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Determination of sectionalising strategies for parallel power system restoration: A spectral clustering-based methodology

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ABSTRACT

Parallel power system restoration (PPSR) accelerates the restoration of a system in complete blackout by restoring isolated sections (islands) of the network in parallel. These islands are defined during the preparation stage of PPSR using a sectionalising strategy that considers system information collected after the blackout and must satisfy multiple PPSR constraints. This paper introduces a methodology based on spectral clustering that, in contrast to existing approaches, uses the physical and inherent properties of the network to determine a suitable solution. An undirected edge-weighted graph is initially constructed based on the electrical distance between buses, and constraints related to transmission line availability and cranking groups are included by modifying the edge-weights of the graph and using a subspace projection. This graph is then used to define islands that have strong internal connections but weak external connections, whilst satisfying the following constraints: blackstart availability, load-generation balance, voltage stability and the ability to monitor synchronisation between adjacent islands. Simulation results for the Institute of Electrical and Electronic Engineers (IEEE) 39- and IEEE 118-bus test systems demonstrate the ability of the methodology to define a strategy that creates strongly connected islands. Additionally, they indicate that the new approach determines solutions that have larger ratios between the inter-cluster electrical distance and the intra-cluster electrical distance for larger systems.

1. Introduction

Power system restoration (PSR) aims to restore systems that have been affected by a partial or complete blackout as quickly and as safely as is reasonable [1]. The availability and deployment of the blackstart units in a system is a key element of restoration, as they provide the cranking power that allows the systems non-blackstart units to be brought online. This cranking task can be accomplished by adopting a build-down strategy, which entails the use of centralised cranking sources to provide cranking power to the entire system [1–3]; however, this approach may take a long time when restoring a large system that is in complete blackout [1,4]. Therefore, parallel power system restoration (PPSR), is commonly adopted by the utilities, as it accelerates the restoration process by sectionalising the area in blackout into multiple islands (subsystems) that are restored in parallel using their own cranking sources [1–7].

PPSR can be divided into three stages [4]:

1. Preparation;
2. System restoration; and
3. Load restoration.

The first task in the preparation stage is assessing the status of the post-blackout system. Then a sectionalising strategy (SS) is defined that considers this new system status and that satisfies multiple PPSR constraints. Finally, the blackstart units are restarted. The system restoration stage involves the energisation of the skeleton of each island to allow the blackstart units to send cranking power to the non-blackstart units in their island. Load is restored during the system restoration stage for the purpose of stabilising frequency and voltage. The load restoration stage involves the load in each island being restored as fully and as quickly as is reasonable [4]. Finally, when most of the load is restored, the islands that have been restored independently are reconnected.

The definition of a suitable SS is a critical task that must be performed by the operators in the control centre during the preparation stage of PPSR [5–7]. This strategy defines the set of lines that optimally sectionalise the entire area that is in blackout into

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multiple islands [1–5]. It is important that the SS is defined using updated system information that is received after the blackout has occurred; this is necessary to ensure that it represents the actual system topology and the availability of its elements [1,4,5]. The most important information for the design of a suitable solution includes [4,5]: the available blackstart capability, the availability of interconnection assistance, the status of non-blackstart units, the status of lines and circuit breakers, and the predicted load levels.

A suitable SS can assist the operators in reconnecting the entire critical load – i.e., load that must be rapidly restored, e.g., hospitals – in a timely fashion [5]. Furthermore, it will aid in restoring the significant load – i.e., the non-critical load – as quickly as possible, when capacity becomes available. [4,5]. To ensure reliable PPSR, it is important that system security is considered during the design of the SS. Therefore, the following constraints should be considered when determining a suitable strategy [1,4,5]:

1. Each island must have at least one blackstart unit;
2. Each island should have sufficient voltage control resources to maintain a suitable voltage profile;
3. The tie-lines between the islands should all have monitoring equipment that allows the synchronisation of the adjacent islands that they separate to be measured;
4. Each island should have sufficient capacity to maintain a satisfactory frequency by matching generation and load; and
5. Each island should be monitored at the system control centre to ensure correct operation.

Numerous system operators have designed sectionalising strategies for the parallel restoration of their systems, e.g., the Mexican system [8], the PJM interconnection [9] and the British network [10]. The design of these strategies has been based on factors like historical asset ownership and operator experience, rather than the study of the physical and inherent properties of the electrical network, to simplify the process of determining the SS. However, this practice raises questions regarding the quality of the restoration planning and the proper exploitation of the physical properties of the system [5–7].

Therefore, this paper proposes a methodology to determine sectionalising strategies that is based on spectral clustering. This methodology uses the physical and inherent properties of the network to determine an SS that satisfies constraints 1, 2, 3 and 4 (these constraints are referred to here as the critical PPSR constraints) with the maximum electrical cohesiveness within the islands created. It is assumed that each island can be monitored by the control centre, which satisfies constraint 5. In practice, the creation of fully observable subsystems for the purpose of restoration is extremely complicated due to the consequences that a large-area blackout produces in the entire power network [4,5].

The concept of electrical cohesiveness that is used in this paper is expressed in terms of the electrical distance between the buses and has previously been used to define zones for system planning and control [11–14]. Introducing electrical cohesiveness as part of the formulation of the SS-problem allows the creation of islands that not only satisfy the critical PPSR constraints but also have strong internal connections (strong cohesion, i.e., small electrical distances, between buses in the same island) and weak external connections (weak cohesion, i.e., large electrical distances, between buses in different islands). This methodology does not use network analysis to determine the optimal solution, which means that the SS can be determined more quickly, as it avoids the need for the extensive use of simulation data to validate the proposed islands.

Moreover, maximising the electrical cohesiveness of the islands serves to reduce the number of tie-lines between the islands and, consequently, increases the number of internal connections. Reducing the number of tie-lines between the islands reduces the number of time consuming tie-line reconnections that must be performed during the resynchronisation of the islands. Increasing the number of internal connections within each island increases the number of paths available for the transmission of cranking power from the blackstart units to the non-blackstart units. Furthermore, the emphasis on creating electrically cohesive islands will mean that the lines that separate these subsystems will tend to be long, weak transmission lines. Thus, the effects of the high charging currents and overvoltages that might arise when reconnecting these long, unloaded lines can be reduced, as these lines will be reconnected at the end of PPSR when the system is nearing full strength [1–3].

The nature of the SS-problem lends itself to being solved using spectral clustering. Thus, we propose the use of constrained spectral clustering to find an SS that satisfies the necessary constraints with the maximum electrical cohesiveness within the islands [15–19]. In the context of power systems, spectral clustering has previously been used to determine controlled islanding strategies [20–23] and to reveal the internal connectivity of the network [24]. This technique can directly determine an "initial SS" that ensures blackstart availability (Constraint 1), excludes critical lines that maintain system voltage stability (Constraint 2) and ensures that the synchronisation across the tie-lines that separate the islands can be measured (Constraint 3). This initial SS is then subjected to a graph theory based refinement algorithm that modifies the initial SS to form a final SS that ensures each island will possess sufficient active power generation to restore the predicted load within the island (Constraint 4). Simulation results for the IEEE 39- and IEEE 118-bus test systems demonstrate the effectiveness of our methodology in determining the SS that maximises the internal electrical-cohesiveness of the islands, whilst satisfying the constraints of blackstart generation availability, load-generation balance, voltage stability and the ability to monitor the resynchronisation of adjacent islands.

The methodology proposed here is for use during the preparation stage of PPSR and can assist operators by quickly providing an SS that satisfies the critical PPSR constraints, which should serve to help ensure the steady-state stability of the future islands. However, whilst a suitable SS increases the likelihood of a timely and successful restoration, the inherent complexity and risk involved in restoration means that no strategy can guarantee a successful restoration [5–7]. Successful PPSR depends on the adequate use of the available resources and proper decision-making during the actual restoration of the islands. Finally, it is important that the methodology is implemented using system information that represents the true topology of the post-blackout system and the availability of its elements.

The paper is organised as follows. Section 2 presents the background material on spectral graph clustering. Section 3 introduces the proposed methodology to determine sectionalising strategies, and Section 4 we study its effectiveness in creating islands that satisfy the critical PPSR constraints. Finally, Section 5 discusses the main strengths and limitations of the new sectionalising methodology, and Section 6 summarises the conclusions drawn from this study.

2. Graph theory and spectral graph clustering

Graph theory involves the mathematical representation of a complex system as a graph, which is made up of nodes and edges. Creating this graph representation allows the application of a number of well-established and powerful techniques, e.g., spectral clustering [15]. Spectral clustering is a computationally efficient graph theory based technique that can partition networks using the eigenvalues and eigenvectors of a matrix associated with the