimize islanding operations plan under severe multiple contingencies.

Graph theory is an efficient searching method for reducing the searching space of splitting scenarios [16–18]. In [16], using wide area measurement system the boundaries of islands are obtained by the weighted time varying graph structure of the network. In [17], the constrained spectral clustering is used to fine islanding boundary with minimal power flow disruption. In [18], the coherent islands are determined using synchrophasor data based on graph modeling. In [19] a combination of graph theory and

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Nomenclature

$P^0_{G_i}$	initial generation of node i
$P^0_{L_i}$	initial load at node i
α_i	weighting factor for load shedding at bus i
$\Delta P^+_{G_i}$	generation increment of ith generator after islanding
$\Delta P^-_{G_i}$	generation decrement of ith generator after islanding
ΔP^{k+}_G	total generation increment at kth island
ΔP^{k-}_G	total generation decrement at kth island
ΔP^k_{im}	total possible power imbalance at kth island
ΔP_{L_i}	load curtailment at ith load point after islanding
ΔP^k_L	total load shed at kth island
δ_i	voltage angle of ith node in power balance constraint
Ω^l	set of all transmission lines
Ω^d_k	set of load points in kth island
Ω^g_k	set of generator nodes in kth island
$\overline{U}_{ij}$	a fixed value of binary variable U_{ij}
$\{\bullet\}^s$	subscript of artificial variables in connectivity constraint
$\{\bullet\}^{max}$	subscript for maximum of a variable
$\{\bullet\}^c$	subscript of artificial variables in grouping constraint
cte	a constant value
f_0	nominal frequency
G_{ij}, B_{ij}	real and imaginary parts of ij element in admittance matrix
H_k	equivalent inertia constant of generators in kth island
$J(i)$	set of nodes connected to node i by a transmission corridor
M	an arbitrary large number
N	number of buses
N^g_k	number of generators in kth island
N_{is}	number of islands (i.e. coherent groups)
N_{line}	number of transmission lines
N_{pq}	number of load points
N_{pv}	number of voltage controlled nodes
N_{sw}	number of allowable line switchings
P_{ij}	active power flow from node i to node j
U_{ij}	binary variable showing the switching of line between node i and j
x_{ij}	reactance between nodes i and j

optimization has been utilized to minimize the real and reactive power imbalance at the resulted islands.

All steady state constraints in each islanding strategy including power balance constraint, slow coherency constraint (i.e. grouping constraint), and connectivity constraint can be merged in a Mixed Integer Linear Programming (MILP) model. Unlike the graph-based splitting strategies, in MILP-based partitioning strategy it is possible to optimize an objective function (e.g. load shedding), while satisfying the related constraints.

In [1] the islanding strategy and adaptive under frequency load shedding have been utilized for self healing in power systems.

However the conventional MINLP-based and MILP-based splitting strategies suffer from two disadvantages including the CPU time of calculation and ignoring the stability considerations. In this paper, BD technique is utilized to solve the proposed MILP formulation. A switching constraint is proposed to speed up the algorithm and reduce the searching space of splitting strategies. Also a new constraint is proposed to improve the frequency stability of the network after partitioning. In this paper, the prediction of islanding is done using the energy based approach proposed in [20]. It is noted that the present paper is focused on the "where to island" issue of splitting strategy. In other words it is assumed that making decision about the timing of islanding (i.e. "when to island" issue) is the task of another program such as methods proposed in [20,21].

1.2. Contributions

The contributions of this paper are as follows.

1.2.1. Decomposition based MILP formulation

A MILP formulation is developed to seek the optimal splitting strategy using BD technique. The proposed MILP formulation is solved using BD technique in which the original MILP problem is separated into a relaxed MILP master problem and one LP subproblem.

1.2.2. Switching constraint

The splitting problem of a large power system has generally a huge searching space (e.g. for IEEE 118-bus network with 186 lines, there are 2^{186} possible (but not practical) choices for system splitting. In this paper a switching constraint is proposed to limit the number of line switchings (i.e. opening points). This constraint reduces the searching space of splitting strategies significantly.

1.2.3. Linear algorithms to check separation and connectivity

Before running decomposition-based MILP formulation the coherent generators are determined using coherency technique. During running MILP formulation and to assure the synchronism of generators in each island, it is required to keep each group of coherent generators in a same island. In this paper the interconnectivity of each island and the physical separation of non-coherent groups of generators are satisfied using a set of linear equations.

1.3. Paper organization

The rest of this paper is organized as follows. In Section 2 the details of the MILP-based splitting strategy are described. Also the proposed Artificial DC Load Flow (ADCLF) algorithms are described in this section. The formulation of the BD-based procedure to solve the splitting strategy is discussed in Section 3. The results of applying the proposed method over IEEE-30 bus and IEEE-118 bus test systems are given in Section 4. Finally, the conclusions are provided in Section 5.

2. MILP-based islanding strategy

The overall structure of the proposed scheme has been illustrated in Fig. 1. The coherent groups of generators are determined using slow coherency technique based on the phasor measurement data. This study could be done offline. After deciding to split, the proposed MILP is solved and the obtained strategy is executed.

In this paper all constraints of islanding problem are combined in a MILP model to obtain the stable islands with minimum load shedding. The objective function is expressed as follows:

$$\textbf{Min} \quad OF = \sum_{i=1}^{N_{pq}} [\alpha_i \Delta P_{L_i}] \tag{1}$$

where the weighting factor α_i is used to consider the priority of different loads. Different constraints are defined to achieve the stable islands as follows.