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A new approach for mitigating blackout risk by blocking minimum critical distance relays

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ABSTRACT

Electric power systems are complex and commonly run near their operational limits. Power systems are basically designed based on the $(N-1)$ criterion. In these systems, total or partial blackouts are unavoidable. Cascading failures following an initial event is recognized as the main mechanism for power system blackouts. Undesirable activation of zone 3 of distance relays due to their local function has been identified as one of the major causes for propagation of cascading failures. In this paper, in order to mitigate the risk of power system blackouts, a novel approach is proposed for recognizing the critical line outages with the highest contribution in cascading failure and preventing their undesirable outage by blocking zone 3 of their distance relay. In this paper, based on the statistical activation of distance relays, a deterministic–probabilistic approach is developed for identifying the critical lines with the highest contribution in blackouts due to activation of zone 3 of their distance relays. In order to avoid interference of relay blocking with the main protection duty of distance relays, the proposed approach recognizes the minimum critical lines with the highest contribution in cascading failure for blocking zone 3 of their distance relays. The proposed approach is demonstrated on the New England 39-bus system and detailed simulation studies carried out to examine the validity and effectiveness of the proposed approach.

Introduction

Electric power systems are intricate and complex systems that commonly run near their operational limits. The phenomenon of cascading failures is a complex process consisting of a sequence of dependent failures of individual components initiating automatically following each other which successively weaken the power system. The potential of cascading failures for propelling system into blackout is recognized as a major threat for system security. The most dominating system characteristic which governs the dynamic of blackout is cascading failure. Modeling the mechanism of cascading failure is very vital for analyzing power system blackouts and utilizing proper remedial actions. Detailed analysis of large blackouts has shown that they involve cascading events in which an initial triggering event activates a series of consecutive failures which may finally lead to blackout of a large area of the grid. For modeling the process of cascading events and simulating dynamic of blackout in power systems, two approaches are possible [1]. The first one is probabilistic approach in which events and process of cascading failures are probabilistically modeled based on the random occurrence of each event. This approach only provides a global understanding of the nature and process of power system dynamic toward blackouts with no detailed insight into the effect of different system components or remedial actions on blackout. In this approach, overall response of the system to such events should be represented [1]. The second one is deterministic approach in which power system components and their behavior are represented with relatively accurate deterministic models. Complete dynamic model of power system requires detailed modeling of system components and their coupling to the rest of the system. Since the physical laws that govern components and their interactions are known, it is possible to simulate the process of cascading events and blackouts. This approach has proven to be effective in evaluating the impact of characteristic of each system component on the system potential for blackout. Also, this approach enables us to examine different remedial actions for reducing the risk of blackout. There are some other approaches for modeling power system blackouts. In [2], power system blackouts are modeled by using DC load flow and standard linear programming optimization of the generation dispatch. In [3], randomly generated tree networks are constructed that abstractly represent influences between idealized components which can be failed or operated according to a Markov model that represents both internal component failure and repair processes and components

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interaction which cause failure propagation. Similarly, [4] has used a Markov model for discrete-state power system nodal components but had failures propagating along the transmission lines of a power network with a fixed probability. DeMarco [5] and Parrilo et al. [6] have addressed the challenging problem of determining cascading failure due to dynamic transients using Lyapunov methods and Karhunen–Loeve and Galerkin model reduction. Transmission Reliability Evaluation of Large-Scale Systems (TRELSS) software is reliability based analysis program which is developed for Electric Power Research Institute (EPRI) for both deterministic and probabilistic studies [7,8]. Brittleness theory is used to analyze the cascading failure of power systems [9]. The objective of cascading failure simulation includes identifying high risk cascading failure processes, evaluating overall risk of cascading failure and the necessary remedial actions. Different objectives impose different requirements with respect to modeling, data, speed, and result processing to get useful outcome [10]. In [11,12], a time domain dynamic simulation based approach using full AC load flow and transient stability calculation including complete model for system components and protection relays is presented for simulating cascading failure and blackout. The main objective is to evaluate the effect of system components characteristics on the process of cascading failure in order to recognize the most critical components and adopting proper remedial actions.

In [13], a new methodology is proposed to distinguish line overloads from actual faults for distance relays. In order to distinguish between line flow transfers from a line outage and an actual fault, the line outage distribution factor and generation shift factor based power flow estimation method, and a secure peer to peer communication structure are adopted. In [14], a non-intrusive agent based relay supervised distance protection scheme is proposed to provide the Zone 3 relays with situational awareness and distinguish a real fault from unreal fault and consequently prevent its undesirable tripping. In [15], a scheme based on the impedance seen by distance relays is presented to calculate zone-3 setting of the relays when faults are simulated on the reach of zone-2 of primary distance relays. In [16], the rare-event simulation technique of splitting to the problem of estimating large-scale blackout probabilities is applied for improving the simulation efficiency in which a stochastic model of cascading line failures is developed. In [17], a new adaptive load encroachment prevention scheme based on steady-state security analysis and adaptive anti-encroachment zone is proposed. The new scheme identifies the vulnerable distance relays through real-time security analysis in order to prevent the undesired tripping. In [18], the analysis and findings of the investigation of the load encroachment phenomena following line overloads after large number of line tripping for the two events that occurred in TNB's (Tenaga Nasional Berhad) Grid in the year 2003 and 2005 are presented. It implies that an examination of the impedance locus trajectory during the overload events have enabled a distinction be made between power swing and load encroachment phenomena. In [19], a novel load blinder scheme for distance protection using artificial neural network is proposed. The proposed ANN-based load blinder scheme is able to discriminate between different heavy loads with a wide range of power factors and different faults with fault resistance. In [20], an intelligent approach is developed to discriminate a fault, stable swing and unstable swing, for preventing undesirable distance relay maloperation using the S-transform and the probabilistic neural network. It focuses on the development of a fast detection of voltage collapse and a three-phase fault at transmission lines by using under impedance fault detector and support vector machine.

In this paper, based on the approach developed in [11], in order to mitigate the potential of cascading failures propelling system to blackout, a deterministic based statistical approach is presented for recognizing the critical lines and blocking undesirable action of their distance relays. For this purpose, with respect to the frequency of undesirable activation of distance relay of each line in the process of cascading failures, a statistical contributing index denoted as Weighted Contributing Order (WCO) is proposed and evaluated. The lines with the highest WCO index are detected as the critical lines whose outage contributes in most blackout scenarios. By blocking undesirable action of the distance relay of the critical lines, their contribution in cascading failures will be restricted which result in reducing the potential of cascading failure for propagation and leading to blackout.

Cascading failure

Cascading failure is the main mechanism for developing large blackouts in electric power systems. Here the term "failure" refers to the outage of power system components due to the action of protection relays for avoiding local damage to the components. System potential for triggering and continuing the process of cascading failures following an initial event is recognized as the risk of power systems for blackout. The preventive methods for mitigating risk of cascading failure are not well developed. Some insights and methods for a statistical analysis of cascading failure are starting to emerge [21]. Large blackouts typically involve many complex phenomena of power system, therefore, the current tools focusing only on a single process like line outage, cannot capture all the interactions contributing in cascading failures. Analyzing all possible processes and interactions in complete detail is a very difficult task. Incorporating power system dynamic stability, components limit, function of relays, operator actions and complex system effects in the mechanism of cascading failure remain as a challenging task [10]. The process of cascading failure is triggered and propagated based on the following characteristics of power systems.

(1) Brittleness and vulnerability of system components due to limit violations is the first step of cascading failure following an initial event. Line overloading, voltage drop, frequency deviation, generator speed deviation, rotor angle swing and power swing are known as the main limit violations.
(2) Protection relays play a very important role in triggering new component outage leading to propagation of cascading events. The main cause for triggering new outage following an initial event is relay function tripping violated elements to avoid local damage. Therefore, limit violation by system components accompanied by relay action constitute the main cause for propagating cascading failure.
(3) On the developed stages of cascading failures, splitting power network into unstable islands can propel power system into blackout.

In fact, the process of cascading failure is relatively slow at its initial stage, but by developing and contributing more components in the process, it speeds up and becomes disastrous for system security.

In this paper, for modeling mechanism of cascading failures leading to blackout, by using simulation approach developed in [11], cascading failure propagation is automatically simulated by self-triggering events as a result of protective relays activation due to violation of system operating limits. For this purpose, following each initial fault and other consequent failures, by means of time domain transient stability calculation including both fast and slow response dynamic of power system components, the dynamic behavior of power system is evaluated. Line power oscillation, voltage drop, frequency deviation and voltage and rotor angle instabilities caused by failures are the main causes for activation