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Initial framwork for a generalized and quantitative resilience evaluation of an evolving power supply system

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Current developments and challenges in the power supply infrastructure in Europe – especially the transition to renewable energies, advancing digitization and the effects of climate change – demand a comprehensive resilience assessment for the whole system. While new vulnerabilities arise due to system evolution, which need to be detected, observed and appropriately treated, the transition also unlocks new methods and abilities to increase the resilience of the power supply system. A resilience assessment can be done by measuring and combining the most relevant system parameters, i.e., performance indicators, to form a resilience metric, where deviations from the optimum directly account for an increased vulnerability (or even damages) of the system under study, i.e. a loss of resilience. Resilience metrics for power grids are extensively discussed in literature. Most of them either focus on a general, qualitative discussion, or concentrate on a single system aspect. The holistic resilience metric for the power supply system developed here, attempts to cover all resilience dimensions on every scale in a quantitative, encompassing way. This metric can account for levels reaching from a local to a supra-regional scale. It is specified to our needs for monitoring an increasingly digitized system and considers aspects arising from a rise in renewable energy. Key Performance Indicators are identified, which distinguish different facets of power supply resilience. Inspecting the KPI evolution in real-time allows an evaluation of the system's performance before, during and after a crisis.

Keywords: Resilience, Resilience Metric, Power Supply System, Digitization.

1. Introduction

The power supply system currently faces a major transition. The shift to renewable energies, accompanied by an advancing decentralization, gives rise to a new structure of the energy supply network. Large power plants (coal, nuclear), currently major contributors to the network's stability, will soon drop out. They are replaced by increasingly digitized, highly distributed facilities (solar, wind), which usually come along with less plannable production curves. New technologies and increasing digitization find their way into the current energy network. At the same time, we observe more frequent and extreme weather events due to climate change.

These extreme weather events, such as heat waves, heavy snowfall and storms, will increasingly threaten a reliable power supply. Additionally, the power system faces physical or cyber-attacks, accidents and equipment failure.

To confront these growing uncertainties, it has become evident, that there is a need to work towards a resilient design of our power supply systems IEEE PES Task Force and Stanković et al.

(2022); Vugrin, Castillo, and Silva-Monroy (Vugrin et al.).

IEEE PES Task Force and Stanković et al. (2022) defines the resilience of a power system by:

> "Power system resilience is the ability to limit the extent, system impact, and duration of degradation in order to sustain critical services following an extraordinary event. Key enablers for a resilient response include the capacity to anticipate, absorb, rapidly recover from, adapt to, and learn from such an event."

The aim of this work is to develop a resilience metric that is tailored to a power supply system, which incorporates many of the mentioned revolutionary developments we are facing, and allows to evaluate the power system's resilience real-time and in a quantitative manner. A nice overview over existing approaches for power system resilience metrics is given in Umunnakwe et al. (2021). The metric developed here is formed by a set of Key Performance Indicators which combine the most relevant system performance indicators. Monitoring them allows to directly assess the resilience of the observed system. The work serves as a conceptual basis for any follow-up resilience assessment of a power system with the named properties.

The paper is organized as follows. The properties of the power supply system of interest are described in section 2. The systematic resilience management process – for which this work will serve as a conceptional basis – is introduced in section 3. The main results are presented in sections 4 and 5. An outlook on how the identified Key Performance Indicators can be used to quantify and evaluate the system's resilience in real-time is shown in section 6. Finally, a conclusion is drawn in section 7.

2. The Power Supply System under Discussion

The power supply system reaches from a local to supra-regional scale. Its main aspects consider the growing importance of renewable energy producers, advancing digitization and especially modern technologies used in this context. These technologies cover resilience converters, Virtual Power Plants (VPPs) and digital substations.

The power system can be differentiated into one part which belongs to the transmission network (characterized by high voltages and few but large connected power producers) and another part which represents the distribution network (characterized by low voltages and small but numerous consumers and producers). The rising importance of renewable energy generation changes the established top-down architecture in power production towards highly Distributed Energy Resources (DERs). It evokes new vulnerabilities to system stability. Modern solutions need to address this. Digital substations are one important modernization in this regard. By collecting more data and allowing a more elaborate analysis of the system state, grid operators gain a deeper understanding of their system. Their control capabilities grow. However, the digitization of substations also adds vulnerabilities, e.g. against cyber-attacks. This needs to be monitored.

Virtual Power Plants represent a compound of several small producers (renewable ones and others) which are under joint control. They simplify the power grid control by grid operators, as they act in some ways similar to traditional, larger power plants.

The growing distribution of renewable energy provides new opportunities. Distribution grids at medium voltage (MV) level will be able to switch to island mode and become autonomous from the transmission grid based on newly implemented hardware like grid forming inverters and local VPPs. We aim to fully depict those developments using our identified performance indicators listed in section 4.

3. Resilience Cycle

A systematic generic resilience management process is set up by Häring et al. (2017) in form of a nine step iterative cycle, which covers resilience quantification and development of the system under discussion. The resilience management process is a further development of the risk management standard, set in ISO 31000 (Purdy (2010)), and has already been applied to networks such as gas and telecommunication or to renewable energy industries (Häring et al. (2021); Köpke et al. (2023)).

One goal of the method described in Häring et al. (2017) is to enhance the management process by quantifying the resilience of a system, especially by plotting and evaluating resilience curves.

The first four steps of the process include a (1) system context analysis, (2) a system analysis, (3) a system performance function analysis, and (4) a disruption identification. These steps deliver the system analysis and a performance as well as threat identification, on which a comprehensive resilience assessment can be performed.

Step (5) and (6) use the first steps as a base, and form the analysis phase of the resilience assessment. They are followed by the evaluation phase consisting of step (7) and (8). Finally, the cycle is closed with step (9) Development and implementation of options for improving resilience.

The goal of this work is to realize step (3) of the resilience management process for a modern power supply system as described in section 2. The resulting metric and the Key Performance Indicators (KPIs) form the basis of any comprehensive quantitative resilience assessment.

On the basis of this work, the resilience management process can be completed in follow-up works by inspecting first the possibility of depicting the evolution of the system KPIs and secondly performing it for all found relevant disturbances of interest (defined in step (4)) during step (5) and (6). The evaluation of the system performance and improvement options are discussed in step (7) and (8). Subsequently, the implementation of the results is performed in step (9).

4. Performance Indicators and Metric

According to Häring et al. (2017), a systematic resilience management process needs to identify and define system performance indicators, which – as a set – cover the resilience behavior of the system comprehensively. To identify a set of performance indicators which fulfills these requirements for the system described in section 2, is the key goal of this work. It lays the foundation for measuring the resilience of the system quantitatively in a later step of the management process.

General metric setups as well as special metrics for cyber systems and power grids are discussed in Koç et al. (2014); Panteli et al. (2017); Linkov et al. (2013). They serve as sources to identify the set performance indicators, which cover the resilience behavior of a modern/near-future power supply system as described in section 2 comprehensively. Technical aspects of the system's resilience are emphasized due to its strong focus on modern and newly used technology in power supply systems rather than management or organizational aspects.

The overall resilience of the power supply system is composed of different facets. These facets are motivated in section 5 under the label of resilience dimensions and help to build a comprehensive picture of the systems resilience. The resilience facets presented here are based on this general motivation but are further customized to our modern/near-future power supply system and emphasize the influences of new and modern hardware (e.g., islanding capability), ICT contributions and an increased number of DER. These facets therefore include the current technical power network stability, but also the capability of the system to turn into island mode.

A comprehensive set of performance indicators has to contain indicators of each facet. The performance indicators of the same resilience facet will be combined into a KPI representing that facet. This can be done, e.g. by a linear combination of the deviation of the involved performance indicators from their nominal value. One can further highlight the influence of certain performance indicators by a specific weighting of the summands.

Depicting the overall resilience of a system by several KPIs enables human observers, e.g., system operators, to gain a direct visualization of the relevant resilience facets of the system under investigation. The construction of KPIs drastically reduces the number of curves which need to be tracked and monitored, and the system state becomes more accessible. Due to the possibility of weighting different performance indicators differently, stakeholders are encouraged to discuss and define the related hierarchy within the indicators so that a joint understanding of relevant system aspects between the involved parties is supported.

On the other hand, the aggregation of information done when constructing the KPIs has the obvious drawback that details of the different performance indicators are lost. Depicting the overall resilience of a system by a bigger number of KPIs allows a higher resolution of the system's resilience, since the resilience performance of each facets is evaluated individually. A balance has to be found between the degree of detail and the benefits of condensing information.

Inspecting the KPI evolution in real-time allows for an evaluation of the system performance before, during and after a disruptive event.

The identified KPIs are listed in the following, together with the contributing performance indicators.

KPI I Status system balance - direct indicators

- voltage
- frequency
- power (not provided)

KPI II Island status

- island - readiness (indicates if island operation is currently possible)
- battery status (solar/wind power storage)
- percentage of the total network capable of islanding

KPI III Destroyed/ inoperable technical and ICT components

- transmission lines/ distribution lines
- ICT components
- percentage control of DER/ VPP

KPI IV Stabilizing capacities

- percentage of production/ DER/ load losses
- Operating reserve (secondary control, minute reserve)

KPI V System loading

- remaining capacities of power lines

KPI VI Redundancies

- ICT infrastructure (maximal, good, satisfactory, critical)
- operational technology (OT) communication existent in case of an IT communication failure
- physical infrastructure
- (n-1) condition satisfied (mandatory on transmission grid level)

KPI VII Completeness of information on network status

- percentage of functioning communication
- percentage available system- and network data
- completeness of warnings and evaluation

KPI VIII System maintenance

- security updates up to date/ ICT component maintenance
- technical inspection on schedule/ complete

KPI IX Threat likelihood

- natural hazards (e.g. current weather warnings)
- malicious/ human threats (e.g., increased ICT attack frequency)

KPI X Societal losses

- number of affected households
- number of affected critical infrastructure
- economical costs

As written above, the selected KPIs are supposed to observe the system's resilience mainly quantitatively before, during and after a disruptive event. KPI X monitors the direct consequences of a power supply outage due to a disruptive event. This KPI is often used in some variations to evaluate the performance and resilience of power supply systems based on historical data Abdelmalak et al. (2023).

Other KPIs, however, are dedicated to evaluating the current status of a system when in normal or abnormal operation (KPI III - VIII). They represent indicators for the stress the system is already exposed to and how capable it is to cope with (another) disruptive event (eg. extreme weather event or cyber-attack). New stress sources, arising from an increasingly digitized system are observed in KPI III, VI and VIII by considering ICT components. Other new stress sources arise from an increasing percentage of distributed renewable energy resources and their less controllable production curves. This is taken into account through KPI IV. An increasingly digitized system's major benefit is the capability to observe major parts of the system in real-time. Its performance in this regard is covered especially by KPI VII.

Modern hardware provides a new resourcefulness of system parts to cope with an actual power supply loss, such as a grid forming converter with battery storage Fraunhofer ISE (2021). This is evaluated by KPI II. Such new developments can drastically reduce the impact of a minor or major system disturbance.

Short-time warnings of an imminent system threat are usually given by monitoring direct indicators of the power network stability (KPI I). Automated and other countermeasures with a quick response can be taken, once this KPI indicates a warning.

Finally, the exposure of the system to threats is evaluated by KPI IX (see Bompard et al. (2013) for a categorization of threats). New threats due to cyber-attacks are taken into account.

The ensemble of all KPIs provides a *resilience metric* in the sense that any deviation from their nominal values (which can be uniformly set to 1, see figure 1) relates proportionally to a loss of resilience, i.e., the larger the deviations the smaller the resilience. As a consequence, monitoring the KPIs produces a comprehensive picture of the overall resilience of the considered power supply system.

5. Covering of Resilience Dimensions

The overall system performance – when disturbed by a disruptive event – is a consequence of a variety of facets comprising the system. In order to organize and depict the resilience of a system in a complete manner, one has to make sure that all these facets are considered in the derived metric.

Four system categories or *resilience dimensions* can be identified. They are given by

- *resilience properties*: robustness, redundancy, resourcefulness and rapidity Bruneau et al. (2003),
- *resilience sectors*: social, organizational, technical and economical Bruneau et al. (2003),
- *resilience phases*: prevent, prepare, protect, respond and recover Thoma et al. (2016),
- *scale*: (in our case) local, regional and supra-regional.

It becomes immediately clear, that the listed system aspects portray independent parts of a resilience discussion. The scale dimension covers the spatial extension of a power supply system, which ranges from local distribution networks and local DERs to the extreme high voltage (EHV) transmission network, whereas the resilience phases depict the temporal behavior of the system. They can therefore be interpreted as *resilience dimensions*, forming a resilience coordinate system, that is used to evaluate the system under discussion.

Ideally, all combinations of resilience dimension elements[a] should be represented by a performance indicator. However, depending on the system under discussion, some combinations are more relevant than others. Furthermore, it is not always possible to get information on every combination for the discussed system.

Table 5 tries to place the described power system KPIs into the resilience dimension coordinate system. As our approach has a strong focus on modern and newly used technology, the technical part is well covered. However, it is evident, that some social and economic aspects are not extensively depicted.

For simplicity, we did not try to incorporate the scale dimension in our description of the KPIs. But it should be noted, that ideally, every KPI should be calculated on every scale, if reasonable.

[a]e.g. protect – rapidity – technical – local, recover – rapidity – technical – regional

Table 1. Table with mapping of the KPIs to resilience dimensions. Two dimensions are given as columns and rows in the table. The third dimension is depicted in form of symbols, which are explained in the legend right at the bottom of the table. The symbols are placed right before the KPI number, sorted into the table. Names in brackets behind a KPI number specify the performance indicator included in that KPI, which in particular covers this combination of resilience dimension elements.

resilience type/ phase	prevent	prepare	protect	respond	recover
social				♠X	♠X
organizational	◇VIII	♡♣II, ♡♣IX, ♡♣VII (evaluation)	◇III (control)	◇II, ♠VII (evaluation)	
technical	♣III,♣V	♣III, ♣IV	♠I	♠IV, ◇VII	♠VII
economical	♣VI	♣V, ♣VI		♠X (costs)	♠X (costs)

♡ – robustness, ♣ – redundancy, ◇ – resourcefulness, ♠ – rapidity.

6. Resilience Quantification

A major goal when using the resilience management process, described in section 3, is to produce a quantitative resilience measurement in the form of resilience curves, as well as an in-time observation of the system's resilience. In the case of our metric, a resilience curve could be drawn and evaluated for every KPI. As mentioned in section 4, some KPI depict the stress level, or the "early warning" for a system under stress, while other KPIs (especially KPI I and KPI X) depict the actual loss in the power supply.

The quantification of resilience real-time requires real-time data provision by all involved stakeholders. This includes network, substation and VPP operators, as well as electric utilities. The real-time information on societal losses, especially the number of affected households and critical infrastructure, can be derived from network operators and local administrations such as municipalities. Economical costs are interesting for all involved stakeholders and can ideally be derived from a cost function, which depends on known information provided in real-time.

Figure 1 shows a conceptual example of the behavior of each KPI category e.g. on a regional level. The depicted course of the KPIs has been artificially constructed based on general knowledge and internal discussions on the expected behavior of the contributing performance indicators.

Additionally, a minimal performance threshold is indicated for each exemplary KPI. In the shown graphs, a disruptive event (e.g. cut of a major transmission line during an extreme weather event) occurs at minute 800. The KPI representing short-term warnings drops below its allowed minimal threshold [b] until countermeasures (e.g. load shedding) stop the fall. The performance of this KPI will be restored within minutes after the disruptive event. The KPI representing the system's stress level drops below its respective threshold as well, due to the destroyed structures, before it slowly recovers. Finally, the KPI representing actual supply losses significantly drops shortly after the disruptive event. Some households and certain critical infrastructure can fall back on their own power supply, which stops running only after some minutes or hours, letting the respective KPI decline further, even several minutes and ours after the disruptive event. Finally, the KPI recovers slowly along with the recovery of the system's

[b] The best example is a drop of the frequency below some specified threshold, like, e.g., the threshold of 49 Hz, set in Commission Regulation (EU) 2016/631 (2016) as the lowest frequency where power generators are required to operate for an unlimited time

stress level.

On the other hand, a performance curve which considers a combination of all KPIs could also be of interest. An example of a weighted total performance curve, combining stress, early warning and an actual loss in power supply caused by a disruptive event (e.g. extreme weather) is shown in figure 2. The KPI combination curve is calculated by weighting the contributions of the individual KPIs in a way that an actual loss in households' power supply (KPI X) is more relevant than the overall stress level of the system (KPI III -VIII). The figure shows a drop of the total performance curve below an exemplary boundary (dotted, horizontal line) due to the drop of the early warning KPI, as well as the drop in the system's stress level KPI. The boundary is motivated by a weighted combination of the minimal performance thresholds of the involved KPIs. It is not a strict threshold in the sense that any breach indicates an imminent total system collapse, but a violation of that boundary might indicate a serious condition of the monitored system, nevertheless. One can further see, that the system did not perform at 100% when the disruptive event occurred, due to the fact that the system was already under stress. (e.g. not all DER under control at that time). That might affect the depth of the drop in the KPI, representing actual supply losses.

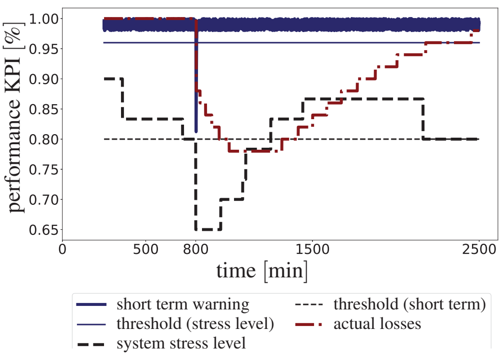

Fig. 1. Artificially created performance curves representing the behavior of three different KPIs before, during and after a disruptive event, occurring at $t = 800$. All KPIs are assumed to be normalized and given in percent of optimal performance. The stress level of the system represents KPI III - KPI VIII. The short-term warning curve represents KPI I (The best example is a drop in frequency below a specified frequency). The actual losses represent KPI X. The horizontal lines (dashed and solid) depict minimal performance thresholds, below which the respective KPI should not fall.

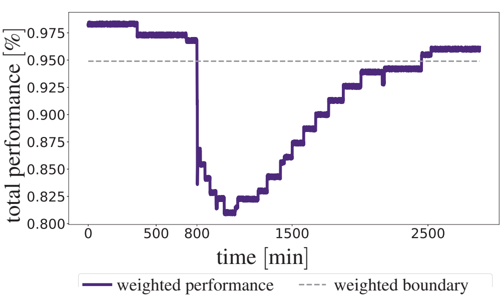

Fig. 2. Weighted combination of the exemplarily created performance curves shown in figure 1 depicting the total system performance, before, during and after a disruptive event occurring at $t = 800$. The horizontal line depicts an artificial boundary, calculated from a weighted combination of the minimal performance thresholds given in figure 1. A drop of the total performance curve below the boundary indicates a relevant disturbance of the system.

7. Conclusion

We presented a new resilience metric, specifically developed for a modern and near future power supply system. The presented KPIs distinguish different facets of the power supply system resilience and ideally evaluate them in real-time. They include not only the direct performance loss of the system in the form of a loss in power supply, but also the overall stress that the system is exposed to, its resourcefulness in reacting to a system disturbance due to the existence or lack of modern hardware, like grid forming converters or digital substations, and early warning signs for an imminent system performance threat.

Furthermore, the established KPI set was mapped to the identified relevant resilience dimensions in order to evaluate the comprehensiveness of the set and identify gaps.

With the presented metric development, a significant aspect of the resilience management process is realized for a modern and near future power supply system.

In future, follow up studies will be conducted together with four expert institutions (Fraunhofer

ISE, IEE, IEG, ISOB-AST) where different data sources, like the simulation results of a model combining a MV grid with a grid-forming inverter, or the results of a model of a digital substation, are used to validate and refine the developed resilience metric. Inspecting simulation results for normal grid operation as well as for system disturbances will allow to assess the practical capabilities of the presented KPIs as well as possible improvements and additions to them.

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