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Review Article

Survey of Power System Restoration Documents Issued from 2016 to 2021

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More than thirty-six partial or whole blackouts, from 2016 to 2021, prove that neither the probability of blackouts can be ignored nor the required plans and the readiness of the utilities for power system restoration can be forgotten. To properly deal with blackouts and minimize the social and economic costs, utilities should prepare a suitable restoration plan in advance to quickly restore the system to the normal state and minimize the restoration time and loss of energy. In this paper, after summarizing major blackouts occurred from 2016 to 2021, the progress in the research reports, industrial documents, and books in the context of power system restoration is reviewed to show and classify the different aspects of power system restoration plans and strategies presented during these years. This review indicates that although there are many published methods and techniques which have tried to give more autonomous solutions, there are still more complexities in power system restoration. However, this paper respects all efforts and attempts and tries to illustrate the achievements, up to now, in power system restoration, as well as research gaps.

1. Introduction

Nowadays, the reduction in power system stability margin, which is a result of the operation of these networks in the market environment and close to the system operating limits, causes utilities to prepare remedial action schemes to deal with major blackouts. Obviously, to properly deal with blackouts and minimize the social and economic impacts of these incidents, a proper restoration plan should be proposed in advance to quickly restore the system to a normal state and minimize the loss of energy. However, several widespread blackouts over the world, such as those mentioned in Table 1, during recent years, show that although such defense plans may improve the stability stiffness, they cannot guarantee stability under high order N-k conditions. The main reason for this drawback is that power system restoration is a complex process and a large number of variables/constraints affect the restoration at each step of the restoration procedure. Consequently, designing the proper restoration plan, not only requires a large number of dynamic simulations to consider the different power system structures (considering equipment availability) and the operating points, but also requires making wise decisions to properly change the operating status to the normal state.

Absolutely, there is not a unique definition for blackout state. Based on the suggestion proposed in [1], for the Ireland grid, a loss of 50% of loads or loss of voltage across the transmission system for more than three minutes indicates that the system is in the blackout state [1]. Generally, a partial or total blackout may cause millions of people to lose power. However, if a blackout lasts several hours, the emergency power supplies of critical infrastructure will become out of service due to lack of supplies and the social and economic costs of the incident will increase significantly [2].

In this respect, to minimize the impact of the power system blackout which is a low probability-high impact incident, transmission system operators (TSOs) should

Table 1: Some major blackouts happened since 2016 up to 2021.

	Date	Country	Severity/affected people	Reason
1	3/3/2016	Sri Lanka	10 million people/16 hours	A severe thunderstorm
2	6/7/2016	Kenya	10 million people/4 hours	A monkey entered to a power station
3	9/1/2016	USA	100,000 customers	Hurricane Hermine
4	9/21/2016	Puerto Rico	Total blackout/2 days	Failure of a power plant
5	9/28/2016	Australia	850000 customers/1826 MW	Two 275 kV line outage due to tornado
6	3/1/2017	USA	21 million people/11 hours	Cascading failure in transmission system
7	3/8/2017	USA	750000 customers	Wind storm rolled through Michigan
8	8/15/2017	Taiwan	1.54 million customers/3.36 GW	Power plant outage
9	8/26/2017	Uruguay	3.4 million people/4 hours	Bad weather condition caused cascading failures
10	9/10/2017	USA	7.6 million people/5 hours	Transmission line tripping and cascading events
11	9/16/2017	Puerto Rico	Total blackout	Hurricane Maria
12	10/30/2017	New England	0.2 million people	Bad weather condition
13	1/10/2018	Sudan	Total blackout	Cascading failures
14	3/2/2018	USA	2 million people	Power failure
15	3/21/2018	Brazil	10 million people//21735 MW/1 hour	Incorrect OC relay's setting in an HVDC substation
16	4/18/2018	Puerto Rico	3 million people/24 hours	Unintentional strike to a transmission line
17	7/3/2018	Azerbaijan	8 million people/8 hours	Unexpectedly high temperatures
18	9/6/2018	Japan	3000 MW/45 hours	Shutdown of generation units in two power plants due to the earthquake with a magnitude of 6.7
19	9/21/2018	Canada	100,000 customers/1 day	Six tornadoes in the Ottawa-Gatineau region
20	12/4/2018	Canada	1400 MW/200,000 customers/several hours	transmission line failures due to the frost build up on shield wires
21	12/20/2018	Canada	0.6 million people/4 hours	Equipment damage due to the wind
22	3/7/2019	Venezuelan	200 million people/10 days	Short circuit occurrence
23	6/16/2019	Argentina Uruguay Paraguay	48 million people/one day	Not available
24	7/19/2019	USA	277000 people/2 days	Storm
25	8/4/2019	Indonesia	20 million people/1 day	Short circuit on a transmission line
26	8/9/2019	England and Wales	One million people/10 days	Lightning
27	9/1/2019	Canada	489,000 customers/1 day	Hurricane Dorian
28	11/1/2019	USA, Canada	2,964,000 people	Storm
29	8/3/2020	USA	6.4 million customers/a few days	Hurricane Isaias

Table 1: Continued.

	Date	Country	Severity/affected people	Reason
30	8/10/2020	USA	1 million customers/48 hours	Derecho event
31	10/12/2020	India	Massive power outage (exact power outage is not available)	Multiple tripping of lines due to cyber-sabotage attempt
32	1/9/2021	Pakistan	Total blackout	Cascading line outage
33	/2/2021	USA	5 million people	Storm
34	5/21/2021	Jordan	Total blackout	Fault in the Jordanian-Egyptian tie-line
35	5/25/2021	Australia	400,000 customers	Fire at a power station
36	8/11/2021	USA	840,000	Storm

perform a timely restoration plan to restore the system quickly to the normal state and minimize the restoration time and loss of energy, which can be used as metric to determine the damage caused by a blackout [2].

However, due to the crisis of the time, the need of selecting the optimum action during the process of energizing equipment, and the necessity to consider different aspects of the network operation, power system restoration becomes a complicated procedure. Especially, since power system restoration lasts several hours, some parts of the restoration plan are usually performed in the daylight and others during the night hours. Therefore, appropriate restoration plans should be prepared in advance to determine optimum restoration trajectory under different topological, weather, and variable loading conditions. Obviously, as mentioned in [3], improving the system modeling, installing the required measurement devices, and improving the operators' training program will speed up the restoration process while enhancing the reliability of the restoration plan and improving the operating condition to satisfy the required steady-state, dynamic, and electromagnetic constraints.

When a small-scale or partial blackout happens, the restoration process can be performed using energized neighboring networks. In such a condition, the ability of adjacent networks in absorbing excessive reactive power (generated by energized transmission lines) as well as their sufficient short circuit capability for equipment energization will maintain the voltage and frequency within acceptable limits, prevent the operation of protective relays, and facilitate the restoration process.

However, when the restoration process begins using cranking power provided by a black-start unit, maintaining load-generation balance, energizing long transmission lines under no-load or low-loading conditions, and transformers or motor energization using limited generation capacity (compared to network recovery by neighboring network) will be more difficult. In such a condition, the self-excitation phenomenon after line energization, excessive under voltage (due to inrush current flowing) or overvoltage (due to the harmonic resonance) after transformer energization, or undervoltage condition after a motor or load energization (especially with high cold load pickup current) may result in equipment damage and cause the protective relays to operate, which may make the restoration to fail or take more time.

Generally, power system restoration approaches may be treated under three stages. First, in the black-start stage, the black-start unit (or the neighboring energized network) is used to build an optimum energized path to the best nonblack start unit (NBSU) with a sufficient capacity to supply the cranking power and restore the NBSU to continue the restoration process. Then, in the network reconfiguration stage, the power generation capacity provided by NBSU is used to connect other transmission lines and substations to the energized subsystem and build optimum paths to restore other NBSUs to maximize the generation capacity. Finally, when the skeleton network is created, the load restoration stage starts in which, those loads which have not been energized in the first two stages will be restored.

Consequently, the restoration of a power system to a normal operating state is a complicated decision-making problem with various constraints. Therefore, it is of great importance to select the optimum restoration plan to bring the network back to a normal condition as soon as possible and minimize the blackout costs. In this respect, a great deal of research works has been published during the last years on power system restoration, each of which has its own characteristics and covers a part of the power system restoration studies. Although some recent studies about the second stage of the power system restoration have been reviewed in [4] and a literature review of methods published from 2006 to 2016 can be found in [5], it seems that a more comprehensive review is required. Therefore, in this paper, recent progress in power system restoration studies will be comprehensively reviewed to summarize and categorize the research works published from 2016 to 2021, while neglecting distribution system restoration. Figure 1 shows an overview of 110 power system restoration documents reviewed in this paper divided into three categories: (1) books, (2) industrial documents, and (3) papers.

The rest of this paper has the following structure. Before proceeding to published papers, Section 2 covers the review of the contents of few books in this area, and Section 3 introduces unclassified documents issued by utilities and/or standards. These two sections are document-based, but the

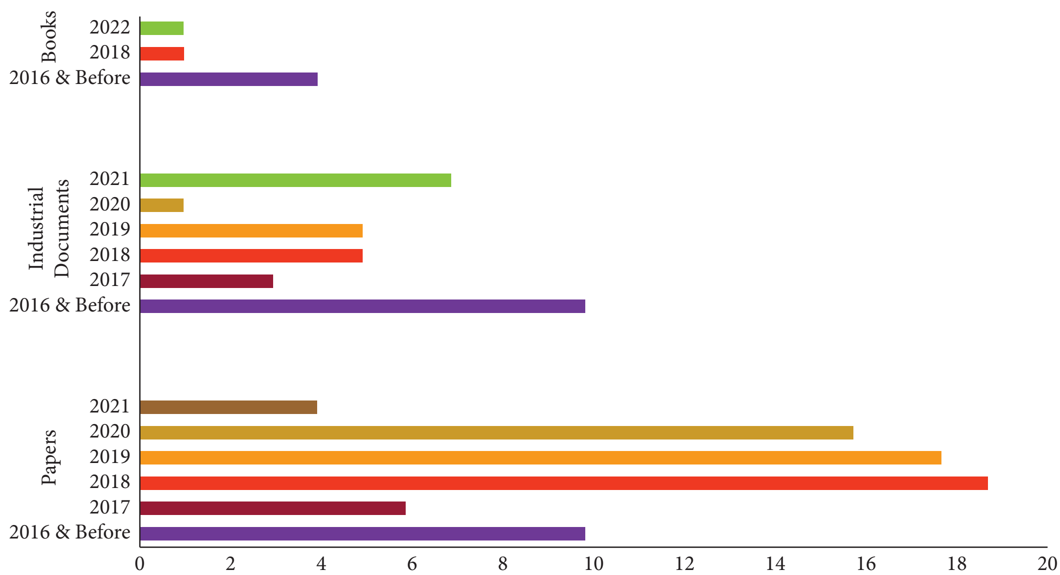


Figure 1: An overview of the reviewed documents in this paper.

rest are topic-based. Sections 4 to 8 review the selected papers in categorized restoration topics including "Restoration Issues," "Availability Assessment of Equipment," "Restoration Plan," "Application of Software Tools," and "Application of Renewable and VSC based Resources," respectively. To categorize the reviewed documents in summary, they are formed in Tables in Section 9. The paper finally concludes after mentioning some research gaps related to power system restoration in Section 10.

2. Restoration in Books

Although, the original purpose of books with a general title of power system operation and control is to introduce engineering and economic issues related to the planning, operating, and controlling of power generation, transmission, and distribution systems in electric utilities; it can be stated that the issue of restoration is a forgotten topic in textbooks of the power system operation and control. According to [6], in 1994, "System operating conditions classified into five states: normal, alert, emergency, in extremis, and restorative and the restorative state represents a condition in which control action is being taken to reconnect all the facilities and to restore system load," and this is the only explanation available in all textbooks related to power system operation.

Besides power system operation books, a single book with a title including restoration and three books with separate chapters on restoration have been yet published as follows (in the order of publication year):

(1) The first restoration textbook was published in 2000 by Adibi as "Power System Restoration: Methodologies and Implementation Strategies [7]." This is a review book, which includes 87 papers on restoration in seven chapters, the title of each chapter is devoted to a basic issue of restoration, i.e., Chapter One: Restoration Overview; Chapter Two: Restoration Techniques; Chapter Three: Restoration Planning; Chapter Four: Restoration Training; Chapter Five: Specific System Restoration; Chapter Six: Knowledge-Based Systems; Chapter Seven: Distribution System Restoration.

(2) The last chapter of "EPRI Power System Dynamics Tutorial," entitled "Power System Restoration," is the second reference in the power system restoration that was released in 2009 [8]. The aim of this chapter is to give (1) Causes of blackouts, (2) Theory of power system restoration, (3) Technical aspects during restoration (theory and practice) including: voltage control, frequency control, and islands synchronizing, (4) Equipment issues related to restoration, (5) Power system restoration frequency asked questions, and above all (6) Lessons learned from actual restoration events: getting ready for the next problem with: backup power sources, black-start generators, circuit breakers, telecommunications, DC control circuitry and interlock schemes, EMS Man-Machine Interface (MMI), protective relays (hardware problems, mal-operation problems, unforeseen problems during restoration process), frequency control process, and voltage control process.

(3) "Restoration of the Electric Power System after an Attack" is the name of the seventh chapter of the book entitled "Terrorism and the Electric Power Delivery System" which was published in 2012 [9]. In this chapter, after enumerating the difference between blackouts by terrorist attacks and by system disturbances or natural events (such as damage to target key substations in a terrorist attack compared to damage to several substations in an earthquake), the complexities of the restoration plan in the event of an attack and in some cases conflict of interests are given. For example, the conflict between rapid restoration and careful study

of a crime scene could result in a serious delay in the restoration process. Solutions to prepare for restoration after a terrorist attack include: (1) identifying power system vulnerabilities and planning for restoration after an attack, (2) providing communication protocols and developing official MOUs to improve working relationships between different entities such as utilities, federal and state governments, public, and law enforcement agencies during restoration, (3) developing and encouraging use of distribution automation and deployment of distributed generation and planning for the use of these facilities in the event of loss of transmission and generation sectors.

(4) "Power System Control Under Cascading Failures: Understanding, Mitigation, and System Restoration" is the title of the third book written by the authors from universities on the importance of power restoration which was published in 2018 [10]. The topics covered in this book are: (1) black-start requirements including constraints during black start, capability assessment, and theoretical fundamentals for optimal installation of BS, (2) hard and soft constraints during restoration including constraints on the infrastructure of power system, and technical constraints in voltage and frequency control studies, capability assessment of generators and self-excitation analysis, transformer energization studies, (3) mathematical restoration algorithms for restoring nonblack start generation units, transmission lines and loads, (4) the effect and importance of renewable energy integration and energy storages in power system restoration and problem formulation with their participation, and finally (5) application of recent technologies in transmission systems such as FACTS, HVDC, and PMU for restoration.

Also, a book entitled "Principles and Practices of Restoration" (in Persian) has been released in 2022 by the authors from universities and industry [11]. This book in nine chapters provides:

(i) Basic concepts in restoration including definition, goals in power system restoration, and reviews the main causes of last blackouts in the world and their restoration process.

(ii) Management principals in restoration, including restoration process, restoration technique, restoration plan, restoration priorities, restoration documents and their contents, restoration support systems, restoration training courses, and restoration table tops.

(iii) Restoration technical considerations in planning (theory and practice with lookup tables) and operation stages (practice with rule of thumb and lookup tables), including black start and self-excitation, voltage and reactive control, frequency control and active power balance, cold load pickup and protection, synchronizing islands.

(iv) A case study of restoration plan including: step by step restoration procedure to restore nonblack start generation units, transmission systems and getting ready to synchronize with neighboring islands.

3. Restoration Guidelines by Utilities

Restoration is inherently a complex process and requires a lot of preparation and coordination between different entities. In this framework, specific instructions and procedures must be prepared in advance and trained and practiced in order to achieve the goals with effective and timely executive management and communication with considering technical conditions.

Accordingly, in all utilities, there are guidelines and standards that specify, how to formulate and implement restoration programs and their requirements, the responsibilities of individuals and various organizations related to restoration, training contents and programs for personnel, and finally evaluating programs and equipment. In these documents, usually, general principles of restoration, definitions and minimum requirements are available to the public, and power system restoration programs are classified documents and are not available to the public.

Restoration documents are usually released as standalone references [12–31] and in some cases as a set of requirements in Grid Codes [32–34].

There are several names for restoration documents such as (1) Electric System Restoration Reference Document [12], (2) Establish, Maintain, and Document a Regional Black start Capability Plan [13], (3) System Restoration Procedure [14], (4) System Restoration Coordination [15], (5) Execution method of Black start test [16], (6) Network Code on Emergency and Restoration Network of Transmission System Operators for Electricity [17], (7) Emergency Operations [18], (8) General principles for restoration of the main electricity network [19], (9) System Restoration Manual [20, 29], (10) System Restoration from Black start Resources [21], (11) Energy system restoration plan [1, 22], (12) Restoration Best Practices Guidebook [23], (13) System Restoration-Regional Reliability Reference Directory [24, 28], (14) System Restoration Plan [25, 26], (15) Executive method for restoration of the main electricity network [27], (16) Reliability Coordinator Area Restoration Plan [30], and (17) Electricity System Restoration Standard [31].

Although the main purpose of all restoration procedures is the same, there are different goals in preparing restoration documents, such as

(i) To present the requirements that each functional entity shall follow in order to perform bulk power system restoration [24]

(ii) To provide general guidelines to be followed in the event of a partial or complete collapse of any of the interconnected electric systems (in a continent) [12]

(iii) To ensure security and continuity of electricity supply (across neighboring countries) by creating harmonized standards and procedures to be applied in the emergency, blackout, and restoration system state(s) [25]

(iv) To reduce restoration time (for a power grid) and ensure a consistent approach across all regions [31]

(v) To ensure the preparation of plans, facilities, and personnel to enable system restoration from black-start resources during restoration [21]

(vi) To maintain the adequacy of the quantity and location of system black-start generators to meet their expected functions as specified in overall coordinated Regional System Restoration Plans [13]

Restoration documents have audiences, including references [12–25] and [26–37]:

(i) Transmission Owners and Transmission Operators
(ii) Neighboring TSOs and the other TSOs in a Synchronous Area
(iii) Generator Owners and Generator Operators
(iv) Distribution Providers and Distribution System Operators (DSOs)
(v) Significant Grid Users (SGUs)
(vi) National Regulatory Authorities
(vii) Reliability Coordinators
(viii) Defense and Restoration Service Providers
(ix) Market participants

Usually, restoration documents include the following headings:

(i) Philosophies and strategies for restoration
(ii) Guidelines about "Human resource management and training," i.e., Role definition, Responsibilities, Communication facilities, Communication protocol with government agencies, Regulators, General public and other operating entities, Tabletop exercise
(iii) Guidelines about "System restoration plan," i.e., Ascertaining System Status, Determining Restoration Process, Disseminating System Status Information, Implementing Restoration Process, Frequency Control, Verify Switching Equipment Constraints, Guidelines for Area Interconnection and Use of External Power during System Restoration, and System Control Progress
(iv) Guidelines about "Ascertaining System Status," i.e., after a blackout, determining transmission, generation, and communication loss, equipment damage, and the extent of the service interruption and during the restoration monitoring electrical parameters
(v) Guidelines about "Black start," i.e., Black Start Capability, Black Start Test, and Block Load Capability
(vi) Guidelines about "Island," i.e., Establish Island, Expand Power Islands, and finally Synchronizing of Islands
(vii) Guidelines about "Transmission restorations," or "Voltage management"
(viii) Guidelines about "Load and Generation restorations" or "Frequency management"
(ix) Guidelines about "Contingency plans for failed restoration scenario"

Utilities, inevitably, review, and update their issued documents, periodically. This updating period varies from at least once every three years up to every year, with urgent conditions for reviewing and improving documents after identifying any unplanned permanent system modifications, or prior to implementing a planned Bulk Electric System (BES) modification that would change the implementation of its restoration procedure.

4. Power Systems Restoration Issues

During the normal operation, power systems usually absorb major disturbances occurred occasionally and maintain the operating point inside the stable region. However, during the restoration procedure, especially in the black-start stage, the limited generation capacity may cause the energized network not to withstand successive changes in the system configuration and loading. In this respect, considering the lessons learned from power system restoration procedures in different power systems [38, 39], accurate electromagnetic, dynamic, and static studies should be performed to analyze the impact of each action (like transformer or line switching) on the protection system, and the stability and security of the network. Therefore, in this section, power system restoration issues will be reviewed.

4.1. Transmission Lines Energization. Generally, in black-start and network reconfiguration stages, the power system operates at low-loading conditions to allocate as much power as possible to auxiliary loads in order to crank NBSUs. In this respect, when a transmission line is energized, the voltage may rise which should be managed to avoid equipment damage (e.g., as a rule of thumb the voltage rise is 1 kV for every 4 MVAr charging current [26]). Such voltage rise depends on the impedance from the line to the generation, charging current, and excitation system of generation units [26]. However, based on the power flow analysis, the voltage rise is usually controlled by reducing the generators terminal voltages [40]. For example, in the restoration plan for the Ireland grid [1], it has been suggested to energize transmission lines when the voltage is about 0.9 p.u.

Also, before the energization of a transmission line, the capability curve of generators should be checked to assure that the generation units have sufficient capability in absorbing the excessive reactive power (usually more than 120% of the reactive power generated by the transmission line [26]). However, it should be noted that reactive power absorption should not cause the underexcitation protection to trip the unit (especially in the black-start stage, where the black-start unit with a limited generation capacity solely energizes transmission lines and cranks NBSU). For this purpose, sufficient load or shunt reactors should be switched on to control the reactive power absorption of generators.

Moreover, detailed electromagnetic studies should be performed to check that the line switching does not lead to harmonic resonance, and also, switching overvoltages is below the acceptable limit [40]. In this respect, a simple algorithm has been proposed in [41] to analyze different factors affecting the overvoltage caused by closing an unloaded transmission line.

4.2. Transformers Energization. Against transmission lines energization which leads to voltage rise, transformer switching may result in under voltage (due to the inrush current) or harmonic resonance overvoltage emerging due to the nonlinear interaction between the transformer core (especially with high residual flux) and lines.

In this respect, [42] tried to predict these temporary overvoltages using an artificial neural network classifier. It is worth noting that the transformer residual flux highly affects the nonlinear behavior of the transformer core and is unpredictable. The network under restoration condition has a low damping ratio resulting in prolonged overvoltages with respect to normal power networks. Therefore, the worst-case should be determined through detailed electromagnetic simulations to accurately analyze the impact of transformer energization in the restoration state [33].

Moreover, an arrester explosion has happened during the black start of a 250 MW generation unit in the Iranian national grid [43], and also, the detailed electromagnetic simulation results presented in [44] (in which the nonlinear behavior of transformer core is modeled using three different models described in References [45–47]) show that the effect of transformer switching transients may result in the explosion of the arrester. Therefore, effective countermeasures (such as controlled switching [48]) should be applied in order to control the overvoltages and keep the arrester safe.

4.3. Self-Excitation of Synchronous Generator. Under normal operation of synchronous generators, the angle λ between rotor field winding MMF and armature reaction MMF is $\pi/2 < \lambda < \pi$. However, during system restoration, the lightly loaded condition causes the generator to absorb reactive power and these MMFs nearly align in the same direction. Therefore, the resultant MMF (and also the terminal voltage and the reactive power generation of lightly loaded transmission lines) will increase, which pushes the generator operating condition towards severe underexcitation mode. This condition may cause the under-excitation protection to trip the generator and the restoration process fails.

In [49], based on data measurements obtained from the self-excitation incident that occurred in the Finnish 400 kV grid, synchronous generator self-excitation during power system restoration has been analyzed. According to this research work, generator, line, and excitation system parameters, as well as the protective relays settings significantly affect the electromagnetic simulations results. Therefore, sufficient safe margins should be considered to determine reliable restoration plans.

It is worth mentioning that a high underexcitation limiter setting decreases the capability of reactive power absorption. On the other hand, a low setting will reduce the synchronizing torque and damping torque. Therefore, the underexcitation limiter setting should be defined carefully [49, 50], at least in power system restoration process.

4.4. Black Start Unit Requirement to Crank NBSU. To bring power system from blackout state back to normal state, black-start units are located in different areas (to be able to perform parallel, bottom-up, and restoration strategy) and are usually a mix of hydroelectric, gas turbine, or diesel power plants (which require low cranking power and have low start-up time). These units which must be available most of the hours in a year (more than 98% as mentioned in [38]) are able to start-up without any external supply within a specified time limit (e.g., less than 30 minutes for hydroelectric and gas turbine power plants mentioned in References. [1, 38]), have sufficient active and reactive power capability to energize several transmission lines and transformers, in order to build the defined cranking path and provide the cranking power to NBSU(s).

Nevertheless, at the black-start stage, due to the limited reactive power absorption and low short circuit capability of the black-start unit, an unpredicted high voltage rise, switching overvoltage, or inrush current may cause the system to recollapse [39, 51]. Therefore, [38] suggests that the black-start unit should be able to complete three black-start processes in eight hours.

On the other hand, the periodic maintenance and test of black-start units cost high, which show that these units should be selected carefully. Therefore, Reference [52] formulates an optimization problem to allocate black-start units, while simultaneously optimizing the restoration plan. For this purpose, a two-stage stochastic program has been solved in which, considering different initial states (i.e., stable islands) of the system after a blackout, the black-start unit allocation is determined in the first stage and the second stage defines the restoration actions.

However, it is worth mentioning that when a number of NBSU are energized, the reactive power absorption, short circuit capacity, system inertia, and active and reactive power reserve of the energized system will increase, which simplifies the subsequent restoration actions [39].

5. Availability Assessment of Equipment for Power System Restoration

Following a major disturbance that causes the system blackout, the blackout area is determined. Then, based on the affected area, an appropriate restoration plan is selected as soon as possible and the restoration starts. In this respect, the determination of equipment availability plays an important role in formulating an effective restoration process.

Equipment availability assessment methods may be divided into two categories, where the first uses historical data to determine a statistical model of equipment availability and the second employs a physical model of the disaster [53].

However, as described in [53], neither of them can appropriately determine the availability of transmission lines after natural disasters. In this respect, in [53], the transmission lines availability is determined using data obtained from the sequence of event records of protective relays which include relay pickup information. For this purpose, two correlation models between the relays operation and lines availability have been proposed which are applied to the differential, distance, and bus bar backup relays. Then using real-time records of the sequence of events, the availability of transmission lines is determined in real-time.

Also, in [54], to improve the system restoration plan after a natural disaster resulted in system blackout, an image processing method, i.e., edge-detection, is used to analyze the satellite images obtained before and after the disaster. Then, these analyzed images have been used by a trained artificial intelligence-based classifier to detect damages probably caused by the disaster.

Furthermore, in [55], the availability of equipment has been estimated to propose a case-sensitive restoration process (i.e., a plan that considers the blackout characteristics like fault information and weather condition). In this respect, the forced outage rate (FOR) has been calculated based on the historical records to determine the availability of equipment. Also, fault diagnosis results calculated based on the alarms of protective relays and an optimization problem have been used to determine the impact of the occurred fault on the availability of equipment. Moreover, an exponential distribution function has been used to estimate the survivability of equipment against a severe weather disaster. Finally, equipment availability has been estimated based on the combination of the above-mentioned equipment availability values to determine an effective restoration plan.

It is worth mentioning that following widespread incident which causes the loss of the network observability, an optimal plan to recover PMUs is inevitable. Therefore, to quickly restore the observability, in [56], the concept of the optimal PMUs sequential restoration plan has been proposed. Also, in this paper, using different objective functions in a mixed integer linear programming problem, the efficiency of the proposed method to improve observability over the restoration time has been assessed.

6. Power System Restoration Plan

After a blackout, TSO analyzes the system state to determine whether a total or partial blackout has occurred. After a total blackout, the "bottom-up" strategy (named "build up" or "build outward," as well, with some argue about how to manage the cranking power) is usually used, by which the system is partitioned into a number of islands and in each island, the black-start units generate the cranking power to restart NBSUs and energize these islands in parallel (as shown in Figure 2). Although this parallel energization will accelerate the restoration process, the time for connecting (synchronizing) these islands and retaining the integrity of the system should be considered.

On the other hand, after a partial blackout, neighboring-energized areas (solely or in combination with black-start units) are usually used in a "top-down" strategy (named "build down" or "build inward," as well, with some argue about how to manage the cranking path) to energize main transmission lines and substations and restore the grid, as shown in Figure 3.

In this respect, most of the research works proposed during the last years have tried to improve the network reconfiguration process in bottom-up or top-down or combined strategies and minimize the restoration time.

In the following subsections, based on the main stages of power system restoration, i.e., black start, network reconfiguration, and load restoration, the recent studies will be reviewed.

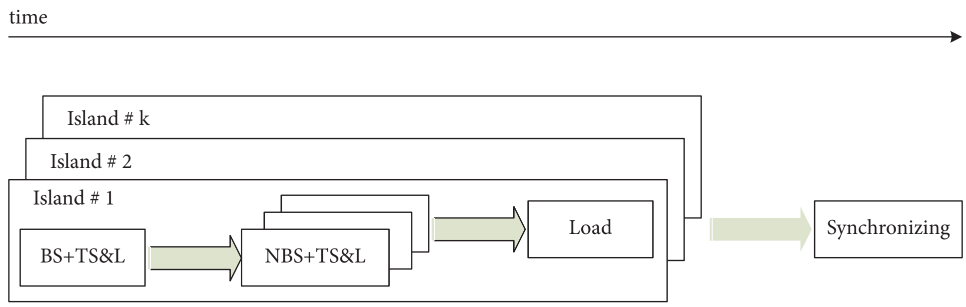
6.1. Black Start

6.1.1. Black Start Source Selection. The first step in preparing a power system to perform a successful restoration procedure is to determine the type and location of black-start sources. Since employing a unit as a black-start source is costly, special attention should be paid, in the planning stage, to select accurately the black-start unit location and type. In this respect, in [57], different types of black-start units, including gas-fired and hydropower, have been compared. Also, it has shown the efficiency of the waste-to-energy plant to participate in a restoration process.

Also, since the efficiency of selecting black-start sources depends on the restoration path, in [52], a new modeling approach and an optimization problem have been proposed and formulated by which, the allocation of black-start units and obtaining a proper energization sequence have been considered, simultaneously.

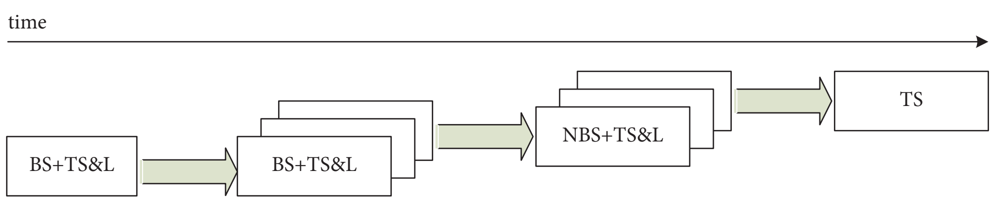
6.1.2. Islanding Strategy. In [58], an efficient sectionalizing scheme for parallel restoration has been proposed. For this purpose, the number of islands has been considered to be equal to the number of black-start units. Besides, the minimum spanning tree (which is, generally, a subset of a network that connects all nodes using branches with the minimum total weights) has been used to determine the skeleton network. Then, based on this skeleton network and the operating constraint of a power system in restoration condition (including black-start ability, minimum output of generating units, and load-generation balance), boundary lines among islands have been identified.

Also, [59] has proposed a sectionalizing procedure for parallel bottom-up restoration of power systems. For this purpose, the system topology has been used to generate a graph where the weight of a branch shows the active power passing through the related transmission line. Then, the terminals of black-start units have been marked with different subsystem labels and these labels propagate to neighboring nodes based on an improved label propagation



BS: Black Start
TS&L: Minor transmission system energizing and minor load restoration
NBS: Non-Black Start generation resource restoration
Load: Major load restoration
Synchronizing: Islands synchronizing

Figure 2: Bottom-up strategy scheme.



BS: Black Start
TS&L: Minor transmission system energizing and minor load restoration
NBS: Non-Black Start generation resource restoration
TS: Major transmission system energizing

Figure 3: Top-down strategy scheme.

matrix. Finally, a refining algorithm has been applied to minimize the power exchange between subsystems, and also, to assure that the obtained islands satisfy the constraints.

Similarly, [60] has proposed a parallel restoration strategy, in which a modified label propagation algorithm with low complexity is used to divide the system into islands to perform a restoration procedure based on the bottom-up strategy.

In Reference [61], an optimization problem has been proposed, solved by discrete particle swarm optimization (DPSO) approach, to sectionalize the network so that the number of tie-lines between islands is minimum. In this islanding strategy, NBSUs are located in different islands, minimum output power constraint of generation units and power flow constraints are considered, and the active power imbalance in each island should be lower than a specified threshold. However, it should be noted that due to the high dimension of the restoration problem, artificial intelligence optimization tools may converge to local optima. Therefore, in [62, 63], considering different constraints, the path optimization problem has been solved by the orthogonal genetic algorithm. The main advantage of this algorithm is that it uses an orthogonal generation of the initial population and orthogonal crossover to thoroughly search the solution space to obtain optimal results.

Besides, for intentional-controlled islanding and black-start allocation, [64] has proposed three different mixed integer program formulations, MIP (i.e., single-commodity flow formulation, multicommodity flow formulation, and a new cut-set formulation), to formulate island energization constraint (to assure that each island contains black-start unit to restore the system without applying power flow equations in the optimization problem), and comparing their efficiency in terms of linear programming relaxation and the computational burden.

Additionally, [65] has proposed a three-step power system partitioning method that minimizes the load-generation imbalance at each island while maintaining stability. For this purpose, firstly, based on the system topology, an undirected graph is created. Then, using the Dijkstra algorithm, the shortest paths from black-start units to NBSUs are determined and those buses that belong to the shortest path will be located in the same island. Finally, at the last step, the obtained islands are changed to minimize the load-generation imbalance.

Furthermore, [66] has proposed a heuristic-based strategy to determine optimum cut-sets to balance the restoration time of islands. For this purpose, the generators are separated into groups (islands) so that each island has almost similar generation capacity and size (i.e., the number of nodes). Then, considering prespecified energization time for each equipment, the proposed method tries to divide the network into islands with as similar restoration time as possible. The procedure is repeated for different values for the number of islands and the best value is used to determine the ultimate islands. Similarly, to deal with the significant number of possible islands, [67] has proposed a method that firstly, using a heuristic technique determines the initial solutions which will guide the discrete Artificial Bee Colony method to determine the optimum solution. The objective function used in this method is to minimize the restoration time by determining islands with identical energizing time and also, to minimize the number of tie-lines to shorten the time required to synchronize the selected islands.

Furthermore, [68, 69] have proposed simplified partitioning procedures, which divide the network into a number of islands based on an optimization problem and virus propagation model-based method, respectively.

6.2. Network Reconfiguration. After a black-start unit creates an energized path and delivers the cranking power to NBSU, the generation capacity will increase. This is utilized in the network reconfiguration stage to restore other generators, build the skeleton network including main substations and branches, and make the system ready for the last stage in the power system restoration process, i.e., load restoration. To achieve this goal, in the network reconfiguration stage, which significantly affects the restoration time, an optimized restoration procedure should be followed to assure successful restoration and minimize the probability of recollapse. In this section, recent studies proposed for network reconfiguration are reviewed.

6.2.1. Optimization of Generators Start-Up Sequence and Restoration Path. The main objective of power system restoration is to reconfigure the network and get the operating point back to a normal state as soon as possible. For this purpose, determining an optimal restoration path (sequence) and energizing the skeleton network to make the system ready for the load restoration stage, significantly affect the feasibility and efficiency of the restoration plan.

In this respect, there are plenty of research works that dealt with the determination of the generators start-up sequence or the restoration path. In such research works, a graph theory-based restoration plan has been usually used. For example, in [70], a simple restoration plan has been proposed in which a Dijkstra-based approach is used to define the power system restoration plan. In addition, [71] has used criteria importance through intercriteria correlation (CRITIC) method to determine the importance of each node based on the seven centrality indexes, in building the skeleton network.

Formerly, in the network restoration studies, the determination of generator start-up sequence (which tries to maximize the generation capacity during the restoration procedure) and restoration path optimization (through which the skeleton network is energized and cranking power is delivered to all NBSUs) have been introduced as two separate problems. However, the simulation results presented in [72] show that to make the restoration procedure feasible, along with the start-up sequence of generating units and the related constraints, the transmission path search and the associated constraints should be considered. In other words, these two steps cannot be studied separately. Therefore, during the last years, these two problems have been usually studied together. For example, an optimization algorithm has been proposed in [72] to determine the NBSU start-up sequence through an optimal path. To reduce the computational complexity of such a problem, a new generator start-up model has been introduced, which leads to linear integer programming formulation and guarantees that the global optimality can be achieved even in large-scale systems. The objective function used in the optimization problem is to maximize the generation capacity of NBSUs over the restoration time horizon while considering the constraints related to the minimum cold-start time of thermal generators, and the active and reactive power balance.

Also, in [73], to achieve a practical restoration plan, a comprehensive system restoration procedure has been proposed, in which determining the restoration sequence of units and making the skeleton-network problems are solved simultaneously. In this research work, to reduce the computational burden, the mathematical model of restoration has been decomposed to generator start-up sequence and transmission lines energization sequence models which are implemented as mixed integer linear programming (MILP) problems. Besides, a load pickup model is used to determine the location and amount of load pickup during the restoration process so that the proposed process satisfies the static security constraint. Similar to most of the methods that propose the restoration procedure, the objective function of this paper is to maximize the generation capacity over the restoration period. Also, the constraints related to the maximum and minimum restart time as well as the cranking power required during the restarting of the NBSUs are modeled.

Furthermore, in [74], the concept of the minimum spanning tree has been utilized to propose a fast and adaptive network restoration procedure, where the restoration of transmission lines and generating units are considered, simultaneously, to decrease the number of candidate restoration plans and reduce the computational burden in selecting the optimal one with the minimum total restoration time. In addition, in this paper, the start-up power and time requirement constraints of NBSUs have been considered.

Besides, in [75], a generator resilience index has been proposed which considers the recovery model (i.e., the required cranking power, recovery time, and the ramp rate) of NBSUs. Then, in the proposed method, using the Dijkstra algorithm, the shortest paths from the energized buses to offline NBSUs have been determined, which are used to calculate the resilience index of each NBSU. Finally, the NBSU with the maximum resilience index is selected as the next generation unit, which should be energized to minimize the restoration time.

Obviously, considering the generation and transmission constraints would improve the efficiency of the obtained plan, and hence, it seems that those methods like [76], which neglect such constraints, would not result in a feasible procedure. In this respect, usually different objective functions and constraints are considered in the literature to obtain a feasible restoration procedure. For example, in [77], the minimum cold-start interval of NBSUs, the maximum hot-start interval of NBSUs, the reactive power absorption capability of generators (overvoltage constraint), and the network security constraints have been considered. Also, in [52], the objective function tries to minimize the amount of unrestored loads, while increasing the number of energized branches and the system inertia (by energizing more generation units) over the restoration horizon.

It is worth mentioning that cold load pickup and/or starting current of motors with a low power factor results in voltage drop and may recollapse the system. Therefore, to provide a realistic restoration plan, [78] has proposed a restoration plan to determine the shortest feasible path to NBSUs to deliver the cranking power, while considering the priority list of loads, cold load pickup, and inrush current of induction motors.

Although some methods have considered the recovery model of generation units and load variations, usually the uncertainty regarding start-up time of NBSUs and the amount of load pickup have not been considered. Therefore, in [79], an optimization method has been proposed that simultaneously considers these two uncertainties. For this purpose, a multiobjective optimization model has been proposed to model source-load coordinated restoration, while considering the uncertainties. Then, the information gap decision theory method has been used to convert the optimization model to a certain one so that the final solution can tolerate the most uncertainty, and also, meet the requirements. Finally, the genetic algorithm finds the optimal solution.

Reference [80] has employed the capability of deep learning tools for fast determination of the restoration process in online applications. For this purpose, the stochastic tree search and the genetic algorithm have been used to determine the optimal sequence of primary actions (i.e., energization of lines, generators, and loads, which changed the system topology), in order to minimize the objective function including the unserved loads, deviation from the predisturbance generation, and system losses. It should be stated that each primary action will be followed by an optimal power flow analysis to determine the required secondary actions like generation rescheduling or changing the tap position of OLTCs to satisfy the security constraints. Finally, the optimal primary action set obtained for the different initial degraded states (i.e., the network state following a blackout) will be used to train an artificial neural network that can be used in online application for fast determination of the restoration sequence. Similarly, [81] has employed Monte Carlo tree search approach to propose a decision-making strategy for generator start-up and line energization sequence.

It is worth mentioning that due to the unavailability of transmission lines (discussed in Section 5), the optimal energization scheme obtained by the above-mentioned approaches may not be feasible. Thus, in [82], an iterative searching method based on mixed integer linear programming has been proposed to determine alternative paths. Also, an evaluation index set has been defined to assess the efficiency of the alternative schemes.

As mentioned earlier, to accelerate the restoration process of power systems (especially in large-scale systems with low reactive absorbing capacity or in the presence of long transmission lines, which generate significant reactive power in low-loading conditions), usually parallel or bottom-up strategy is used to quickly restore each island and then, the energized islands will be synchronized. However, due to the lower amount of power generation and consumption, the control of voltage and frequency in these islands may be challenging. For example, following the blackout in the Jakarta power grid in August 2019, the blackout area was partitioned into smaller subsystems to use the black-start units and those generators which have been tripped to house load (four units out of 55 generation units) to restore the network in parallel. Nevertheless, due to some difficulties mentioned in [83] (for example, the inability of operators to properly set generation mode to isochronous or droop mode control), these resources could not create energized islands, and hence, the bottom-up strategy was not effective. Accordingly, the operators used the top-down strategy to energize transmission lines and transfer power from the east to the west. However, due to the long transmission lines and high charging current, it took a long time to restore this grid using a top-down strategy.

In this respect, [84] as well as its shrunken version [85], have presented the results of the research performed to find the advantages and disadvantages of the restoration plan tested in the Italian electric network in November 2016. In these research works, a dynamic model has been presented to validate the efficiency of the voltage and frequency control during a bottom-up restoration test perform in the Northern Italian electric network. Similarly, [86] has presented a procedural approach proposed for the Italian grid, which utilizes frequency and voltage behaviors as predictors to assess the practicality of a restoration path in a bottom-up strategy, while considering different loading and distribution generation scenarios.

Moreover, in [87], two methodologies have been employed to solve the proposed bi-level restoration model for maximizing the system resiliency (minimizing the impact of the blackout in terms of load shedding, restoration time, and network connectivity) during the system restoration. For this purpose, five resilience indexes have been used to quantify the system resiliency. Then, a mixed integer nonlinear programming model has been proposed to maximize the resiliency in a parallel restoration scheme.

6.2.2. Synchronization of Energized Island. To complete network reconfiguration and get ready to perform load restoration (to restore those loads which have not been energized yet), the tie-lines should be closed to synchronize the parallel (energized) adjacent islands. For this purpose, the voltage phase angle across any tie-line called standing phase angle, SPA, should be smaller than a specified threshold to prevent damage to system equipment and dynamic instability. For this purpose, in [88], an approach has been proposed, by which with considering power system operating constraints, the generators bus voltages have been used as a fast control action to achieve the desired SPA in a short time. However, if the intended SPA cannot be achieved, the next priority would be generation rescheduling and load curtailment.

Also, in [89], a multiobjective model manages the SPA reduction and load restoration problems. For this purpose, using an optimization problem whose objective function includes SPA between adjacent islands and unsupplied energy, the optimal amount of restored load at each bus is determined so that the SPA, energy not recovered, and inrush power flow due to the thermostatic loads is minimized, while fulfilling operating constraints.

Moreover, in [90], without considering the procedure used to create parallel energized islands, a system robustness-based method has been proposed to determine system areas whose stability stiffness should be firstly improved by closing tie-lines and interconnecting energized islands. The proposed technique can prevent any unsuccessful connection of islands that has previously occurred during the restoration of the Brazilian Interconnected Power System (BIPS) in 2009.

6.3. Load Restoration. In the black-start stage, in which the black-start unit with usually a small generation capacity is used to energize a path and deliver power to an NBSU, the load restoration is used to allow the black-start unit to generate the minimum allowable output power. However, in the network reconfiguration stage, in which the generation capacity has increased, more loads are restored to maintain load-generation balance, and it is possible to restore important loads during the restoration period of NBSUs. In this respect, before the third stage, the load pickup is mainly used to control the system frequency. However, the third stage of the restoration procedure is devoted to load restoration in which as much load as possible is restored within a minimal time.

Obviously, in this stage, the dynamic behavior of the network against the energization of industrial loads (which includes induction motors) and cold load pickup should be analyzed carefully to maintain voltage and frequency within the acceptable limits and prevent unsuccessful load restoration [72, 78, 89].

In this respect, in [91], a procedure for load restoration has been proposed that determines the load restoration during the different stages of the restoration process, while considering renewable energy resources.

Also, [92] manages the load restoration procedure to assure early restoration of near and important loads, using an objective function that considers the effects of load importance and the distance from a load to generators. For this purpose, at each step, the greedy algorithm is used to select the load that will be restored without violating the system frequency.

7. Application Software Tools for Power Systems Restoration

As mentioned, power system restoration is a complicated procedure and it is necessary to use intelligent software tools which offer recommendations to the operators and reduce the time of reaction to events.

In [93], the laboratory prototype of hybrid intelligent multiagent systems of heterogeneous thinking (HIMSHT) which can be used to solve power networks restoration planning has been described. The output of this system is determining the sequence of the equipment switching and a plan for switching and restoration tasks. Similar to most of the above-mentioned methods, the objective of the plan is to minimize the energization time of main loads, maximize the restored loads, and maximize the reliability index of the network. Also, to analyze the performance of the proposed methods, the problem of restoration of a regional power system grid has been used as a test case.

Also, as described in [94], to propose a comprehensive restoration plan which can be verified from the static and dynamic point of view, by integrating a real-time dynamic simulation engine and EMS functions tools, a new platform has been prepared which can be used to compute, simulate, and evaluate different restoration plans. By this tool, the procedure of restoration is divided into four steps. Firstly, the strategies and scenarios are determined. Then, to minimize the restoration time, the restoration plans are obtained using automatic computations. In the third step, the performance and security indices are used to analyze the plans obtained. Finally, based on these indices, the best plan is determined. Accordingly, based on the continuous interactions between these tools, an appropriate sequence of actions for the restoration process has been proposed to achieve the restoration aim, while satisfying both static and dynamic constraints.

8. Application of Renewable and VSC-Based Resources in Power Grids Restoration

Due to the widespread use of distributed generation resources, especially renewables, the classical operation of power networks, where conventional synchronous generators were the only supplier of loads has changed. Accordingly, concepts such as microgrids have emerged and distribution networks play a more active role in voltage and frequency regulation.

Traditionally, the distribution systems might be restored after the transmission system has been energized. Nevertheless, in active distribution systems, distributed energy resources and electrical energy storage systems with black-start capability may supply some consumers and decrease the impact of blackouts [95]. However, distributed nature, as well as weather-dependent characteristics of renewable resources, will increase the complexity of obtaining an optimal solution [2].

On the other hand, due to the emergence of grid-scale renewable resources and continuous increase in the penetration level of these resources, considerable research works have been published to utilize these resources in a grid-forming strategy (rather than a grid-following strategy) for power system restoration [96].

Some major challenges in restoring power grids using renewable energy resources may be summarized as follows [3, 97]:

(i) Any changes in weather conditions usually change system frequency unless a proper control system is used to provide positive/negative reserve. Also, these changes may make the restoration plan unsuccessful, due to the minimum power generation limit of conventional units.

(ii) In contrast to wind farms (especially offshore resources), which can generate power during day and night, photovoltaic resources only generate power during the daylight, and the generation changes when the clouds pass over the photovoltaic system. Since the restoration period prolongs several hours, an appropriate restoration procedure should be used during the day and night when photovoltaic resources are used.

(iii) The system inertia decreases as the penetration level of these resources increases. Therefore, during the restoration of a network using such resources, low inertia of the grid will increase the probability of the recollapse if unpredicted events occur.

(iv) Usually, large-scale renewable resources are directly monitored by operators and secure communication links should be available when a blackout occurs. Also, TSO usually does not monitor small or medium-scale resources and when these resources get back to the network, they may have an adverse effect on load-generation balance.

In this respect, formerly, system operators remove renewables from the network to prevent any disturbances caused by these resources. Nevertheless, according to the following capabilities, it seems that these resources can be used to restart the power network after a blackout:

(i) The penetration level of these resources has increased significantly during the last years.

(ii) The start-up time and the required power of these resources are significantly lower than conventional resources.

(iii) The inverter-based renewable resources can rapidly change their active and reactive power output to balance and control the voltage and frequency within the acceptable limits.

(iv) Synchronverter-based operation of renewable resources can improve the system inertia.

(v) Energy storage systems (ESSs) can be used as a black-start unit to generate cranking power or to damp voltage and frequency caused by weather changes (for example, a 15 MWh battery park in Germany has been successfully tested in 2016 to generate cranking power for quick restarting in the event of a blackout [98]. Also, a 33 MW/20 MWh battery energy storage system has been used on 10th May 2019 for black-start of a 44 MW combined-cycle natural gas turbine in California [99]).

Moreover, after the 69 MW Dersalloch onshore wind farm, as the first black-start wind farm in the world, re-energized a part of the Scotland grid in 2020, these resources are considered as reliable black-start resources for the restoration procedure in the future power grids.

In this regard, in [100], considering four different grid-forming control strategies, the performance of an offshore wind farm, as a black-start unit, against transformer energization, converter precharge and deblocking, and load pick-up has been analyzed. The results presented in this study have verified the capability of grid-forming wind power plants in participating in the restoration process. Also, based on grid codes and some blackout incidents, [101] has analyzed the requirements of black-start resources and the capabilities of wind turbines in participating in the restoration process. Similarly, [102] has described challenges faced by offshore wind farms to provide black-start service and also, proposed different solutions to overcome the incident problems. Besides the time-domain simulation results proposed in [103], this paper has introduced the capability of an offshore wind power plant along with STATCOM (which can provide fast and dynamic reactive power management) and a battery energy storage (which is able to regulate frequency by injecting active power) installed at the point of common coupling of the wind farm in providing a reliable black-start service. Furthermore, [104] has presented control schemes for grid-forming offshore wind farms and HVDC converters. Also, this paper has shown simulation results performed to energize an onshore AC terminal of the network using an offshore wind farm. Similarly, based on the time-domain simulation results, [105] has investigated the capability of offshore wind farms in energizing power systems.

In addition, a number of studies have been published to analyze the performance of other renewable resources in power system restoration. For example, in [106], a study has been conducted in a simple grid to check the possibility of energization of a solar power plant terminal by a small hydropower plant to supply power to some consumers after a blackout. Also, [107] has studied the possibility of employing a cluster of renewable resources in a microgrid to supply cranking power to an NBSU. Besides, based on the fuzzy chance-constrained model, [108] has proposed a coordinated operation method of energy storage systems and restored generation units to maximize the restored critical loads and satisfy the constraints during the restoration procedure, while considering the uncertainty of load.

As described in [109], the field test results show that VSC-HVDC can be treated as a great black-start source in power system restoration because it can excellently control voltage and frequency, independently adjust active and reactive power, and also execute soft energization to prevent inrush current and overvoltage problems, after an equipment energization. Then, the requirements for VSC-HVDC

Table 2: Timeline and summary of review on restoration documents.

Year	Industrial documents	General topics (Lessoned learned, guidelines, issues)	Papers and books: Black start — Renewable and VSC-based resources	Black start — Conventional resources	Network reconfiguration — Restoration plan	Network reconfiguration — Availability of equipment	Application of software	Load restoration
Before 2016 mentioned in this article	[12] [13] [14] [15] [16] [17] [18] [32]	[7] [8] [9]			[45] [46] [47] [48] [49] [50]			
2016	DGA Comparison of major Blackouts and Restoration [3] FERC-NERC, review of restoration and recovery plans [35]	Review on system restoration methods [5] Experience from black start mock drills in India [39]			Proposing ANN for estimation of TOVs [42] Orthogonal GA-based islanding (parallel restoration) [63]			
2017	IGMC General principles for restoration [19] Establishing a network code on electricity emergency and restoration [36] CIGRE, system restoration procedure and practices [37]		Analyzing the capability of the offshore wind farms in black start [105]		Graph theory-based islanding (parallel restoration) [58] Building skeleton network based on node importance [71] A generator start-up model to optimize lines and NBSU startup sequence [72] A method to control SPA by generator bus voltages in bottom-up restoration [88] Robustness based-technique to determine tie-line switching order [90]			

Table 2: Continued.

Year	Industrial documents	Papers and books						
		General topics	Black start		Network reconfiguration			Load restoration
		(Lessoned learned, guidelines, issues)	Renewable and VSC-based resources	Conventional resources	Restoration plan	Availability of equipment	Application of software	
2018	FERC, system Restoration from Black start Resource [21] PSE, Energy system restoration plan [22] US Department of Energy, Restoration best practices guidebook [23] NPCC, System Restoration [24] NCER: System Restoration Plan [25]	Restoration Requirement [40] Lessons learned from restoration of BC Hydro [38] Restoration after cascading failures [10]	Analyzing the possibility of energization using hydropower plant [106] Assessment of application of distributed energy resources in restoration [97]	An optimization method to consider uncertainty in start-up time of NBSU and load pick-up [79] Application of Monte Carlo tree search approach to determine NBSU and line energization sequence [81] Optimal black start allocation [52]	Graph theory-based islanding (parallel rest) [60] Orthogonal GA-based islanding (parallel restoration) [62] Graph theory-based islanding (parallel restoration) [65] Heuristic-based strategy to minimize parallel restoration time [66] Bee Colony method to minimize parallel restoration time [67] Grid partitioning based on optimization problem [68] Multiagent based method for distribution network restoration [76] Application of deep learning for fast determination of restoration process [80]	Based on satellite images [54]	A platform for restoration plan considering static and dynamic aspects [94]	A method to control load energization during restoration [91] A greedy algorithm to determine load energization [92]

Table 2: Continued.

Year	Industrial documents	Papers and books						
		General topics	Black start		Network reconfiguration			
		(Lessoned learned, guidelines, issues)	Renewable and VSC-based resources	Conventional resources	Restoration plan	Availability of equipment	Application of software	Load restoration
2019	NYISO System Restoration Manual [20] VSE, Transmission Code [34] Freq. regulation model and experience from black start test in Italian grid [84, 85] A Report about utility-scale ESSs [95]		Assessment of application of renewable energies in restoration [96] Requirements of wind turbines for restoration [101] A control schemes for grid-forming operation of offshore wind farms in restoration [104] Analyzing black start using a cluster of renewable resources in a microgrid [107] A study to use VSC-HVDC as a black-start source [109] Functional validation HVDC in black-start [110]	Control measure to maintain arrester safety during trans. switching [44] Analyzing self-excitation in Finnish Grid [49] MIP formulation for controlled islanding and black start allocation [64]	Optimization of generators start-up seq. [70] MILP formulation to Simultaneous gen. and skeleton network startup sequence. [73] Simultaneous determination of lines and units restoration sequence to min. restoration time [74] A min. cost max. flow model to optimize restoration [77] Determining of NBSU start-up seq. using a resilience index [75] A minimum cost flow model to evaluate alternative paths for restoration [82] A bi-level restoration method to maximize system resiliency during restoration [87]	Based on relays data [53]		
			Analyzing the application of ESSs in restoration [108]					

Table 2: Continued.

Year	Industrial documents	Papers and books						
		General topics	Black start		Network reconfiguration			Load restoration
		(Lessoned learned, guidelines, issues)	Renewable and VSC-based resources	Conventional resources	Restoration plan	Availability of equipment	Application of software	
2020	Design of restoration Plan for EirGrid [1]	Blackouts, restoration, and islanding [2] Basic issue about restoration planning [51] Experience from restoration in jakarta power grid [83]	A report about black start using ESSs in Germany [98] A report about black start using ESSs in California [99] Analyzing the offshore wind farm in restoration [100] Challenges faced by offshore wind farms in black start [102]	Online evaluation of line switching overvoltage [41]				
			Comparison of different black start units [57]		Graph theory-based islanding (parallel restoration) [59] DPSO based-islanding (parallel restoration) [61] Grid partitioning based on virus propagation model [69] A procedural approach to check the feasibility of a restoration strategy [86] An optimization to control SPA and minimize unsupplied load in bottom-up restoration [89]	Based on historical data, relays data, weather condition [55]	HIMSHT to deter. the sequence of switching [93]	

Table 2: Continued.

Year	Industrial documents	Papers and books						
		General topics	Black start		Network reconfiguration			
		(Lessoned learned, guidelines, issues)	Renewable and VSC-based resources	Conventional resources	Restoration plan	Availability of equipment	Application of software	Load restoration
2021	For ontario power system (i) Restoration guideline (ii) Restoration strategy Restoration requirement [26] Grid code for great Britain [33] UK dep. for business, energy and industrial strategy electricity, system restoration standard [31] California ISO, reliability coordinator area restoration Plan [30] PJM manual, system restoration [29] System restoration plan [28] IGMC, executive method for restoration [27]	Review on network reconfigure-tion [4]	Analyzing black-start capability of wind farms [103]		Determination of optimal path to NBSUs considering priority and loads characteristics [78]	PMUs sequential restoration plan [56]		
2022	Principles and practices of restoration [11]							

in the black-start procedure have been assessed. Also, in this paper, time-domain simulations have been used to analyze the performance of VSC-HVDC for soft energization of major generating units. Similarly, [110] deals with functional validation of the control system of the HVDC interconnection between France and Spain to be employed in black-start operation, using a real-time simulator.

9. Summary of Review

Table 2 summarizes this review on restoration documents published from 2016 up to 2021, by presenting the time-line and their fundamental concepts.

10. Research Gaps

As described in the previous sections, in recent years, extensive research works, industrial documents, and books have been published to give details of power system restoration steps and major problems which may make the restoration process to fail. These general guides are usually used in offline studies to obtain the best restoration trajectory through which the operating point can be moved to a normal state as soon as possible. However, owing to different system topologies (in black-start state) and operating conditions, a large number of dynamic simulations are usually required to design a restoration plan in advance. In addition, based on the availability of equipment, dynamic simulations may also be required in online application (during the restoration) which will slow down the equipment energization and restoration process. In this regard, it seems that more studies should be performed in the future:

(i) Online identification of faulted apparatuses: as described above, detection of faulted equipment is a prerequisite for selecting a suitable restoration trajectory. Obviously, fast and online identification of faulted apparatuses will not only reduce the probability of failure in the restoration process but also reduce the restoration time.

(ii) Online calculation of static and transient overvoltages: having limited static and transient overvoltages are the main concerns in line energization during restoration process. These requirements have been provided by offline methods, such as preparing lookup tables, and/or employing estimation methods by artificial intelligence (AI). Although employing these methods can maintain most of the results needed, the vast combination of equipment and operation points may either oblige to have many cases to be simulated for creating those tables or training cases for AI. In this regard, online calculation of static and transient overvoltages on transmission lines, applicable to restoration process can prevent the onerous number of simulations, as well as providing more helpful results.

(iii) Reliable indices for estimation of self-excitation occurrence: having more accurate and flexible indices according to offline data, such as topological data will increase the probability of successful restoration.

(iv) Online estimation of maximum allowable load step: restoring loads at the first stages of restoration process is vital to provide stability of the black-start generators. On the other hand, any load entry makes the frequency to have a drop, which may be intolerable. Online estimation of maximum allowable load which can be connected at each step is of great significance.

(v) Transmission network expansion according to restoration requirements: in order to have a trade-off between restoration requirements and economic concerns, proposing transmission network expansions (including black-start units, non-block start generation plants, transmission lines, and auxiliary apparatuses) is one of the prerequisites of flexible power system upon restoration process.

11. Conclusions

A large number of blackouts occurred during the last few years show that the probability of blackouts cannot be ignored and to properly deal with blackouts and minimize the social and economic costs, utilities should prepare a suitable restoration plan in advance to quickly restore the system to the normal state and minimize the restoration time and loss of energy. Although some recent studies have reviewed power system restoration plans, it seems that a more comprehensive review is required. Therefore, in this paper, recent progress in power system restoration studies have been comprehensively reviewed to summarize and categorize the research works, industrial documents, and books published from 2016 to 2021.

This paper reviews more than a hundred documents directly related to the topic of power system restoration. The reviewed documents have shown that

(i) The concept of power system restoration still attracts researchers.

(ii) The requirement of proposing real-time decision support systems is on the table and is not fully covered.

(iii) The challenge of handling possible hidden failures in apparatuses or out-of-service equipment during the restoration process, in the planning stage, has no clear solution, yet, and is put on the responsibility of operators during the operation.

(iv) Availability of renewable generation resources has some usefulness in power system restoration, while challenges appeared should be cared of.

(v) The challenge of prioritizing in expansion of power system regarding reliability in proceeding the restoration plans has not yet become a main concern. In other words, it is required to find how the resources for expansion of power system should be prioritized, in order to enhance the reliability of restoration plans in the three stages, including the black-start stage, network reconfiguration stage, and load restoration stage.

Finally, the gaps/requirements for better planning and following restoration procedure have been highlighted.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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