Electric Power Systems Research 182 (2020) 106238

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Advanced techniques of power system restoration and practical applications in transmission grids

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ARTICLE INFO

Keywords:
Power system restoration
Approximate dynamic programming
Solution space reduction

ABSTRACT

Optimal restoration of a real-time power system following a disruption is a complex process. In view of that and with increase in frequency and severity of power system outages across the US and their impact on consumers and utilities, North American Electric Reliability Corporation elevated the standard of compliance for power system restoration. While several utilities have proposed solutions addressing the elevated standards based on dynamic programming, they could not address the issues for large-scale power systems and real-time operations including those using steady-state and transient analysis due to the curses of dimensionality. In this paper, we introduce a restoration process based on approximate dynamic programming integrated with solution space reduction methodology. The main theoretical foundations of the methodology and key algorithms used in this restoration process include the knowledge of power system engineering, complex network science, concepts of graph theory, and dynamic programming in operation research. We first use the proposed method to demonstrate an optimal restoration process on the IEEE 118-bus test system and then on a 2000-bus synthetic test system. This method addresses the concerns related to the curses of dimensionality and simplifies the solution space and thus can be applied to various complex real-time operation settings.

1. Introduction

A power system subjected to a power outage needs to be quickly restored to an optimal system operating configuration such that it can be re-synchronized to the grid. The complexity of the power system requires such restoration process to be subject to steady state and dynamic constraints of the network including those related to the generation, transmission and distribution, and load.

Though historically negligible and infrequent, power system outages across the US for the last 15 years are on the rise at an alarming rate [1]. The outages are mainly caused from disruptions on the distribution system, both in terms of the duration and frequency of outages. While not very frequent, any damage to the transmission system can result in major power outages that can affect large numbers of customers and can cause major economic disruptions [2].

Power system operators have to deal with the most important task of system restoration following a disruption. The formalism of such restoration process can be highly complex involving a large number of generation, transmission and distribution, and load constraints. Such complexities warrant the operators to employ off-line solution plans to re-synchronize the newly formed islands post disruption. Therefore in practice, power system restoration should be achieved optimally according to different objectives such as maximizing generation capacity and quickly re-energizing major transmission corridors in order to minimize the impact of blackout and recover the load. These considerations make the power system restoration a multi-objective and multi-stage non-linear integer programming problem [3]. For such a problem, several approaches have been proposed that range from heuristics-based methods and expert systems based methods to mathematical programming (MP) solutions. The authors in [4] discuss about re-energizing large portions of electric power system with minimum switching. Similarly, [5] introduces optimized plans to minimize the time required for restoration after a power outage. In [6], the authors highlight a method with symbolic and numerical computational

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https://doi.org/10.1016/j.epsr.2020.106238
Received 1 December 2019; Accepted 19 January 2020
Available online 06 February 2020

knowledge based on system operator's heuristics. The method targets the restoration of power supply without overloading any transmission line. The authors in [7] present a heuristic non-linear programming method that makes the least increment in the ratio of losses and loads served. These methods require excessive computational time to solve the combinatorial optimization problem and may not be adequate for real-time operation. Subsequent studies presented expert systems (ES)-based methods. [8] introduced a prototype ES for bulk power system restoration which is based on object oriented programming techniques for efficient processing. The authors in [9] presented a real-time ES based on acquired knowledge and heuristics with two modes: online and offline. [10] uses general-purpose restoration knowledge base ES and not specific system details for restoring system blackout. [11] summarizes other research works based on ES for power system restoration. These methods based on ES require specialized software which makes the process of restoration time-consuming for the operators. Additionally, mathematical programming (MP) [12], soft computing [13] and combinations of above approaches [14–16] are some of the other approaches that may not be considered reliable in terms of solution accuracy at specific and crucial times.

In addition, there have been several power system restoration techniques proposed [17]. A short-term prediction model of system demand has been proposed in [18]. The authors in [19] illustrate the operating procedure to blackstart a generating station from a remote combustion turbine generator. Overvoltage issues in power system restoration have been discussed in [20]. An approach to standing phase angle reduction was introduced in [21,22] which reduces the delay in power system restoration. The authors in [23] focus on the issues related to protective system during restoration when the power system undergoes continuous changes. Authors in [14] proposed one of the few applications to practical real-time situations for power system restoration. Many of the existing power system restoration methods are based on the theoretical foundation with very limited scope of applicability in practical real-time situations and so many may not be ideal in dealing with restoration in complex large-scale power system networks. Not only a restoration method needs to be efficient and quick, it should also be in compliance with the latest industry standards.

2. Power system restoration

After a power outage or blackout, the power system needs to be restored to its normal operating condition. The restoration process aims to reduce the impact of outage and subsequently mitigating it. Power system restoration focuses on dividing the system into different stages involving different sections such as generation and transmission grid restoration which primarily ensures the voltage level maintenance along with security followed by load restoration which is targeted at minimizing the overall impact of the outage [24]. As the power system has expanded in every aspect over last few decades, the frequency of power outages has also increased resulting in requirement of improvement in the standard of compliance. In this paper, we focus on improving transmission level restoration based on the latest system restoration standards.

2.1. NERC requirements for system restoration

Due to the concerns related to increasing frequency and severity of power outages in an interconnected power system network, North American Electric Reliability Corporation (NERC) elevated the standard of compliance for restoration by adopting revised Emergency Operations and Preparedness (EOP) reliability standards [25,26]. The critical importance of having advanced analytics and techniques that can be applied to real-world restoration planning and real-time decision support has been recognized and is becoming an issue of vital interest for the power community.

The revisions carried out by NERC are deemed important for reliability of the North American bulk power system. The NERC standards EOP-005-2 [25] and EOP-006-2 [26] proposed to have a definite procedure for Blackstart and required Generator Operators (GOP) to meet the requirements for the Transmission Operators (TOP). Thus, the operators must be able to identify the Blackstart capabilities so that generation utilization can be maximized and an optimal start-up sequence can be initiated. On the hindsight, most power system operators rely on off-line restoration plans that only deal with certain contingencies and outages. The power network planners and operators have found it challenging to address NERC's elevated standards regarding restoration at planning stage, let alone meet the demands in real time. This issue has become more serious as recent changes in generation mix have prompted operators to reassess Blackstart needs. Even though NERC has revised the standards to provide enhanced reliability, it still remains a long standing challenge to meet these standards for the power industry.

2.2. Efforts to meet NERC requirements

In order to overcome the challenge for power system operators to meet the NERC standard regarding restoration, several methods have been proposed to provide optimal solutions [27,28]. Most of the proposed solutions are limited to a theoretical discussion with very few extending the findings and applying them to a practical real-time situation. Out of those, two major efforts in this area have been carried out by Power System Engineering Research Center (PSERC) [14] and Electric Power Research Institute (EPRI) [29,30].

1. *PSERC's methodology:* PSERC's effort follows a practical approach with an adaptive strategy for power system restoration [14]. The procedure is governed by a strategy module which centrally controls four major operation modules: (1) Generation Capability Optimization; (2) Transmission Path Search; (3) Constraint Checking; (4) Distribution System Restoration. The restoration process with central strategy module is illustrated in Fig. 1.
   In this methodology, PSERC adopted a goal oriented restoration process involving a different problem formulation for each of the modules. The overall objective is to maximize the total number of transmission lines energized along with the feeders for all the time intervals and in addition allowing the increase of overall system generation capacity for start-up power requirements as shown below in (1).

$$\max \sum_{t=1}^{N_T} \left[\sum_{l=1}^{N_L} (\omega_l^t \cdot L_l^t) + \sum_{i=1}^{N_B} (\omega_i^t \cdot P_i^t) \right]. \quad (1)$$

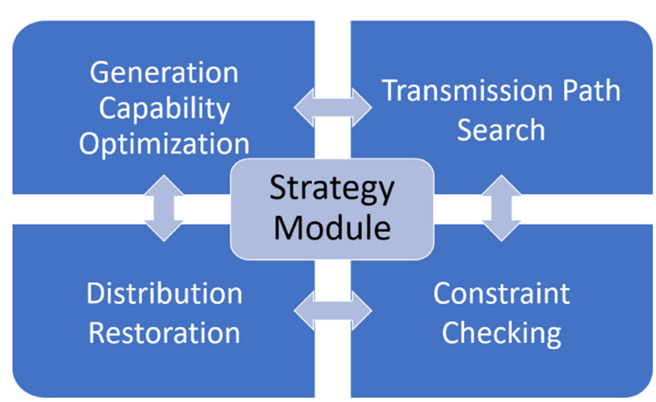

Fig. 1. Illustration of PSERC's restoration process.

$s.\ t.$ Critical Min. &Max. Time Intervals
Start-up Power Requirement
Flow capacity of transmission lines.

where N_T is the total number of time intervals, N_L is the total number of transmission lines, N_B is the total number of buses and for the time interval t, transmission line l and bus i, ω represents the respective weighting factors, L is the status of lines and P is the active power. The objective function in (1) is subject to physical constraints such as flow capacity of transmission lines, generation limits with other start-up power requirements. In addition, the model also considers the minimization of de-energized load for the start-up period.

2. *EPRI's methodology:* EPRI developed tools to provide decision support to system restoration planning citing that the system reliability is directly affected by the efficiency of system restoration [29,30]. On-line restoration process after a blackout requires the operators to adapt to actual outage scenarios and available resources. In order to cater to the on-line restoration process, EPRI developed two tools: (1) *System Restoration Navigation (SRN)*: This was intended to be used for offline planning at the initial stage and further on for dispatcher training and online decision support for power system restoration; and (2) *Optimal Blackstart Capability (OBC)*: This was designed to assist system restoration planners in evaluating system Blackstart capabilities and determining the optimal locations and amounts for additional Blackstart resources.

The methodologies proposed by PSERC and EPRI, although designed to address the elevated system restoration requirements, could not address the issue for large scale power systems and the changing dynamics of real-time operation. The methods are subject to the limitations of dynamic programming (DP) [31] which have been highlighted and addressed upon in this study.

In this paper we introduce the key ideas with associated algorithms that have made a significant breakthrough in development of system restoration technique. They have not only been used in improving the effort and time of planning but has also made the real-time application very possible. The proposed method is based on Approximate Dynamic Programming (ADP) [31] which addresses the key limitations of DP and uses structural analysis to reduce the solution space. This allows the proposed ADP-based method to create a feasible restoration plan of a large-scale power system along with completions of sophisticated simulation tests including steady state AC power flow analysis, frequency dynamic stability analysis and electromagnetic transients analysis in a significantly shorter duration of time when compared to other existing platforms. Currently, the work is being used to integrate the solver engine and automated techniques into a software package that are designed for off-line system restoration planning. Also based on this study, we propose to extend the work further so that it can be used for real-time applications.

The rest of the paper is organized as follows. Section 3 highlights the challenges of application of DP in real world scenarios with its NP-hard nature and addresses them with the introduction of ADP-based backward thinking. Section 4 proposes ADP-based technique with the simplification of solution space based on structural analysis that significantly reduces the complexity of the problem. Section 5 presents the integrated method developed using ADP-based technique that uses a strategy to divide the problem into various sub-problems in order to evaluate overall optimal solution to the original problem. In Section 6, the integrated method is used to illustrate system restoration on IEEE 118-bus test system. The efficacy of restoration process is illustrated by comparing restoration plans with different sequences and priorities. The proposed restoration process is further validated by developing a restoration plan on a 2000-bus synthetic test system. In Section 7, conclusions are drawn and the feedback of the proposed integrated method from the users/community is mentioned.

3. Approximate dynamic programming-based technique

The advanced system restoration technique has taken an unconventional approach which is based on dynamic programming (DP). The DP approach allows recursive optimization that includes backward induction process and provides a systemic way to address a multi-stage non-linear integer programming problem.

3.1. Dynamic programming approach

Historically, DP approach has been used to recursively optimize a multi-stage non-linear problem. It is an algorithmic technique which divides the problem into several sub-problems and solves each sub-problem individually. The results are stored and may be accessed whenever required to solve other sub-problems. Selection of solutions of different sub-problems forms a sequence of decisions which is called policy. The policy which yields the most favorable result is considered to be the optimal one.

The solution in DP approach can be optimally extended based on the state of a partial solution of a sub-problem. Further decisions in the subsequent states are made based on the consequence of previous decisions. This requires to keep track of all the previous partial solutions which increases the size of the state space. DP faces the challenge of the curse of dimensionality which can be addressed by using ADP approach.

3.2. Limitations of dynamic programming

The inherent nature of non-linear integer programming problems presents three challenges of the curse of dimensionality in the development of this technology. These three challenges are: (1) size of *state space*; (2) the size of *action space* or *feasible region*; and (3) size of *outcome space*. These challenges act as major limitations to any dynamic programming model since the number of variables and stages increases rapidly thereby increasing the number of calculations required and hence the computational effort. It is due to these challenges of the curse of dimensionality that PSERC and EPRI could only address small scale problems, possibly localized and could not address large scale real-time problems. Consequently, EPRI's tool has been used for training restoration drills while PSERC's model works as a research grade solution. Moreover, both of the tools only concern steady state stability.

3.3. Approximate dynamic programming

The limitations of DP due to the curses of dimensionality cause the model to fall short when dealing with real-time problems. In order to overcome such limitations, ADP-based modeling framework offers strategies for tackling the curses of dimensionality in large, multi-period, stochastic optimization problems.

As the algorithm steps forward in time, it may take many iterations before the costs incurred in later time periods are correctly transferred to the earlier time periods. To overcome this, the ADP algorithm can also be used with a double pass approach consisting of a forward pass and a backward pass. In the forward pass, we simulate decisions moving forward in time, remembering the trajectory of states, decisions, and outcomes. Then it is followed by a backward pass strategy that determines a decision, given the available information at the current state, updating the value functions moving backwards in time using the trajectory information [31].

For ADP, the principle of optimality determines a sequence of optimal decisions or choices at each stage which is defined by a policy or decision function. This sequence of sub-problems is solved recursively as a natural form of Bellman equation [32] as shown in (2).

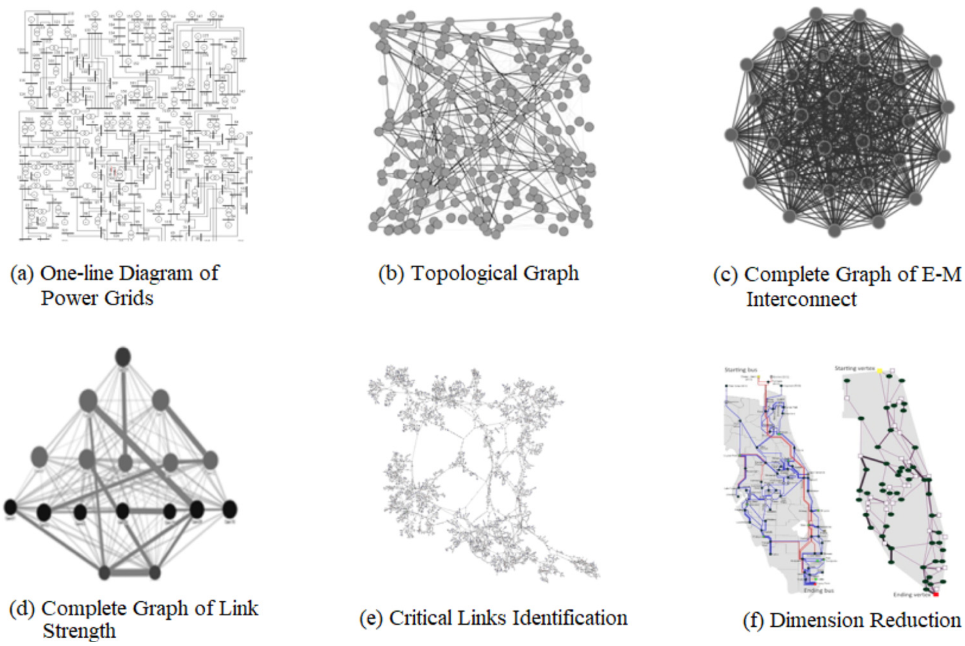

Fig. 2. Illustration of solution space reduction.

$$V_t(S_t) = \max_{x \in \mathcal{X}} [C_t(S_t, x_t) + \mathbb{E}\{V_{t+1}(S_{t+1}|S_t, x_t)\}], \tag{2}$$

where each possible state S_t maps to a decision x_t for each stage at time t in the planning horizon. The state space $\mathcal{S}$ determines the evaluation of value function $V_t(S_t)$ for all states within a reasonable time along with the addition of decision space $\mathcal{X}$.

4. Proposed ADP with solution space reduction

Different from the perspectives provided by the existing theories of power system analysis and techniques of optimizations, the solution space reduction technology is developed based on graph theory and advanced complex network techniques. The technique is useful in identification of critical components in a weighted network, and it also highlights the relation between global performance of power grids and localized interactions, and successfully addresses the long-standing real-world power system problem. In addition to the complex networks techniques, we use additional information about the strength of the links to incorporate the electro-magnetic properties, transient behavior and laws of physics underlying the power grid.

The solution space reduction technology shown in Fig. 2 is based on four key algorithms:

1. *Topological representation:* The first algorithm considers a power system network, shown in 2 (a), and produces a corresponding topological graph representation to allow structural and criticality analyses. The graph representation of a power system network utilizes vertex-edge diagrams, where each bus is represented by a node and the connection between buses by an edge/link. This is illustrated in Fig. 2(b);
2. *Complete graph and link strength determination:* The second algorithm generates a complete graph representing electro-magnetic links between all the nodes, shown in Fig. 2(c), and estimates link strength or weights of the edges/links in the complete graph for a given problem, illustrated in Fig. 2(d). Due to the difference in link weights in finite identical complete graphs, there could be infinite number of graphs distinctively different from each other that may change the performance of power grids. Thus a simple representation of link strength can be used as the “link-weight” of edge. Isolating edges with a different link-weight range may produce different graph representations for the similar power system network. This is further discussed in the following algorithm;
3. *Structural analyses and criticality identification:* The third algorithm uses criticality and structural analyses to find the winning probabilities of possible solutions and determine the categories of granularity as illustrated in Fig. 2(e), in which various critical components can be distinguished. The most significant part of the reduction process is the criticality identification which is based on the representation of link-weights of the edges. This involves algorithms primarily based on planarity test of the weighted structure to characterize the set of planar graphs; and planarization which involves removal of a certain number of vertices with least link-weight edges connected to it ensuring a minimal impact on the criticality of the graph. This ensures minimal impact on the reduced graph. Since only the critical links are considered and with the planarization of the graph, the dimension of the problem is reduced thereby making the problem simple. This is shown in Fig. 3;
4. *Reduced space solution:* The fourth algorithm solves the optimization problem in the reduced solutions space by either avoiding lower winning probability options or selecting high winning probability options based on link strength information. This results in a condensed solution space with critical components, as illustrated in Fig. 2(f).

The advanced algorithm with reduced solution space can carry out all stability analyses to allow feasibility studies, as illustrated using a

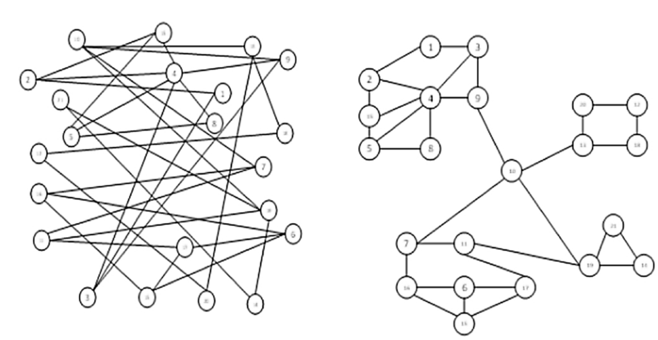

Fig. 3. Critical component identification.

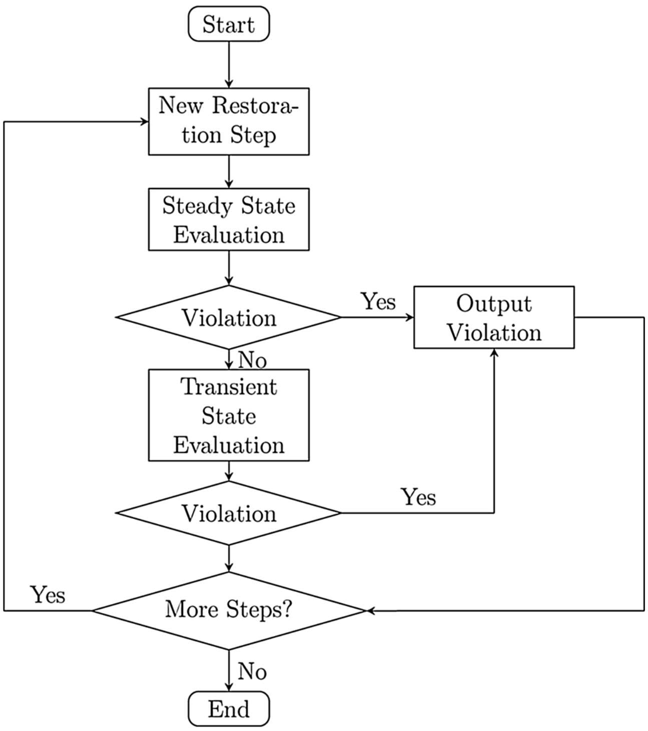

Fig. 4. Restoration process involving transient state evaluation.

flowchart in Fig. 4 and it can be applied to most optimization problems with different objective functions. The aforementioned algorithms and structural analysis have been integrated to address the real-world restoration problems and incorporated into a commercial analytical tool, named Brightstart®, that has been tested, validated and used by Independent System Operator (ISO) such as ISO New England, Southwest Power Pool and the associated transmission owners (TOs) [33,34].

5. Integrated tool for system restoration

The development of the integrated tool with a number of automated analytics allows it to be NERC compliant with standard power system models. This method still follows the standard model of restoration and the optimization problem presented here is similar to the existing models involving automated modeling, path searching, simulation and feasibility studies. However it simplifies the analysis with the application of ADP based formulation with involvement of complex networks science and graph theory based solution space reduction technique. Further, the solution is based on an algorithm which uses an optimal strategy to obtain restoration path by dividing the problem into various sub-problems.

Further the model can be utilized for real-time scenarios due to its capability to carry out steady-state, transient and dynamic stability analyses as opposed to only steady-state analysis in the existing models. Such a model formulation of optimal decision in each backward induction step is similar to Bellman equation as shown in (3) below.

$$V(X_0) = \sup_{(U_t)_{t=0}^{N_T}} \left[\sum_{t=0}^{N_T} \left(\sum_{j=1}^{N_G} G_j(U_j) + \sum_{i=1}^{N_D} D_i(U_i) + \sum_{k=1}^{N_L} L_k(U_k) - f_c(U_c) \right) \right], \tag{3}$$

where

$$\begin{aligned} U_t &= \{u_{g,j}^t, u_{d,j}^t, u_{l,k}^t, P_{g,j}^t, V_{\text{set}}^j, P_i^t, Q_i^t, Q_{\text{shunt},s}^t\}, \\ U_j &= \{X_t, u_{g,j}^t, t, \omega_j^g, P_{g,j}^{\min}, P_{g,j}^{\max}, T^{\min}, T^{\max}, j, P_{g,j}^t, R_j, V_{\text{set}}^j\}, \\ U_i &= \{X_t, u_{d,i}^t, t, \omega_i^d, P_i^{\min}, P_i^{\max}, P_i^t, Q_i^{\min}, Q_i^{\max}, Q_i^t\}, \\ U_k &= \{X_t, u_{l,k}^t, t, \omega_k^l\}, \quad \text{and } U_c = \{N_{\text{GS}}^t, N_{\text{DS}}^t, N_{\text{LS}}^t, t\}. \end{aligned}$$

where P, Q represent the active and reactive power respectively, associated with the generators in the network, G_j represents the set of generation output, D_i represents the set of loads, L_k is the set of status of transmission lines, f_c is the set of operating frequencies, R_j is the ramping rate of generator j, u is the decision variable for various subproblems and ω represents the weight associated with various elements in the system. The above objective function is subject to constraints similar to those of the PSERC model in (1).

In order to obtain a solution to the Bellman type equation in (3), the following algorithm is used to select the most probable/optimal set of elements and state path at each stage of restoration:

- The problem in (3) is divided into a set of overlapping sub-problems;
- An optimal strategy, $\pi^* = \text{argmax}_\pi V(X_0)$, is constructed which is used to generate the choice at the current restoration stage, such that the solution space is reduced on the basis of the importance of the state sequence and an optimal path of restoration;
- This strategy, π^*, is used to find the sub-problem solutions at all stages for the overall optimal solution of the original problem described by (3).

Since the essence of ADP is to replace the true value function with the statistical approximation, based on the algorithm mentioned above, the problem function in (3) can be framed as an objective function for each sub-problem as shown in (4).

$$V(X_s) = \sup_{(U_t)_{t=s}^{N_T}} \left[\sum_{t=s}^{N_T} \left(\sum_{j=1}^{N_G} G_j(X_t, U_t) + \sum_{i=1}^{N_P} D_i(X_t, U_t) + \sum_{k=1}^{N_L} L_k(X_t, U_t) - f_c(U_t) \right) \right], \tag{4}$$

where X_t and U_t represent the state at stage t and the decision that optimizes the value of the subsequent stages, respectively. Eq. (4) can be rewritten in Bellman equation form as shown in (5).

$$V(X_s) = \sup_{U_s} (T(X_s, U_s) + V(X_{s+1})), \tag{5}$$

where $T(X_s, U_s)$ represents the elements of (4) for $t = s$. The dimensionality of the problem can be reduced if the important states of transition function, $S(X_t, U_t) = X_{t+1}$, to the global optimal value can be percepted and quantified by an associated weight a_s^{ij}. Hence the optimal decision can also be obtained based on the weights. Further with the assumption of a perception function based on weights, the Bellman equation in (5) can be approximated as

$$V(X_s) = \sup_{U_s} (F\{V(X_s)\} \cdot T(X_s, U_s) + V(X_{s+1})), \tag{6}$$

Table 1
Comparison with existing restoration plans.

Restoration plans	Blackstart unit	Steady-state violations	Computational time
Restoration Plan A	10	No	113 s
Restoration Plan B	10	No	55 s
Restoration Plan C	10	No	10 s

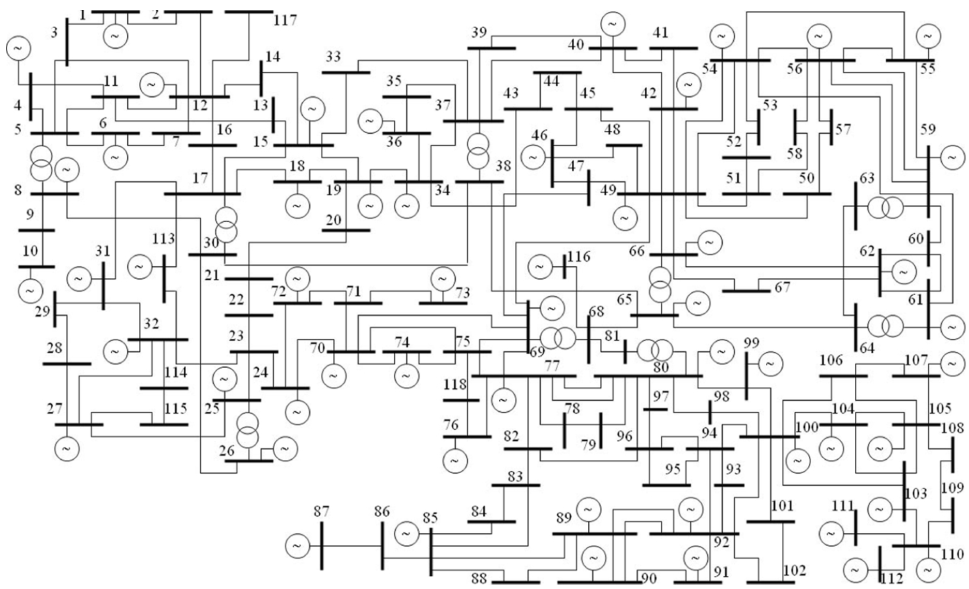

Fig. 5. IEEE 118 bus system.

Table 2
Restoration Plan III.

Sequence No.	Bus No.	Bus (From)	Bus (To)	Type	Bus (From)	Bus (To)	Output (MW)
1	12	Txxxxxxh	Txxxxxxh	Gen			47
2	12	Txxxxxxh	Sxxxxxxd	Branch	12	11	
3	11	Sxxxxxxd	Sxxxxxxd	Load			70
4	11	Sxxxxxxd	Oxxxe	Branch	12	11	
5	12	Txxxxxxh	NxE	Branch	12	16	
6	16	NxE	NxE	Load			25
7	16	NxE	Sxxxxxxn	Branch	16	17	
8	17	Sxxxxxxn	Sxxxxxxn	Load			11
9	17	Sxxxxxxn	Dxxxxxk	Branch	17	31	
10	31	Dxxxxxk	Dxxxxxk	Load			21.5
11	31	Dxxxxxk	Dxxxxxxe	Branch	31	32	
12	32	Dxxxxxxe	Dxxxxxxe	Load			7.37
13	32	Dxxxxxxe	Cxxxxxxr	Branch	32	33	
14	33	Cxxxxxxr	Cxxxxxxr	Load			7
15	33	Cxxxxxxr	Txxxxxn	Branch	33	24	
16	24	Txxxxxn	Txxxxxn	Load			13
17	24	Txxxxxn	Pxxxxxxh	Branch	24	70	
18	70	Pxxxxxxh	Pxxxxxxh	Load			8.25
19	70	Pxxxxxxh	Sxxxxxxt	Branch	70	75	
20	75	Sxxxxxxt	Sxxxxxxt	Load			2.94
21	75	Sxxxxxxt	Txxxxr	Branch	75	77	
22	77	Txxxxr	Txxxxr	Load			3.81

where $F\{V(X_s)\} = a_s^{ij}$ is the assumed perception function with $i \in X_s$, $j \in X_{s+1}$.

The reduction in dimensionality as a result of approximation on the basis of assumed perception function makes the process of restoration explicit. The restoration path is based on the only critical links of the network. These links due to their strengths are deemed to sustain when subjected to transient switching and various steady-state conditions. This improves the quality of the restoration path without concerning associated voltage violations. The advantages of using solution space reduction based on approximation is illustrated in the next section with an IEEE 118-bus test system and further validated using 2000-bus synthetic test system.

6. Illustration of system restoration

In this section, we demonstrate the restoration process using the ADP-based method on the IEEE 39-bus test system [35], IEEE 118-bus test system [36] and a bigger 2000-bus synthetic test grid system [37]. The capability of the method is highlighted by specifying a Blackstart unit in these systems and carrying out feasible restoration plan. The feasibility of the restoration plan is validated based on steady-state analysis, transient analysis and frequency dynamics of the system.

6.1. IEEE 39-bus system

We use IEEE 39-bus test system for illustration of ADP-based method for power system restoration. Further the results are compared with the existing restoration methods. The IEEE 39-bus system is a standard test system composed of 39 buses with 10 generators and 18 loads connected [35]. The net generation and load capacity is 5266.69 MW and 5222.80 MW, respectively.

6.1.1. Generation restoration

One of the critical requirements after a system blackout is the assurance of reliable shutdowns of nuclear generators. Therefore it is imperative to have a feasible restoration plan for expeditious

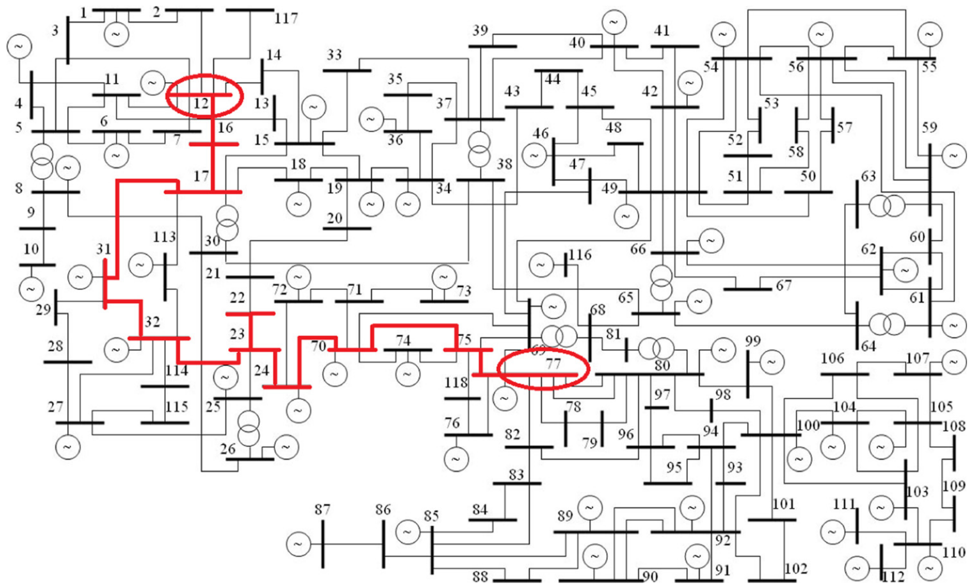

Fig. 6. Restoration Plan III on the IEEE 118-bus system.

Table 3
Comparison of restoration plans.

Restoration plans	Blackstart unit	Restored bus	No. of sequences	Steady-state violations	Transient violations
Restoration Plan I	12	77	27	No	Yes
Restoration Plan II	12	77	10	Yes	–
Restoration Plan III	12	77	22	No	No

restoration of off-site AC power sources to the nuclear station.

In this section, we illustrate the generation restoration using the ADP-based proposed method and compare the results with the existing methods. Bus 10 in the test system is considered to be the Blackstart unit for restoration of the generators. The methods are used to create restoration paths and the time taken by each method is compared and is illustrated in Table 1. Different restoration plans are devised based on existing methods. In this comparison, Plan A is based on an optimal starting sequence derived from the combination of all possible sequences [38]. This exhaustive selection process makes Plan A computationally challenging and hence makes it slow. Plan B is based on Dynamic Programming where the restoration problem is divided into time intervals [39]. The computational time in this case is also quite large. Plan C is based on the proposed ADP-based method.

6.2. IEEE 118-bus system

We further demonstrate the restoration process on the IEEE 118-bus system illustrated in Fig. 5. In this system, there are 54 generator units and 99 load units with a peak demand of 4242 MW. For this study, we assume generator at bus 12 to be the Blackstart unit and for demonstration of restoration process, we assume a nuclear generator station located at bus 77.

6.2.1. Generation restoration

In this study, we simulate a restoration scenario using different restoration plans devised using the proposed method. The method is used to create a critical restoration path from the Blackstart unit at Bus 12 to the nuclear station assumed to be located at bus 77 in the test system. We test 3 different plans to restore the system: Restoration Plan I generally renders priority to the final outcome without focusing on the criticality of the path; Restoration Plan II is based on the simple distance rule; and Restoration Plan III uses an alternative restoration path based on the proposed ADP-based algorithm with solution space reduction. Plan I and Plan II show steady-state and transient violations for different cases while Plan III avoids such steady-state and transient violations based on alternative restoration path as shown in Table 2.

6.2.2. Ideal restoration plan

As discussed earlier, Restoration Plan I prioritizes restoration of off-site power sources to the nuclear power station without any specific rules, and so it may be seen as a pure vanilla case. The restoration path starts with energization of Blackstart unit at bus 12 and after 27 sequences, the off-site power sources to the nuclear power station at bus 77 is restored. This restoration plan shows no steady-state violations. However, when subject to worst-case switching transients, it may show transient voltage violations at certain locations in the path. Restoration Plan II on the other hand follows most existing restoration plans in utilities which are manually created by operators based on the simple distance rule. This rule selects restoration paths using minimum distance. Although this rule may work in several simple cases, it does not guarantee feasibility for all complicated systems. For example, in the 118-bus test case restoration plans created by simple distance rule generate a quick path with only 10 sequences but it also shows voltage violations which may cause instability issues. Hence, considering the real-time dynamics of a power system Plan I and Plan II may not be feasible.

The proposed ADP-based method is then used to create an alternative Restoration Plan III which utilizes the ADP algorithm with backward induction along with solution space reduction. This plan reduces the dimensionality of the problem using the perception function and it can reach an optimal decision by avoiding use of any risky branches in the restoration path that can cause transient over-voltage violations. This plan, shown in Fig. 6, takes 22 sequences to successfully restore bus 77 in the test system. This makes Restoration Plan III more robust and ideal for real-time scenarios. The comparison of the three plans based on voltage violations is illustrated in Table 3. Based on the comparison, Restoration Plan III is selected while Restoration Plans I

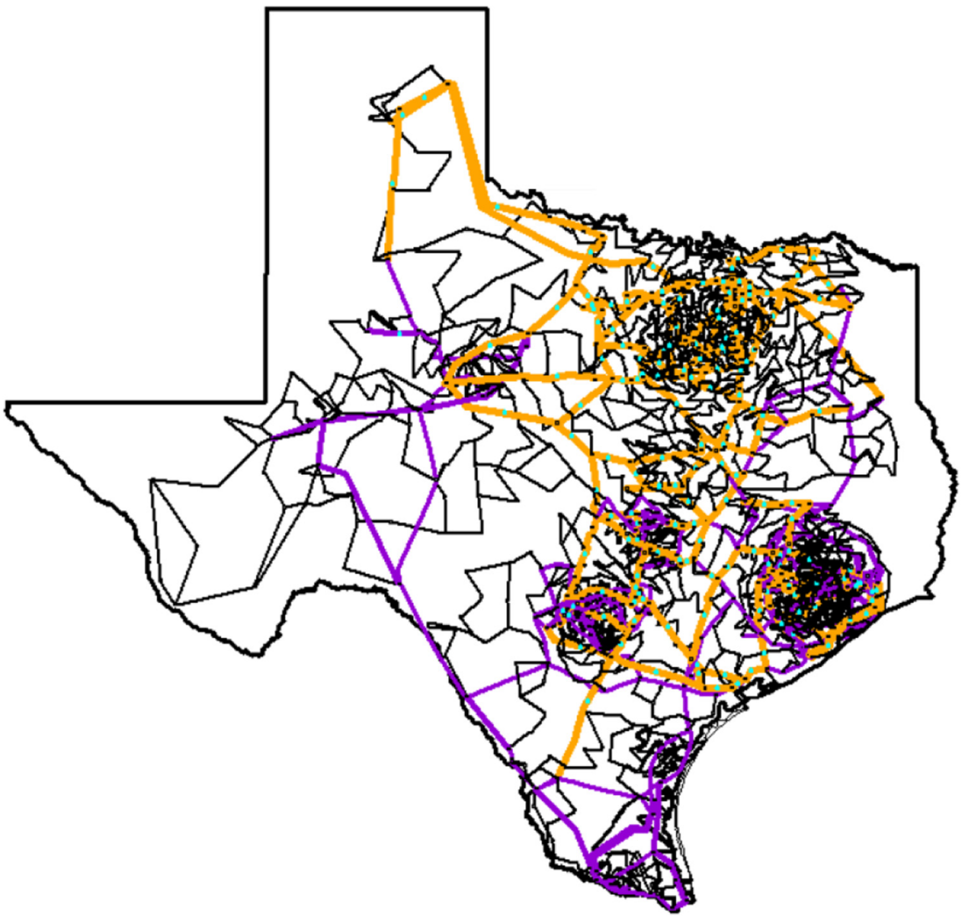

Fig. 7. 2000-bus synthetic grid test case [37].

Table 4
Restoration plan for 2000-bus synthetic test system.

Sequence No.	Bus No.	Bus (From)	Bus (To)	Type	Bus (From)	Bus (To)	Output (MW)
1	5262	Gxxxxe3	Gxxxxe3	Gen			390.249
2	5263	Gxxxxe4	Gxxxxe1	Transf	5263	5260	
3	5317	Gxxxx10	Gxxxx20	Branch	5317	5401	
4	5401	Gxxxx20	Gxxxx21	Transf	5401	5402	
5	5402	Gxxxx21	Gxxxx21	Load			65.97
6	5405	Sxxxxxxl1	Bxxxxxd0	Branch	5045	5120	
⋮							
364	6211	Mxxx5	Mxxx6	Transf	6211	6212	
365	6212	Mxxx6	Hxxxx1	Branch	6212	6020	
366	6020	Hxxxx1	Hxxxx1	Load			16.53
366	6215	Mxxx9	Mxxx9	Gen			16.53
367	6216	Mxxx10	Mxxx4	Transf	6216	6210	
368	6212	Mxxx6	Kxxx0	Branch	6212	3014	
369	6216	Mxxx10	Mxxx10	Gen			22.002

and II are discarded.

6.3. 2000-bus synthetic test system

We further check the validity of the proposed method and demonstrate the restoration process on a bigger and more complex 2000-bus synthetic test grid system which is overlayed on the geographic footprint of a real power interconnection [37]. The system on the map of the region is shown in Fig. 7. In this system eight major geographic areas are identified which comprise of a total 1500 substations. The system is considered to operate at two nominal voltages, 345 kV and 115 kV.

6.3.1. Generation restoration

In the system, we consider generator at Bus 5262 located in Zone 1 as the Blackstart unit and assume a nuclear generator station in Zone 1 at Bus 6216. We devise a restoration plan for the nuclear generator station using Restoration Plan III which is based on the proposed ADP algorithm with solution space reduction. It is shown in case of the IEEE 118-bus system in Section 6.2, the Restoration Plan III does not exhibit any steady-state and transient violations and thus prove to be better than Restoration Plan I and Restoration Plan II.

The restoration plan for the nuclear generator starting from the Blackstart unit at Bus 5262 utilizes 369 sequences to reach the target generator at Bus 6216. The restoration plan model based on solution space reduction takes approximately 4 min to simulate and is illustrated

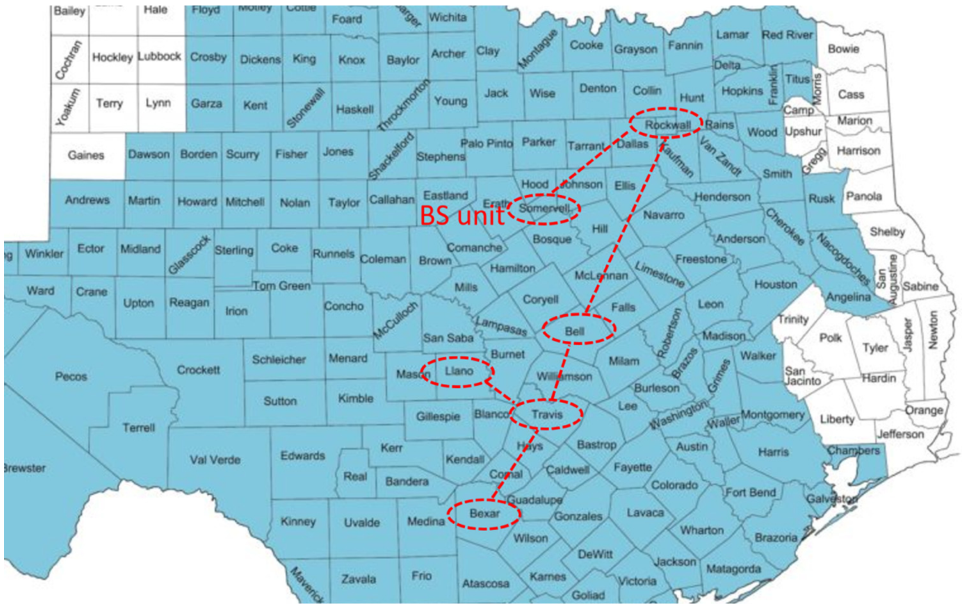

Fig. 8. Restoration plan on the county map of a real power interconnection.

in Table 4. The restoration plan is also illustrated on the county map of the power system with Blackstart unit in Somervell county as shown in Fig. 8.

7. Conclusion

We have described the key ideas and major algorithms that are based on complex networks science, advanced stochastic optimization techniques and theory, and experience of power engineering to address the system restoration problem in large-scale power systems. The solution has addressed a long standing issue with significant breakthroughs to system restoration technology. The most critical parameter is the experience of power companies that are using the solution for various applications. These applications range from creation of new restoration plans to validation of existing restoration plans and non-restoration testing along with the satisfaction related to the computational times for different applications. Moreover as a part of standard procedure, the temporary restoration path must be studied by BrightStart® when the primary path and alternate path of the system restoration plan are not available due to outages and the outage recall time has been determined to be greater than 24 h [40].

7.1. User experience

A number of power companies are getting aware of this breakthrough and the technology has been used for generate solutions, validation and testing by a number of ISOs and TOs, such as NERC compliance studies to ensure the availability of Blackstart resources and feasiblity of restoration plans. The technology have also been used for assessment of Blackstart resource testing under foreseeable blackstart conditions such that the resources can effectively restore the bulk-power system following a widespread outage [33]. The results have been discussed in various venues. For example, Southwest Power Pool (SPP) in its system restoration report has cited the use of the method for review and testing of existing restoration plans in an effort to optimize the plan and identify the issues associated with the existing plans of TOs [34].

7.2. Computational time

The proposed method has been used by many companies for different applications and the computational times observed have considerably improved the performance and analysis. For example, the creation of restoration model takes less than 5 min on a Pentium-4 processor of a laptop computer for an approx. 3000-bus system. Validation and enhancement of over ten comprehensive restoration plan of over 10 TOs only takes about 3 days which includes the time spent in gathering information, communication with restoration plan owner for missing information and corrections. Other testing procedures take only a few minutes to execute for a large-scale power system with over 2000 buses.

The applications, benefits and advantages of the integrated tool that uses this method can be found summarized in their reports and meeting minutes that are publicly available [33,34].

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgements

The authors would like to thank Northeast Power Coordinating Council (NPCC) Restoration Working Group, ISO New England and Southwest Power Pool (SPP) and the TOs involved for their support in validation of the research work.

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