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Master Thesis

Topology-aware communication node placement for power grid restoration

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Abstract

The increased interconnectedness between Power Systems (PS) and Information and Communication Technology (ICT) systems (e.g., cellular) pose new challenges for the Smart Grid. Natural disasters (like earthquakes and tsunamis), cascading failures, cyber-attacks, and other critical events have a detrimental effect on PS operations. As a result, it can bring it to a blackout state, where multiple PS and Base Station (BS) nodes collapse suddenly, dividing the network into several disconnected segments known as islands. This thesis defines an *island* as a connected set of BS nodes. The recovery of the BSs should happen in an accelerated and topology-aware manner while considering the interdependencies between BSs and PSs [VTdM21].

However, wide-area outages hinder the rapid recovery of the whole ICT infrastructure, and temporary Repair Resources (RRs) should be placed. This leads to the Relay Node Placement (RNP) or Network-partition problem, which has been extensively studied in Wireless Sensor Networks (WSN). However, this approach has not applied to managing communication gaps between the components of the PSs. In this situation, re-establishing network connectivity is essential to preventing severe damage to the Smart grids in which the role of ICT systems in aiding restoration operations is crucial and strongly desirable.

Such a problem has been generally formulated as a Steiner Minimum Tree (SMT) problem by considering that each island is a terminal, e.g., by choosing a single node in an island to act as an interface point. That is why such a formulation is inappropriate since the island's size is not taken into account. So, a new Power System Aware - Connected Inter-Segment Topology (PSA-CIST) algorithm inspired by the Connected Inter-Segment Topology (CIST) is introduced to solve this problem [SY11a]. The main objective of the algorithm is to identify the best triangular subsets of islands by finding the best possible connection between the BS nodes of the islands via SMT or Minimum Spanning Tree (MST) while minimizing the required number of RRs and maximizing the number of PS nodes. Similarly, connecting the remaining islands by federating RRs along the MST edges. The performance of PSA-CIST is validated through simulation results which demonstrate the significance of PSA-CIST and its benefits compared to CIST in most cases.

Contents

1. Introduction

Communication plays a very crucial role in providing reliable, efficient, and secure generation, transmission, and distribution of electricity. However, the rising interconnectivity between PS and ICT systems presents additional difficulties for smart grids. During an emergency situation (like a hurricane or fire) or any other disastrous incident harms the PS operations, which as a result, can cause a blackout like Power Outages in Texas [Cam21]. In this situation, the ICT system recovery should happen quickly and with topology awareness while considering the inter-dependencies between ICT and PS [VTdM21]. Thus, the iterative restoration of the PS nodes allows for the formation of self-contained microgrids, supplies local communication resources, and creates communication islands, as shown in Figure 1.1. After the disaster, some of the BS and PS nodes stopped working (area highlighted in red), which as a result, divided the whole connected network of BS and PS into multiple islands (highlighted in green). However, the wide-area failures make it difficult for the whole ICT infrastructure to recover quickly and necessitate the use of temporary RRs to establish communication between remote PS nodes as well as a merging process formed between microgrids.

While communication repair scheduling has been extensively studied in Internet Service Provider (ISP) and WSN, this approach has not been applied to manage communication gaps between the PS nodes and their components while considering PS topology and interdependencies with the ICT network [VTdM21]. Furthermore, multiple potential solutions such as Device-to-Device (D2D), relays, and moving cells should be considered for the wide-area cellular networks. In recent years, the debate will likely come to an end with Long-Term Evolution (LTE)-A based Fifth-Generation (5G) mobile wireless technology is established as the global future grid communication networking standard due to a convergence of several cellular advanced technologies and convincing techno-economic trends [AM16].

This paper will investigate the RNP approach for re-establishing inter-island connectivity. It is usual to assume that Relay Nodes (RNs) or RRs are more substantial, mobile, and expensive than BS nodes, e.g., vehicular base stations, unmanned aerial vehicle (UAV)-mounted base stations. Considering the possible cost of RRs and difficulties in installing them, it is desirable to minimize the number of RR nodes required in most scenarios while maximizing the number of PS nodes connected via RRs. The majority of the approaches in the paper that try to solve this problem represent an island by only one node and aim to form SMT with the fewest possible Steiner points [LX07] [LX99]. Furthermore, the diameter of the island and the

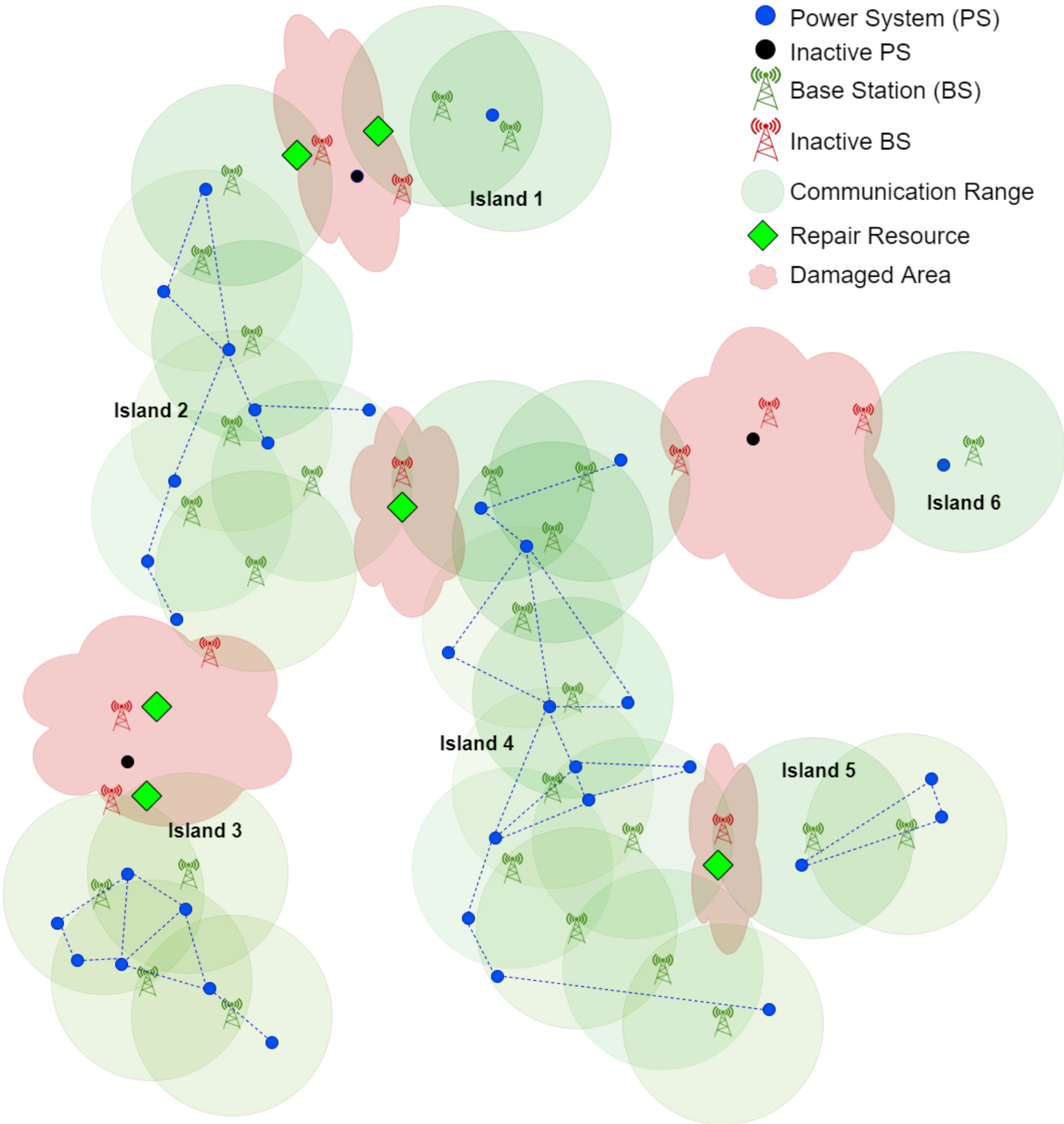

Figure 1.1.: After disaster, whole connected network is partitioned into multiple islands

distance between the two islands may vary depending on the scope of the damage. As a result, representing an island with a single node may deploy more RRs than required.

In comparison with other existing approaches, this thesis considers all nodes of the individual islands in determining the location of RRs for reconnecting islands. It proposed an algorithm inspired by CIST and named it PSA-CIST. The PSA-CIST algorithm not only concentrates on minimizing the required number of RRs (like

CIST) but also tries to maximize the number of PS nodes to be connected by placing those RRs and connecting the islands accordingly. In this study, if there is an inter-island MST edge connecting two islands, then they are regarded as neighbors. In the first step, the PSA-CIST algorithm works like CIST by finding the MST of the network and generating a list "P" of all three islands' subsets, ensuring that one island is a neighbor of the other island [SY11a]. PSA-CIST considers each BS node (Isd^i, Isd^j, and Isd^k) in P and finds a triangle connecting Isd^i, Isd^j, & Isd^k, where each vertices/node of the triangle is on a different island and requires the minimum number of RRs as well as the maximum number of PS nodes connected through RRs for all possible triangles whose vertices are in Isd^i, Isd^j, & Isd^k, respectively. Next, it counts the number of RRs required and the number of PS nodes connected via steinerizing SMT and MST edges. In the next step, PSA-CIST picks the optimal entry in P between the minimum number of RRs required while maximizing the number of PS nodes connected via RRs using the Compromise Programming method and federates the respective islands. In the following iterations, entries with already covered islands are not considered to avoid redundancy. Finally, PSA-CIST federates the remaining disconnected islands via steinerizing specified inter-island MST edges. The simulation results show the significance of the proposed algorithm and give some statistical data that PSA-CIST performs better than CIST.

The main objective of this thesis is to determine the optimal location for the RRs (represented by vibrant green diamond shape) placement in damaged areas in order to connect islands and support PS restoration, as shown in Figure 1.1. Given the interconnected ICT and PS topology, the goal is to:

1. Describe an approach to determine the minimum number and position of repair communication nodes (RRs) required while considering the maximum number of PS nodes to be connected via RRs for restoring inter-island connectivity.
2. Test the approach for the different ICT and PS topologies.

The remainder of the work is as follows: In Chapter 2, state of the art is discussed. Chapter 3 provides a brief overview of Kruskal's MST algorithm, SMT of a triangle, and the fundamental definitions along with the CIST algorithm. The methodology of this thesis consists of system modeling with the problem statement and the proposed PSA-CIST algorithm, along with pseudo code and all assumptions, which are depicted in Chapter 4. Followed by Chapter 5, where the realization and implementation of the PSA-CIST and CIST algorithm are presented. Chapter 6 provides the performance results analyzed with different PS Topologies. Finally, the conclusion obtained from these results is given in Chapter 7, along with future work.