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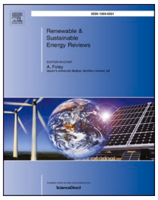

Black start from renewable energy resources: Review and a case study of Great Britain

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ABSTRACT

Black start is the restoration of an electrical power system following a total or partial system shutdown. A loss of supply of this magnitude is a most unusual event but must be anticipated as it has significant societal and economic consequences. Many countries are moving towards a low-carbon electricity system, and the fossil generators that currently provide black start capability are being replaced by renewable energy generators, many of which are individually of limited capacity. This reduction in the number of large conventional generators is leading to a need to reconsider black start practices and to question whether restoration of a de-energized network through a skeleton transmission system should be replaced by establishing multiple power islands each with smaller generating units. Using academic studies and the results of two innovation projects recently completed in Great Britain (GB), this study reviews the established power system black start practices and the participation of renewable energy resources in the black start. After traditional black start practices are reviewed, the challenges and solutions for using renewable energy sources and distributed energy resources to support black start are investigated. Restoration control and planning strategies in academic studies are discussed. Then the evolving power system black start practices in GB are discussed, and the methodologies and findings of two innovative black start projects in GB are reviewed.

1. Introduction

Fossil fuel thermal generating plants in many countries are being replaced by low-carbon energy sources to reduce CO_2 emissions. This is leading to a radical reappraisal of how the power system is operated. Restoration following a shutdown, known as black start (BS), is one of these important aspects of power system operation [1,2]. BS enables the power system to return to a normal operating state following a partial or complete shutdown, securely and rapidly [3,4].

Restoring a power system can be divided into three distinct phases: preparation, system restoration, and load restoration [4,5]. In the first phase, the system status is assessed and a target system for restoration is defined, then the system is divided into subsystems, and the approach to restoration is determined. The second phase is the starting of BS resources and energizing the key transformers and the transmission lines that supply essential loads such as auxiliary power to non-BS generating units. In the last phase, unserved loads are restored according to their criticality [5,6].

Two key factors are required for delivering a successful restoration: the availability of BS resources and the previously prepared restoration plans. A BS resource should have the capability to restart a part of the power system after an outage. Restoration plans determine the sequences of starting BS resources, establishing the energization paths, and picking up loads. Each action of the plan should be tested through desktop studies and/or field tests under both steady-state and transient operating conditions.

In existing industry practice, BS is initiated at the transmission level by fuel-based generators or hydropower units restarting a skeleton transmission network [7–9]. Converter-connected renewable energy sources (RES) like large wind farms (WFs) and photovoltaic (PV) stations connected at the transmission level, and distributed energy resources (DER) connected to the distribution system including small-scale synchronous generators, energy storage systems (ESS), wind turbines (WTs) and PV units are excluded from the initial phases of a BS to ensure the stability of the restored system [1]. As fuel-based generators are retired, the capacity of traditional BS providers will decrease significantly. The roles of RES and DER in restoration are being reconsidered by both industry and academia.

This study conducted a review to provide a useful reference for

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Nomenclature

BESS	Battery energy storage system
BS	Black start
CCGT	Combined cycle gas turbine
DC/AC	Direct/alternating current
DER	Distributed energy resources
DERMS	Distributed energy resource management system
DFIG	Doubly-fed induction generator
DNO	Distribution network operator
DRZ	Distribution restoration zone
DRZP	Distribution restoration zone plans
DRZ-C	Distribution restoration zone control system
ESS	Energy storage systems
GB	Great Britain
HiL	Hardware-in-Loop
HVDC/HVAC	High-voltage direct/alternating current
LJRP	Local Joint Restoration Plans
LV	Low voltage
MILP	Mixed integer linear programming
MVDC	Medium voltage direct current
NG:ESO	National Grid ESO
OCGT	Open cycle gas turbine
OWF	Offshore wind farm
PV	Photovoltaic
RES	Renewable energy sources
SGRE	Siemens Gamesa Renewables Energy
SPEN	Scottish Power Energy Networks
SPR	ScottishPower Renewables
TSO	Transmission system operator
VPP	virtual power plant
VSC	Voltage source converter
VSG	Virtual synchronous generator
WF	Wind farm
WT	Wind turbine

further studies and implementation of restoration in low-carbon power systems. Several reviews on black start and restoration have been carried out both in academia and industry. A bibliographical survey of publications covering the 1980s and 1990s and a review of the research from 2006 to 2016 applying to transmission system restoration are presented in Refs. [2,3] respectively. However, these early studies discuss little on the participation of RES and DER in BS.

Recognizing their increasing importance in the power system, large-scale renewable plants such as wind farms have been investigated to contribute to restoration and improve the speed of grid recovery [10, 11]. Driven by grid codes, state-of-the-art WTs already possess some of the functionalities needed for restoration, e.g., frequency control and voltage support. ENTSO-E, the organization of the transmission system operators (TSOs) in Europe, has included BS as an optional requirement for both synchronous and converter-based power-generating units [12]. A review of the ongoing research on BS services from off-shore wind farms (OWFs) is provided in Ref. [10]. In Ref. [11], functional requirements for BS from WTs and OWFs are investigated.

As the energy system shifts towards a greater use of distributed energy resources, the applications of DER to improve the resilience of power systems have been extensively studied [13]. DER can supply local load by forming islanded microgrids and contribute to faster restoration of the whole system. DER can operate individually to provide BS service. Meanwhile, a large number of small DER can participate in BS as a collective in an aggregated manner.

In [14], a review of energy storage-based BS services and the different energy storage methods employed for BS is provided. In Ref. [15], the black-start load restoration optimization problems from modeling techniques to solution methods in active distribution systems and microgrids are reviewed. In the review of power system resilience presented in Ref. [13], as one aspect to enhance resilience, restoration strategies using DER and microgrids with distribution automation after natural disasters are discussed.

While these reviews in Refs. [10,11,13–15] concentrate on specific RES categories or specific problems of power system restoration, there is a lack of a systematic review on the participation of RES in the whole three stages of both transmission system and distribution systems restoration.

Beyond studies by researchers in academia, industry practices have been reviewed. A review to assess and verify the electric utility industry's bulk power system restoration plans and related standards was carried out in 2014 by the Federal Energy Regulatory Commission, the North American Electric Reliability Corporation, and Regional Entities [8]. BS services for the Belgian electricity network were reviewed in 2018 [16]. In 2019, the National HVDC Centre investigated the potential contribution of VSC-HVDC interconnectors for restoration in Great Britain (GB) [17]. In 2022, the Pacific Northwest National Laboratory conducted a review of traditional BS practices in the United States [1]. The potential and challenges of using RES and DER in BS restoration have attracted more and more attention from industry in recent years [1, 16,17].

National Grid ESO (NG:ESO), the electricity system operator of GB, explored the technical viability of providing BS from non-traditional generation technologies including large wind power plants and DER comprehensively in 2019 [18]. Further, NG:ESO developed alternative methods for BS from smaller DER in the Distributed Re-Start project in collaboration with Scottish Power Energy Networks (SPEN) [19]. To the best of the author's knowledge, this is the first real systematic implementation of BS using DER and has allowed NG:ESO to procure black start from DER through tenders as business as usual. Meanwhile, a live trial at Dersalloch Wind Farm by SPEN, ScottishPower Renewables (SPR), and Siemens Gamesa Renewables Energy (SGRE) used wind power to energize transformers and restore a section of the transmission network [19,20]. A review of the series of reports on the studies of these projects is carried out in this work.

Based on the analysis of scientific papers, international grid codes, and standards along with the reports of the live trials in GB, this study addresses the following concerns for restoration with RES: (1) What roles can various RES connected to transmission systems or DER in distribution systems play in restoration? (2) How should RES be controlled during restoration? (3) How could multiple RES, DER, and other resources be coordinated? (4) How will a restoration plan be developed with the participation of RES and DER?

This paper provides comprehensive updates on power system restoration. The novelty and contributions of this review are: 1) compared to existing reviews, it highlights critical research gaps, emerging trends, and solutions in modern power system restoration using renewables like RES and DER, covering from the three-level control methods to the restoration planning using RES for transmission systems and DER for distribution systems; 2) it explores the latest findings of live trials of black start using DER in GB; 3) it identifies under-research areas within the research field and provides a road map for future research; and 4) it provides insights and recommendations that can inform policy-makers and industry practitioners on planning and implementation of RES and DER in restoration.

The review is organized as follows. Firstly, established BS practices are reviewed in Section 2. Then, the challenges and roles for RES and DER participating in BS are discussed, and the corresponding control methods are introduced from three levels in Section 3. Further, a literature review on restoration planning strategies considering both RES in transmission systems and DER in distribution systems has been provided in Section 4. The practices and solutions to BS from DER in GB are explained in Section 5. In Section 6, future research directions are discussed. Finally, the conclusions are stated in Section 7.

2. Review of established black start practice

Fig. 1 illustrates the framework of established black start practice [2–6].

2.1. Technical challenges during black start

Operating the power system in the initial phases of BS presents challenges not encountered during normal operation [2–6]. The main technical issues are as follows [21–24].

(1) Active power and frequency control. The simultaneous connection of a number of loads, or block loading, will lead to frequency drop or even instability, especially considering cold load pick-up [25–27]. Hence the loading of demand blocks is recommended to be limited to no more than five percent of the total synchronized generation [25].
(2) Reactive power and voltage control. In the early stages of restoration, there is a risk of voltage rise caused by long, lightly loaded transmission lines which are highly capacitive [28].
(3) Transient over-voltages. Energizing transmission lines, cable circuits, and transformers during a BS may result in large inrush currents and consequent transient over-voltages [29–31].
(4) Self-excitation. When long transmission lines are energized by a synchronous generator in a BS, self-excitation may occur due to resonance, resulting in excessive voltage rise [32,33].
(5) Protective relaying. The settings of protection schemes may not be appropriate during restoration because of low short-circuit levels [34,35].

2.2. Key technical requirements of BS resources

The fundamental procedures of a successful restoration include the self-start of BS resources, the energization of part of the transmission network, and the restoration of loads [36]. Accordingly, a generation source should meet the following criteria to qualify as a BS provider.

(1) Self-starting. A generation site is considered self-starting if the power required to start can be met independently of the wider network within a timescale specified by the system operator. For the GB system, BS resources are required to be able to energize part of the national transmission network or the distribution system within 2 h of instruction [36].
(2) Grid-forming. The grid-forming capability of a BS resource means it can establish a voltage reference and control the voltage and frequency of the section of the system to be restored independently.
(3) Reactive power and voltage control. A BS resource must be capable of balancing reactive power and regulating voltages in the restored system. In GB, the minimum absorption capability of a generating plant connected at 400 kV or 275 kV is taken to be 100MVar [36].
(4) Block loading. Block loading capability refers to the quantity of demand that can be connected simultaneously with the frequency and voltage of the system in an acceptable range. Traditionally a capability of 35–50 MW was required by NG:ESO with the frequency kept within 47.5–52 Hz [36].
(5) Active power and frequency control. A BS resource must be capable of managing system frequency in a power island by regulating its active power output.
(6) Availability. To be ready for a system shutdown at any time, high availability of both the main and auxiliary power of BS resources is essential. In GB, backup fuel supplies are required to enable the BS service to be available typically 90 % of each year and for BS resources to operate for a minimum duration in the range of three to seven days [36].

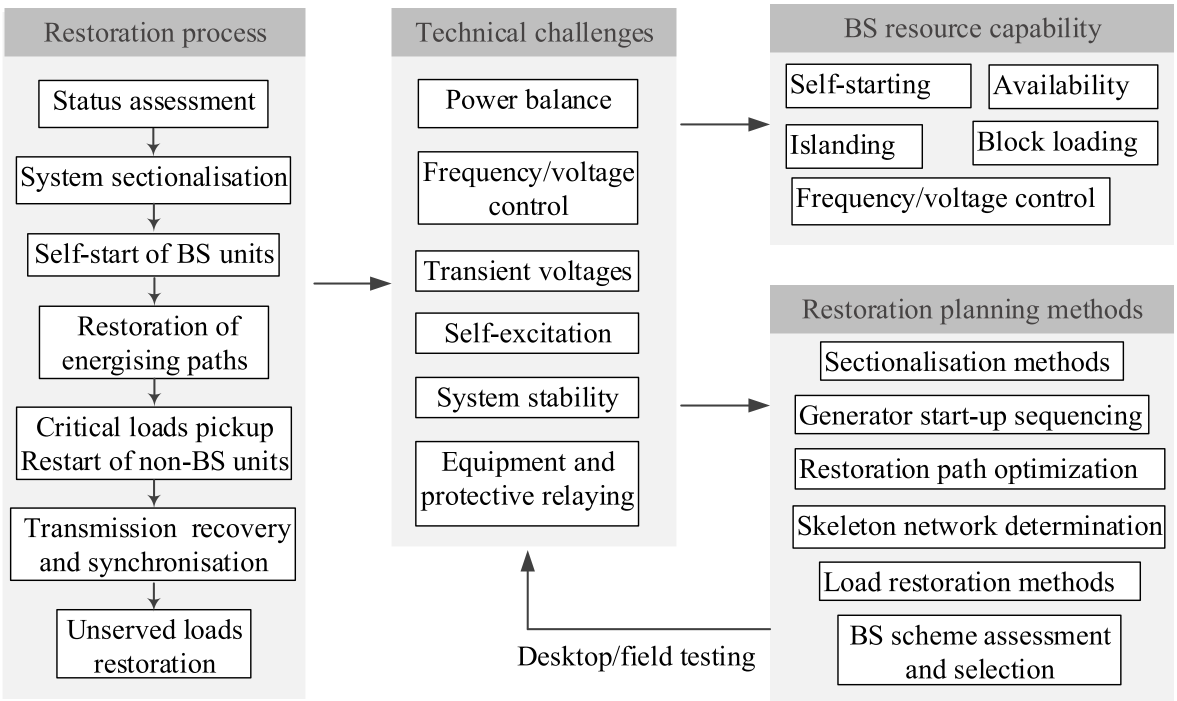


Fig. 1. Framework of established black start practice [2–6].

In the established BS practice, BS resources are transmission-connected synchronous generators. Generally, hydropower units and gas turbines in open cycle have been the BS units of choice [37]. Small steam power plants can be equipped to be BS resources with auxiliary generating units like gas turbines or diesel generators providing the necessary start-up power [38]. Large generating units can serve as BS resources if they can disconnect from the network during a system disruption and supply their own auxiliaries by successful trip-to-house load operation [39,40].

2.3. Restoration strategies and planning

Two basic restoration strategies have been developed, which are the top-down strategy and the bottom-up strategy [6]. A top-down restoration strategy is to build a skeletal version of a transmission network - called the skeleton network using external sources and neighboring high-voltage direct/alternating current (HVDC/HVAC) interconnectors to provide auxiliary supplies to non-BS units and re-energize parts of the distribution network [41–43]. The bottom-up restoration strategy is to use internal BS units to energize electrical islands which are synchronized with each other later. In a small system with only one BS resource, non-BS generators and loads are brought online in a sequential manner, while for a large power system with multiple geographically dispersed BS resources, multiple electrical islands are created and expanded in parallel before being synchronized to form a larger system.

Restoration plans are prepared in advance to help system operators make decisions [44]. A restoration plan can be designed using operators' experience or by solving optimization problems. Generally, optimization models are built to help determine the sequence in the restoration process, in which economic objectives are to be maximized in the presence of various system operational constraints. Optimization methodologies, including expert systems, meta-heuristics methods, artificial neural networks, fuzzy logic methods, and mathematical programming methods have been investigated to assist in decision-making of all stages of BS, i.e., sectionalizing strategies [45,46], BS generators selection [47,48], generator start-up sequencing [49], restoration path reconfiguration [50–52], load restoration methods [53,54], and integrated restoration planning [55–60].

3. Converter-connected renewables participating in a black start

3.1. Challenges and solutions

Converter-connected RES have some advantages when supporting a BS process, such as high speed of self-starting, ramping, and dynamic response [61–64]. They can start up using internal ESS or diesel generators due to their low demand for auxiliary power. However, there are some challenges to overcome: (1) the output power of these RES is subject to weather conditions; (2) almost all current RES operate in grid-following mode and cannot initiate a BS; (3) the inrush currents in the energization of transformers pose risks to converters considering their limited overcurrent capability; (4) the control of multiple converters needs to be coordinated for voltage and frequency regulation, power sharing and synchronization.

To tackle these problems, two solutions have been suggested to allow RES to contribute to restoration.

1. RES can be equipped with grid-forming capability and act as BS units independently [65–80]. To achieve this, enough wind or solar power is needed and RES control schemes should be modified from grid-following to grid-forming.
2. RES collaborate with external grid-forming BS resources to perform a BS [81–87]. Currently, RES join and contribute to a BS after the system voltage is established by diesel or biomass-powered generators, or ESS units with grid-forming converters.

3.2. Control strategies in BS schemes

3.2.1. Converter-level control strategies for BS

Grid-forming capability is essential to initiate a BS from RES. Grid-forming control for converters was initially developed for BESS to operate islanded microgrids [87], and has been extended to larger systems for both BESS and RES in recent years. Various grid-forming control strategies have been proposed, e.g., droop methods, power synchronization control, virtual synchronous generator (VSG), synchronverter, matching control, direct power control, etc. [88–90].

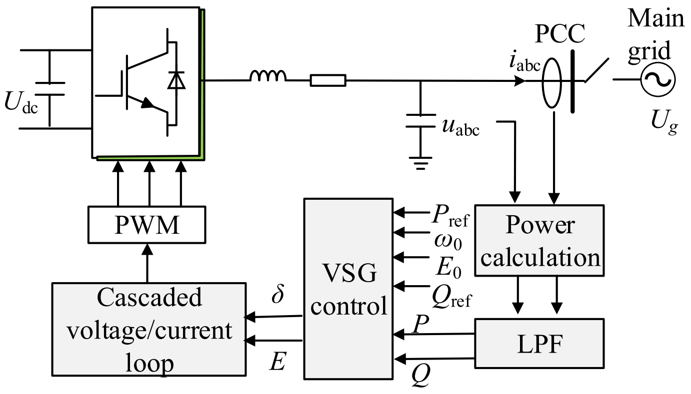
In [65], a droop-based control scheme for BESS to perform BS of medium voltage distribution networks is proposed, with a reference modifier included in the droop and voltage loops to limit inrush currents during transformer energization. In Ref. [66] transformer energization methods suitable for BS from converter-based resources are identified and a voltage ramp-up time estimation method for soft energization is introduced. In Ref. [67] modified grid-forming VSG control with functionalities of soft energization, voltage support, and smooth grid-synchronization is proposed and validated through simulations and Hardware-in-Loop (HiL) demonstration.

In [68], the suitability for BS of grid-forming control techniques including droop, power synchronization control, VSG, and matching control is studied through performance evaluation against various disturbances and soft-start compatibility, indicating that the four controllers have comparable performance, while VSG has more flexibility due to its tunable virtual inertia. Fig. 2 shows a typical VSG control for BS application. Fig. 2(a) presents the structure of VSG, and Fig. 2(b) gives the detailed block diagram. As can be seen in Fig. 2, VSG is a modified droop method, usually implemented using P/f and Q/V loops. The P/f loop generates the synchronizing angle, whereas the Q/V loop provides the voltage amplitude reference. Besides the basic droop mechanism, the swing equation of a synchronous generator is integrated into VSG to emulate the rotor inertia. For the BS application of VSG, two types of modifications are required. First, in the VSG voltage loop, the constant voltage reference is modified by a ramping value for soft energization compatibility. Second, grid synchronization functionality is integrated by introducing the error signals between the synchronizing voltage amplitudes and phase angles.

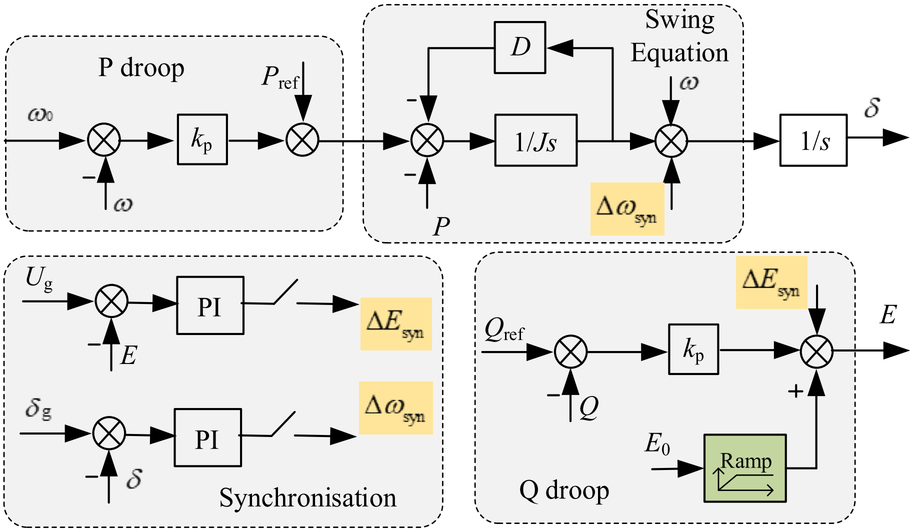
In these studies, grid-forming converters are tailored to deal with the challenges in a BS process. Voltage ramping methods have proved to be effective to mitigate the inrush currents of transformer energization and switching impulse of re-synchronization. It is worth noting that these control methods are suitable for converters of RES both at the transmission system and DER at the distribution systems.

3.2.2. RES-level control strategies for BS units

Much research has been done to enable RES such as PV units and WTs to act as BS units. In Ref. [69], a strategy is proposed for centralized PV power plants to operate as BS resources. A VSG control approach is used for grid-forming, primary frequency control, and inertial response. In Ref. [70], a VSG-based converter control method and a rotor speed/pitch controller are designed for WTs to participate in BS and verified in a laboratory test with WT HiL simulation. In Ref. [71], a voltage and frequency control strategy with pitch angle control is proposed for the islanded operation of a full converter WT, and in Ref. [72] reactive power synchronization and an active power sharing control have been proposed for the control of the system voltage by WTs operating in parallel. In Ref. [73], a BS sequence and the corresponding control strategy are proposed for Type 3 WTs, and a distributed PI control method is devised for dividing responsibility for frequency control among multiple WTs. In Ref. [74], a stator flux control scheme based on droop mechanisms is proposed to enable WFs equipped with DFIGs to achieve grid-forming capability. In Ref. [75], a VSG control based on rotor flux orientation is proposed for BS applications of DFIGs, including a torque-frequency droop synchronizing loop and a reactive-voltage droop control. These approaches are applicable to both individual WT



(a) Structure of VSG



(b) Detailed block diagram of VSG

Fig. 2. VSG control for BS application.

or PV units in distribution systems and centralized WF or PV plants in transmission systems.

OWFs have the potential to make a useful contribution to grid restoration since wind conditions offshore tend to show less fluctuation than on land. A BS sequence using VSC-HVDC linked OWFs and the corresponding control strategies are proposed in Ref. [76] and the energization of on-shore and off-shore HVDC converters is studied in Ref. [77]. In Ref. [78], different grid-forming control strategies for HVDC-connected OWFs participating in restoration are analyzed. Hard-switching and soft-start methods for energization of the offshore network using grid-forming WTs are compared in Ref. [79]. In Ref. [80] virtual resistance is added to the grid-forming converter of WTs in OWFs to reduce the terminal voltage and thus limit the inrush transient during the energization of the transformers.

It can be seen from these studies that RES such as PV units or WTs can deliver a successful BS without relying on additional generators. However, challenges exist to maintain a stable system by these intermittent converter-connected RES. The controllers of PV units and WTs need to be redesigned. Modified grid-forming methods are employed for grid-side converters, and the output power is controlled to balance the load demand considering the stable operation and interaction of multiple RES. Moreover, sufficient sunlight or wind and accurate forecasts of the output of PV units or wind turbines are essential to ensure adequate headroom.

3.2.3. System-level coordinated control strategies of RES in transmission systems

If a renewable is equipped with the grid-forming and power-balancing capability, it can act as a BS unit; or it can contribute to BS as a non-BS unit by collaborating with external BS resources.

Transmission-connected WFs and PV stations generally coordinate with ESS or diesel generators in restoration. Var resources can be utilized for reactive power balance during energizing transformers and cables. These approaches have been studied by a number of researchers. The feasibility of using PV power stations equipped with battery energy storage (BESS) is evaluated in Ref. [81], and a model predictive optimal control to manage the output power of PV and BESS during BS is proposed. A coordinated frequency control strategy of a WF with permanent-magnet synchronous generators (PMSG) to energize a local power network is proposed in Ref. [82]. Field tests carried out on an actual WF are described in Ref. [83], where mobile diesels with var resources are used to control the voltage and frequency. The WTs were started sequentially and limited their output to 10%–20 % of their rated capacity until the WF was connected to an adjacent thermal power plant. In Ref. [84], a frequency regulation strategy for BS of WFs with ESS was based on hierarchical model predictive control. In Ref. [85], a voltage regulation strategy using model predictive control is proposed for WFs to start up thermal power plants considering the dynamic response of WTs, ESS, and static var generators. A start-up sequence for modular multilevel converter-based HVDC-connected OWF using a diesel generator as the AC source is investigated in Ref. [86].

3.2.4. Coordination control systems for DER-based distribution system restoration

DER in distribution systems usually have greater quantity and diversity compared with large RES plants connected to transmission systems. For efficient management of distribution systems with high penetration of DER, hierarchical microgrid control systems [91–93] and aggregator-based approaches such as virtual power plant (VPP) or distributed energy resource management system (DERMS) [94–96] have been designed.

The control architecture of a microgrid system can be centralized, decentralized, or hybrid [91–93]. Master-follower control is a widely-used centralized scheme in islanded microgrids. In this scheme, one grid-forming resource operates as a master and is responsible for maintaining voltage and frequency. The remaining resources are slave units operating in grid-following mode. Centralized schemes strongly rely on fast and reliable communication systems. In decentralized schemes, each unit uses only local information for voltage and frequency regulation and load demand sharing. A simple decentralized strategy is droop control. The performance in a decentralized scheme might be poor due to a lack of system-wide coordination.

A compromise between a fully centralized scheme and a fully decentralized scheme can be achieved through a hierarchical control scheme comprised of three control levels: primary, secondary, and tertiary. The primary control achieves frequency and voltage regulation as well as power sharing in islanded mode using local measurements without communication. The secondary control restores the voltage and frequency offsets caused by the primary control, using a central controller or distributed multi-agents. Autonomous agents can use local information and information from neighboring agents through a sparse communication network to achieve cooperative goals. The tertiary control is responsible for the optimal operation of an individual microgrid or multiple microgrids and interaction with upstream system controllers. Tertiary control can be considered part of the upstream grid, and for islanded microgrids, secondary control can be the highest hierarchical level [91–93].

In restoration using DER, the energization of distribution power islands is similar in functionality to the microgrid concept. Single master operation microgrid control [97–100] and droop control [101] are most commonly used to form multiple isolated microgrids. A distributed secondary control strategy for restoration through dynamic microgrid formation is proposed in Ref. [102] using a sparse and static communication network. A hierarchical distributed controller is proposed for the coordination of multiple BS DER in Ref. [103], in which droop control is used as primary control and secondary control is designed based on the consensus algorithm for voltage/frequency regulation, dynamic microgrids formation, and synchronization.

Aggregator-based methods can be used for DER coordination in restoration to reduce the control and communication complexity. The aggregator-managed DER with grid-forming ability can contribute jointly to supporting the frequency and voltage independently, while the grid-following DER can contribute to providing active and reactive power to critical loads. In Ref. [104], a hierarchical framework for restoration is proposed in which aggregator-managed DERs and utility-managed DERs are coordinated. In Ref. [105], a synchronous VPP framework which consists of grid-forming DER is proposed, which can provide adjustable inertia support by coordinating the grid-forming control parameter settings. In Ref. [106], a sequential restoration framework that coordinates the distribution system operator and the VPPs is designed based on a hierarchical structure. In Ref. [107], a decentralized control strategy combined with droop control in DERMS for restoration is proposed, and the control strategy of ESS and intermittent PV units and WTs presents a master-slave relationship.

Table 1
BS schemes using converter-connected RES.

References	BS Resources	Description
[69]	centralized PV power plants	• The PV plant operates as a BS resource without relying on battery banks. • A VSG control approach, associated with traditional primary frequency control.
[70]	VSG controlled WTs	• BS of an isolated grid area with WT. • verified with WT HiL simulation.
[71,72]	full converter WTs	• control scheme of WTs for islanded operation and restoration of local load.
[73]	Type 3 WT/WF	• an autonomous frequency regulation method. • a restoration sequence for WT is devised.
[74]	DFIG WT/WF	• a stator flux control scheme based on droop mechanisms with grid-forming capability. • turbine control not covered.
[75]	DFIG WT/WF	• a VSG control based on rotor flux orientation. • a WT control scheme to meet load demand. • a secondary voltage and frequency control at connection points of wind farms.
[76,77]	OWF	• start-up of an onshore grid through a high-voltage AC export cable. • droop-controlled WTs. • voltage control during cable energization.
[78]	HVDC-connected OWF	• different grid-forming strategies.
[79]	OWF	• hard-switching and soft-start methods for energization of the offshore network.
[80]	OWF	• virtual resistance in the converter control to reduce transients during transformer energization.
[81]	PV + BESS	• PV as the main resource and BESS as the auxiliary resource • the optimal number of PV modules and the power output of BESS are estimated.
[82,83]	PMSG-based WF + mobile diesel	• mobile diesel power generation is used as the main frequency reference. • the PMSG-based WT are started sequentially to self-start the whole WF.
[84]	WF + ESS	• hierarchical model predictive control method of WF-ESS for frequency regulation during BS. • ESS assist WF in providing frequency response.
[85]	WF + ESS	• voltage control of WF-ESS to deal with disturbances of ancillary machine start-ups.
[86]	HVDC-connected OWF	• start-up sequence using a diesel generator.
[102]	DER	• distributed secondary control strategy for restoration by dynamic microgrid formation.
[103]	self-organizing inverter-based DER	• a distributed control approach for coordinated operation among multiple BS DER.
[104]	DER	• hierarchical framework for coordination of aggregator-managed and utility-managed DER.
[106]	DER	• sequential restoration framework coordinating distribution system operator and the VPPs.
[107]	DER	• a decentralized control strategy combined with droop control in DERMS for restoration.

Table 1 summarizes studies that have looked at BS schemes using converter-connected RES. Compared to PV units and WTs, diesel generators or ESS are reliable and ready to operate in grid-forming mode as BS resources. RES of PV units and WTs can participate in restoration after the system is established without changing their traditional grid-following control methods. However, the installation of external BS units leads to higher costs. Multiple uses of ESS with other applications could lower the cost of BS. PV units and WTs can act as BS units if the control systems are updated with power balancing and grid-forming capabilities. Microgrid control methods or aggregator-based approaches like DERMS or VPP provide a solution to the coordination of DER for BS in distribution systems. In the Distributed ReStart project, a control system is designed for BS from DER, which is elaborated in

Section 5.4.

4. Restoration planning strategies considering RES

4.1. Restoration planning using RES at the transmission level

RES could play an important role in accelerating system recovery. However, appropriate procedures and optimization models need to be studied to ensure a rapid and safe restoration. A number of studies have been carried out and solutions are developed for RES to participate in different stages of restoration, including generator start-up [108–111], load restoration [112–115], and complete restoration [116–120].

To determine the generator start-up sequence, in Ref. [108], a mixed-integer linear programming (MILP) generator start-up formulation is proposed where RES act as auxiliary BS resources and probabilistic constraints are used to deal with the uncertainties of RES power forecasts. In Ref. [109], a robust generator start-up strategy is obtained with linearized dynamic frequency response constraints. In Ref. [110], the generator start-up sequence is optimized for restoration using transmission-level microgrids which are integrated with various RES and BESS. A scenario generation and reduction method are applied to model uncertainties of forecast errors of RES and the MPC technique to mitigate the inaccuracy of the forecast power. In Ref. [111], a WF and a BESS system are coordinated to form the BS resource to improve system restorability. Scenarios are generated and reduced to model the uncertainty of wind power outputs.

To restore load rapidly, in Ref. [112], a load restoration method using online wind power and load data is proposed and a scenario-based linear programming model is developed. In Ref. [113], a robust optimization model for the dispatch of WFs is proposed to make full use of wind energy in restoration and is solved using the artificial bee colony algorithm. In Ref. [114], a robust distributed load recovery model for parallel restoration of transmission systems considering uncertainties of wind power is proposed, where the complex non-convex model is solved by iteratively solving the small-scale MILP problem. In Ref. [115], a deep learning-based model-free robust method is proposed for bulk system load restoration considering wind power uncertainties, which is fast and suitable for online application.

To deliver a complete restoration in an efficient way, in Ref. [116], the contribution of both WFs and PV systems is optimized in a complete restoration including three stages of generation restoration, transmission system restoration, and load pickup. In Ref. [117], the impact of wind power is explored through a scenario-based stochastic MILP model considering various factors, including wind generator location, penetration, fluctuation, and uncertainty inertia control capability. In Ref. [118], a multi-objective restoration model considering the coordination of BESS and intermittent RES is proposed to decide the restoration strategy, and the schedule of BESS is further optimized to fully utilize the available generation capabilities. Ref. [119] proposes a two-stage adaptive robust optimization model for the coordination of WF and pumped storage hydro units to determine the generators' start-up sequence, the energized transmission paths, the load pickup sequences, and the power dispatches of WF and pumped storage hydro units. In Ref. [120], a bi-level coordinated power system restoration model considering the contribution of multiple flexible resources is proposed. The generator startup sequence and the skeleton network are defined in the upper level and the maximum restorable load is determined in the lower level.

To enhance the resilience of power systems, the interdependency of the power transmission network and the natural gas transmission network is raising more attention in restoration. In Ref. [121], a skeleton-network restoration strategy for integrated electricity-gas systems is proposed to determine the restoration priority of critical components. In Ref. [122], a restoration sequence optimization model is developed with repair modes, repair time, and recovery costs taken into account. In Ref. [123], a distributed model is proposed to determine the restoration sequences of generators considering the dynamic characteristics of the gas transmission network. In Ref. [124], a two-stage restoration model for an integrated electricity-gas system based on distributionally robust optimization is developed.

Table 2 summarizes studies on restoration planning strategies with the participation of renewables at the transmission level. In these studies, the ultimate aim is to restore the system as rapidly as possible. RES could contribute to restoration by coordinating with other generators and ESS or improving their dispatchability. The key issue in optimization is how to model the uncertainty of the RES. Both model-based and data-driven algorithms are investigated, and two optimization methods for restoration planning under uncertainty are investigated, including scenario-based stochastic programming and robust optimization models.

4.2. Restoration planning of distribution systems using DER

A conventional BS strategy usually relies on generation connected to transmission networks. Originally, load restoration in distribution systems referred to keeping the power supply to the load affected by a fault in a branch through switch operations. However, in recent years, extensive studies have been done on resilience-oriented restoration, i.e., utilizing DER to energize part of networks and serve critical local loads after a system-level blackout caused usually by extreme events [125–127].

In studies of load restoration strategies, dispatchable DER such as gas turbines or BESS including mobile power resources are generally operated as BS units, and MILP models are built to maximize the total priority weighted load picked up in medium voltage distribution systems [128–140]. Uncertainties of intermittent DER power and load are considered using scenario-based stochastic programming methods [128–132], robust optimization [133,134], model predictive control [135], and data-driven optimization [136,137].

Models in these studies of [128–140] are generally formulated as a single-step optimization problem, which provides a final configuration of the restored system. To ensure a successful restoration, a feasible restoration sequence is needed [141−1148].

In [141], a three-stage restoration procedure is presented based on the concept of a network cell. An optimal sequence of switching operations is determined by a branch and bound algorithm and validated by both load-flow calculation and dynamic simulations. In Refs. [142,143], a sequential service restoration framework is proposed for balanced and unbalanced distribution systems to restore critical loads by forming multiple isolated microgrids. An autonomous sequential switching methodology based on a Petri net and game theory is proposed in Ref. [144]. In Ref. [145], a graph-reinforcement learning framework for restoration is proposed to improve the efficiency and scalability of conventional reinforcement learning algorithms. In Ref. [146], a sequential restoration model considering restoration path optimization is proposed, which is formulated as a mixed-integer second-order cone programming problem.

Beyond the steady-state operation constraints, dynamic and transient constraints are incorporated into the optimization models to ensure a safe and stable restoration. In Ref. [100], a sequential service restoration formulation for master-follower microgrids is proposed considering the frequency response and dynamic stability. In Ref. [147], a two-level simulation-assisted sequential service restoration model is proposed for unbalanced distribution systems, which includes frequency response constraints by interfacing with a transient simulation model.

It is worth mentioning that the studies for restoration planning using DER are generally resilience-oriented, which means that the blackouts are caused by disastrous events. After disasters, some generation units might be out of service, and part of the transmission or distribution networks might be damaged. Considering the uncertainties of damage, restoration using microgrids with dynamic and adjustable boundaries is studied in Ref. [148]. In Ref. [149], a dynamic restoration method is proposed by coordinating an event-driven repair crew dispatch model and the transient frequency-constrained sequential cold load pickup model. In Ref. [150], control of dispatchable and renewable DER, topology reconfiguration, as well as the dispatch of repair crews and mobile emergency generators are coordinated to enhance restoration capability. In Ref. [151], an optimal service restoration model for resilient distribution systems considering the coordination with damage assessment and the restoration schedules are dynamically updated with the reveal of the damage status. Moreover, the interdependence between cyber sectors and physical sectors is considered in load restoration in Ref. [152]. Distribution system service restoration methods are proposed considering the power-gas interdependency and cold load pickup conditions in Ref. [153].

Table 2
Restoration planning strategies using renewables at the transmission level.

References	Objectives	Models	Descriptions
[108]	restore the generation capacity in the shortest time	a scenario-based MILP generator start-up formulation	probability constraints to address uncertainty
[109]	minimizing the overall economic loss for the beginning period of restoration	a mixed integer non-linear robust programming	robust optimization for generator start-up with dynamic frequency regulation
[110]	to maximize energy capability and minimize load curtailment of the transmission-level microgrids	scenario-based MILP using model predictive control	transmission-level microgrids with various RES as BS resources
[111]	improving the defined system restorability	a scenario-based MILP model	a WF and a BESS coordinated to be BS resource
[112]	to maximize a risk-return trade-off function of utility value	a scenario-based linear programming model	using online data in optimal load restoration in an uncertain condition
[113]	maximizing the power dispatched from WFs in restoration	a non-linear robust optimization model	robust dispatch optimization for WFs with power control capability
[114]	to maximize load restored in parallel subsystems considering global coordination	robust distributed restoration models	robust and independent decision-making for subsystems
[115]	maximizing the load recovery amount in each step of the restoration	a deep learning-based model-free robust method	two deep neural networks trained to mimic the model optimization
[116]	to minimize the overall restoration time and the unserved load	non-linear optimization for a complete restoration	the three stages of BS combined into one model and solved simultaneously
[117]	to maximize the total power supply and the load served	a scenario-based stochastic MILP model	an offline restoration planning tool considering wind energy
[118]	to minimize the outage duration of the critical loads	a multi-objective optimization model	coordination of BESS and intermittent RES
[119]	to minimize the unserved load	a two-stage adaptive robust optimization model	WF and pumped storage hydro coordination in all restoration phases
[120]	to maximize generation capacity, two network-topology indices, and restorable load	a scenario-based bi-level coordinated power system restoration model	generators start-up strategy, restoration path, and load restoration coordinated
[121]	to minimize the restoration cost and the penalty cost of skeleton-network efficiency loss	a MILP problem by linearization methods	a skeleton-network restoration model of integrated electricity-gas systems
[122]	total resilience maximization	a MILP problem by linearization methods	coordinating the restoration of power and gas systems
[123]	to maximize the generation capability of the power system	a mixed integer nonlinear program	restoration sequences of generators considering interdependency with gas
[124]	to minimize the interruption costs and the operational risk	a two-stage distributionally robust optimization model	considering interdependency with gas and flexible reserve capacity allocation

Table 3
Restoration planning of distribution systems using DER.

References	Objectives	Models	Description
[141]	to maximize the sum of restored loads power weighted with their priority levels	a knapsack problem formulation and graph theory	network cell-based restoration using DER with BS capability
[142,143]	to maximize the total weighted restored energy for the entire time horizon	a MILP model	optimal control sequence for controllable switches, ESSs, and dispatchable DER
[144]	to maximize critical load pickup	a Petri net-based sequential switching strategy	PN-based autonomous restoration of distribution system using game theory
[145]	to maximize the restored load	a graph-reinforcement learning framework	power system topology linked with a graph convolutional network
[146]	to maximize the restored active load	a mixed-integer second-order cone programming	restoration path optimization using a new set of radiality constraints
[100]	to maximize the active power restored and minimize total restoration time	a MILP model	considering both energy optimization and dynamic stability of the system
[147]	to maximize the total restored loads with priority factors over a rolling horizon	a MILP optimization model and a transient simulation model	including frequency dynamics constraints in the model
[149]	to maximize the capacity of energized loads	a second-order cone program	coordinating repair crew dispatch model and transient frequency-constrained sequential cold load pickup model
[150]	to maximize the total weighted restored energy over the scheduled horizon	a MILP problem after linear approximation	various DER, repair crews, and mobile emergency generators coordinated
[151]	to maximize weighted load restoration during the scheduling time horizon	a MILP problem after linear approximation	considering the coordination with damage assessment
[152]	to minimize multi-objective functions including load unserved time and repair time	a MILP problem by linearizing these nonlinear terms	coordinating the repair crews, the distribution system, and the emergency communication
[153]	to maximize the picked-up loads considering cold load pickup conditions	a trilevel MILP formulation	coordinating repair crew dispatch problem for the interdependent power and natural gas systems

Table 3 summarizes studies on restoration planning strategies with DER at the distribution level. Compared to the procedures of BS at the transmission level where non-BS thermal generators are generally restored and the transmission networks are expanded first, the typical aim for BS in distribution systems is to restore critical loads using local DER after interruptions caused by disastrous events. Therefore, it is necessary to consider the repair process, mobile emergency generators, the damage to the cyber sector, the independency of power system with gas system, etc.

Meanwhile, coordinated restoration strategies are proposed for integrated transmission and distribution networks in Refs. [154–157]. Load restoration schemes are proposed considering interactions between the transmission and distribution systems and the capabilities of renewables in Refs. [154,155]. In Ref. [156], a decentralized data-driven load restoration scheme for transmission and distribution systems with high penetration of wind power is proposed. In Ref. [157], an optimal generator start-up sequence scheme considering the support of RES at both transmission and distribution levels is developed. Coordination between the transmission and distribution systems can make full use of RES, but its application and implementation are much more complex.

5. Black start from RES – A case study of GB

5.1. Evolving black start practice in GB

In established practice, NG:ESO adopts a restoration strategy following Local Joint Restoration Plans (LJRP) in conjunction with TSOs and Distribution Network Operators (DNOs). NG:ESO is responsible for the overall BS service in GB. TSOs have the responsibility to build and operate the national transmission system, i.e., the 400 kV or 275 kV systems in the whole of GB and the 132 kV networks in Scotland. DNOs are responsible for maintaining and operating the distribution networks, including networks at 132 kV and below in England and Wales and 33 kV and below in Scotland [158]. The principle of an LJRP is illustrated in Fig. 3. A number of designated BS power stations start up and establish islands with sections of the power network and loads, then these islands are synchronized through a skeletal transmission network and non-BS generators are started [36]. To achieve a relatively uniform restoration of the whole transmission system, the country is split into six zones with up to three BS providers in each zone. Fig. 4 depicts the TSO and DNO license areas as well as the outlines of BS zones in GB [158,159].

The traditional BS portfolio of the GB system was made up of coal stations, open/combined cycle gas turbine (OCGT/CCGT) gas stations, and hydro stations. Although there are a number of hydroelectric stations in GB, most of them are relatively small and connected at the distribution level and so were not considered as BS units. Coal stations were the predominant BS providers before 2016. Alternative solutions have been integrated into the ESO contracting process with the phase-out of most coal-fired power plants, including sites with trip-to-house load and interconnectors [36]. In the Distributed Re-Start project, to utilize the significant proportion of smaller DER in distribution networks, a distribution restoration zone (DRZ)-based scheme was developed. In this scheme, a section of the distribution network where DER is located restores part of the local network and loads, or even acts as a virtual service provider to the transmission level to energize the wider skeleton network. DRZ-based restoration plans (DRZP) are designed to work in parallel with the existing LJRP to form a full restoration strategy. The ESO’s vision is to provide competitive BS resources to networks of different voltage levels by the mid-2020s [36,160].

In the live trials of the Distributed Re-Start project, the BS resources included a hydro generator, a biomass steam generator, and a grid-forming BESS. Meanwhile, the BS capability of grid-forming WTs has been tested at Dersalloch Wind Farm by SPEN, SPR, and SGRE [161–164].

A timeline in Fig. 5 illustrates the evolving BS practices in GB and the live BS trials from non-traditional technologies.

5.2. BS trials of the grid-forming Dersalloch Wind Farm

This project by SPEN, SPR, and SGRE investigated a 69 MW site connected to the SPEN network with 23 variable speed WTs as shown in Fig. 6 [165]. The WF was operated in VSG-control mode for nearly six weeks. Different parameter settings were applied to the WTs and a large data set was collected, with which the responses of WTs and the WF to various disturbances such as load step response, interconnection tripping, and frequency events, were investigated. According to the recorded data, the WTs with relatively high inertia levels could respond rapidly to common frequency disturbances [161–164]. It was also demonstrated that a small number of VSG-controlled WTs could maintain the stability of the system in islanded mode.

In this trial, to supply the required reactive power of energization of the local network, four WTs (A1, A2, B9, and C17) equipped with VSG control were started, each with a 125kVA diesel generator supplying their auxiliary power. Then sections of the transmission network were energized successfully, i.e., to the 132 kV network through a 90MVA step-up transformer and then to the 275 kV network through a 240MVA transformer at the New Cumnock substation. Finally, the grid-following WTs were started up after the energized system was stable.

The Dersalloch Wind Farm trials successfully demonstrated the

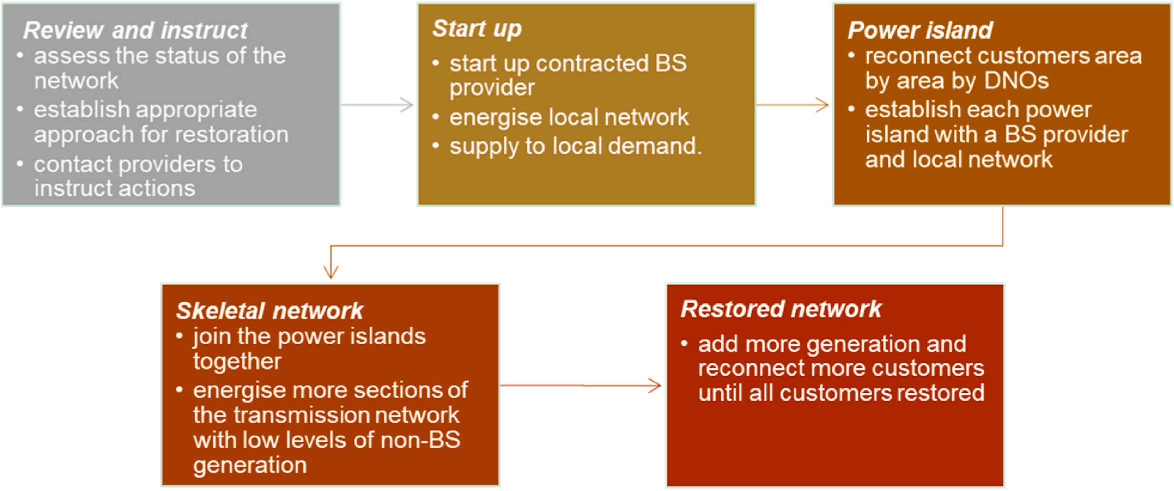


Fig. 3. Restoration process following LJRPs in GB [36].

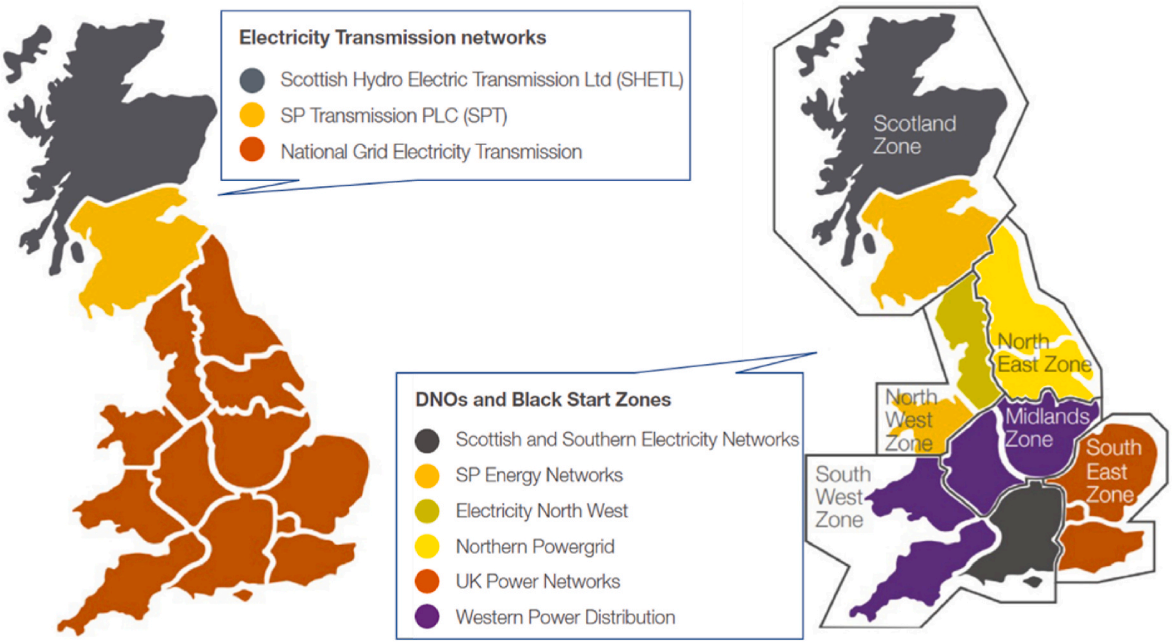


Fig. 4. The TSO, DNO licence areas and the outlines of BS zones in GB [158,159].

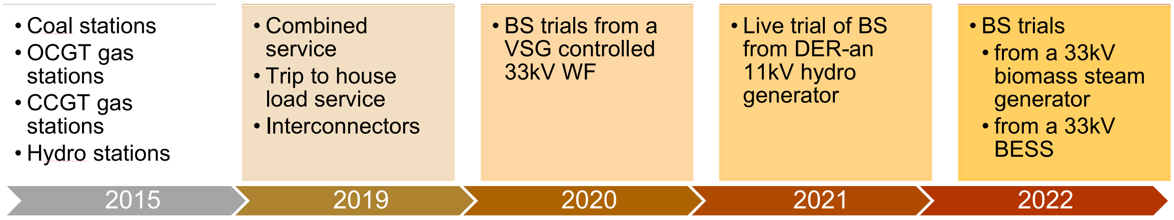


Fig. 5. Timeline of evolving BS practices in GB [158,165].

potential island operation capability and BS capability of WTs equipped with grid-forming control. However, adequate wind speeds were essential.

5.3. The distributed Re-start project

The goal of the Distributed Re-Start project was to use DER in distribution networks to deliver BS services by establishing power islands, re-energizing parts of the transmission network, and accelerating the wider system restoration.

In the project, DER with BS capability including synchronous generators and BESS connected at 11 kV or 33 kV, equal to or greater than 10 MW, were defined as anchor generators; other DER like WT or PV units join the power islands established by anchor generators to accelerate the restoration [166].

To investigate the viability of BS from anchor generators, case studies were undertaken to identify the barriers and challenges based on a combination of detailed offline analysis, desktop exercises, HiL testing, and real-life trials [167].

In the first stage of the project, ten Scottish Power Distribution and Scottish Power Manweb networks with different kinds of DER and different network topologies and characteristics [168] were selected as case study networks, in which various restoration options and restoration plans were developed. Steady-state, dynamic, transient, and harmonic studies as well as protection assessments were undertaken through desktop simulations. In the second stage, live trials were undertaken on three typical trial networks [165,169,170].

At one live trial site, an 11 kV hydro generator was used as the anchor generator along with two 33 kV connected wind farms to establish a stable power island and energize the 275 kV network. At another live trial site, temporary diesel generators provided the auxiliary supplies of the 11 kV biomass steam anchor generator that restored the local distribution network and the local transmission network up to 400 kV. In addition, HiL simulations were performed to observe the behavior of protection and the BS capability of grid-forming DER. At the third live trial site, a grid-forming BESS was tested to restore the network [165].

Through these simulations and live trials, several technical challenges were identified, and potential solutions were proposed, including block load pick-up of small DER, voltage transients generated by transformer energization, transient recovery voltage and rate of rise of recovery voltage challenges of switchgear, automation, grid-forming power converters, PLL stability, and protection performance [165,170,171].

5.4. Concepts developed in the distributed Re-start project

A DRZ-based restoration strategy was proposed, and an automated control system known as the DRZ control system (DRZ-C) was developed for the coordination of systems and equipment.

5.4.1. The DRZ-based scheme

A DRZ is a predefined part of a distribution system that has at least one anchor generator in it and synchronization points to the transmission network [169]. It can energize part of a transmission network or serve local loads. Fig. 7 illustrates the six main stages in the proposed

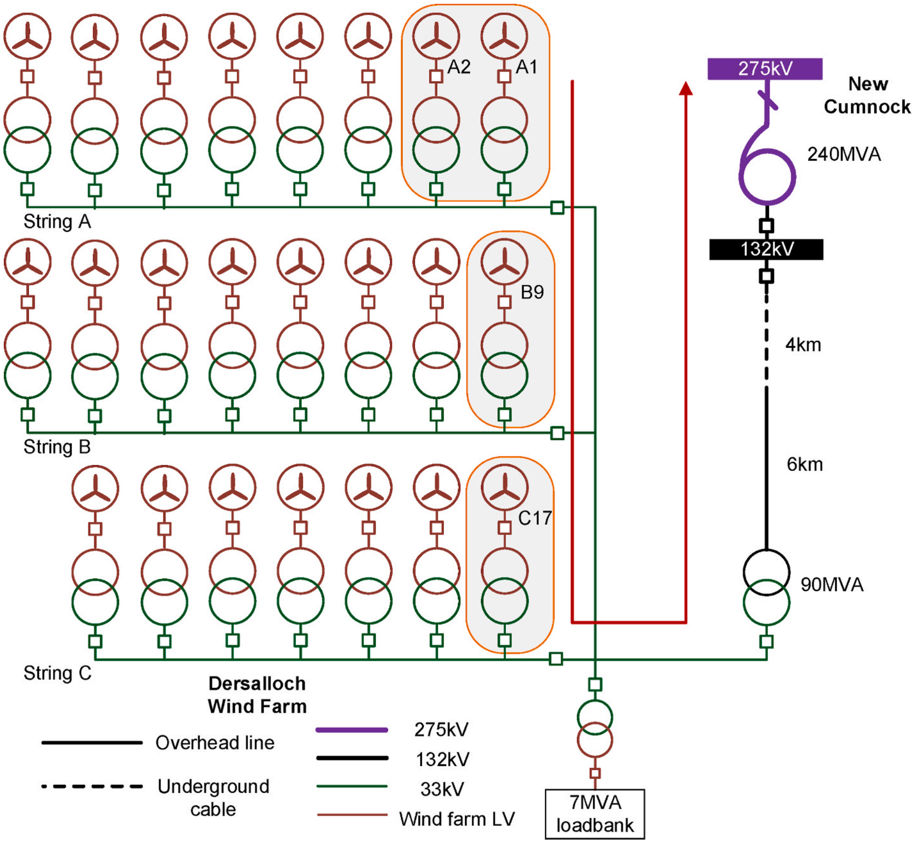


Fig. 6. Dersalloch Wind Farm network and transmission network [165].

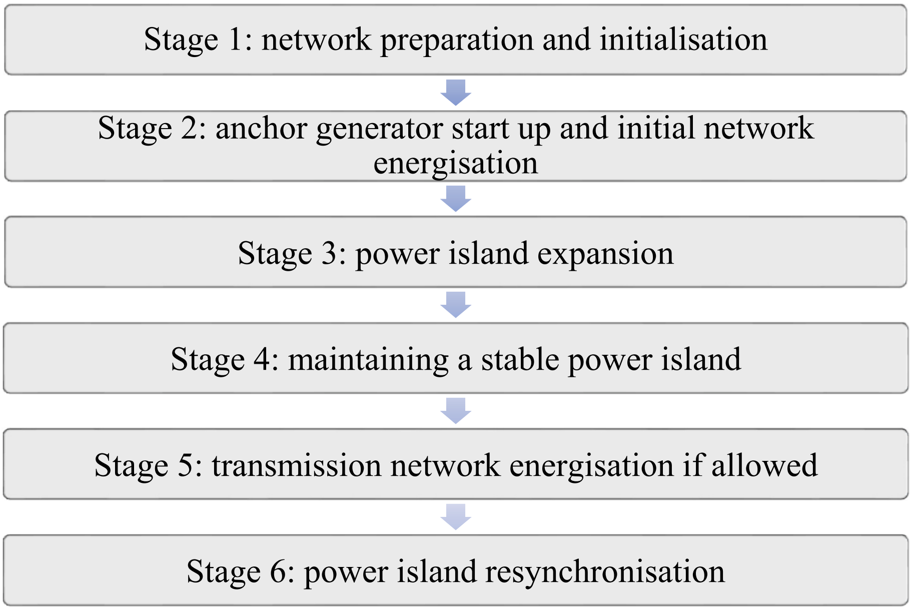
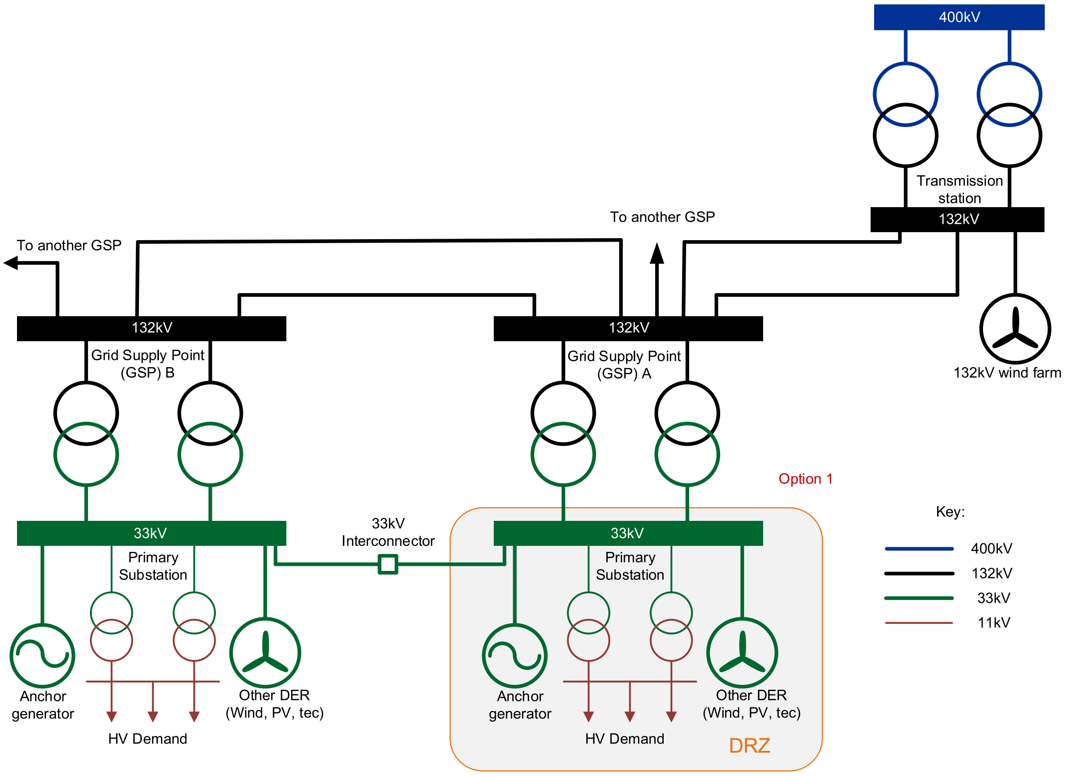


Fig. 7. Stages of BS based on DRZP [166].

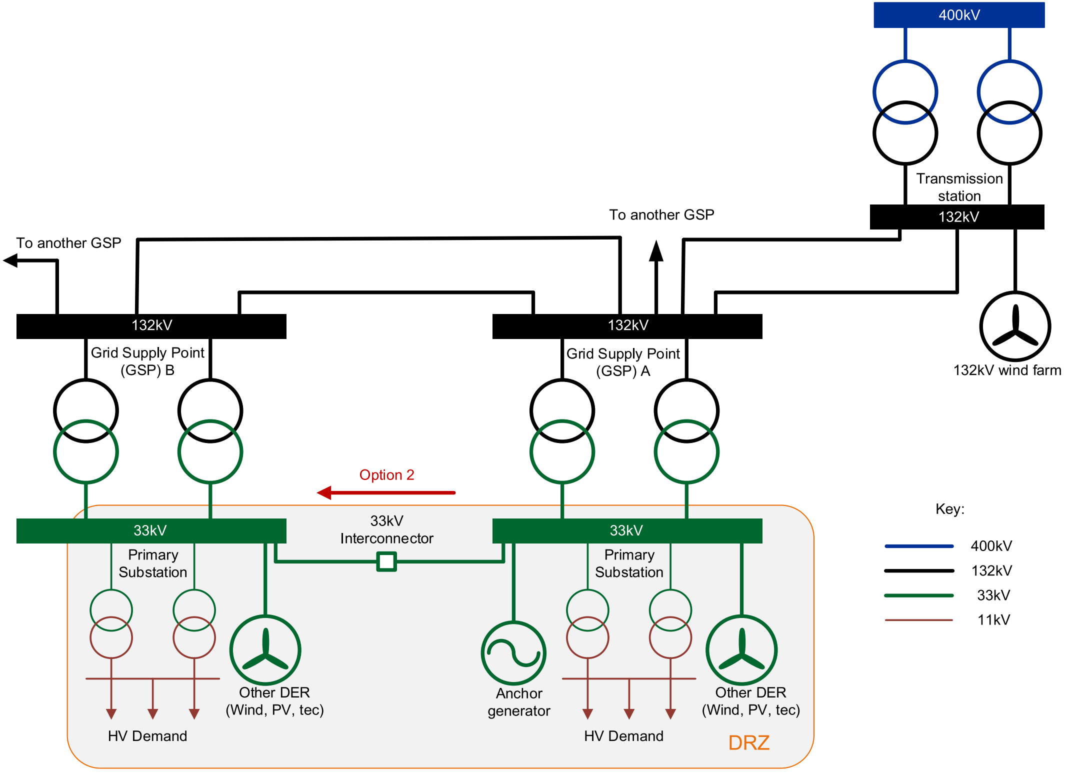
DRZ-based restoration scheme [166].

In a DRZ-based scheme, the power island would be maintained or expanded after being established by an anchor generator. Six different restoration options were developed and tested. Fig. 8 shows the options for restoration with DER units connected to a 33 kV distribution network [158].

- Option 1: Local network growth only. A DRZ would supply maximum local demand at 33 kV and wait for synchronization with the external network.
- Option 2: Distribution level network growth. A DRZ would expand to serve the load of an adjacent 33 kV distribution network through the 33 kV interconnection.

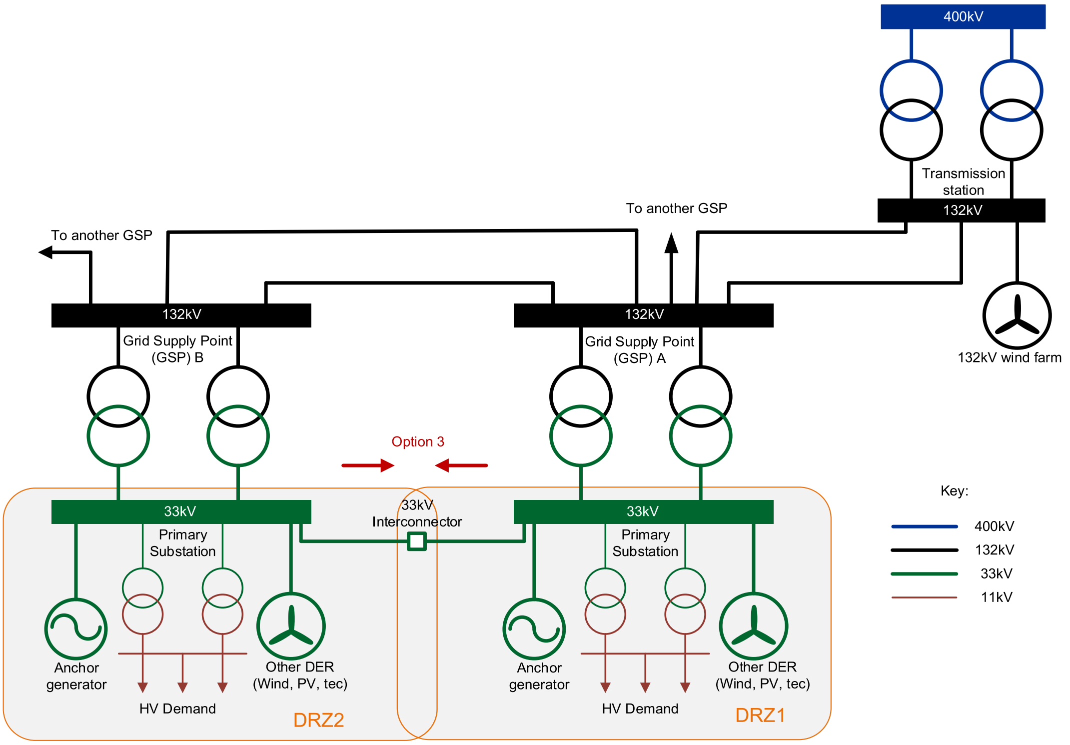


(a) Option 1

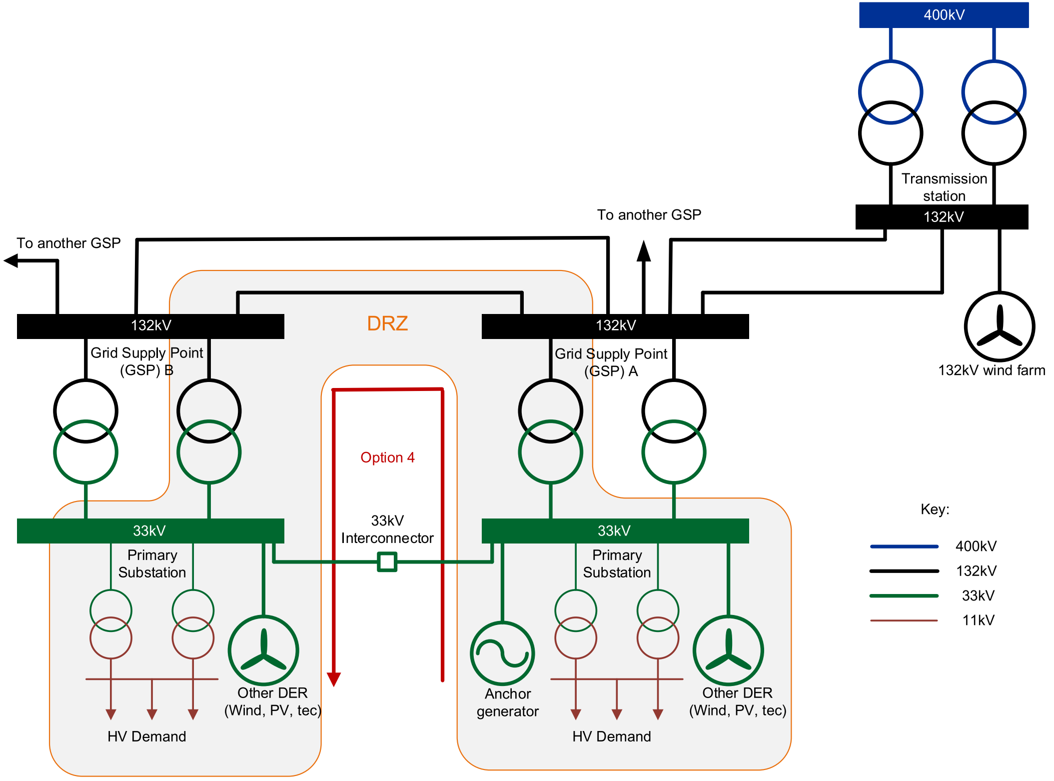


(b) Option 2

Fig. 8. DRZ-based restoration options [1158]



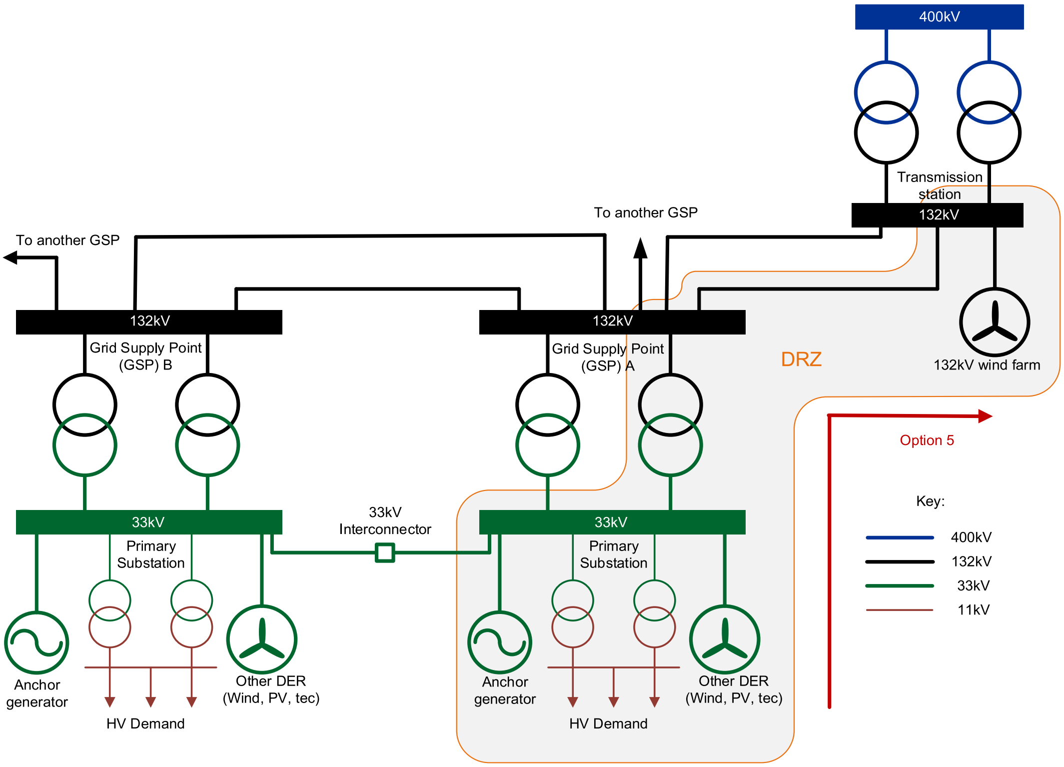
(c) Option 3



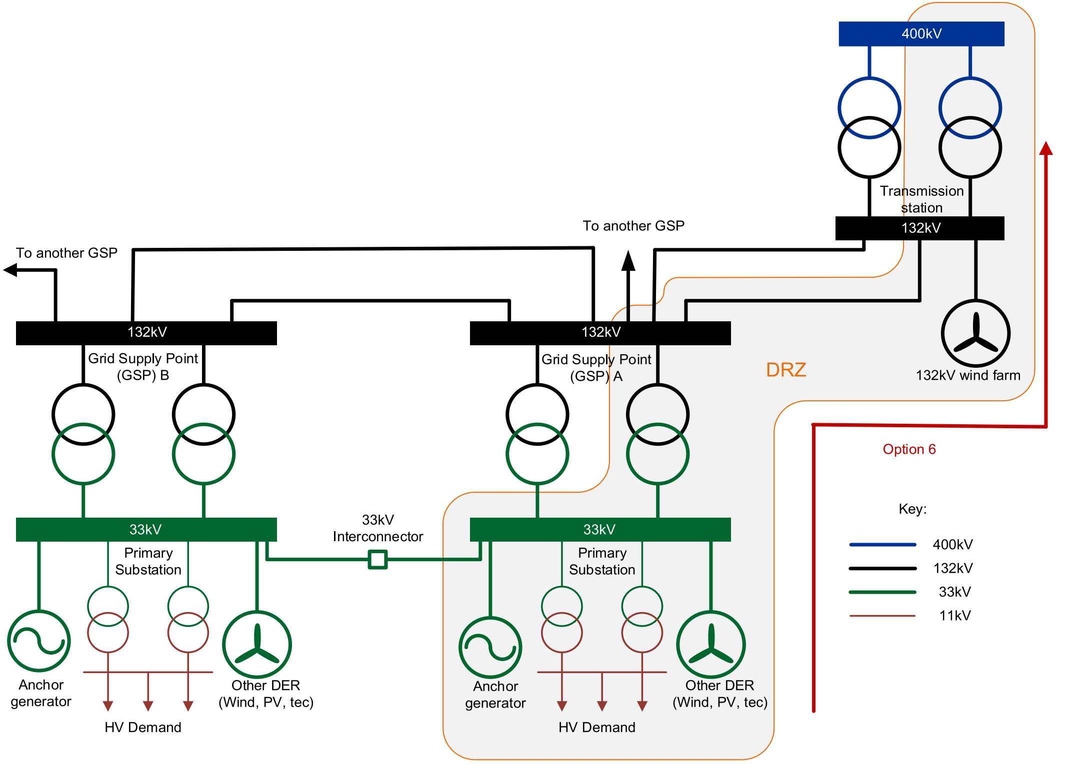
(d) Option 4

Fig. 8. (*continued*).

- Option 3: Synchronization of a parallel DRZ. A DRZ would be synchronized to an adjacent DRZ via interconnection to form a larger island.
- Option 4: Distribution network growth through transmission circuits. A DRZ would expand through transformers and the 132 kV lines to restore an adjacent 132/33 kV substation and connect more loads and DER.



(e) Option 5



(f) Option 6

Fig. 8. (*continued*).

- Option 5: Inclusion of transmission connected RES in a DRZ. A DRZ would expand through transformers and the 132 kV lines to connect additional RES at the 132 kV level.
- Option 6: Skeleton network energization by a DRZ. A DRZ would energize a 132 kV connected resource and the transmission network up to 400 kV through grid transformers.

5.4.2. *Functional requirements of anchor generators*

The requirements of anchor generators were proposed in the project [166] as shown in Table 4. While the basic principles are maintained, specific requirements are tailored according to the capabilities of DER, network characteristics, and the restoration plan for a DRZ.

5.4.3. *The DRZ control system*

To deal with the technical challenges and organizational impacts of delivering a successful BS service, an automated control scheme, called DRZ-C, was designed and located in the distribution system as illustrated in Fig. 9 [158]. Its basic objective is to establish a power island through initiating energization, connecting and dispatching DER, and restoring local loads. When a power island is formed, the DRZ-C will coordinate the anchor generator, other DER, and flexible demand to maintain the stability of the system and supply a capability at the point of connection to assist with wider network energization. To achieve these goals, a DRZ-C should have the following functionalities [166].

(1) Fast balancing: to identify disturbances in a DRZ and to trigger an action of a load bank or BESS to maintain power balance.
(2) Slow balancing: to observe the loading of all DER and manage the anchor generator and load bank/BESS to keep power balance in a longer time scale and to ensure enough resources are available for fast balancing.
(3) Wider network synchronization: to manage a DRZ for synchronization with another DRZ or a wider network. After synchronization, the DRZ-C follows the instructions from the control room and provides real and reactive power services.
(4) Wider network energization: to coordinate the control modes of all resources to prepare for energization and send the real and reactive power information to the control room before, during, and after energizing the wider network.

Four schemes of DRZ-C were designed by different companies, among which the one by General Electric was adopted for HiL testing at the National HVDC Centre [158].

Table 4
Comparison of proposed functional requirements of anchor generators and existing BS generators [166].

Functional Requirement	Existing Requirement	Proposed DER Requirement
Time to connect	≤2 h	≤8 h
Service availability	≥90 %	≥90 %
Resilience of supply-service delivery	≥10 h	≥72 h
Resilience of supply-availability to start up	≥72 h	≥120 h
Frequency control	Existent on large power stations	Fast-acting proportional frequency control
Voltage control (Reactive capability)	Existent on large power stations; reactive capability ≥100MVAr Leading	Continuous steady-state voltage control at the point of connection; minimum of 0.95 leading/lagging power factor
Block loading size	≥35 MW	≥2 MW (site specific depending on DRZ)
Sequential start-ups	≥3	≥3
Short circuit infeed	100MVA (at t > 80 ms)	≥1 x DER MVA rating (at t ≥ 10s)

5.4.4. *The timing of a restoration process*

An example of the timeline throughout a DRZ-based restoration is illustrated in Fig. 10. This is divided into six periods in line with the stages shown in Fig. 5. In the first pre-energization period, the BS declaration, information gathering and instruction of the DRZ are performed, which will take up to 8 h under reasonable worst-case conditions. Then in the second phase, the start-up time of the anchor generator is expected to be 1 h considering the worst case of a steam generator. In the third stage, 1 h is needed for the DRZ expansion and energization of top-up service providers. In the fourth stage, the time for block loading is estimated to be 2 h on the assumption that an average of 10 min is needed to pick up each block load. Then 2 h are considered necessary to energize the transmission network. The last resynchronization stage is determined by the restoration of adjacent DRZs and the wider networks.

6. Discussion and future research directions

As the carbon intensity of power systems reduces and the energy landscape evolves, the BS and restoration strategies must adapt accordingly. The review indicates the promising potential and technical solutions of two non-traditional BS approaches: BS from RES and BS from DER. Through the extensive literature review, it can be concluded that black start and restoration operations in future power systems are expected to embody several key features and challenges.

(1) Diversification. A wide range of different energy sources and storage technologies is required to create flexible and resilient power units capable of supporting restoration processes. Integration of renewables in BS procedures is a trend. Variability and intermittency of intermittent renewables may affect reliability during black start. Pairing renewable resources with ESS ensures a consistent power supply during restoration. Beyond the frequently studied PV systems, WT, pumped hydro storage, and batteries, more recent hydrogen technologies such as hydrogen fuel cells, hydrogen storage systems, and hydrogen turbines offer promising solutions. Meanwhile, the grid structure is becoming increasingly diverse, with integration of AC and DC systems. Restoration frameworks and methods are lacking to effectively model diversified and complex grid scenarios during BS operations.
(2) Decentralization. Decentralization involves distributing power generation and control across numerous smaller DER rather than relying solely on large, centralized power plants. A challenge is the complexity of coordinating multiple DER. Microgrids and aggregated DER through collective management and coordination like DERMS or VPP offer enhanced flexibility, resilience, and sustainability in BS operations. Other issues are the regulatory and policy barriers to decentralized BS implementation and vulnerability to cyber-attacks due to increased reliance on communication systems.
(3) Power electronics-dominated. Power electronics will be central to enabling future BS capabilities, providing the foundation for managing voltage, frequency, and power flow in future BS. Most RES, DER, and ESS are integrated into power systems through converters. Moreover, the continued expansion of HVDC and medium voltage direct current (MVDC) systems will provide controlled power injection to weak grids across diverse geographic regions, and enable renewables like offshore wind and solar to support BS efforts. Static synchronous compensators can provide dynamic reactive power support and stabilize grid voltage during the BS process. While power electronics offer flexibility and efficiency, they also introduce complexities in BS. The key challenges are lack of inherent inertia, low short-circuit

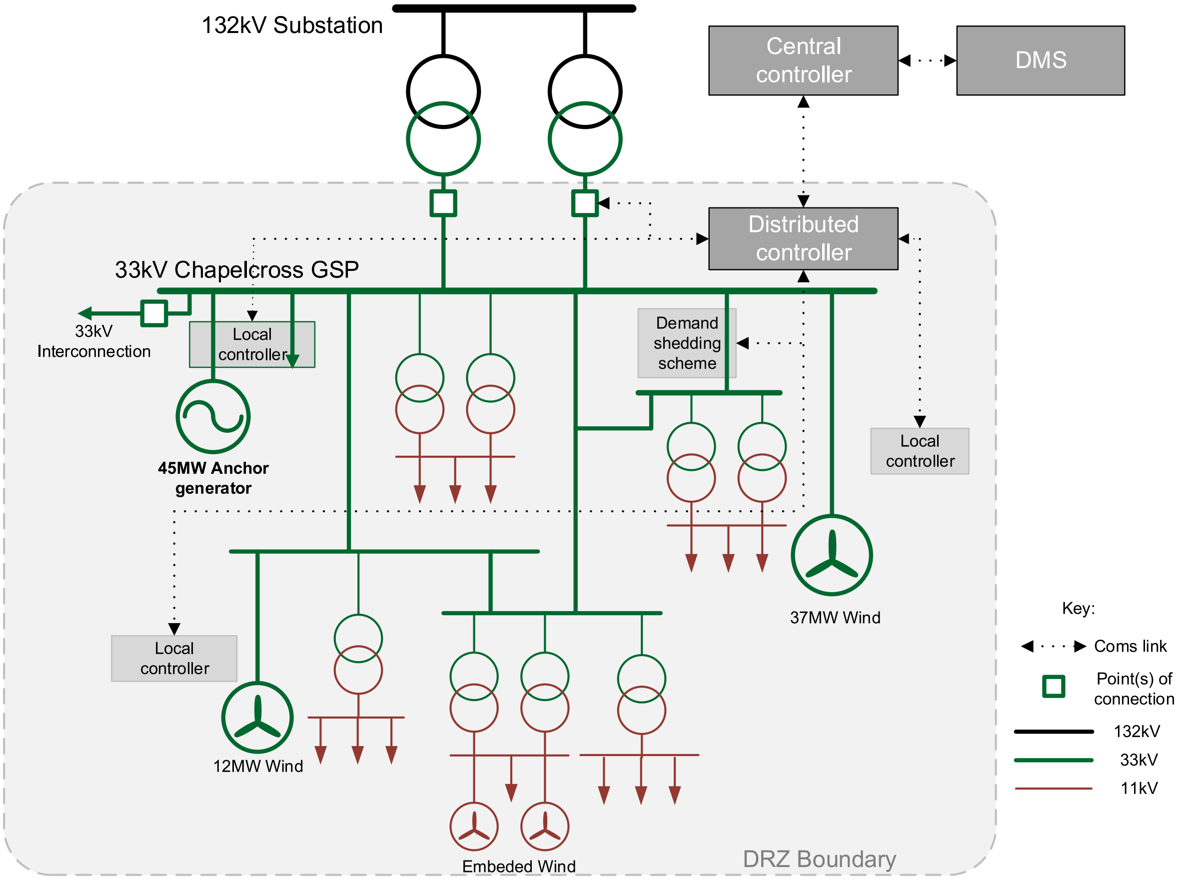


Fig. 9. Conceptual DRZ-C architecture [158].

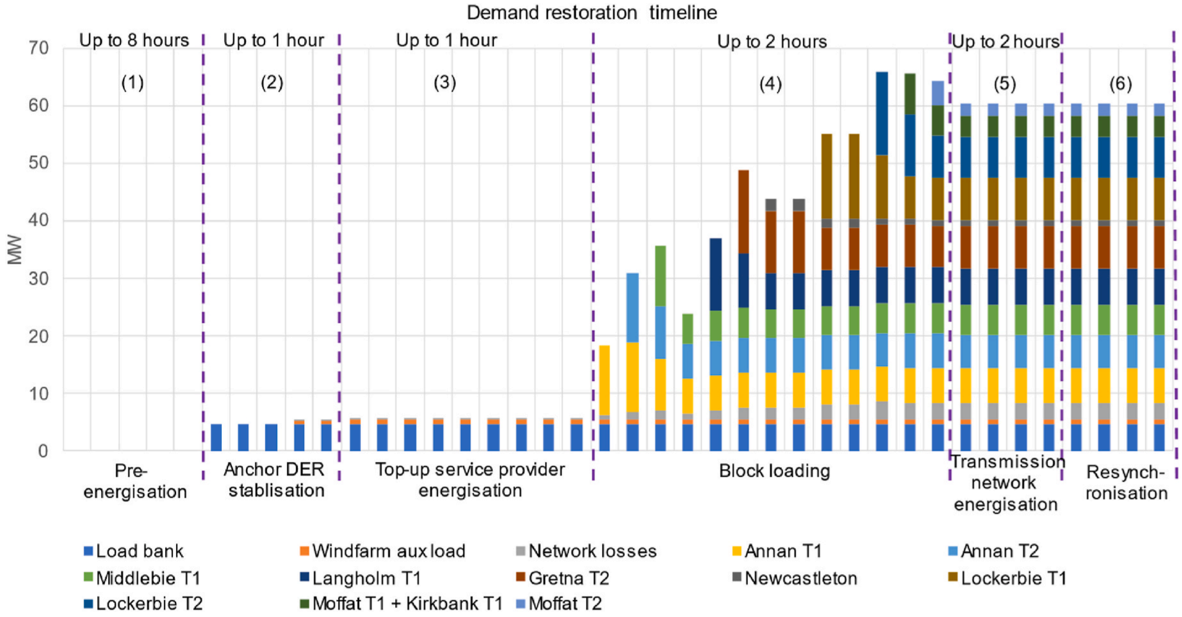


Fig. 10. Indicative restoration timeline using reasonable worst-case timings [158].

capacity, complex control and coordination, dependency on communication systems, limited overload and fault tolerance, and cybersecurity vulnerabilities. Meanwhile, existing black start modeling tools are often designed for traditional synchronous machines and may not accurately represent the behavior of power electronics-based resources.

(4) Resilience-orientated. The resilience of modern power systems has attracted great attention in the face of increasing extreme events. BS operations after extreme events including natural disasters, cyber-attacks, and technical failures present more challenges, such as infrastructure damage, communication disruptions, and limited resource availability. Key BS resources

and infrastructures may be unavailable, and restoration plans may not account for the specific impact of natural disasters, resulting in longer restoration times. Balancing priorities between restoring critical loads and stabilizing the broader grid is challenging.

Even though a number of studies have focused on BS from RES and DER, efforts are still needed to meet future BS requirements. Future research directions are summarized hereafter:

(1) Advanced grid-forming technology

As shown in the studies reviewed, grid-forming technology plays a potentially strategic role in the BS of future power systems. However, grid-forming converters require advanced control algorithms to manage power flows and maintain voltage and frequency stability during BS operations considering the transient disturbances introduced by transformer energization, load pickups, and synchronization. Algorithms should incorporate predictive and adaptive models to anticipate grid disturbances and proactively modify power flows to stabilize the system during BS. Meanwhile, the coordination of multiple grid-forming converters to work harmoniously demands highly efficient and scalable control algorithms. Decentralized control frameworks can be developed for multiple grid-forming converters to operate autonomously while maintaining overall grid coordination. Moreover, the interaction between grid-forming and grid-following RES during BS has not been thoroughly addressed. In the design stage, the planning of grid-forming and grid-following converters deserves to be explored.

(2) Automation, control and protection

Automation and control systems are required to coordinate diversified BS resources, especially DER. Many existing DER converters are not equipped with any communication capabilities, and decentralized or distributed control methods with limited or zero communication are promising for the coordination of DER in BS. Thus, distributed control frameworks that can facilitate BS using decentralized energy resources need to be explored. Cyber-resilient control and communication systems should be designed to ensure secure and reliable automation of BS processes. Artificial intelligence-driven automated control systems can be developed for real-time decision-making of optimal restoration sequences based on real-time system conditions and historical data.

Moreover, the restored systems in the early stage of BS from converter-based RES have much lower fault levels which might be insufficient for the existing protection to detect or operate. Meanwhile, BS involves gradual grid restoration, leading to constantly changing system topology. Therefore, adaptive protection schemes are required to be developed in which relay settings can be adjusted dynamically based on real-time system conditions. Coordinate between local and system-wide protection layers and the unique response characteristics of grid-forming and grid-following converters in restoration need to be investigated.

(3) Restoration planning and testing

Restoration frameworks need to be developed for coordinated BS involving diverse energy resources of RES, DER, microgrids, and ESS. BS plans involving diversified resources need to be well-designed to ensure a secure restoration. In restoration planning, most literature employs optimization algorithms to model the static behavior of power systems and ignores dynamic performance, which may be unrealistic. Developing restoration plans that consider both static operational constraints and dynamic differential constraints will lead to more accurate solutions.

In established practice, restoration plans should be tested through desktop studies and/or field tests to ensure a secure process. Considering the dynamics and complexity of converter-based resources, complete tests are essential to verify the full functionality of the BS service using RES and DER. Therefore, high-fidelity simulation tools and HIL testing for new diversified technologies need to be developed to accurately represent the complexities of BS operations and ensure reliable performance in real-world scenarios. Digital twin technology for real-time simulation and testing of BS processes under different scenarios can be explored to assist in BS planning. Meanwhile, advanced simulation models should be established that accurately represent the dynamic interactions between various resources, DERMSs, VPPs, and the grid during BS operations.

(4) Restoration strategy after extreme events

Decentralized DER-based BS solutions demonstrate great advantages in supporting localized restoration after extreme events. Robust communication networks should be designed to ensure command and control during extreme events. Meanwhile, pre-event hardening strategies to reinforce infrastructure against extreme weather can contribute to a more reliable restoration, and advanced weather forecasting can be used to make flexible scenario-based restoration plans tailored to specific disaster types. Models and solutions need to be investigated further to perform effective restoration integrating pre-event hardening strategies with advanced weather forecasting.

Risk assessment methods should be investigated to identify and evaluate the potential threats and vulnerabilities that could impact power system operations, and then restoration under different extreme event conditions. These should be used to develop restoration plans that can withstand a wide range of disruptive scenarios. The state of both power and other infrastructures like communication, gas, and transportation and the availability of emergency resources like mobile ESS will affect the process of restoration. Thus, multi-disciplinary research is required to achieve an efficient and realistic restoration considering the interdependency between power systems and the closely related infrastructures and resources, so that models that capture the interdependencies between various grid components and external infrastructures will be developed, and restoration plans should be developed to make full use of various resources.

(5) Policy, regulatory, and economic aspects

BS using RES and DER involves multiple entities with heterogeneous ownerships, ranging from a variety of DER providers, aggregators, DNOs, and TSOs. Mutual agreements and interconnection protocols should be established. Commercial solutions need to be developed. Policies and market mechanisms that reward BS services and incentivize grid resilience investments need to be developed. Updated regulatory standards should be established to allow BS from RES and DER.

7. Conclusions

In summary, this review paper provides a comprehensive overview of using RES in transmission or DER in distribution systems for power system restoration. The capability of BS resources is the first requisite to ensure a successful restoration. In this review, the challenges of RES participating in BS and the roles RES and DER can play in a BS process are discussed. The corresponding control methods for RES and DER in restoration are presented, including the control methods for individual converters and integrated resources to meet the requirements of BS capability, and the coordinated control of multiple RES and DER in BS. The review also covers the restoration planning strategies using both RES at the transmission level and DER at the distribution level. Beyond academic papers and considering industry practices, this review explores the studies of the BS trials at Dersalloch Wind Farm and the Distributed Re-Start project. Throughout this review, critical issues and future directions in power system restoration research are emphasized.

These encompass grid-forming technology, automation, control and protection, restoration planning and testing, interdependencies with other infrastructures, and regulatory support for practical applications. The findings of the Distributed Re-Start project provide valuable commendations by proposing a DRZ-based framework, designing the corresponding coordination control system, and enabling BS from DER.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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