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ComPSim: A Community based Smart Grid Testbed for Holistic Resilience Analysis

Amulya Sreejith*, Prudhviraj Dhanapala*, Adithya Melagoda†, Seyyed Amin Enderami‡,
Visvakumar Aravinthan†, Anil Pahwa*, Balasubramaniam Natarajan*
*Department of Electrical & Computer Engineering, Kansas State University
†Department of Electrical & Computer Engineering, Wichita State University
‡Department of Civil, Environmental & Architectural Engineering, University of Kansas

***Abstract*—This paper presents a novel approach to designing a smart grid testbed, that advances the state of knowledge on power system resilience analysis by including the social aspects of the community in simulation. The proposed Community-based Power Simulation virtual testbed, termed ComPSim herein, integrates non-physical dimensions of the community into the smart grid infrastructure system. The ComPSim test bed can be applied to identify the social impacts of power system disruptions. The testbed takes into account diverse socioeconomic characteristics of the community, enabling targeted analysis and policy formulation. This research highlights the need for integrating community's social and economic facet into future infrastructure planning and decision efforts.**

***Index Terms*—Smart Grid Testbed, Co-simulator, Community resilience, Social vulnerability**

I. Introduction

The resilience of power systems is of critical importance, particularly in the face of increasing challenges such as natural disasters, cyber-attacks, and climate change. Resilience of the power system has a multidimensional nature that encompasses various aspects such as robustness, adaptability, reliability, and recovery. Resilience ensures the continuity of the power supply and the ability to withstand and recover from disturbances. There is an increased need to develop decision support tools to enhance the resilience of the power system considering various aspects which include, interdependencies with other physical and social infrastructure. Analysing vulnerabilities of an actual physical grid by inducing failures and observing impacts on a functional system is not feasible. Digital twins and simulation testbeds are critical in this regard. Over the years, researchers have developed various testbeds and simulation tools that can support modeling, analysis, and decision making in the power system domain. A testbed can be defined as "an environment with enough supporting architecture and metadata to be representative of one or more systems such that the testbed can be used to (1) design experiments, (2) examine model or system integration, and (3) test theories" [1]. Actual test systems require field data that takes time to obtain, clean and build representative models and simulations. Testbeds on the other hand, can be used to test, verify and validate fundamental ideas, theories and algorithms with a level of generalizability.

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Most of the existing power grid testbeds are highly infrastructure focused and do not consider the community aspects. This is especially problematic for resilience analysis because the true impact of grid failures can only be assessed if we are able to model the social, health, economic, and other costs incurred by the community being served. To effectively enhance power system resilience, it is essential to consider the community's perspective and incorporate community-based parameters and metrics into the design of decision support tools. These metrics encompass social, economic, and cultural aspects that influence the relationship between the power system and the community it serves. Incorporating these parameters ensures that decision support tools consider the unique needs and vulnerabilities of various communities.

Understanding the importance of community-based parameters in power system resilience studies, we have developed ComPSim, a community-power virtual testbed. The purpose of this paper is to describe the rationale and a general methodology for developing a smart grid testbed that includes interdependent power and social infrastructures, along with other relevant socio-economic information.

A. Related Work

In a survey conducted to define the requirements of a testbed [1], the most common response received was that at a minimum, a testbed should (1) represent reality (2) should be broadly applicable (3) Should be replicable/reliable, and (4) Be open source. An overview of existing testbeds and characteristics of the proposed testbed is given in Fig.1.

In the realm of power system analysis, IEEE standard testbeds [13] are conventionally utilized for various studies such as reliability, short circuit and open circuit tests, insulation design, and harmonic analysis. These standard testbeds provide essential data on buses, line configurations, transformers, load configurations, and capacitor banks. Certain research has included detailed interdependent infrastructure modeling [14], while other researches like IN-CORE [15] have presented community resiliency analysis that includes the effects of earthquakes, tornadoes, tsunamis on water, power, and buildings. Testbeds such as the CLARC database [16]

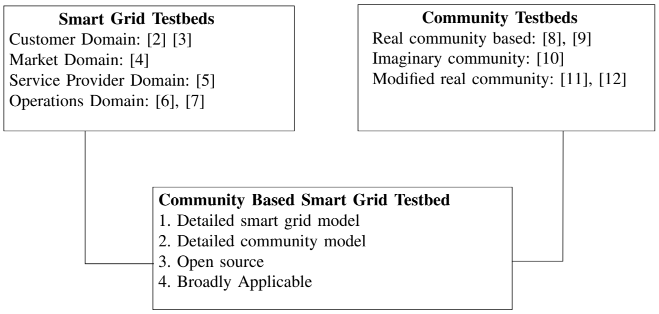

Fig. 1. Literature Review and Proposed Testbed

offer a comprehensive framework to model the impacts of extreme risk events on interconnected civil and social infrastructure systems. Despite its realistic portrayal of communities and their infrastructure, the CLARC database lacks the depth needed to model actual power systems. The consideration of the actual power system configurations remains a critical factor in these community-focused testbeds.

To address this gap, testbeds facilitating co-simulation of interconnected networks are essential to evaluate technical feasibility of resiliency planning. Although many researchers have attempted to incorporate additional modules tailored to specific research requirements [17], [18], the detailed modeling of both infrastructure and community in a single testbed is a challenge. The inclusion of social aspects of the community to ensure an equitable distribution of electricity is evident in [19], where the authors simulated the effects of power line and transformer outages in disadvantaged and non-disadvantaged communities, classified according to the distance from the substation transformer and income levels. Nonetheless, more robust metrics such as social vulnerability scores are imperative to quantitatively represent community social statuses, facilitating fair power system planning and operation. Moreover, to validate the technical accuracy of the considered network, co-simulation modeling remains an integral requirement.

B. Gaps and Contributions

It can be inferred from the literature review that although existing test beds for power system studies have made significant contributions to power system resilience analysis, these testbeds have several limitations. Existing smart grid testbeds lack community representations that can hinder their effectiveness in addressing community-centric aspects. Similarly, community testbeds only sparsely represent the infrastructure without involving the specifics of system modelling. Resilience analysis of smart grid systems in the face of extreme hazard events is crucial for ensuring reliable and sustainable energy supply. Based on the identified limitations of existing testbeds, we propose a one-of-a-kind virtual testbed that bridges the gap between the existing infrastructure and community testbeds. The major contributions of the research are as follows:

1) We build a detailed database that included power infrastructure data, with an overlay of social, economic, and cultural dimensions and hazard information, leveraging the data from New Hanover County and the CLARC database.
2) We use the power and community database to build a simulation based testbed that can be used for resilience analysis studies. Scenario analyses within the testbed is used to evaluate different power system resilience strategies and their impacts on the community and assess the effectiveness of resilience measures.

The remainder of the paper is organized as follows. The overview of the testbed and details of the database are explained in detail in Section. II. In Section III, the framework for developing testbed use cases and outlining resilience analysis objectives is elaborated. Lastly, Section IV provides insights into the conclusions drawn, challenges encountered, and outlines directions for future research endeavors.

II. Database and Tool Structure

A. Overview of the proposed simulation tool

The development of the testbed involves two major steps:

1) Database Development: The database development stage involves the creation of an artificial dataset for both the smart grid infrastructure and community that is similar to a real world. We collect data from multiple datasets and overlay them to create a dataset that includes information about the power system along with community and hazards data.

2) Simulation Modeling: The simulation stage involves integrating all data to build a co-simulator that includes the grid infrastructure and community aspects. The simulation platform can take multiple datasets and all of the different datasets are to be properly aligned for effective analysis.

Fig.2 shows the overall layout of the testbed. It consists of five modules, namely (a) Power infrastructure Module, (b) Hazard and vulnerability module (c) Community module (d) Integrated Simulation module, and (e) Resilience analysis module. A detailed discussion on each module is provided along with details of dataset in subsequent subsections.

B. Database Development

We use data from multiple databases and logically integrate them to create an artificial data set that can be used to build the testbed. While actual field data can provide better insights, it can lead to major security concerns. Thus we use a combination of publicly available actual data and synthetically create the other data. For this, we leverage the CLARC dataset which is defined as "An Artificial Community for Modeling the Effects of Extreme Hazard Events on Interdependent Civil and Social Infrastructure Systems". The data set is structured as a GIS database in Microsoft Access. Every component is represented by a node, arc, or polygon. GIS mapping ensures that multiple infrastructure data and community demographic data are aligned well.

We modify the CLARC data and include system parameters to model the power system. The power system data in CLARC includes the locations of the transmission and distribution substations and the various loads under each distribution

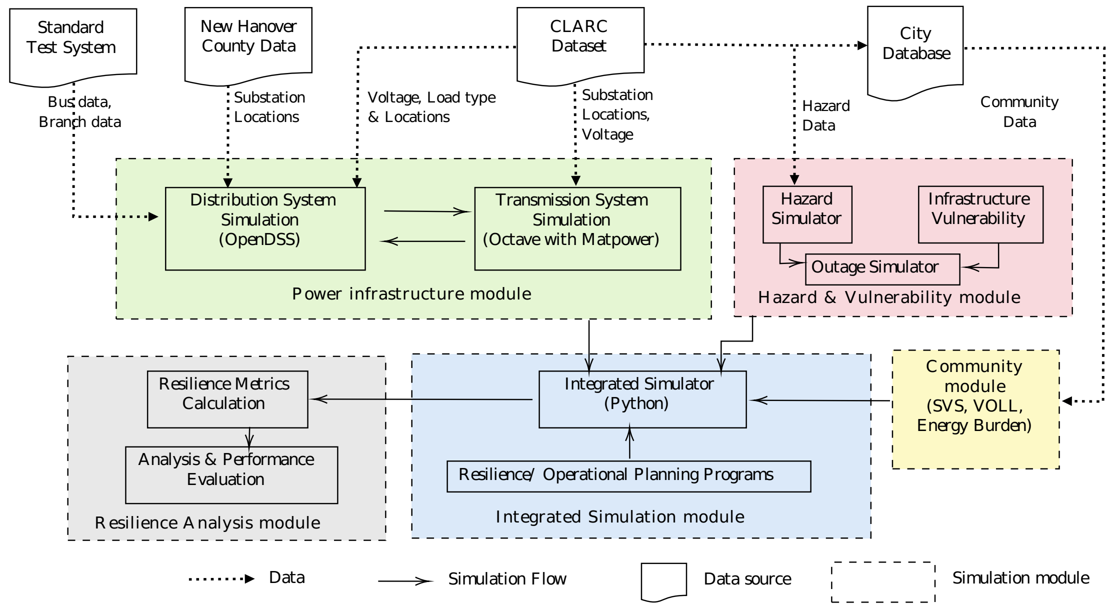

Fig. 2. ComPSim Testbed Layout

substation. The load values, however, are badly scaled and not practical. We modify the load values to represent actual field loads. For example, the typical power for a hospital is given in CLARC as 50kW and the modified value is 500kW.

To build a power flow simulation model, it is also necessary to have the parameter values of electric lines such as resistance, reactance, limits, etc. To include these electric parameters, we overlay the 240 node Iowa distribution system [20] with three feeders under each substation and assign the various loads to each node.

CLARC also gives community demographics such as population, and average income. However, the data is at a census tract level and does not encapsulate the varied demographics considering energy burdens, value of load etc. Community demographics for each node are assigned randomly based on a uniform distribution considering the average income as the mean value. Other parameters are also assigned randomly.

The detailed step by step methodology for development of the dataset is given below:

1) Substation location: The distribution substation locations are identified using Openstreetmaps database.
2) Map to CLARC data: Map substations to CLARC distribution substation nodes, identify the loads under each substation, and obtain the distance of the loads from substation. (Refer Table.I).
3) Load data: Assign kW values to loads based on typical load values and the size of the load identified from county map and data.
4) Other system data for simulation: Assign loads to feeders based on their positions on a real map. Map each load node to nodes in the 240 bus Iowa test system based on length.
5) Community data: Assign community data to each residential node using a stochastic assignment.

C. Power infrastructure Module

The smart grid infrastructure module is built using a co-simulation. The foundation of the co-simulator lies in the integration of various open source tools. The distribution system simulation is performed using OpenDSS as it provides a robust platform for modeling and analyzing distribution networks. A detailed representation of all components, such as transformers, feeders and loads, is provided using data from the Iowa 240 bus distribution system [21], allowing an accurate assessment of the behavior of the power system at the distribution level.

For transmission system modeling, Octave with Matpower offers a powerful open-source framework. Matpower provides comprehensive functions for power flow analysis, optimal power flow, and contingency analysis in transmission networks. By utilizing Octave, a high-level programming language, we leverage Matpower's functionalities for accurate transmission system modeling and analysis.

The core of the co-simulator is a python based module. This module integrates data from both distribution and transmission systems to enable transmission-distribution co-simulation. In addition to acting as the integration between the two softwares, other resilience analysis programs can also be developed using python by effectively utilizing the community and hazard data.

D. Hazard and Vulnerability Module

The tool's hazard module is responsible for generating disaster scenarios and initiating infrastructure failures based on their vulnerability. It uses a probabilistic model to calculate the probability of failure for each infrastructure component. This probability is determined by multiplying the probability of the hazard, the probability of the component being exposed to the hazard if it occurs, and the probability of the component failing if it is exposed to the event. The probability of failure of component i due to a hazard h is given by,

TABLE I
CLARC DATASET MAPPING AND MODIFICATIONS

Data	Mapping to Real data	Mapping/ Modification to CLARC	CLARC Database Location				
			Input (Observe the values below)			Output (Value in given column)	
			Table	Column	Value	Table	Column
Distribution Substation	GIS Locations from Open-streetmaps	Mapped to CLARC nodes 3004-3016 (3009 excluded)	Master_Nodes	Definition	Dist_Substation	Master_Nodes	ID_Master_Node (Eg:3004, 3005)
Load Type	–	Identify loads under each substation.	Master_ARCs	From_ID_Master_Node To_ID_Master_Node	'Distribution Substation', 'Load ID'	Master_Nodes	Definition (Eg:Loads 'Intersection', 'Cell_tower' under 3004)
Load Value	Approximate Size of load	Modify Power_Use data based on size of load	Master_ARCs	From_ID_Master_Node To_ID_Master_Node	'Distribution Substation', 'Load ID'	Master_Nodes	Power_Use
Load location	–	For each load type, get distance from substation.	Master_ARCs	From_ID_Master_Node To_ID_Master_Node	'Distribution Substation', 'Load ID'	Master_ARCs	Shape_Length

$$p(f_i) = p(h)p(e_i|h)p(f_i|e_i) \tag{1}$$

where, $p(h)$ is the probability of occurrence, $p(e_i|h)$ is the conditional probability of component i being exposed to the hazard if it occurs, and $p(f_i|e_i)$ is the conditional probability of failure of component i if it is exposed to the hazard.

For hazard events, the dataset must provide the event's location, impact radius, and intensity level (low, moderate, high, extreme, or random). The conditional failure probability $p(f_i|e_i)$ depends on the intensity level, and the probability of exposure to the event $p(e_i|h)$ is calculated based on the distance of the component from the location of the event and the impact.

E. Community module

The community modeling module integrates community data from various sources such as city data, census data, university research data, and data from other government and private agencies. These data are then used to calculate the community metrics relevant for resilience studies. Social vulnerability assessment, which refers to the susceptibility of communities to the impacts of natural hazards or outages based on their social characteristics and the availability of resources, is a crucial aspect in understanding community resilience to natural hazards and disasters. In the proposed tool, the community data available from census and city maps is used to calculate the community metrics using appropriate formulae.

An improved social vulnerability score would include various factors such as race, ethnicity, housing tenure, poverty level, education level, age, disability, and other factors. These factors influence a community's ability to prepare for, respond to, and recover from natural disasters. To include these factors, we use the Social Vulnerability Score (SVS) [22] as a robust and scalable social vulnerability index. The SVS is based on a deductive approach, where indicators are aggregated while equally weighted. It uses data from the five-year estimates of the American Community Survey (ACS) and employs a set of indicators of social vulnerability, including race, ethnicity, housing tenure, poverty level, education level, age and disability. The SVS calculates the arithmetic mean of the indicator values and categorizes the results into discrete vulnerability zones for easier interpretation.

F. Integrated Simulation module

The integrated simulation module collects data from all the previous three modules and uses these data to perform simulations considering various resilience analysis and enhancement programs. These include (a) Planning programs: Hardening, coordination, resource allocation, restoration and reconfiguration programs (b) Operation programs: Optimization, coordination, restoration, Security, Protection (c) Combined Planning-Operation programs. These programs are written using python program owing to the availability of large number of libraries for optimization, and scientific calculations. Section.III-B includes more details about some of the resilience planning programs implemented within the tool.

G. Resilience Analysis module

The built-in resilience metrics within the system assess the overall impact of infrastructure disruptions and the effectiveness of subsequent repair actions. These resilience metrics offer valuable insights for identifying optimal resilience strategies or interventions.

For example, Value of lost load (VoLL) is a metric that signifies the importance of load in the given electrical power system [23]. The loads in the network which influence the social factors like quality of life, quality of service etc., should be considered important or critical. Some of the loads that are considered in the high VoLL category are hospitals, water treatment plants, waste water pumps, and commercial stores. The VOLL can be extended to the residential level by considering the loss incurred to the user due to unavailability of the power supply.

Energy Burden [24], [25] is a measure to assess the affordability of energy for households and is particularly relevant for low-income households or communities that may struggle to pay their energy bills. If the cost of electricity paid by a customer l is given by C_l and the Income is I_l, the Energy burden B_l is given by,

$$B_l = C_l/I_l \tag{2}$$

A high energy burden indicates that a significant portion of a household's income goes towards meeting energy needs, potentially leaving less money available for other essential expenses like food, healthcare, and education.

III. Community-centric analysis framework

This section explains the generalized framework for utilizing the testbed for community centric smart grid analysis and sample use-cases possible using the testbed.

A. Framework for Testbed use-cases

Multiple entities can work together and use ComPSim for various resilience studies as indicated in Fig. 3. Creating a comprehensive case study using the testbed involves defining use cases, challenges, and research objectives for the system.

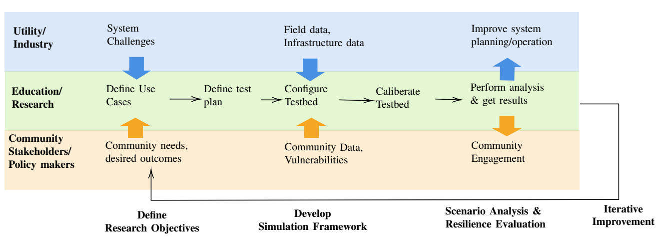

Fig. 3. Framework for ComPSim testbed use-cases

Initially, the testbed must be configured and a test plan must incorporate field data, infrastructure data, and community data to address vulnerabilities and community needs. By performing analyses and obtaining results, one can evaluate desired outcomes and improve system planning and operation iteratively. Community engagement with stakeholders, utilities, industry, and education/research institutions plays a crucial role in calibrating the testbed and developing a simulation framework. Scenario analysis and resilience evaluation are performed iteratively to assess the system performance and identify areas for improvement, aligning with the community's interests and overall goals. The case study thus showcases the testbed's efficacy in enhancing system resilience and addressing real-world challenges while engaging various stakeholders to ensure sustainable and efficient infrastructure management and community well-being.

B. Resilience analysis case-studies

The proposed testbed has the capability to be used for improving the resilience of the community. In most of the existing work, the resiliency analysis is carried out considering the technical aspects of the power systems. After an extreme weather event or any other outage scenario, the recovery of loads is usually based on factors like the switching sequences, and priority of loads, without considering who is getting impacted by considering these factors. However, the ComPSim testbed provide the opportunity to examine and develop, novel load recovery options that consider community along with the physical infrastructure. Some of the possible resilience analysis functions that can be carried out using the proposed tool are as follows:

- SVS based resiliency analysis
- VoLL based resiliency analysis
- Energy burden based resiliency analysis
- Equity aware solar PV hosting capacity
- Complex network resiliency analysis

In achieving the above goals, co-simulating the transmission and distribution power systems in combination with community data gives more flexibility in planning and operation.

1) SVS based resiliency analysis: The SVS of the community not only indicates an abundance of Distributed Energy Resources (DER) but also can imply other electrical resources include battery energy storage system, diesel generators, fly wheel mechanism, thermal storage, etc. Availability of all these resources in the electrical power system, improves the resiliency planning metric [26] and it is a reasonable assumption that the community with low social vulnerability level should have necessary smart technology to improve the operational resiliency for their own power demand. To this end, the community with exceptionally low social vulnerability level can support their neighboring communities to meet a minimum of the critical loads during an emergency.

2) VoLL based resiliency analysis: Resilience analysis can be performed considering VoLL in planning resilience enhancement programs. The cost of power system outages (C_o) to a community can be measured using the following equation:

$$C_o = n_{ac} t_o \Gamma_{ac} \tag{3}$$

In this equation, n_{ac} is the number of affected customers, i.e, the total number of customers who experienced a power outage and t_o is the outage duration. Γ_{ac} is the value of lost load per customer per hour and it refers to the economic value of electricity to customers, which can be estimated using a variety of methods, such as surveys, market prices, or economic models.

3) Energy burden based resiliency analysis: Energy burden is an important consideration in understanding energy equity and the impact of energy costs on vulnerable populations. The proposed decision tool supports communities of different income levels to reduce their energy burdens and allows the equitable use of the electrical network.

4) Equity aware solar PV hosting capacity: The data base of the proposed decision tool provides the opportunity to plan the installation of new solar PV energy sources in communities. Communities that are vulnerable to be given great importance during planning and support the reliable power supply to underserved communities during outage scenarios.

5) Complex network resiliency analysis: Due to the availability of information and co-simulation type of modeling, the resiliency analysis of interdependent systems which are popularly known as a complex network is possible through the proposed tool. Typically, there is an interdependence of electricity, water, and transportation networks. It is possible to extend the testbed for resiliency analysis of the combined infrastructures by giving priorities for various demands associated with each to improve the Quality of Life.

IV. Conclusion

The resilience of power systems is becoming increasingly critical, given the escalating challenges posed by natural disasters, cyberattacks, and climate change. Achieving power system resilience requires considering various aspects such as robustness, adaptability, reliability, and recovery. While existing testbeds and simulation tools have made significant contributions, they have limitations in representing community perspectives. To bridge this gap, we have developed the ComPSim to integrate power and social infrastructures with socio-economic data, ensuring inclusivity and equity in resilience strategies. By combining detailed power and community databases, the ComPSim facilitates scenario analyzes to evaluate power system resilience strategies and their impacts on communities. Our research addresses the need to consider community-centric aspects in power system resilience studies, providing a valuable tool for decision-making and enhancing the resilience of power systems to benefit all stakeholders.

The power network is also dependent and affects other infrastructure facilities and thus, the testbed is being improved to include interdependencies with other infrastructure systems such as water network and transportation. Future work includes combining the different infrastructures, and socio-economic factors using heterogenous graphs to better encapsulate the interdependencies. By continuing to refine and improve the ComPSim, we aim to contribute to more equitable and sustainable power systems that better serve the needs of diverse communities in the face of extreme events.

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