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Blackout prediction in interconnected electric energy systems considering generation re-dispatch and energy curtailment

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HIGHLIGHTS

- Proposing a new approach for predicting and mitigating blackout in power systems.
- Proposing an optimization model to split a power system into isolated islands.
- Developing a blackout predictor using the information gain of input impedance data.
- Splitting an unstable electric energy system with minimum energy curtailment.

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ABSTRACT

Blackouts or cascading outages are costly events that threaten the integrity of electric energy systems around the world. Controlled splitting is executed as the last countermeasure to reduce the undesired economic and social consequences of a blackout. In this paper, a new two-stage scheme is proposed to predict the risk of a blackout in electric energy systems. In the first stage, the boundaries of electric islands are determined using a Mixed Integer Non-Linear Programming model that minimizes the cost of generation re-dispatch and load curtailment. In the second step, a data-mining technique is perfected to predict the risk of electrical separation of an electric island from the rest of the network. Each predictor is trained based on the phasor-measurement data taken at the synchronous generator terminals. Using a wide-area measurement system, the required phasor measurements are gathered and processed in the Energy Management System. Various scenarios, including the island and non-island conditions, are generated and then utilized by the decision-tree classification technique to predict the risk of a blackout. The proposed algorithm is simulated over the IEEE 39-bus test system to demonstrate its performance in online applications.

1. Introduction

1.1. Background and literature review

Energy security is defined as the reliable and uninterrupted supply of energy that is sufficient to meet the needs of the economy, and is at the same time, reasonably priced [1]. Based on this definition, four dimensions of energy security including physical, economic, social, and environmental aspects are defined. In a blackout, as a physical disruption, the electric energy production is stopped temporarily [1]. The supply disruption of an energy source causes damage, and the economic system of a country incurs costs in terms of Gross Domestic Product (GDP) loss [1,2]. The critical infrastructures are directly and interdependently impacted by major power outages. The main undesired consequences of a power outage include traffic paralysis, communication interruption, social disorder, financial and stock-market interruptions, industrial safety issues and damages, government and health-sector issues, water supply and transportation issues, manufacturing concerns, food distribution, etc. [3]. As an example, after the 2003 US and Canada blackout, 61,800 MW of power was lost for up to two days. The total impact on US workers, consumers, and taxpayers was a loss of approximately $6.4 billion directly due to the effects of electric power [4].

Because of economic reasons, electric energy systems are operated near their stable boundaries. Under heavy-load conditions, a severe contingency (i.e., a simultaneous outage of two or more important equipment), may initiate cascading outages and the power system may lose a large amount of equipment. This

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Nomenclature

$\boldsymbol{CR_{ij}}$	correlation ratio between machines i and j
$\boldsymbol{\delta}$	rotor angle of machine
$\boldsymbol{Z}$	impedance
$\boldsymbol{\rho_i^+, \rho_i^-}$	cost of increasing and decreasing power generation at ith node
$\boldsymbol{\Delta P_{G_i}^-}$	incremental generation re-dispatch
$\boldsymbol{\Delta P_{G_i}^+}$	decremental generation re-dispatch
$\boldsymbol{\Delta P_{L_i}}$	load curtailment at *ith* load point
$\boldsymbol{\lambda_i}$	cost of load curtailment at ith node
$\boldsymbol{N_g}$	number of generation units
$\boldsymbol{N_l}$	number of load points
$\boldsymbol{N}$	number of nodes
$\boldsymbol{N_{is}}$	number of electric islands
$\boldsymbol{\Omega^g}$	set of generation units
$\boldsymbol{\Omega^d}$	set of load points
$\boldsymbol{\Omega^l}$	set of transmission lines
$\boldsymbol{P_{Gi}^0}$	initial active power generation at ith node
$\boldsymbol{P_{Li}^0}$	initial consumption at ith node
$\boldsymbol{U_{ij}}$	connecting check binary variable
$\boldsymbol{V_i}$	voltage magnitude of bus i
$\boldsymbol{\theta}$	voltage angle of bus i
$\boldsymbol{Y}$	admittance matrix
$\boldsymbol{m_k}$	arbitrary column in Y_k
$\boldsymbol{n_k}$	dimension of square matrix Y_k
$\lvert \boldsymbol{Z}_1 \rvert$	impedance sample after fault occurrence
$\lvert \boldsymbol{Z}_2 \rvert$	impedance sample before fault clearing
$\lvert \boldsymbol{Z}_3 \rvert$	impedance sample after fault clearing
$\lvert \boldsymbol{Z}_1^w \rvert$	$\lvert Z_1 \rvert$ for West island
$\lvert \boldsymbol{Z}_1^s \rvert$	$\lvert Z_1 \rvert$ for South island
$\lvert \boldsymbol{Z}_1^N \rvert$	$\lvert Z_1 \rvert$ for North island
$F(C_n, D_j)$	frequency of data with negative class
D_j	set of training input data at node j
$F(C_p, D_j)$	frequency of data with positive class
$E_A(D)$	entropy of attribute A over D
$\boldsymbol{Q_{Gi}}$	reactive power generation at ith node
$\boldsymbol{Q_{Li}}$	reactive power load at ith node
$\boldsymbol{P_{ij}}$	the active power flow across line ij
H_i	inertia time constant of ith machine
$\boldsymbol{\omega_{COI}}$	center of Inertia speed
$\boldsymbol{\delta_{COI}}$	center of Inertia rotor angle

situation is a cascading failure, and it may expose the power system to a partial or complete blackout.

This paper focuses on the prediction and mitigation of blackouts, which are key challenges in every energy-management system. The mitigation of a blackout depends on the use of preventive or corrective measures. Preventive measures are considered in power-system expansion planning, and include installation of adequate power plants and transmission circuits. Preventive measures are long-term solutions for blackout mitigation. Different long-term strategies can be implemented to reduce the risk of blackouts, such as integration of distributed generators at load centers [5], demand side management using autonomous polygeneration [6], strategic application of microgrids [7], intelligent multiagent system theories [8], optimal design and operation of distributed energy systems [9,10] and transmission networks [11]. The roles of distributed generators and autonomous microgrids (MGs) in increasing the stability, reliability, and economy of electric energy systems have been discussed in [12–14]. Energy Management Systems (EMSs) have corrective measures for blackout mitigation. Among these measures, the last resort is the intentional splitting of an interconnected power system into stable isolated electric islands. During a cascading failure or blackout, a group of generating units or power plants tends to be electrically separated from the rest of the network. This condition is called uncontrolled islanding and it may cause a blackout due to which many load centers and generation units will be lost. Controlled splitting or islanding is the last corrective measure to avert this cascading failure and reduce the extent of a blackout. Controlled islanding refers to splitting an interconnected power system into a number of stable independent islands at suitable times and proper locations [15]. To have an efficient controlled islanding, the blackout must be predicted before experiencing a critical transition. In each controlled islanding strategy, two different issues: “where to split?” and “when to split?” must be considered. Many approaches have been presented to address the “where to split” issue of a large power system following a widespread contingency. For the “where to split” issue, the proper points of splitting are found using the coherency coefficients of synchronous generators or through combinations of optimization techniques and graph-theory methods [16–21]. For the “when to split” issue, the blackout is predicted using suitable measurements [22–24]. In [22], the time of controlled islanding (i.e., “when to island”) is predicted by a decision tree (DT) using phasor measurements. In [23], a DT-assisted scheme has been presented to determine the timing of controlled islanding in real time using phasor measurements. In [24], the security boundaries are determined by the rules of DTs that are developed from the generated knowledge bases. The previous proposed schemes for the “where to split” aspect act based on the graph theory, without considering the cost of generation re-dispatch or load curtailment. Furthermore, the simultaneous modeling of “where to split” and “when to split” aspects have not been considered in literature. The intention of this paper is to consider both aspects sequentially. The former issue is considered using a Mixed Integer Non-Linear Programming (MINLP) model and the latter issue is implemented using the DT technique. The DT technique predicts the blackout using the impedance measurements at generator terminals.

1.2. Contributions

This paper presents a new two-stage algorithm to predict the risk of a blackout in interconnected power systems. In the first stage, the boundaries of electric islands (i.e., the splitting points) are determined using an MINLP formulation to reduce the cost of generation re-dispatch and load curtailment. The proposed MINLP formulation is an efficient alternative for the graph-based methods. In the second stage, a DT classifier is trained for blackout prediction in each electric island. The proposed classifier predicts the blackouts using the information gained from the input phasor measurements. In other words, the proposed scheme acts as a wide-area blackout predictor that predicts the electric separation of each island from the rest of the network.

1.3. Paper organization

This paper is organized as follows: In Section 2, a simple cascading outage (i.e., blackout) is simulated for a typical two-area test grid. In Section 3, the formulation of the proposed MINLP-based splitting strategy and the fundamentals of the DT classifier are