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A new coordinated design of sectionalizing scheme and load restoration process considering reliability of transmission system

Mohammad Reza Esmaili[a], Amin Khodabakhshian[a,*], Rahmat-allah Hooshmand[a], Pierluigi Siano[b]

[a] Department of Electrical Engineering, University of Isfahan, Isfahan, Iran
[b] Department of Industrial Engineering, University of Salerno, Salerno, Italy

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ABSTRACT

One of the most important processes during load restoration is to use a suitable sectionalizing scheme to enhance the stability, especially when two islands are synchronized. In this regard, this paper provides a new scheme for the coordination of sectionalizing and load restoration to enhance the power system performance before and during the synchronization of islands. In doing so, there will be contradictory objective functions including maximizing the quality of sectionalizing process, minimizing the maximum standing phase angle (SPA) between islands, and minimizing the sum of energy not supplied (ENS) with unavailable energy capability (UEC) between all *N-1* contingencies. Therefore, a multi-objective problem is defined as a mixed integer non-linear problem (MINLP). Also, a reliability-based index is defined to determine the quality of each island. Then, the θ-based water cycle algorithm (θ-WCA) is used to obtain the best Pareto optimal set. Two IEEE 39-bus and 118-bus power systems are used for validating the proposed method. The simulation results imply that the system can benefit from this scheme not only to have the good quality of sectionalizing, but also to enhance the power system performance during load restoration and the synchronization of islands.

1. Introduction

After having a blackout in power system in order to reduce the economic losses and social problems a fast power system restoration should be carried out [1–3]. During the restoration process which includes three steps of start-up of generating units, reconfiguration and synchronization of islanded subsystems, and restoration of loads, sectionalizing the subsystems plays a vital role to pickup critical loads before synchronization. The other key problems are the minimization of energy not supplied (ENS) with unavailable energy capability (UEC), and reducing standing phase angle (SPA).

To accelerate the restoration process, sectionalizing a power system into several high quality islands and the parallel restoration of these islands are the most efficient tasks which are performed by system operators [3–6]. Different sectionalizing strategies have been well developed in recent years [7–12]. A systematic algorithm is proposed in [7] for modifying the sectionalized network based on wide area measurement system so that the observability of every power plant or substation in every island is guaranteed. In [8], an ordered binary decision diagram-based approach is addressed to sectionalize a power system considering black-start capability, active power balance and voltage stability constraints. The results in [8] are optimized in real time after occurring unpredictable changes in power system conditions. A complex network theory based on community structure is used for sectionalizing the power system during restoration in [9]. In this paper the separation process of subsystems is performed by computing a modularity index, called betweenness, for each transmission line. Then, the line that has the maximum value of betweenness is removed. In [10], a scale-free network strategy is developed to determine the consistent restoration paths for specified scenarios that can be used in unexpected conditions. A partitioning approach based on cut-set matrix, defined as a technique in graph theory, is proposed in [11] for the parallel restoration of subsystems. The main constraints of the restoration such as active and reactive power control, black-start capability for their synchronization are considered in [11]. In [12], a spectral clustering technique is applied to obtain the subsystems considering the constraints addressed in [11]. The method proposed in [12] presents a mathematical model to measure the quality of an island, which is defined as the strength of connectivity between all nodes in each island.

One of the important issues affecting the qualification of each island is the reliability of the composed subsystems in restoration process, which, to the best authors' knowledge, has not been considered in the literature. The failure of any system equipment can significantly affect

* Corresponding author.
E-mail addresses: m.r.ismaili@eng.ui.ac.ir (M.R. Esmaili), aminkh@eng.ui.ac.ir (A. Khodabakhshian), hooshmand_r@eng.ui.ac.ir (R.-a. Hooshmand), psiano@unisa.it (P. Siano).

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Nomenclature

Symbol	Description
$P_m^{\max}$	maximum value of *m-th* restorable load
P_m^t	the value of *m-th* restorable load at *t-th* time step
T	total number of time steps
$P_{j\max}$	maximum output power for NBS unit j
P_{jstart}	required start-up power for NBS unit j
G	total number of NBS units
M	total number of restorable load
$T_{j\min}$	certain time interval that NBS unit *j* need to be ready for receiving crank power
$T_{j\max}$	maximum time interval for starting the NBS unit *j*
$t_{j_{path-opt}}$	time interval needed to energize the optimal path to NBS unit *j*
$P_{igen-opt}(t)$	generation capability of BS unit *i* for cranking the power through the optimal transmission path
Q_{g_i}	output reactive power of the *i-th* generator
Q_{l_j}	demanded reactive power at *d-th* PQ bus
B_{ij}	the transfer susceptance between bus *i* and bus *j*
G_{ij}	the transfer conductance between bus i and bus j
θ_{ij}	standing phase angle of two adjacent buses i and j
$\theta_{ij}^{\max}$	the maximum allowable standing phase angle for transmission system
δ_{ij}	the difference value of phase angle between bus i and bus j which are in the same island
t_{jstart}	starting time of NBS unit j
S_{ij}	loading of transmission line which is located between bus i and bus j
$R_c(t)$	the reliability of the connection
$R_{line}(t)$	the reliability of transmission line
$R_{BR_1}(t)$	the reliability of the first circuit breaker
$R_{BR_2}(t)$	the reliability of second circuit breaker
λ_c	the failure rate of the connection
λ_{line}	the failure rate of transmission line
λ_{BR_1}	the failure rate of the first circuit breaker
λ_{BR_2}	the probability of the second circuit breaker
ζ_j	the weighted factor of the j-th bus in an island
d_j	the sum of electrical distances which is related to the j-th bus of an island
ρ_j	the degree of a bus in an island
K	the total number of islands
C	the total number of N-1 contingencies

the performance of the restoration process, e.g. any problem in the generators start-up will interrupt the load energizing [13–14]. Also, it is evident that the cranking power of generators must be transferred via more reliable cranking path. In this regard, the reliability of a cranking path is defined as the successful restoration rate of all transmission lines in that cranking path and the optimal sections are determined where the maximum reliability is achieved.

The second key problem of the restoration process in coordination with sectionalizing is the minimization of ENS and UEC [15–18]. The impact of the number of partitions and their boundaries on the restoration process is developed in [15]. ENS is considered as the objective function in [15] and it is minimized by genetic algorithm to obtain the optimal subsystem boundaries. A sectionalizing strategy based on black-start capability enhancement is given in [16] to optimize the start-up sequence of non-black-start units (NBSUs) and to maximize the speed of the power system restoration. A sectionalizing method based on the coordination of non-black-start generation and restoring critical loads is proposed in [17] to accelerate the power system restoration at the initial stage. In [18] a two-step sectionalizing strategy is given for parallel power system restoration. In this plan, two Boolean programming problems of constrained quadratic and constrained linear models are optimized for the simultaneous performance of the power system sectionalizing and NBSUs grouping. Also, the AMPL/CPLEX solver is used for minimizing the number of interconnected lines, optimizing the start-up sequence of generating units and maximizing the electrical distance of the interconnected lines between adjacent subsystems.

The standing phase angle (SPA) reduction is the third key and the most important problem that dispatchers and operators of power systems usually have to cope with during closing a breaker between two adjacent subsystems [19]. Large values of SPA could result in dangerous disturbances such as power swings and cause the subsystems to be separated again [20]. The suitable SPA values for a stable power system are determined according to the level of the operating voltage, dynamic and steady state conditions [20].

In all papers related to the subject of sectionalizing strategies, as mentioned above, different constraints such as observability, load-generation imbalance, voltage stability, non-black-start units grouping, the quality of islands and minimizing ENS and UEC have been studied. However, the coordination of sectionalizing and load restoration for reducing the SPAs of interconnected transmission lines between adjacent subsystems has not been addressed. Since there are different phase angles in different end buses, the break point location between two islands can affect the SPA value during different time steps of load restoration. Therefore, three key problems (sectionalizing the system, SPA reduction and load restoration) should be simultaneously considered in a restoration scheme.

As will be given in this paper, the sectionalizing problem can be solved by the optimal determination of the load restoration time and its final amount in each bus before synchronizing adjacent islands. In the proposed method, a reliability-based quality index is presented to evaluate the quality of each island considering the weights of buses which are addressed in [9,12]. Also, the optimal selection of the interconnection line between adjacent islands will be obtained in order to reduce the maximum SPA between islands and also to expedite the start-up time of NBSUs. In doing so, a multi-objective function is defined to acquire the best Pareto optimal set. These objective functions are the minimization of the maximum SPA among SPAs of all interconnecting points, the minimization of both ENS and UEC of the system and the maximization of the worst quality between all *N-1* contingencies. Since the number of decision variables is very high, a heuristic technique based on the behaviour of the nature, called θ-based water cycle algorithm (θ-WCA) is applied to obtain the Pareto optimal solutions. The high level of efficiency, accuracy and robustness to search the Pareto optimal solution and the finding capability of WCA make it be a desirable approach for solving the MOP addressed in this paper [21]. Also, as shown in [1] WCA algorithm generally gives better solutions than other algorithms, such as GA and PSO, in addition to its efficiency in terms of the number of function evaluations (computational burden) for almost every problem. Moreover, adding the technique θ into WCA saves the time of the searching process and increases the algorithm speed [22]. The main contributions of this paper are as follows:

- Coordination of both sectionalizing and load restoration process,
- Presentation of a reliability-based index to qualify the sectionalizing schemes,
- Providing the synchronization of adjacent islands in each restoration time step by reducing the maximum SPA,
- Considering all objective functions related to the power system restoration simultaneously, and
- Presenting a θ-based water cycle algorithm (θ-WCA) for searching the optimal decision variables.