Proceedings of the 7th International Conference on Climate Change, Vol. 7, Issue 1, 2023, pp. 14-30

ISSN 2513-258X online
DOI: https://doi.org/10.17501/2513258X.2023.7102

POWER SYSTEMS RESILIENCE ENHANCEMENT: A REVIEW OF OPERATIONAL ENHANCEMENT APPROACHES

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Abstract: Power system resilience enhancement (PSRE) describes approaches used in reducing the extent of direct impacts caused by climate change and approaches in quickly restoring the grid functionality to its usual status. Recently, much research has been conducted on PSRE approaches to the effects of climate change. There are abundant review papers on PSRE to the impacts of climate. But there are no significant amounts of review papers focusing on operational resilience enhancement approaches on the entire power system, particularly with the focus and classifications suggested in this paper. Operational resilience-oriented modelling approaches and strategies have been comprehensively reviewed across five distinct dimensions including operational strategy, enhancement type, hierarchy, modelling methods and model formulation. A standard literature review process was followed to identify articles, with the initial search covering PSRE in general. Out of these, papers focusing on operational resilience enhancement were selected. The selected papers were classified according to the operational enhancement approaches, enhancement types, modelling methods, model formulation and the enhanced hierarchy criteria. The operational approaches, which include distributed energy resources, microgrids, preventive control, response, design standards upgrade, advanced visualisation and situational awareness systems and advanced and adaptive restoration operational techniques, were reviewed. The study reveals that for a single operational approach, different enhancement techniques can be employed using different modelling techniques. However, limited studies have so far explored an entire grid improvement as opposed to transmission and distribution structures. In addition, among the optimisation, probabilistic, simulation and AI based modelling methods, optimisation approaches have been extensively used. As lots of assumptions were built to demonstrate the resilience challenge solutions, the adoption of authentic existing power system data related to the severities of each event and system resource data may be appropriate in demonstrating resilience improvement solutions. There are very limited studies that combine these modelling approaches in one study. Research gaps and directions for future research have been suggested in this paper.

Keywords: operational measures, resilience, climate change, extreme weather, power systems resilience enhancement, modelling

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Introduction

Electricity remains the backbone of any developed community. The modern society depends on a consistent and reasonably priced delivery of electricity. Power systems are constructed to withstand stochastic element outage under the N-1 security theory (Li et al., 2017). However, recently several natural disasters have caused extraordinary challenges to power systems due to climate change, emphasising the position that power systems are unprepared for extreme events of large scale and severity level (Lin et al., 2018). Since its introduction, the resilience of vital infrastructure, specifically power systems, has become the core of utilities and investigators (Lin et al., 2018). Resilience is categorised into infrastructural and operational (Wang et al., 2016). Operational resilience concentrates on what happens during and immediately after a major interruption, that is decreasing the proportion of disconnected customers or the reconnection time of all affected customers (Panteli, Pickering, et al., 2017). Since disastrous events can hardly be stopped, human operators are expected to prepare for and react to prospective severances sufficiently so that power systems can effectively ride through and recuperate from such occurrences. As it is necessary to maintain the essential loads intact throughout calamities, the resilient and reliable supply of power is critical to ease the citizens' distress triggered by disruptive events (Li et al., 2017). Preparatory resilience enhancement measures are critical to guaranteeing a resilient power system. The concept of grid preparedness and resilience against natural hazards has become a paramount risk management strategy under climate change, which hinges on identifying, developing, and implementing approaches for restraining the impact of natural disasters and the successive wide-area, long-duration power outages (Arab et al., 2021). This paper concentrates on the operational approaches which improve power system restoration time. It was shown in the literature (Panteli, Pickering, et al., 2017) that for distribution networks it is more resilience-effective to make the network smarter and more reactive to extreme weather instead of making the network more redundant in terms of energy flow level components. In addition, although smart resilience approaches are deemed short-term, they are economical and simpler to implement (Panteli & Mancarella, 2015). Further, these measures are deemed smarter and more cost-effective (Huang et al., 2017).

In recent years, much research has been conducted on power systems enhancement approaches to effects of climate change. There are abundant review papers on power systems resilience enhancement due to impacts of the climate. (Lin et al., 2018) summarized the recent major research efforts on key strategies for improving power system resilience. The most-investigated problems were categorized according to their problem category, stage, hierarchy, and model. Resilience-oriented modelling and approaches based on microgrids (MGs) within the elements of modelling aims and metrics, resilience scenarios, modelling methodologies, and strategies and topologies were comprehensively reviewed in (Wang et al., 2020). Methodologies regarding operation and control of networked MGs were reviewed and summarized by (Chen et al., 2021). (Mahzarnia et al., 2020) presented a comprehensive classification of the measures to improve the power system resilience, which was mainly based on the occurrence time of the event. From their perspective, the resilience measures were classified into two general categories of preservation measures and recovery measures. The measures and strategies for enhancing resilience in each of these categories were precisely discussed. In addition, each category of resilience enhancement measures was broken down into subcategories, based on the practicality of measures at different levels of the power system, including transmission and distribution. (Hosseini & Parvania, 2021) discussed the potential applications of supervised and unsupervised AI-assisted techniques that help solving stochastic decision-making and high-dimensional data classification for resilient operation of power distribution systems. A comprehensive survey on current research of enhancement strategies of proactive resilience of power systems was introduced in (Mohamed et al., 2019). The utilization of MGs for improving power system resilience was extensively presented. In addition, they highlighted the proactive strategies based-machine learning for resiliency enhancement of power systems. The optimization-based and machine learning-based methods for proactive strategies design were also compared. In (Li et al., 2017) operation and management of networked MGs to enhance power system resilience were reviewed. Transmission network reconfiguration optimization models for grid resilience was comprehensively reviewed. Optimization approaches for the evaluation of modelling and simulation of transmission network reconfiguration problem were discussed in (Aziz et al., 2021). In this paper, operational / smart resilience-oriented modelling approaches and strategies have been comprehensively reviewed across five distinct dimensions, i) operational strategy, ii) enhancement example / type iii) enhanced hierarchy iv) modelling methods and iv) model formulation. Although the previous reviews that have been highlighted contribute significant and relevant power system resilience knowledge, there are not significant numbers of review papers focusing on operational resilience enhancement approaches on the entire power system, especially with the focus and categorisations proposed here. Accordingly, this paper covers a gap in this particular area, and better informs researchers on how smart resilience enhancement strategies are modelled by the community. Furthermore, it proposes challenges and future research directions to help investigators focus their work. Section II highlights the research review methodology; section III presents results and discussions while conclusions and recommendations are drawn in section IV.

Methodology

A standard review methodology was used. The first literature search was on power system resilience enhancement. Out of these, papers focusing on operational resilience enhancement were selected. In this paper, references (Gao et al., 2016; Panteli, Mancarella, et al., 2017; Panteli, Pickering, et al., 2017; Panteli, Trakas, et al., 2017; Nezamoddini et al., 2017; X. Liu et al., 2017; Huang et al., 2017; Lu et al., 2018; Yang et al., 2018; Lai et al., 2018; Poudel & Dubey, 2019; Taheri et al., 2019; Yan et al., 2019; Shen & Tang, 2019; J. Liu et al., 2020; Nazemi et al., 2020; Ghiasi et al., 2021; Kamruzzaman et al., 2021; Zhao et al., 2021; Kumar et al., 2021; Biswas et al., 2021; Mohammadi Darestani et al., 2021; Oh et al., 2021; Sun et al., 2021; v Mohan et al., 2022;) were selected and reviewed. They can be categorised based on the following criteria, see Figure 1. A detailed list of the papers is presented in Table 1.

Operational strategy: Literature has so far presented different operational enhancement strategies including distributed energy systems, MGs, preventive control, response, design standards upgrade, network reconfiguration, advanced visualisation and situational awareness systems and advanced and adaptive restoration. The hierarchy, type of enhancement, modelling approaches and formulation are explored in this part.

Hierarchy: the power system is a hierarchical system that consists of generation, transmission, and distribution. Sometimes the term grid may be used to stand for the entire system. Since disasters mostly affect any of these, this approach looked at which of the studies focused on what hierarchy, i.e., transmission, distribution, and grid.

Type of enhancement: this centred on the specific enhancement approaches used.

Modelling approaches: modelling strategies used to enhance the resilience was explored in this case. Investigated modelling approaches were optimisation, probabilistic, artificial intelligence (AI) based and simulation approaches.

Model formulation: how the different enhancement approaches were modelled was investigated.

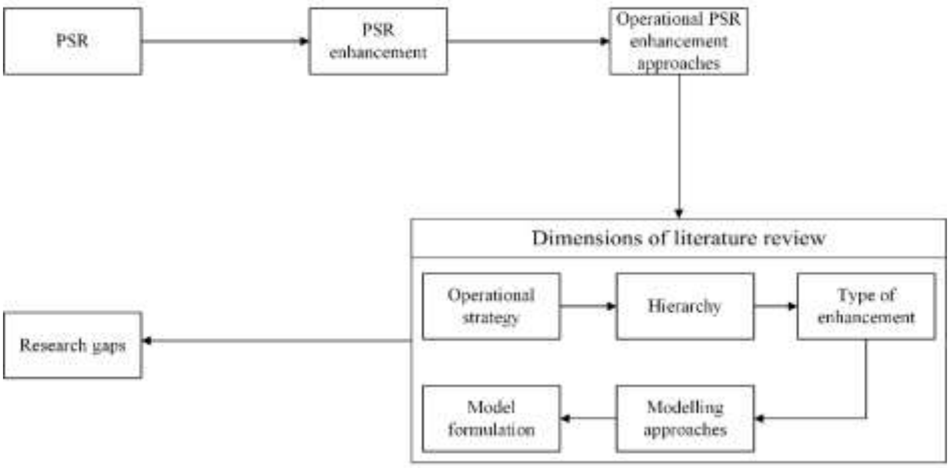

Figure 1. Study criteria

Table 1. Detailed list of selected references

Operational strategy	Refs.	Hierarchy			Modelling approaches			
		Transmission	Distribution	Grid	Optimisation	Probabilistic	AI based	Simulation
DERs	(Lai et al., 2018)	✓			✓			
	(Nazemi et al., 2020)		✓		✓			
	(v Mohan et al., 2022)		✓		✓			
MGs	(X. Liu et al., 2017)			✓		✓		✓
	(J. Liu et al., 2020)		✓		✓			
	(Biswas et al., 2021)		✓		✓			
Preventive control	(Panteli, Pickering, et al., 2017)	✓						✓
	(Yan et al., 2019)	✓			✓			
	(Taheri et al., 2019)		✓		✓			✓
	(Mohammadi Darestani et al., 2021)		✓			✓		
Response	(Huang et al., 2017)			✓	✓			
	(Panteli, Trakas, et al., 2017)	✓				✓		
	(Panteli, Mancarella, et al., 2017)	✓				✓		
	(Yang et al., 2018)			✓				✓
	(Zhao et al., 2021)	✓						✓
	(Ghiasi et al., 2021)		✓		✓			
Design standards upgrade	(Nezamoddini et al., 2017)	✓			✓			

	(Lu et al., 2018)	✓					✓
	(Shen & Tang, 2019)		✓			✓	
Advanced visualisation and situational awareness	(Gao et al., 2016)		✓		✓		
	(Kamruzzaman et al., 2021)			✓		✓	
	(Oh et al., 2021)			✓		✓	
	(Sun et al., 2021)	✓				✓	
Advanced and adaptive restoration	(Poudel & Dubey, 2019)		✓		✓		

Results and discussions

Results suggest that extensive operational resilience enhancement techniques have so far been proposed in literature. These techniques fall under the scope of different operational resilience enhancement strategies which include distributed energy resources (DERs), microgrids, preventive control, response, design standards upgrade, advanced visualisation and situational awareness systems and advanced and adaptive restoration. The subsequent subsections will present the enhancement techniques, hierarchy, modelling methods and model formulation for each of these operational resilience strategies. A summarised visual image of the results is presented in Figure 2.

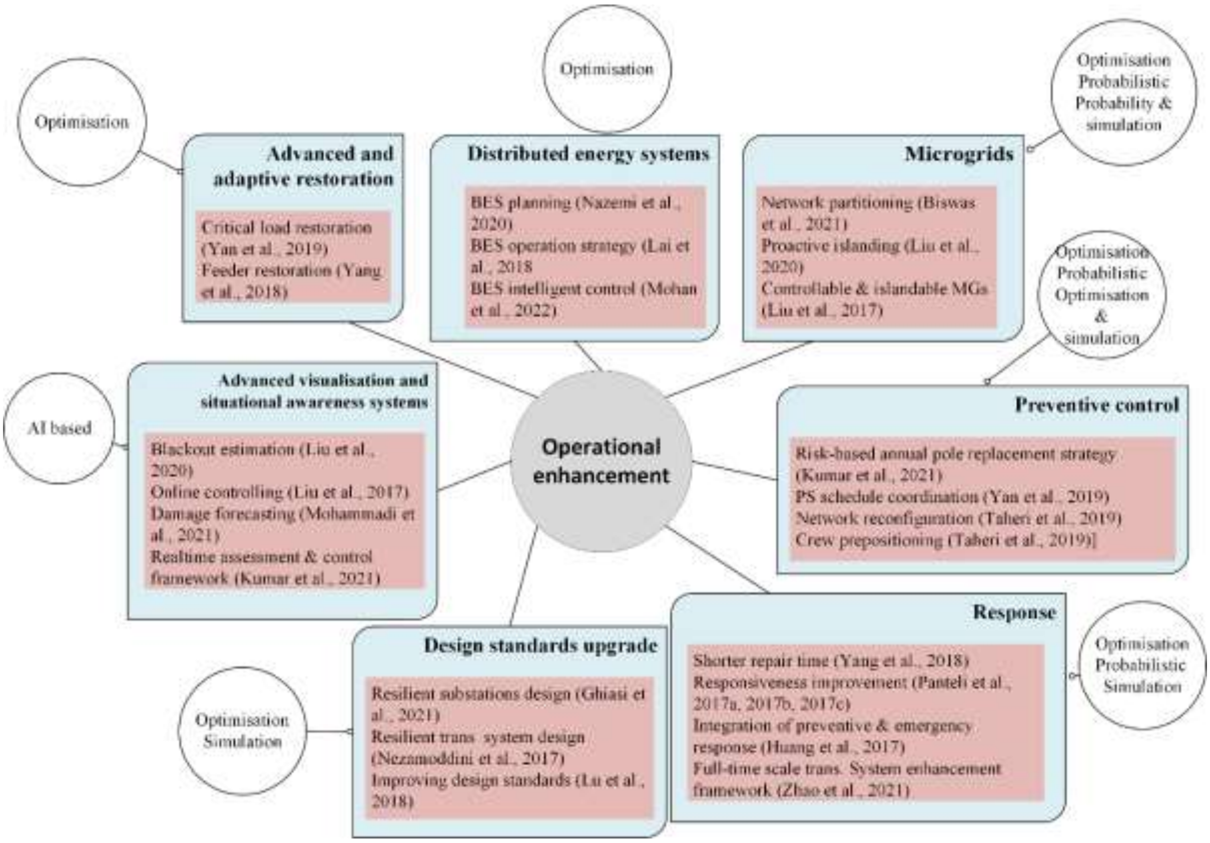

Figure 2. Summary of power system resilience operational improvement measures and their respective improvement techniques and modelling methods

Distributed energy resources

DERs are commonly used in restoration of vital loads points during disasters. Ref (Lai et al., 2018; Nazemi et al., 2020; v Mohan et al., 2022) presented DERs in the form of battery energy storage system (BESS) planning (Nazemi et al., 2020), battery energy storage (BES) operation strategy (Lai et al., 2018) and intelligent control of BES (v Mohan et al., 2022). (Nazemi et al., 2020) evaluated resilience-driven BESS planning through optimum position of BESS systems and sizing. An algorithm was exercised to select candidate nodes for BESS position. The selection relied on which nodes would better supply the required essential loads with a bigger number of connected line segments. During an earthquake, an uninterrupted supply of essential loads was maximised using an optimisation engine. This was attained by maximising the quotient of BESS discharge energy during emergency times and the demand energy by essential loads for the distribution system. (Lai et al.,

2018) suggested a BES operation strategy as dispatchable and energy resource. The restoration model emphasised the actions of the operator during a restoration process and sought to decrease energy not supplied (ENS) before the disabled lines were restored. ENS for a power system which had generators and utility scale BES was minimised using an optimisation engine. In (v Mohan et al., 2022), an intelligent control of BES was proposed and examined to minimise the shedding of critical loads and maximising the duration of service time of the critical loads during a disaster. The resiliency enhancement was achieved through a dynamic optimisation, Fuzzy-based control of charging rate of BESS, priority in critical load supply and BESS charging, and flexible dispatch interval were used. Dynamic optimisation sought to minimise the needed energy and the accessible energy using a mixed integer linear programming. To control the charging and discharging rate of the BESS a Mamdani-based fuzzy logic controller was established. Battery state of charge (SOC) and restoration times were used as the inputs to fuzzy control. The BESS was divided into segments. The priority between the critical loads and BESS (whether to supply the loads or charge the BESS) was chosen depending on the SOC of BESS. In the first segments, ultimate importance was given to the supplying essential loads.

Microgrids

A chance for MG typology is when DERs and loads are grouped to create a system which supplies essential loads and help with function renovation during and after outages (Biswas et al., 2021). The potential of using MGs as operational resilience improvement approaches through network splitting (Biswas et al., 2021), proactive islanding (J. Liu et al., 2020) and controllable islandable MGs (X. Liu et al., 2017) was explored in literature. (Biswas et al., 2021) were motivated by maximisation of the number of internal loads supplied to minimise service interruption for a given demand and generation setting. The problem was modelled by allowing for the distribution network model, power flow model, limitations and connection to the grid forming generators. As the main grid was presumed unavailable due to effects of climate change, the network was built in such a way that each distribution node had related demand and supply capacity. The power flow model comprised stochastic generation which could either be photovoltaic generators, diesel generators, or thermal co-fired power plants (CHPs), and inelastic loads. Existence of grid forming generators for each network split of a MG was a key requirement. Stochastic optimisation was practised to take care of the unpredictable variables like stochastic grid forming generators. To maximise fault seclusion and connection restoration, (J. Liu et al., 2020) utilised mixed-integer linear programming in preventive islanding. Preventive islanding was executed to soothe the effects of flaws in the degradation phase by splitting up a distribution structure into numerous independent islands ahead of severe events. The allocation of remote-controlled switches (RCSs) in the pre-event stage, which includes the switching process of RCSs in the fault seclusion stage and the service restoration stage, was optimally determined for instant fault seclusion and connection restoration. The solution was modelled in four portions, preventive islanding and RCSs allocation, dilapidation model, fault seclusion and service restoration. Preventive islanding and RCSs modelling was restricted by investment level, radial topology and no-load shedding prior to the intense event. Only controllable DERs were considered because stochastic generators may be affected by weather during disasters. Fault seclusion was done to reduce the area of the faulted zones established in the dilapidation stage. Quick service restoration based on the RCSs was modelled. Only lines versed with RCSs were switched for quick restoration. The usage of numerous MGs which allow controllability and islanding for grid resiliency was modelled in (X. Liu et al., 2017) employing both Markov model and the Monte Carlo simulation method. The coordination between MG availability and power grid recovery process executes an indispensable assignment in power grid resilience. During severe events, the power grid condition changed from the grid status to MG status with a defined failure rate when MG loads were supplied by local DERs in an island mode. Based on the pre-determined repair or recovery rates, the status of the power grid either went back to normal status or to the contingency status. This status transition was achieved using a Markov chain process. The alterations in the expected demand not supplied, loss of load possibility, number of lines on outage due to severe events and difficulty level of grid recovery were observed using Monte Carlo simulations to evaluate the effectiveness of the MGs.

Preventive control

Preventive control measures including risk-based annual pole replacement (Mohammadi Darestani et al., 2021), optimal coordination of power system schedules (Yan et al., 2019) and network reconfiguration and repair crew prepositioning (Taheri et al., 2019) have been studied. To accomplish a risk-based annual pole replacement, probabilistic methods were utilised to line up poles based on the drop in risk of power outage in the distribution network when a pole is replaced (Mohammadi Darestani et al., 2021). Expected outage reduction and national electric safety codes strategies were applied to a power distribution system with over 7000 nodes. An effective method to recovery was to order repair and restoration so that at each moment, the highest possible number of customers got their power back. Failed nodes were ordered based on the number of power outages that they caused, and connections whose restoration brought back power for the most customers were repaired first. Available repair staffs at any time in the restoration procedure were allocated to repair failed poles depending on the ordering. This process was repeated till the last failed pole was fixed and the whole distribution system was back online. Unpredictable occurrence of disasters was considered when approximating the likelihood of failure of poles. Optimum coordination of power system schedule was suggested in (Yan et al., 2019) to improve the ice-covered power grid. The maximisation of the safety of transmission infrastructure and guaranteed continuity of power delivery during icing disasters used an optimization method. The two-step structure for the resilience improvement scheme was utilised. The ice thickness was predicted initially, which was used for the following day unit commitment and the pre-placement of mobile DC de-icing devices (MDIDs). The schedule was strong enough to accommodate the ice thickness prediction error. An optimisation model bringing together the real-time power system dispatch, de-icing programme, and MDID routing was proposed where these parameters were adjusted from intermittently subsequent to the revised ice thickness projection. Network rearrangement and repair team prepositioning ahead of distribution system failure was proposed in (Taheri et al., 2019) as proactive operational actions. This depended on the probable effects of the impending disruption which were simulated using Monte Carlo. Team prepositioning was meant to accelerate the anticipated post disturbance processes. Previous knowledge of available repair team was assumed. Distribution line fragility curves were utilised to predict damages. The fragility curves and the intensity of the forthcoming event were used to denote the failure possibility of lines under severe weather. Failure possibilities were fed to the Monte Carlo simulation process as input data to generate probable situations. After the stochastic damage approximation, the output gave information on severity, faulted lines, and fault locations. The optimisation model was formulated next to decrease the expected load shedding caused by the disruption over all generated situations. The model was fed by network technical data, geographical information of the system elements like physical switches, team players, and fault positions, and the time the disturbance strikes, and line damages occur in different circumstances as input data. An optimal schedule of actions before the disturbance was then determined.

Response

The major role for operational resilience enhancement is to decrease the response time during emergencies. Literature offers different mechanisms for improving the operational resilience through response measures which includes shorter repair times (Yang et al., 2018), responsiveness enhancement (Panteli, Mancarella, et al., 2017; Panteli, Pickering, et al., 2017; Panteli, Trakas, et al., 2017), resource enhancement (Panteli, Mancarella, et al., 2017), combination of preventive and emergency response (Huang et al., 2017), full-time scale transmission system improvement framework (Zhao et al., 2021). (Yang et al., 2018) simulated the effect of reduced repair time on the grid performance by decreasing the time to repair (TTR) by 0.5. TTR was also used by (Panteli, Pickering, et al., 2017) to simulate the efficacy of improved response time on transmission network. Unlike in (Yang et al., 2018), (Panteli, Pickering, et al., 2017) assumed that the weather event had no effect on TTR, that is, no multiplication factor was used for raising the normal TTR for higher wind speeds. While (Yang et al., 2018) reduced TTR by 0.5, (Panteli, Trakas, et al., 2017) evaluated responsiveness by lowering the mean time to repair (MTTR) by 20 percent. Probabilistic method was used to monitor this effect on the transmission system. The decrement of MTTR was also implemented by (Panteli, Mancarella, et al., 2017) with an extension to increasing the number of repair team. On a different note, (Huang et al., 2017) suggested an integrated resilience response framework which integrates the preventive and emergency response through optimisation approaches with the intention of minimising the operating costs and load shedding while maximising power output of the generator. Proactive response included generator re-dispatch and network switching, while emergency response considered generator re-dispatch, network switching and load reduction. Various mathematical simulations substantiated the effectiveness of the suggested framework and the efficacy of the solution approach. Situational awareness is the pillar of resilience decision making as it provides critical information about power grids and natural disasters. The power outage predicting was performed because it links power grids to natural hazards. The outage prediction was used to develop effective preventive and emergency response approaches. (Zhao et al., 2021) proposed a full timescale transmission system improvement framework, whose effectiveness was simulated on an IEEE RTS-79 test system. The approach was to detect key lines, and then de-ice and maintain according to priority.

Design standards upgrade

Boosting the design standards normally enhances robustness. Authors have investigated this area though the designing of resilient substations (Ghiasi et al., 2021), resilient designing of transmission lines (Nezamoddini et al., 2017) and the general improvement of design standards (Lu et al., 2018). (Ghiasi et al., 2021) utilised an optimisation engine to optimally build resilient substations. To realise this, substation installation costs, reliability / resiliency costs and model limitations were accounted for. Previous knowledge of substation position and loads were assumed. All loads and losses were also presumed to be served by the substation. The installation costs comprised of land acquisition, construction of transformer and equipment costs. To add in the cost of resilience, the cost of demand not supplied was computed. Lastly, the model was constrained to make sure that load boundaries, voltage angles, voltage boundaries and feeder currents and voltages were held within recommended ranges. (Nezamoddini et al., 2017) ultimately designed resilient transmission structures to minimise energy not delivered. To realise this, the authors developed an optimisation model to select the optimum investment decision for the resilient design of the transmission infrastructures to physical attacks. They also assessed the impairment caused by the physical attacks in terms of load shedding. A mixed integer linear programming to minimise the investment expenditures so that the threat of the load shedding surpassing a certain tolerance value, after an attack to the power grid, be less than the threat tolerance value, specified by power system operators. To upgrade the strength of the transmission infrastructure to ice stresses, the increase in the design strength was simulated by moving the fragility curve to the right (Lu et al., 2018).

Advanced visualisation and situational awareness systems

Artificial intelligent (AI) strategies were employed to make the power grid smarter to climate change impacts through blackout estimation (Shen & Tang, 2019), online controlling (Kamruzzaman et al., 2021) damage forecasting (Oh et al., 2021) and real time grid evaluation and control framework (Sun et al., 2021). Whilst AI based means were used to build an algorithm for robust estimation in (Shen & Tang, 2019), simulation approach was used to assess the efficacy of the methods by fitting the blackout size data from the US power grid. The number of affected customers, demand loss and blackout duration hours were all considered. To accomplish online control of the power grid, (Kamruzzaman et al., 2021) used prior experience learning to inform grid training. In (Oh et al., 2021), real storm and event data were utilised to validate the effectiveness of the proposed impairment forecasting method. Impairment predicting acquaints preparedness decision making which supports reduction of the duration of outage hours or reduction of the magnitude of the impacts. (Sun et al., 2021) utilised power control signals and local measurements data to evaluate and control the transmission system in real time.

Advanced and adaptive restoration

(Gao et al., 2016; Poudel & Dubey, 2019) investigated advanced and adaptive restoration through critical load restoration (Gao et al., 2016) and feeder restoration (Poudel & Dubey, 2019). In both studies, optimisation approaches were used, and distribution systems were regarded. Whilst (Gao et al., 2016) maximised system resilience while minimising average voltage changes amid restoration, (Poudel & Dubey, 2019) executed a joint maximisation of post-restoration reliability of restored loads and assignment of DERs for an impartial restoration of the essential loads. To acquire the optimal essential load restoration in (Gao et al., 2016), a service restoration technique that applied MGs with insufficient generation resources to provide for essential load on distribution feeders following an intense event was proposed. A two-objective chance-constrained plan was used. The initial objective was to maximise the amount of energy delivered to essential loads weighted by their significance while another objective was to minimise the voltage deviation. Constraints on service duration, generation resources, power flows, and network topology were considered. The concept of continuous operating period was effectuated to evaluate the accessibility of MGs for service restoration and the duration for which the MGs were able to supply individual sets of essential loads with insufficient generation resources. A Markov chain-based operation model of MGs was proposed to evaluate continuous operating period. A scheme table that collects viable restoration paths was set up at the beginning. Then a linear integer program was employed to choose paths from the strategy table and formulate the restoration strategy in the second step. A framework to reinstate power delivery to the critical loads in an event of a intense disaster by optimally using DERs was proposed in (Poudel & Dubey, 2019). The recommended framework is suitable to all dispatchable DERs with capability and reserve energy. The model imagined that the distribution circuit was fitted with adequate remote-operated switches that could be controlled as per the intended plan and that non-critical loads were disconnected from the grid prior to restoring the critical loads. Additionally, radial topology of each restoration path was maintained and DERs were not connected. The distribution system was presumed to span a small geographic area and that all distribution lines were symmetrically affected by the disaster situation with an equivalent probability of failure.

Gaps and recommendations

Even though extensive research has been conducted on operational resilience enhancement, there are gaps which form basis for future research direction or resilience decision making. These are evaluated in this section and are summarised in Table 2. Although adequate literature has concentrated on developing relevant and effective resilience models and strategies which may form a basis for future studies in terms of replication or otherwise, numerous challenges still need to be considered and integrated into operational models to better approximate and accomplish the preferred level of resilience during extreme events. The cost-effectiveness of various operational measures is yet to be studied. This provides foundations for resilience decision planning more especially for long term operational measures. Very limited studies concentrate on making the entire grid smart. Of the reviewed literature, only about 17 % explored the possibility of improving the entire grid using operational strategies. While different modelling approaches have been explored, only about 4% of the reviewed papers integrated these modelling approaches in their studies. The integration could offer advanced and more accurate solutions. Another challenge is on the use of assumptions because most modelling fomulations are based on these. While these assumptions make modelling easier, they may not be a true reflection of the conditions in the real system. Of the operational resilience strategies found in literature, none have explored power regulation or policy as an operational enhancement strategy. Regulations governing the power systems should be able to support power system resilience. Also, integration of operational enhancement approaches has been understudied. These may offer optimal results and could form basis for resilience cost-benefit analysis. It has also been observed that load curtailments improvements have so far been on the distribution loads. However, transmission loads such as transmission substations could also be candidates for resilience improvement plans. The evaluation of the effectiveness of the proposed resilience enhancement techniques are made on the standard test systems, which are usually ideal systems with failures parameters that do not equal to the real power systems. There is potential risk that the same techniques that seem to work on the standard test systems may not be replicated on a real power system. Although situational awareness is considered fundamental in preventive approaches, no studies have extensively assessed disaster with respect to grid exposure as means of informing long term operational resilience improvement. Finally, although situational awareness is considered as the fundamental aspect of preparedness and proactive measures, less attention has been given to disaster assessments as far as power system exposure is concerned. Knowledge of grid elements that are exposed to both historical and future disasters could go a long way in preparing the grid for the worst disasters.

Following the above narration, future research directions are highlighted hereafter. Studies highlighting cost effectiveness of different operational resilience strategies need to be conducted to define the accurate cost of resilience. Since climate change impacts affect the entire grid, boosting the operational resilience of an entire grid may offer a holistic improvement solution. Also, integration of modelling approaches may offer advanced solutions as opposed to mono-methods. This may require advanced modelling skills and computer power. The use of real power system authentic historic data related to the severities of each event in any geographic area to select most applicable resilience enhancement solutions. In addition, studies which need to evaluate the capacity of policy to support resilience may offer a better platform for government to be part of power system resilience plans. Since modelling assumptions may have accuracy impacts on the effectiveness of proposed methods on the real power systems, validation with their associated system resource data, such as available crews and the duration taken to restore the power system, can provide accurate response measures. Finally, disaster mapping needs to be included in resilience assessment studies because these disasters are location specific and could provide key information in resilience planning. Since these disasters are expected to increase in their occurrence and intensity due to global warming, mapping potential disasters by considering climate change may offer the prediction of future catastrophes.

Table 2. Summary of gaps and future research direction

Gaps	Recommendations for future research
Cost-effectiveness of operational measures not studied.	Studies highlighting cost-effectiveness of various operational measures
Limited studies on the entire grid	Research that considers boosting the resilience of an entire grid
Integration of modelling approaches	Modelling of operational measures using integration of modelling methods
Assumptions are not a true reflection of the conditions in real systems	Use of real power system accurate historical data
Power regulation and policy not studied as an option for boosting grid resilience	Evaluation of existing regulation on their capacity to support resilience
Integration of enhancement approaches	Studies on how combination of enhancement approaches could further improve resilience
Transmission loads yet to be candidates for load curtailment reduction	Review the possibility of maintaining supply to substations using operational measures
Application of proposed methods on real power systems is limited	Testing of proposed methods on the real power systems
Disaster assessment as a means of situational awareness is lacking	Disaster mapping and zoning with consideration of changing climate

Conclusions

A modern economy depends on consistent and reasonably priced delivery of electricity. However, lately several natural disasters have caused extraordinary challenges to the power system due to climate change, emphasising the position that the power system is unprepared for extreme events of large scale and severity level. This paper carried out an extensive review of existing research regarding the operational strategies to achieve resilience, considering their operational resilience-oriented modelling approaches and strategies across five distinct dimensions, i) operational strategy, ii) enhancement example / type iii) enhanced hierarchy iv) modelling methods and iv) model formulation. Distributed energy resources, microgrids, preventive control, response, design standards upgrade, advanced visualisation and situational awareness systems and advanced and adaptive restoration operational techniques were reviewed with respect to their modelling methods and formulations, and the associated grid hierarchies and specific enhancement types. Different enhancement types were explored. The study suggests that either optimisation, probabilistic, simulation, AI based or a combination of simulation and probabilistic methods or combination of simulation and optimisation methods were used to model operational enhancement. Among these modelling methods, optimisation approaches have been extensively used. There were very limited studies that combine these modelling approaches in one study. The study further reveals that although different enhancement types have been studied to achieve the respective operational strategies, limited studies were reported regarding the entire grid as opposed to transmission and distribution structures. To formulate the enhancement types, different approaches were employed. The general trend was the use of assumptions especially in optimisation methods. To model measures under preventive strategy, prior knowledge of existing or historical hazards and their associated impacts were used. The aim was to reduce the magnitude of the historical impacts. Formulating models under AI based strategies was data intensive. There is need for accurate historical power system data to inform grid learning. Also, real power system data was necessary to validate the methods. Knowledge of network topography and available electricity generators is key in formulating MGs based measures. In modelling DERs, determining DER location was critical. Response and design standards upgrade measures were formulated by reducing the TTR and shifting the fragility curves to the right, respectively. Since many assumptions were made to model the resilience challenge solutions, the use of accurate real power system data related to the intensities of each event and system resource data may be useful in modelling resilience improvement solutions. We hope this review can help governments, utilities, and researchers around the world to grasp the latest research directions of power system resilience.

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