



# Resilience of Electrical Distribution Systems with Critical Load Prioritization

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**Abstract.** In the highly interdependent environment of a large city, failures in the electrical distribution system can cause direct or indirect consequences to other critical infrastructures and to the Human Well-being Level (HWL) of the citizens. This paper discusses the electrical distribution system in terms of how topological reconfiguration, together with prioritized system recovery can maintain a high level of Human Well-being resilience during system failures. The Infrastructure Interdependencies Simulator (i2SIM) is used to prioritize load restoration and load shedding algorithms. To validate the proposed approach, spanning tree search algorithms, load shedding schemes and optimization methods are applied to find optimal restoration strategies on a standard IEEE 30-node system and on a 70-node distribution system with critical loads.

**Keywords:** Electrical distribution system restoration · i2SIM  
Human Well-being Level · Smart city resilience · Load shedding  
Spanning tree algorithms

## 1 Introduction

Society is strongly dependent on a resilient electricity supply to maintain its Human Well-being Level (HWL) [1]. Electricity supply interruptions lead to direct consequences for the HWL and will in general have an impact on other dependent critical infrastructures, such as water supply, emergency services, and information and communication technologies (ICT) [2]. For instance, in the Italian blackout of 2003, unexpected failures of a power station caused the simultaneous shutdown of the tele-communications and supervisory control and data acquisition (SCADA) network of the power system; the failures in the tele-communications system, in turn, caused further failures in the power supply network resulting in a large cascading event [3]. Another example of such interdependencies-related event happened in the same year in the USA [4]. In this event, smaller partial power system failures as well as computer and human mistakes led to cascading effects that ultimately resulted in a large magnitude event. These examples illustrate the need to consider critical infrastructure interdependencies when assessing the whole system resilience.

The Human Well-being Level - Distribution System Restoration (HWL-DSR) method proposed in this paper combines optimal topological reconfiguration with system recovery according to the criticality of the loads.

A number of solutions including mixed integer non-linear programming [5, 6] and heuristic search [7] have been proposed for the reconfiguration problem. However, previous research [8–10] indicates that the Spanning Tree Search algorithm requires less computing time and fewer operations of the reconfiguration switches.

Resilience oriented critical loads’ restoration has been proposed in [11, 12]. Generally, these approaches aim at measuring the adequacy of the electrical system to supply the demand of electricity after the contingency. Alternatively, critical infrastructure interdependencies for DSR have been considered and analyzed, for example, in [13–15]. The concept proposed here of Human Well-being Level (HWL) [1] considers both the power system’s performance and performance of the other interdependent networks, simultaneously.

The paper makes the following contributions:

- The concept of resilience using the HWL-DSR is proposed. The Infrastructures Interdependencies Simulator (i2SIM) is used to establish the criticality of the loads’ restoration sequence;
- A Shortest Path Tree Search and a Hybrid Load Shedding Scheme are proposed to minimize the number of switching operations while maximizing the HWL-DSR resilience;
- The importance of considering the interdependencies in DSR is illustrated by analyzing the results of two alternative optimization algorithms.

The remainder of this paper is organized as follows. Section 2 presents the problem formulation and implementation procedure. Graph search schemes are described in Sect. 3. Section 4 tests load shedding schemes and electrical constraints in the MATPOWER simulation environment. i2SIM is introduced in Sect. 5 to take into account the criticality of the loads. Section 6 presents simulation results using the standard IEEE 30-node distribution system and a 70-node 4-feeder system together with i2SIM. Conclusions and future work are presented in Sect. 7.

## 2 Problem Formulation

The resilience of the system of Critical Infrastructures (CI) considering the interdependencies among these CI can be measured in terms of the Human Well-being Table (HWT) [1]. The HWT is an example of the input-output HRT table concept [16] that relates an output resource or index value to a series of inputs. Table 1 shows an example of an HWT for some sample city. The output column  $y$  of the table gives the level of well-being, which in this simple example depends on the availability of electricity, water, services, and ICT. The least available resource determines the output level. To bring the level of well-being to 50%, we first need to restore services to 14 hr/day. Then restoring electricity to 22 hr/day, services to 18 hr/day, and ICT to 12 hr/day will bring the well-being level to 75%.

In mathematical terms, the HWL is defined as a function of  $N$ -nonlinear, independent eigenvectors, one for each human need, and its value is determined by the output level that corresponds to the least available input resource, as follows,

**Table 1.** Human Well-being Table.

Human Well-being Table (HWT)				
$y_n$ (HWL) (%)	$x_{n1}$ (electricity) (hr/day)	$x_{n2}$ (water) (hr/day)	$x_{n3}$ (service) (hr/day)	$x_{n3}$ (ICT) (hr/day)
100	24	24	24	24
75	22	20	18	12
50	18	16	14	6
25	12	12	12	2
0	0	0	0	0

$$y_n = \min(x_{n1}, x_{n2}, \dots, x_{n\max}) \quad (1)$$

Resilience index (2) is a measure of for how long and by how much the HWL stays below the “normal” value (100% in Table 1) before the system is restored.

$$R = \frac{\sum_0^M y_n \Delta t_m}{t_M - t_0} \quad (2)$$

The better the restoration strategy, the less time the well-being level will stay below the normal level and the higher the R value will be.

In this paper, the electrical distribution network is assumed to be radial and a number of simultaneous faults are assumed (Fig. 1).

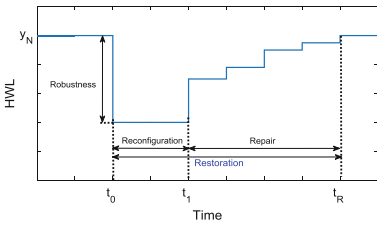
For the electrical service to be considered “available”, the electrical constraints of operation need to be satisfied:

$$V_i^{\min} < V_i < V_i^{\max}, i \in I \quad (3)$$

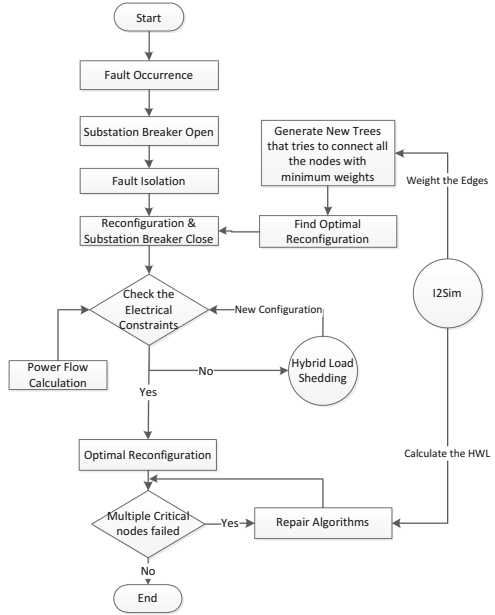
$$|I_l^{\min}| < |I_l| < |I_l^{\max}|, l \in L \quad (4)$$

$$P_f^2 + Q_f^2 < (S_f^{\max})^2, f \in F \quad (5)$$

$R$	Resilience of the HWL for the restoration strategy	$N$	Total number of independent eigenvectors (columns) of the HWL
$y_n$	Particular HWL value	$m$	$m$ -th time step
$t_0$	Initial time when contingency occurs	$n$	$n$ -th independent eigenvector (column) of the HWL
$M$	Total number of time steps	$\Delta t$	Time step for each restoration process
$t_M$	Time when restoration process completes	$V_i$	Voltage at node $i$
$I_l$	Current at line $l$	$P_f$	Active power injected into feeder $m$
$Q_f$	Reactive power injected into feeder $m$	$S_f^{\max}$	Maximum capacity of feeder $m$
$I$	Set of all nodes	$L$	Set of all lines
$F$	Set of all feeders		



**Fig. 1.** Interdependent- infrastructures resilience index in terms of the Human Well-being Level



**Fig. 2.** Flow chart of proposed algorithm

In the paper, the following variables are defined:

The HWL-DSR algorithm follows these steps (Fig. 2):

1. Map the initial configuration of the distribution network into a graph  $G$  using an adjacency matrix;
2. The failure locations are isolated by the remotely controlled switches (RCS) and the status of the line switches is updated to  $G$ ;
3. The optimal connection is found using a spanning tree search. The network switches are opened or closed accordingly;
4. Power flow calculations are performed to check the electrical constraints (3)–(5), using the MATPOWER toolbox in MATLAB;
5. If there are no electrical constraints violations, a candidate post-contingency reconfiguration is obtained; otherwise, a load shedding scheme is applied;
6. If the number of faults is larger than the number of repair crews, prioritization of repair is applied, according to i2SIM. After all faults are repaired, the HWL returns to the normal state.

To simplify the problem, the following assumptions are made:

1. A balanced three-phase network is considered; hence the system is represented by single-phase circuit;
2. Repairing time for per crew is constant for each fault removal;
3. Load demands are constant during restoration period;
4. Each branch and bus is equipped with a remotely controlled switch and optimal allocation of a limited number of switches is not considered in this paper.

### 3 Graph Search Schemes

Using graph theory, we can map each bus and each branch in the electrical distribution system into a vertex and an edge. The system can then be represented as a graph  $G(V, E)$  using a sparse adjacency matrix. The reconfiguration of the distribution system is essentially the reconnection of the graph  $G(V, E)$ .

Distribution systems are normally operated in radial configurations [17], with the primary substation in the root node and all other nodes connected without loops. The resulting structures correspond to spanning trees in graph theory, containing all the vertices without any loops [18]. Compared with mixed integer non-linear programming and heuristic searches, the spanning tree search requires fewer switches' commutations and less computational time [9]. For a multi-feeder system, the tree graph can be viewed as a forest (a graph with more than one tree). If all the roots of the trees can be centralized and viewed as one main root, as in [9], then the multi-feeder system optimization problem can be reduced into a single feeder problem.

When a fault occurs, the circuit breaker at the primary substation of the faulted feeder will disconnect the supply to the feeder and all loads in the feeder will stop being supplied. If reclosing is unsuccessful, the substation breaker will stay open until the fault is isolated. With the substation breaker open, sectionalizing breakers along the feeder can be opened to isolate the faulted section. The substation breaker can then be reclosed and supply can be restored to the loads upstream from the faulted section towards the substation. If next the normally-open tie switches between feeders are closed, the downstream feeder load can be fed from a different primary substation. Spanning tree search schemes can be used to restore most of the load without violating electrical constraints. The distribution system is required to maintain a radial structure during the reconfiguration process.

Two different search schemes were tested in this work: (a) The Minimum Spanning Tree (MST) Search, and (b) The Shortest Path Problem.

The minimum spanning tree search aims at connecting all nodes in such a way as to achieve the least total weight in a connected graph, following Prim's algorithm [19]. Certain edges can be weighted so as to force the structure of the tree. For example, we can assign a higher weight to a line with normally open switches, which reduces the possibility of electrical and operational violations.

The shortest path problem aims at finding a path between two nodes (or vertices) in a graph such that the summation of the weights of its candidate path is minimized [20].

A Shortest Path Tree (SPT), rooted at a specific vertex, is a spanning tree  $T$  of  $G$ . This tree ensures that the path distance from root to any other vertex in  $T$  is the shortest. The original SPT is modified in our strategy according to the criticality of the vertices. The nodes connected to critical infrastructures, such as hospitals, water stations, ICT-network, etc., are defined as critical nodes. In contrast, those with low criticality, such as most of the residential, commercial and industrial loads, are pre-defined as non-critical nodes.

In this paper, instead of searching for all equally-weighted vertices in the shortest fashion, the SPT searches for the critical nodes at the beginning. This presents two advantages: it prevents the supply of the critical loads from being shed and, at the same time, it reduces the computational time.

## 4 Load Shedding Schemes

During faults, load shedding schemes are needed to maintain the electrical operating limits. There are typically two load shedding approaches: load curtailment and pruning.

Load Curtailment is characterized by the ability to alter the amount of electrical power consumed by a specific load bus [21]. This traditional approach seeks to optimize the power flow so that load and generation match precisely, and prevents electrical violations (3)–(5) as well as transient voltage stability conditions. If electrical violations occur at critical loads, non-critical loads should be curtailed. This paper adds a fast voltage stability index from [22] to determine the sequence of curtailment of non-critical loads. This strategy helps to preserve the critical loads and eliminate the unstable lines.

However, this approach requires extra network reconfiguration switches, with corresponding additional capital costs to install these breakers, and additional operations for each breaker, with a corresponding increase in breaker wear, malfunctioning, and decreased reliability [23].

We propose a hybrid load shedding scheme that combines load curtailment and pruning (Fig. 3). Pruning alone aims at isolating functional sections of the power system so that a contingency does not cascade [24] and avoids violations from reconfiguration. The required switching operations are comparatively lower than with the load curtailment approach. However, the disadvantage is that critical load preservation may not be guaranteed if there is not an adequate placement of the pruned buses.

In our proposed hybrid scheme, the system always tries to remove the leaf nodes first (nodes with degree one) until all remaining leaf nodes are critical nodes. Then load curtailment is performed. This results in reduced switching operations while preserving the critical loads.

## 5 The Infrastructure Interdependencies Simulator (i2SIM)

i2SIM [16] is a tool for modelling interdependencies among complex critical infrastructures. In this work, i2SIM is used to determine the sequence in which critical loads must be restored (if required) after the topological reconfiguration is achieved. Two

different optimization methodologies are tested, a global optimization algorithm (GOA) and a greedy algorithm.

The GOA tries to maximize the resilience for the entire time line of the event, while the Greedy Algorithm chooses what appears to be the optimal immediate choice at every moment [25]. The computational complexity for GOA increases exponentially with the number of critical loads as well as with the number of vertices and edges in the graph. However, since there is a low possibility of there being a large number of unsupplied critical nodes [26], and this possibility is further reduced by load reconfiguration, it is possible to simplify the GOA algorithm as follows:

- Not all critical nodes are considered in the GOA;
- Multiple critical nodes with no faults between them are viewed as one group and these nodes are restored simultaneously;
- Critical nodes of the same type, or nodes within a certain area, can be categorized into one group.

## 6 Test Cases and Simulation Results

In this section, the proposed reconfiguration strategy is applied to two systems: (a) an IEEE 33-bus one-feeder system to validate the reconfiguration scheme, and (b) a 70-bus four-feeder system that illustrates the importance of infrastructure interdependencies in recovering the Human Wellness Level.

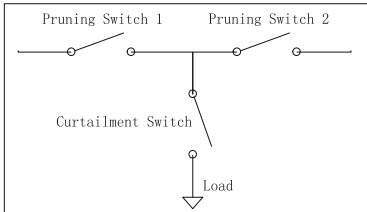
Multiple line faults and multiple critical nodes are generated for each test system. The computational tasks are performed on a personal computer with an Intel Core i5 Processor (2.66 GHz) and 8-GB of RAM.

### 6.1 Test System A—IEEE 33-Bus System

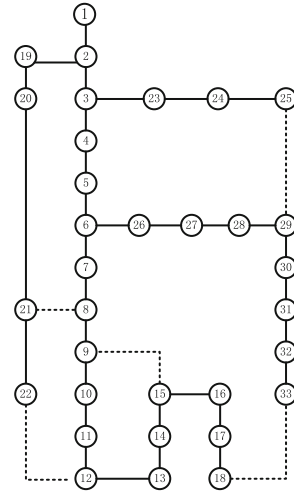
This test uses the IEEE 33-bus 12.66 kV radial distribution system, with 5 tie switches. The specific data, including active loads, reactive loads, branch impedances, etc. are identical with [27]. Two scenarios, with different fault locations and optimization methodologies, are studied:

**Scenario (1) Validation of the Proposed Reconfiguration Scheme.** The proposed reconfiguration scheme using the MST search, without a load shedding scheme and without i2SIM, is compared with case 3) of test system A of [13]. The results, using the methodology in this paper and the methodology of [13], present identical profiles, including loads, branches, fault locations (line 5–6, 8–9, 3–23, and 15–16), critical load locations (node 5, 11, 3, 15, 19, 21, 26, 28, and 29). The results are also almost identical regarding the total weighted and supplied active load after reconfiguration: 83.62% for our result and 83.42% for [13]’s, respectively. These results validate our basic reconfiguration scheme (Fig. 4).

**Scenario (2) Validation of the Hybrid Load Shedding Scheme and the Spanning Tree Search Algorithm.** In this scenario, in order to make the results more obvious, we assign the critical load busses (16, 17, 18, 29, 30, and 32) far away from the root



**Fig. 3.** Demonstration of hybrid load shedding



**Fig. 4.** Initial configuration of IEEE 33-Bus System

**Table 2.** Comparison of reconfiguration solutions

	Load curtailment with MST	Pruning with MST [9]	Hybrid load shedding with MST	Hybrid load shedding with SPT
Critical load preservation (%)	100	67.9	100	100
Shed load (kW)	3027.9	1975.1	3018.7	2920.2
Number of switch operations*	28	8	22	17
Minimum nodal voltage (pu)	0.9021	0.9024	0.9050	0.9099

\*Every single tie, sectionalizing and curtailment switch operation accounts in the total number of switch operations

node, we set one failure location (line 2–3) close to the root node, and we include an extra line (line 16–17) between the critical nodes.

The results from Table 2 are based on four different reconfiguration methodologies. For the more severe scenario, the pruning scheme with MST cannot preserve the critical loads, although it has the lowest amount of shedded loads and switching operations. The rest of the three methodologies are capable of preserving the critical loads with almost the same amount of shedded loads. The hybrid load shedding with SPT has the best performance in terms of the least number of switching operations, and will be the strategy adopted for improving the Human Wellness Level.



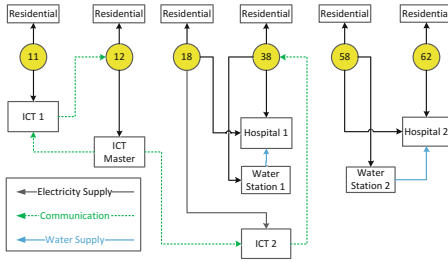


Fig. 5. Scenario (4) i2SIM interdependencies

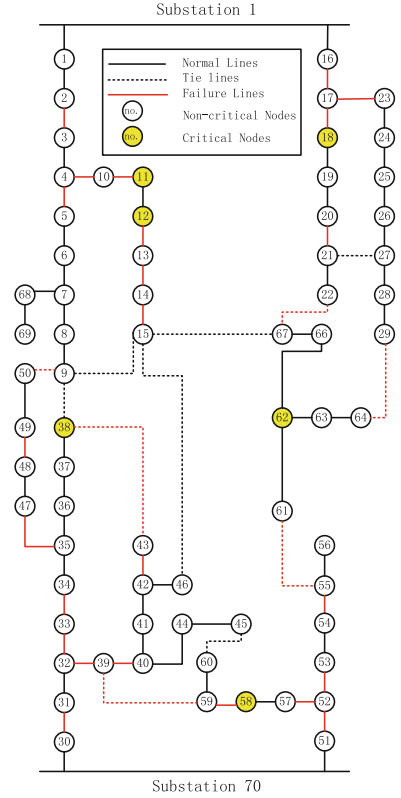


Fig. 6. 70-node radial distribution of Scenario (3)

## 6.2 Test System B - 70-Node System

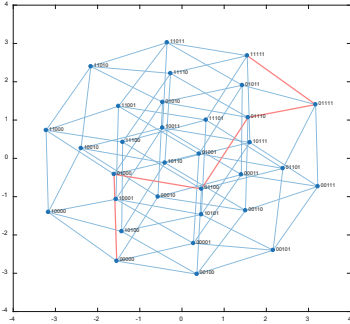
This system is an 11-kV radial distribution system with two substations, 4 feeders, 70 nodes, and 78 branches (including 11 normally open tie switches) [28], as shown in Fig. 6. In this case, we assume there are 6 critical nodes (12, 18, 27, 38, 58, and 62) and that a severe natural disaster causes 30 failure locations on different lines selected randomly. We consider two cases: (a) Without i2SIM (Scenario 3), and (b) With i2SIM (Scenario 4). The scenario without i2SIM corresponds to the “standard” reconfiguration strategies. The result is that not all critical loads get reconnected, that is, no tie switches can help the restoration of some of the critical loads. The scenario with i2SIM includes 6 critical interdependent nodes, including 2 hospitals, 2 water stations, 2 ICT agents, 1 ICT master agent, and 6 residential loads. With respect to Table 1,  $y_n$  represents the availability of each infrastructure. This system is shown in Fig. 5.

Two optimization methodologies (Global and Greedy) are tested.

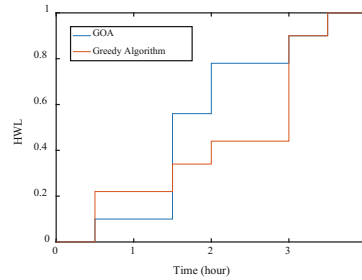
In the GOA methodology, the electricity supply is set as the only input (binary) to i2SIM, i.e. the status of each supply node is 1 or 0, and a binary number can be used for

the node status. For example, given five critical nodes 01000 indicates that the second critical node has service “on”.

Each binary status of the node supplying electricity is transferred into a decimal number before implementing the shortest path algorithm to find the global optimal operation sequences. The simplified scheme is as described in Sect. 4, that is, the adjacent critical nodes (11, 12) are regarded as one variable. Figure 7 gives the repair sequence (2–3–4–5–1) for each failure location to prioritize the post-contingency response when emergency crews are limited.

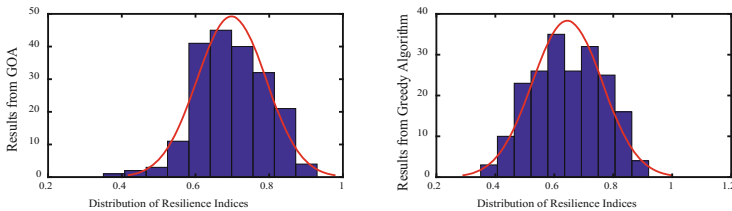


**Fig. 7.** Results of simplified critical-node repairing sequence from i2SIM based on GOA



**Fig. 8.** HWL results for GOA and greedy algorithm

For comparison, a greedy algorithm was also implemented to find the local optimal solution. The outputs from the HWL in i2SIM are shown in Fig. 8 throughout the recovery process. The global optimized repair sequence with i2SIM has the highest overall resilience index, which validates our proposed strategy (Fig. 8).



**Fig. 9.** Results of objective R from two optimization algorithms

**Randomly Distributed Failure Locations.** To test the effect of the fault location on the optimization results, the failure locations are randomly selected for 200 different cases. The Gaussian distribution results of the resilience objective R are shown in Fig. 9. The mean values for the GOA and Greedy Algorithms are 0.7211 and 0.6439, respectively. This result validates that for the interdependent DSR, the GOA enhances the resilience of the HWL better than the greedy algorithm.

## 7 Conclusion and Future Work

The proposed strategy for Human Well-being Level based Distribution System Restoration (HWL-DSR) combines a shortest path tree search algorithm and a priority-load load-shedding scheme, scheduled by i2SIM, to find an optimal distribution reconfiguration and restoration sequence that maximizes the availability of the most critical loads without electrical system violations. By using the HWL table, the proposed solution maximizes the Human Well-being resilience. The proposed framework can be applied both for long term planning and for optimal fast response during extreme contingencies.

The study cases assume radiality of the distribution system network, which is the most common scheme in current electrical distribution systems (DS). As technology improves, smart DS of the future will incorporate islanded sub-regions and mesh schemes. Further work is needed to extend this work for more complex interdependent schemes.

The paper assumes that the load demand and the generation are constant during the restoration period. A more accurate scenario will have to consider the variability of the load during the daily cycle, as well as the effect of the intermittence of the renewable energy sources (e.g., wind and solar).

In current electrical distribution systems, not all load nodes are equipped with remotely-controlled disconnect switches, and many of these switches have to be operated manually. This brings about the additional dimension of optimizing the repair crew transportation time needed to open or close the disconnect switches.

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