

Chapter 4

Resilience Metrics Development for Power Systems



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Abstract The purpose of this chapter is to explain the metrics were used for quantifying the resiliency of power system. Also, will determine how which metrics are calculated for which system under what conditions. Distribution and transmission infrastructure that is expanded over a wide geographic area, is always affected by weather-related disasters which occur continuously. Therefore, a safe and reliable operation is essential to have a resilient power system, which survives in hard conditions. The metrics investigated in this chapter are quantitative, which are defined based on the topology, hardware, and the efficiency of the system, reliability indices, and also the type and severity of the threat. The accurate assessment of each of these metrics can help to properly understand the concept of resilience in power systems. Also, we can obtain an appropriate assessment of the power network resilience by selecting the proper set of these metrics according to the type of threat and our goal.

Keywords Power system restoration · Quantitative resilience · Reliability indices
Resiliency metrics

Nomenclatures

B	Brittleness
C_B	Betweenness centrality
C_{dn}	Cost of lost demand d at bus n
C_{ei}	Load curtailment in event e_i
C_n	Clustering factor
$d(n_i, n_j)$	Equivalent distance between nodes n_i and n_j
$D(t)$	Percentage of the infrastructures damage
D_G	Diameter of the considered complex grid (graph G)

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e_i	i th extreme event
e_n	The number of joint couples between all neighbours of node n
f	Brittleness distribution
f_c	Critical section of a complex network
K	Total number of lines that are on the outage
k_n	Total number of neighbours of node n
L	Laplacian matrix
l_G	Length of the graph G
M	The number of graph nodes
n	An event which caused violation in voltage level
N	The number of loads in a particular area of distribution system under consideration
n_0	The number of costumers which experienced an outage
N_q	All the similar PNs for the q th FN
P_d	Conditional probability
P_{ei}	The probability of power grid experiencing event e_i
q	Total number of FNs
r_i	Resiliency of a single load
s	The number of graph sections
$S(t)$	Percentage of supplied power
S_e	Set of all disasters in which caused the system loads to exceed the generation capacity
T	Time period
t_{down}	Down time
$t_{down,i}$	A portion of period T , that the load i cannot receive power
T_s	Capacity of local energy storage systems
t_{up}	Up time
$t_{up,i}$	A portion of period T , that the load i can receive power ($t_{up,i} = T - t_{down,i}$)
V	Graph connector weights
$v_r(t)$	Recovery speed
w_i	Weight of the i th factor that affects the grid recovery process
θ	Outage index
θ_{max}	The time that all costumers experienced an outage
ϕ	Resistance
σ	Measure of the severity of the extreme event
λ	Failure rate
μ	Repair rate
Λ_2	Algebraic connectivity of the power distribution network
Υ	Amount of intensity of a natural disaster
η_i	Value of the i th factor that affects the grid recovery process
P_d^T	Total active power of the power system in normal operating condition
$P_{dn,i}^{ \varepsilon}$	Active power at load point n after the restoration plan i regarding disturbance ε at time t
$P_{dn}^{ \varepsilon}$	Active power demand of bus n at the end of disturbance ε

$\Psi_{i,n,d,t}^{\lambda}$	Flexibility of the demand d at the load point n for the i th plan of restoration at time t
$\Psi_{i,n,d,t}^{\mu}$	Outage cost restoration of demand d at bus n for i th reconfiguration plan at time t
$\Psi_{i,n,d,t}^{\sigma}$	Restoration capacity of load d at bus n for i th reconfiguration plan at time t

4.1 Introduction

It is necessary to track resiliency metrics to be able to determine that, in the operation of the power system under low-probability high-impact events, which goals have been achieved and which one not been achieved. Resiliency metrics are used at different levels for different intentions. Some of the purposes are relevant to the national or regional macro policies and some others to a local or tools aspect. As an example, what is the effect of the resiliency on the economic damages caused by natural disasters at the national or regional level? For a power plant operator, it can be essential to know how many and what types of spare parts are available. Considering each purpose of the system needs a unique set of metrics. Because one set of metrics does not support all the goals of the system. Then this chapter first reviews the existing metrics for measuring resiliency of electrical systems, then a strategy will be developed that can be used to determine the appropriate set of resiliency metrics according to the goals pursued from the system. In the event that national or regional macro intentions are considered, greater focus will be on strategic aspects of the metrics set. In this case, matters like budget, availability of equipment, number of generators and operators, speed and accuracy of response teams, schedules, existing technologies such as smart grids, etc. will be considered. But if local aims are taken into account, the operational aspects of the electrical system are used to define the resiliency. In this case, matters like timely detection of the outages, fast recovery after disasters, convenient repairs, system efficiency, reliability indices, system hardening, improving social welfare, etc. are considered.

The necessity of quantifying resilience metrics is an important challenge, which mostly depends on how to define the resiliency.

Resiliency may sometime be considered as the time for recovery of power system after a disaster. In a complete definition, in addition to the time required for recovery, the capability of the system to withstand malicious events, system adaptability, and desirable extensibility can be considered as principal resiliency characteristics. Resiliency can be calculated mathematically as the area under system's performance curve.

Resilience metrics must have some basic features. These features are essential for the development of a comprehensive metric. In other words, a general metric must [1]:

- *Be useful.* A comprehensive metric must be helpful for decision making incorporate system planning, real-time actions, and policy determinations.
- *Provide a comparable structure.* Calculation of this metric for different systems should provide comparable information.
- *It must be usable in operational and planning contexts.* Operational contexts such as pre-configuration the system before a disaster and planning contexts such as implanting of electric conductors.
- *Be comprehensive and extensible.* The appropriate index should be extensible over time and must be calculated with the advancement of technology and equipment in complex computational methods.
- *Be quantitative.* The appropriate metric should be quantitatively quantifiable.
- *Consider uncertainties.* It is very important that the resilience metric should reflect the system's uncertainties.
- *Consider the recovery/restoration time of the system after a disaster.* An appropriate metric of resiliency should somehow take into account the duration of outages.

4.2 Resiliency Metrics, Different Definitions

The resilience metric may have terms of a threat or a set of threats. In fact, this criterion answers the question of “resilient to what?”. Usually, resiliency is considered against natural disasters such as earthquakes, storms, floods, etc., but these studies can be generalized to sudden human-caused events such as accident and war. It can be observed that the natural disasters tend to follow cycles. The time interval between the onset of an event up to the occurrence of another can be classified into four phases [2]:

- *Phase 1 (During the event):* The length of this phase (Δt_1) can be a few minutes to a few days. In this situation, the main purpose is to reduce the damages and loss of services.
- *Phase 2 (Immediate aftermath):* This stage takes a few days to several weeks. The main goal of this period is to start recovery and repair actions. This phase lasts Δt_2 and ends when these activities are almost completed.
- *Phase 3 (Intermediate aftermath):* This phase usually lasts from a few weeks to several months and sometimes interference with phase three. In this phase, the main objective is to investigate the disaster's effect on a specific part of the power system by calculating the system efficiency indices and assessing the extent of the damage.
- *Phase 4 (Long-term aftermath):* This stage may take a few months to several years. In this phase, the main goal is to prepare for the occurrence of the next disaster using the results obtained in phase three. These preparations include corrective actions, modification of the operational strategies, and the strengthening of infrastructure. this phase ends with the onset of the next event.

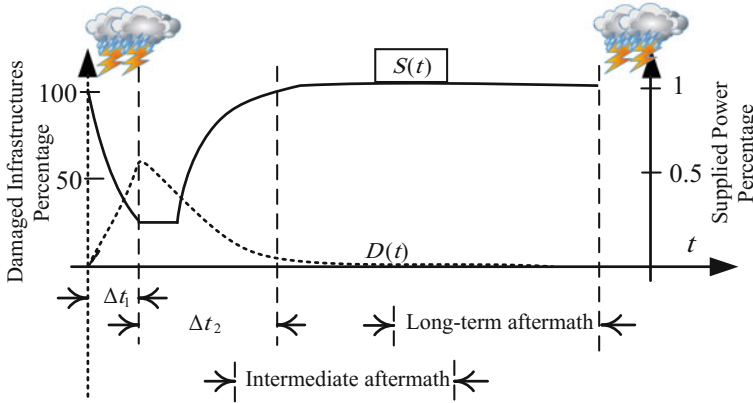


Fig. 4.1 Representation of different phases of the extreme event [2]

Figure 4.1 shows the different phases of the time horizon immediate following a disaster occurrence until the next disaster.

Although the resilience measures are used to evaluate the consequence of a disaster, it must also be used to assess the ability of power grid in cover its objectives. This means that the performance of the system affects the resiliency measures directly. For example, the area under $S(t)$ in Fig. 4.1, which is a measure of the loads supplied by the power grid during and after the disaster, is a performance-based metric for resiliency [2]. Equation (4.1) describes this metric mathematically.

$$R_1 = \int_t S(t)dt \quad (4.1)$$

Another measure based on the quality of the power network service described by (4.2), which is the number of events that, as a result of their occurrence, the network voltage falls outside of the standard range.

$$R_2 = \sum n \quad (4.2)$$

where n is an event which caused the voltage level of the power grid to violate the standard ranges.

According to U.S. Presidential Policy Directive 21 [3] (PPD-21), the resiliency is defined as: “the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions.” In this definition, resiliency includes “the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents.” Therefore, based on the four main characteristics stated in the definition of the resiliency, i.e. withstanding capability,

recovery speed, planning capacity, and adaption capability [4], a quantitative metric for the resiliency of a single load in a period of time ($T = t_{up} + t_{down}$) can be mathematically modeled by (4.3).

$$r_l = \frac{t_{up}}{(t_{up} + t_{down})} \quad (4.3)$$

In (4.3), downtime (t_{down}), which is related to the hardware aspects of the power system and human-related processes, shows the system's recovery speed. The ability of the power grid to withstand the disaster is related directly to its hardware and equipment characteristics, which t_{up} shows this index. It should be noted that several references have proposed similar relationships to measure resiliency in other systems, such as communication sites [5], supply networks [6], and urban infrastructure systems [7]. According to [2], it is possible to define the resiliency of the power generation resources for N loads as:

$$R_L = \frac{\sum_{i=1}^N t_{up,i}}{\sum_{i=1}^N (t_{up,i} + t_{down,i})} \quad (4.4)$$

Equations (4.3) and (4.4) are similar to the equation of availability in reliability theory, but an infinite number of repair and failure sequences are used for calculating of the availability measurement where the measures of the resiliency of (4.3) and (4.4) can be based on a single sequence in duration T .

Suppose that n_0 number of the total customers (N) in a given region under study at the time interval T experienced an outage. In this case, the outage index is calculated by (4.5) [2].

$$\theta = \frac{n_0}{N} \quad (4.5)$$

This is the equivalent to the SAIFI in IEEE Standard 1366 that is widely used to assess the outages of the power systems.

In Ref. [2], the recovery speed (v_r) for the N number of customers is defined as (4.6).

$$v_r(t) = \frac{d\theta}{dt_r}, \quad t_r = t - t_{|\theta=\theta_{max}} \quad (4.6)$$

For one customer $N = 1$ and thus n_0 is 1 or 0. Assume the customer has experienced an outage ($n_0 = 1$). In this case, since all the customers experienced the outage, dt_r can be taken equal to T_{down} , as a result:

$$v_{r,i}(t) = \frac{1}{t_{down}} \quad (4.7)$$

In a similar manner disruption speed for a group of customers and a single one can be calculated as (4.8) and (4.9) [2], respectively.

$$v_d(t) = \frac{d\theta}{dt}, \quad \text{for } t < t_{|\theta=\theta_{\max}} \tag{4.8}$$

$$v_{d,i}(t) = \frac{1}{t_{up}} \tag{4.9}$$

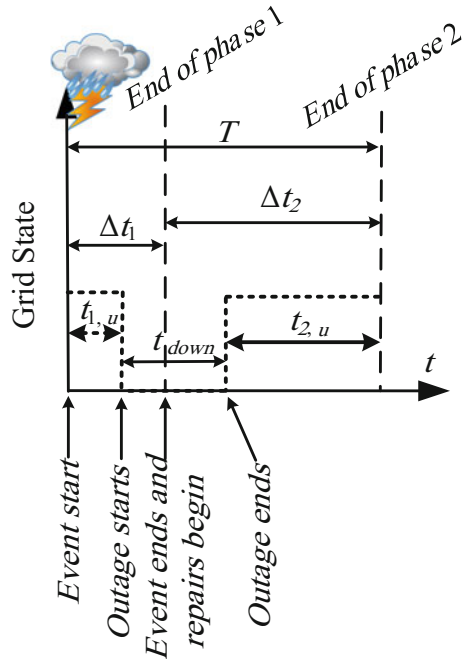
It is clear that the (4.7) and (4.9) are analogous to the concepts of repair rate (μ) and failure rate (λ) in reliability theory, respectively.

The power network’s ability to withstand a destructive event can be measured by a metric called resistance, which is defined for a single customer by using (4.10) [2].

$$\varphi_I = \frac{t_{1,u}}{\Delta t_1} \sigma \tag{4.10}$$

where $t_{1,u}$ is Δt_1 in Fig. 4.1, which the customer still receives power before the outage. σ can be specified as a function which represents the severity of the destruction of the extreme event and can be defined for different types of hazards such storm, flood, earthquakes, etc. [7]. It has to be noted that $\sigma > 0$. In order to better understand the time intervals, Fig. 4.2 shows the details of the time periods of the first two phases of a disaster (phases 1 and 2 shown in Fig. 4.1).

Fig. 4.2 Details of the time periods of the first two phases of a disaster



Also, the resistance of φ for N loads is defined by (4.11) [2].

$$\varphi = \frac{\sum_{i=1}^N t_{1,u,i}}{\theta_{\max} N \Delta t_1} \sigma \quad (4.11)$$

In this state, in addition to the importance of the time which loads can receive power under the disaster conditions ($t_{1,u}$ in Fig. 4.2), the maximum amount of lost power of the customers experienced the outage is also very essential.

Brittleness is the amount of damage which the power system receives from a disruptive event and is calculated for N loads using (4.12).

$$B = \frac{\theta_{\max}}{D} \times 100 \quad (4.12)$$

where D is highly related to the characteristics of the infrastructures.

The dependency of one infrastructure to the other ones is defined as [8] “a linkage or connection between two infrastructures, through which the state of one infrastructure influences or is correlated to the state of the other”. In accordance with Refs. [2, 8], it is possible to quantitatively measure the dependence of the loads to the power grid by resilience-oriented adjusting the amount of energy storage resources. The level of dependency of a load from the power grid may be calculated based on r_l of (4.3) as [2, 8]:

$$R_L = 1 - (1 - r_l)e^{-\mu T_s} \quad (4.13)$$

According to (4.7), μ is equal to the inverse of t_{down} .

Reference [2] represents the intrinsic relation between dependence with the concept of resilience and how energy storages may or may not lead to a loss of power for customers during an outage as follows:

$$\frac{1}{\mu} \frac{dR_L}{dT_s} = (1 - r_l)e^{-\mu T_s} \quad (4.14)$$

Hence,

$$R_L = 1 - \frac{1}{\mu} \frac{dR_L}{dT_s} \quad (4.15)$$

As a result,

$$\frac{1}{\mu} \frac{dR_L}{dT_s} = -R_L + 1 \quad (4.16)$$

where $t_{down} = 1/\mu$, shows how much restrictions there is locally for a shift in local resilience by attaching new energy storage systems near the load or it is indicating

in order to obtain the same local system resiliency, how much more or less energy storage devices have to be available.

Reference [9] defined a multiple-component resiliency metric for power distribution system based on the network topology as:

$$\mathfrak{R}_\tau = \sum_{j=1}^{\eta} V_j \lambda'(i, j) \quad (4.17)$$

where η is the number of metric components. V is equal to:

$$V = [A_{fc} \quad B_D \quad C_{C_B} \quad D_{l_G} \quad E_{C_n} \quad F_{\Lambda_2}]^T \quad (4.18)$$

In (4.18) A, B, C, \dots, F are the obtained weights to indicate the importance of its corresponding measure. $\lambda(i, j)$ is an element of $\vec{\mathfrak{R}}_\tau \vec{\mathfrak{R}}_\tau^T$ and given by:

$$\lambda'(i, j) = \frac{\lambda(i, j) - \min_{i=1}^{\eta} (\lambda(i, j))}{\max_{i=1}^{\eta} (\lambda(i, j)) - \min_{i=1}^{\eta} (\lambda(i, j))} \quad (4.19)$$

$$\vec{\mathfrak{R}}_\tau \vec{\mathfrak{R}}_\tau^T = \begin{matrix} & f_c & D & C_B & l_G & C_n & \Lambda_2 \\ \begin{matrix} f_c \\ D \\ C_B \\ l_G \\ C_n \\ \Lambda_2 \end{matrix} & \begin{pmatrix} 1 & a & b & c & d & e \\ 1/a & 1 & f & g & h & i \\ 1/b & 1/f & 1 & j & k & l \\ 1/c & 1/g & 1/j & 1 & m & n \\ 1/d & 1/h & 1/k & 1/m & 1 & o \\ 1/e & 1/i & 1/l & 1/n & 1/o & 1 \end{pmatrix} \end{matrix} \quad (4.20)$$

where a, b, c, \dots, o are weight coefficients in the interval $(0, 1]$ [4].

$$\vec{\mathfrak{R}}_\tau = [f_c \quad D_G \quad l_G \quad C_B \quad C_n \quad \Lambda_2] \quad (4.21)$$

Assume the power distribution system demonstrated by a graph $H = (M, S, V)$ comprising of M nodes, a set of section (edges) S with each element connected from node x to node y with a corresponding weight V .

In (4.21) D_G (the optimal (shortest) path between the farthest nodes) calculated as:

$$D_G = \frac{2E}{|N|(|N| - 1)} \quad (4.22)$$

l_G represents the length of the graph and obtained by (4.23).

$$l_G = \frac{\sum_{i \neq j} d(n_i, n_j)}{N(N-1)} \quad (4.23)$$

C_B is the betweenness centrality of the graph and calculated as:

$$C_B(i) = \sum_{n_i \neq n \neq n_l} \frac{n_k \rightarrow n_l, n_i}{n_k \rightarrow n_l} \quad (4.24)$$

where $n_k \rightarrow n_l, n_i$ is 1 if the optimal path between the node n_k to n_l passes through n_i and 0 if n_k to n_l does not pass through n_i . The phrase $n_k \rightarrow n_l$ is to show the optimal (shortest) path between the nodes n_k and n_l [9].

C_n in (4.21) shows the clustering factor of the power distribution system and calculated by (4.25) [9].

$$C_n = \frac{2e_n}{k_n(k_n - 1)} \quad (4.25)$$

Algebraic connectivity of the power distribution network is indicated as Λ_2 and is calculated by (4.26).

$$\Lambda_2 = \text{eig } L_{(i,j)}^2 \quad (4.26)$$

where Laplacian Matrix is obtained as [9]:

$$L_{(i,j)} = \begin{cases} \text{deg}(n_i) & \text{if } i = j \\ -1 & \text{if } i \neq j \text{ and } n_i \text{ is adjacent to } n_j \\ 0 & \text{otherwise} \end{cases} \quad (4.27)$$

There are more metrics which can be used for defining resiliency of a power system and (4.21) is only one combination.

In Ref. [10] six metrics that can measure the operational resiliency of microgrids have been identified based on graph theory and Choquet integral. This definition is based on three main assumptions:

- The number of paths between supply and load nodes affects the resiliency.
- Increasing the ratio of power supply resources to system loads improves (increases) the system resiliency.
- The increase in the number of switches in the system will increase the system resiliency, while the increase in the number of switching actions required to connect critical loads to the power supply will reduce the system resiliency.

For the six resiliency metrics defined in Ref. [10] it is assumed the power distribution system is equivalent to a graph that has n nodes and their nodes are connected to one another by e branches. In this equalization, the buses and lines of the power distribution system are demonstrated with nodes and branches, respectively.

Branch Number Impact (BNI) This measure is equal to the ratio of the total number of joined branches for each *RIWL* in a *PN* to the number of all *CLs* [10].

$$BNI_q = \frac{\sum_{k=1}^{N_q} \frac{\text{Nodes in } RIWL \text{ for } kth \text{ } PN}{\text{Number of } CLS \text{ in } kth \text{ } PN}}{N_q} \quad (4.28)$$

Overlapping Branches (OB) This metric is equal to the total number of joint branches in each *PCWL* in a *PN* [10].

$$OB_q = \frac{\sum_{k=1}^{N_q} \text{common branches in } kth \text{ } PN}{N_q} \quad (4.29)$$

Switching Actions (SA) This measure represents the total number of switching operations (change in the state of switches, i.e. closed to open and vice versa) needed to connect all the *CLs* to sources through different *FNs* [10].

The Number of Resources (NoR) It is equal to the ratio of the total number of possible resources utilized to supply all *CLs* to the number of all *CLs* in each *PN* [10].

$$NoR_q = \frac{\sum_{k=1}^{N_q} \frac{\text{Resources supplying all } CLS \text{ in } kth \text{ } PN}{\text{Number of } CLS \text{ in } kth \text{ } PN}}{N_q} \quad (4.30)$$

Route Abundance (RA) This is the ratio of the total number of routes that is possible for all *CLs* joining to all resources to the total number of *CLs* in each *FN* [10].

$$RA_q = \frac{\text{Routes joining all } CLS \text{ to all resources in } qth \text{ } FN}{\text{Number of } CLS \text{ in } qth \text{ } FN} \quad (4.31)$$

The Probability of Accessibility and Penalty Factor (PoA & PF) This metric is based on two factors: the probability of availability of the source, and the losses in distribution or penalty factor *PoA* & *PF* for a *FN* is calculated by (4.32) [10].

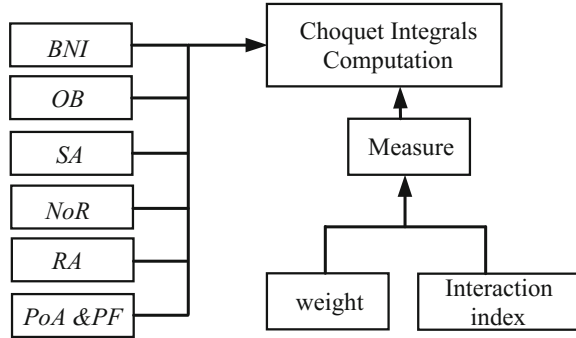
$$PoA \ \& \ PF_q = \frac{\sum_{k=1}^{N_q} PoA \times PF \text{ for } kth \text{ } PN}{N_q} \quad (4.32)$$

Figure 4.3 shows the framework that is used in Ref. [10] for quantifying resiliency in a power distribution system using graph theory and Choquet integral computation.

Reference [11] is introduced four metrics as (4.33) to measure the resiliency of power grid under extreme events.

$$\mathfrak{S} = \{K, LOLP, EDNS, G\} \quad (4.33)$$

Fig. 4.3 Flowchart of quantifying resiliency in power distribution system [10]



In (4.33) K demonstrates the expected number of lines are on outage due to the inordinate event and is calculated as:

$$K = \int_0^{\infty} kf(k)dk \tag{4.34}$$

$$f = P_d(k|Y) \tag{4.35}$$

where, P_d refers to the conditional probability of outage of k lines in Y [11].

$LOLP$ and $EDNS$ which are known reliability indices [12] are modified in Ref. [11] and defined as survivability following extreme events.

$$LOLP = \sum_{e_i \in S_e} P_{e_i} \tag{4.36}$$

$$EDNS = \sum_{e_i \in S_e} P_{e_i} C_{e_i} \tag{4.37}$$

where C_{e_i} is obtained using optimal power flow (OPF) [11].

Parameter G in (4.33) measures the complexity of grid restoration. It must be mentioned, the power system restoration process after an extreme event, depending on the kind and amount of intensity of the disaster and the extent of damage to the critical infrastructures of the system, may take several hours to several days. The grid recovery index is expressed as (4.38) [11].

$$G = \sum_{i=1}^5 w_i \eta_i \tag{4.38}$$

where $\sum_{i=1}^5 w_i = 1$

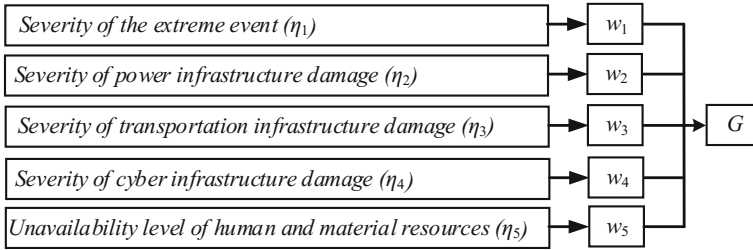


Fig. 4.4 Grid recovery index factors [11]

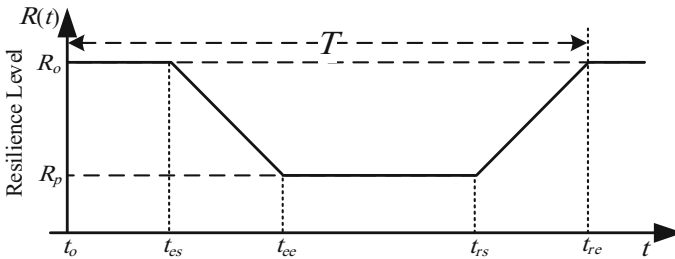


Fig. 4.5 The resilience level of the power system under a natural disaster

where, w_i and η_i are described in Fig. 4.4.

In accordance with Refs. [13, 14], the resilience level of the power system under a natural disaster can be plotted as in Fig. 4.5 in five-time intervals. The first stage, which covers the time interval $[t_0, t_{es}]$, shows the system’s resilience level before the horrible event. The devastating event starts at time t_{es} and continues until the time t_{ee} . During this period, the level of resilience of the system gradually decreases from the initial value R_o to its minimum value, i.e. R_p (the gradient depends on the structure and capabilities of the power network). The preparation is then followed to start the recovery process at the fastest possible time interval, i.e. $[t_{ee}, t_{rs}]$. With the onset of restoration process at time t_{rs} , the level of resilience of the power system gradually returns to its original state (the desired value before the disaster, R_o). The time after t_{re} is the state of resilience after the completion system recovery process.

Reference [14] has considered a set of network performance indices as a benchmark for measuring the resilience level of the power system against extreme events and called it as $\Phi\Lambda E\Pi$.

In this definition, Φ represents the number of lines that are tripped per hours (during the extreme event occurrence) and calculated by (4.39):

$$\Phi = \frac{R_p - R_o}{t_{ee} - t_{es}} \tag{4.39}$$

The parameter Λ refers to the amount of power system resilience level reduction due to the occurrence of a malicious event (number of lines tripped) and is equal to:

$$\Lambda = R_p - R_o \quad (4.40)$$

The time duration that it takes to start the restoration/recovery process after the occurrence of an extreme event represented by E and is equal to:

$$E = t_{rs} - t_{ee} \quad (4.41)$$

After the start of the recovery/restoration process, the number of lines that are retrieved per hour is shown using Π and is equal to:

$$\Pi = \frac{R_o - R_p}{t_{re} - t_{rs}} \quad (4.42)$$

In addition to the $\Phi\Lambda E\Pi$ metric, for calculating the lines that were in service from the beginning of the disaster to the end of the recovery/restoration process (the lines that have not experienced the outage), a criterion called the *Area* is defined and, in accordance with Fig. 4.5, is equal to [14]:

$$Area = \int_{t_{es}}^{t_{re}} R(t)dt = \frac{\Lambda \times (t_{ee} - t_{es})}{2} + (R_p \times (t_{rs} - t_{es})) + \frac{\Lambda \times (t_{rs} - t_{re})}{2} \quad (4.43)$$

Similarly, by plotting the variations of resilience level of the critical infrastructures under a natural disaster, we can also calculate the $\Phi\Lambda E\Pi$ and *Area* metrics for them [14].

Reference [15] has improved the power system resiliency based on the grid reconfiguration. In this regard, three metrics have been suggested for quantitative evaluation of power system resiliency.

$$\Psi = [\Psi_{i,n,d,t}^\lambda, \Psi_{i,n,d,t}^\mu, \Psi_{i,n,d,t}^\partial] \quad (4.44)$$

In (4.44) when the i th plan of the network reconfiguration is considered at time t , $\Psi_{i,n,d,t}^\lambda$ calculated as:

$$\Psi_{i,n,d,t}^\lambda = \frac{\sum_{i \in I} \sum_{n \in N} P_{d_n,i}^{|\xi|}}{P_d^I} \quad (4.45)$$

The term $\Psi_{i,n,d,t}^\mu$ in (4.44) is equal to:

$$\Psi_{i,n,d,t}^\mu = \sum_{i \in I} \sum_{n \in N} C_{dn} (P_{d_n,i+1}^{|\xi|} - P_{d_n,i}^{|\xi|}) \quad (4.46)$$

The last parameter of Ψ in (4.44) is $\Psi_{i,n,d,t}^\partial$ which is calculated as:

$$\Psi_{i,n,d,t}^\partial = \sum_{i \in I} \sum_{n \in N} \frac{P_{d_n,i}^{|\varepsilon} - P_{d_n}^{|\varepsilon}}{P_d^T - P_{d_n}^{|\varepsilon}} \times 100 \quad (4.47)$$

4.3 Conclusion

In this chapter, quantitative metrics that were proposed in the literature to assess the resilience of power systems were explained. Researchers have proposed different metrics for the resiliency of power grid in various viewpoints such customer perspective and power distribution level. Physical structure and network topology, severity and type of the threat, system performance under malicious event, restoration/recovery time after the disaster, network reliability indices, number of critical infrastructures such as transformers, storage resources, distributed energy resources etc., are effective in the assessment of the power network resiliency. In a general viewpoint, resilience metrics may be classified in three categories such simulation-based methods (whose are based on the performance of the system), analytical methods (whose are based on the probability and reliability indices), and statistical analysis of historic outage data. It should be noted that the power system planner can use one or a several numbers of the metrics for an accurate measurement of the resilience of the power system for a specific event with a known severity considering the purpose of system planning.

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