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Multi-Dimensional Output-Oriented Power System Resilience based on Degraded Functionality

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***Abstract*—Power systems serve social communities that consist of residential, commercial, and industrial customers. As a result, the disaster resilience of a power system should account for social community resilience. The social behavior and psychological features of all stakeholders involved in a disaster influence the level of power system preparedness, mitigation, recovery, adaptability, and resilience. Hence, there is a need to consider the social community's effect on the power system and the dependence between them in determining a power system's resilient to human-made and natural hazards. The social community, such as a county, city, or state, consists of various stakeholders, e.g., social consumers, social prosumers, and utilities. In this paper, we develop a multi-dimensional output-oriented method to measure resilience. The three key ideas for measuring power system resilience are the multi-dimensionality, output-oriented, and degraded functionality aspects of the power system. To this end, we develop an artificial society based on neuroscience, social science, and psychological theories to model the behavior of consumers and prosumers and the interdependence between power system resilience, comsumer and prosumer well-being, and community capital. Both mental health and physical health are used as metrics of well-being, while the level of cooperation is used to measure community capital resilience.**

***Index Terms*—Power systems; Resilience; Community resilience; Social science; Artificial society**

I. Introduction

Unlike cascading failures that originate at a local point in a power system (a short-circuit at a bus or a generator outage or a line outage) and spread throughout the system via successive equipment outages, such as occurred in the 2003 Northeast blackout, natural disasters typically result in the physical destruction of some segments of the power transmission and distribution overhead lines and substations, which in turn may induce cascading outages that can result in large-scale blackouts and consequently significant financial losses. Power system engineers and researchers try to make power systems resilient to various types of disasters. However, they neglect the fact that disaster resilience and risk management in a power system are interrelated [1]. To increase the electric energy availability at the local level, the social community may be incentivized by electric utilities to participate in both active demand-side management and demand response via rebates on its electric energy consumption and an increase in community capital. Indeed, the cooperation among social communities and power systems is essential for the efficiency and effectiveness of community services and the reliability of the infrastructure and community within the disaster cycle (mitigation, preparedness, response, recovery). The social community's influence and dependence on a power system must, therefore, be taken into account in order for a power system to effectively withstand human-made and natural events.

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II. Motivation

A. Impact of Community Resilience on Power System Resilience

A power system is an integral part of the society that it serves [1]. To have a resilient power system, community capital functionality [2], and community well-being is essential. The ultimate aim of the power system is to satisfy demand and balance power. In conventional power systems, the generation side deals with various challenges. In modern power systems and smart grids and with the emergence of the Internet and the energy of things, consumers can play a crucial role in fulfilling the aims of an electric power grid and help the generation side to increase its operational efficiency. The consumer can participate in active demand-side management and decrease their demand during disasters. In addition, the prosumers can share their electricity with their neighborhood and support critical loads. The customer's willingness to help power utilities to overcome a disaster depends on customer satisfaction and cooperation. In addition, sharing electricity is entwined with the level of cooperation of the community. Without a healthy community where the costumers are willing to cooperate, a power system may face problems in responding to and recovering from a disaster.

B. Impact of Power System Resilience on Community Resilience

Due to the interdependencies among critical infrastructures, an interruption in electricity may result in the shutdown of the communications system, the Internet, the water supply, and the gas supply, among others. Hence, power system vulnerability can decrease community infrastructure functionality during a disaster. Power system availability influences the community's well-being in various ways, i.e., its mental health, anxiety, fear, and physical well-being This in turn influences and changes the community's capital.

C. The Need to Integrate Social Behavior and Computational Social Science into Power System Resilience

Power system resilience should aim at satisfying community resilience. To consider and model the effect of community

[1]Society can be a county, city, state, province, country, to name a few.

[2]This is the capacity of a society to deliver and create trust and collaboration between its citizens with social activity services.

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well-being and functionality on the power system functionality and vice versa requires the use of computational social science. The social science community's widely-used approach to modeling a community's behavior is to create an artificial society, which consists of a multi-agent-based model to model the micro-macro levels of interdependence and behavior [2]. Hence, an artificial society is used here to investigate the power systems' effect on community well-being and the functionality of a community's capital and vise versa.

III. Resilience and Related Concepts

A. Defining Community and Power System Resilience

To define the resilience of a community or of a power system, we first define the concept of functionality and its degraded version. **Community functionality** is defined as the ability of a community to operate in a normal manner by providing all the essential services to its community members during normal conditions. **Power system functionality** is defined as the ability of a power system to operate in a normal state by providing electricity to all the customers at the rated frequency and voltage without violating any voltage or power constraints in the system. **Community degraded functionality** is defined as the ability of a community to operate in a degraded manner by providing some, but not all, essential services to its community members during a specific type of disaster. **Power system degraded functionality** is defined as the ability of a power system to operate in an emergency or in extremis state in that some of the voltage or power constraints are violated and not all of the customers are supplied with electricity. Community and power system resilience is related to community and power system degraded functionality. We improve upon our previous definition [3] on community and power system resilience as follows: **Community resilience to a class of disasters** is defined as the multi-dimensional ability of a community to operate at a degraded level of functionality so that it has the ability to mitigate, respond, and recover from that specific class of disasters with minimum physical losses and human injuries and deaths. **Power system resilience to a class of disasters** is defined as the multi-dimensional ability of a power system to operate in at a degraded level of functionality so that it has the ability to bounce back and recover from that specific class of disasters with minimum physical losses.

Note that the multi-dimensional ability of a community is dependent on the various dimensions of a community, i.e., the social community, the critical infrastructure, institutional functionality and community capital, economic functionality. There are two main approaches to measuring resilience: the capacity-oriented method and the output-oriented method. Two common types of capacity-oriented methods involve survey-based methods and index-based methods [4]. Although multi-dimensional capacity-oriented methods are common in the literature, the output-oriented methods are usually not investigated from a multi-dimensional standpoint. In this paper, we develop a multi-dimensional output-oriented method to measure resilience. According to the literature, there are six general types of functionality (that is dimensions): well-being functionality, economic functionality, infrastructure functionality, institutional functionality, community capital functionality, and ecological functionality. From the power system point of view, well-being functionality, infrastructure functionality, and community capital functionality are very important. To achieve power system and community resilience, all three of these functionalities should be satisfied. In general, well-being functionality is measured by community mental well-being and physical well-being. Additionally, the level of cooperation is a measure of the functionality of community capital.

B. Concepts Related to Resilience

Mili *et al.* [1] propose four critical time periods as follows: the normal period, the window of opportunity, the disaster period, and the recovery period. Before a disaster occurs, the community is in homeostatic balance. This means that the community functions well and satisfies all its needs represented by a set of constraints; in short, it is in a normal state. During and just after a disaster, the community is in homeostatic imbalance since some of the constraints are violated. The community is in an emergency or in extremis state. Corrective or in extremis actions should be taken to bring the community back to its normal state. The ability of the community to bounce back and recover with minimum losses characterizes its resilience. Resilience consists of various factors, i.e., preparedness, mitigation, response, and recovery.

It is important to understand that resilience is different from robustness. Mili [5] states that "the robustness of a system to a given class of perturbations is defined as the ability of the system to maintain its function when it is subject to a set of perturbations of this class, which may induce changes in its structure." Robustness comes with brittleness. The latter is synonymous with rigidity relative to a small tensile stress. For example, a glass is brittle since it breaks with a relatively smooth fracture. In contrast, fragility is synonymous with the ease to obliterate and damage. This is indicative of resilience, which is, thus, the converse of robustness. Both resilience and robustness are the desired features of a system associated with a particular class of disturbances. Of course, there is a trade-off between them: the more resilient the system is, the less robust and hence, the more fragile it is. On the other hand, the more, robust the system is, the less resilient and, hence, the more brittle. These features have different trends for a variety of classes of perturbations. For example, if the community has already experienced a hurricane, it is more resilient to the hurricane than to other types of hazards.

C. Disaster Losses

Community losses consist of social community, economic, infrastructure, institutional, community capital, and ecological losses. Social community losses comprise human death tolls and trauma, among others. Infrastructure losses include physical losses to critical infrastructures, e.g., to power systems. Power system losses include losses in equipment, human resources, and institutional losses and investment costs to rebuild the part of the infrastructure that has been destroyed. These losses can apply to each generation, transmission, and distribution company depending on the disaster type. Note that the losses in one category can induce further losses in another category. For example, power system losses induce a lack of electricity. Without electricity, there is no business. Hence, the economic losses are increased. On the other hand, with a great deal of economic losses, the budget to invest in power system recovery is increased. The importance of losses is not taken into account in the literature, which over emphasizes recovery time. The aim of resilience is to minimize the losses with a minimum possible recovery time.

IV. Building An artificial Society of Power System Stakeholders

In order to capture emergent processes and understand multi-dimensional power system resilience, We develop a multi-agent-based stochastic dynamical model to capture the dynamical change of community well-being, community capital, and power system and community functionality. In the proposed model, agents consist of consumers, prosumers, and utilities. Note that all of the variables, parameters, and functions introduced take values between 0 and 1.

A. Well-Being Functionality

We develop an artificial society to model dynamical change in community well-being during a disaster. Community well-being functionality consists of two main dimensions, i.e., mental health and physical health.

1) Dynamic Mental Health Modeling: We consider negative feelings, fear, and anxiety to be indicators of mental health. These negative mental features are emotions for which an incremental change, $\Delta(X^E_{ti})$, is obtained from

$$\Delta(X^E_{ti}) = \alpha'^E_{ti}(f(\hat{X}^E_{ti}, X^E_{ti}) - X^E_{ti})\Delta t, \quad (1)$$

where X^E_{ti} is associated with a negative emotion of agent i at time t. Note that a value of 0 or 1 for X^E_{ti} respectively means a low level or a high level of negative emotion. Here, α'^E_{ti} denotes the pace of the dynamic emotional change; $f(\hat{X}^E_{ti}, X^E_{ti})$ denotes the level of the effect of the absorption and amplification model on end-user emotion [3], [6]; $\hat{X}^E_{ti}$ denotes the level of the effect of the diffusion of the emotion among consumers and prosumers, the level of cooperation among end-users, and the availability of electricity on an agent's emotions [3]; and α'^E_{ti} is the strength of the connection of consumers/prosumers *i* at time *t* [6]. The latter is expressed as

$$\alpha'^E_{ti} = \frac{\sum_j \alpha^E_{ij} X^E_{tj}}{\sum_j \alpha^E_{ij}}, \quad (2)$$

where α^E_{ij} is the the strength of the connection between two consumers/prosumers *i* and *j*. Here, a value of 1 for α^E_{ij} means a high level of strength connection. In (1), $f(\hat{X}^E_{ti}, X^E_{ti})$ is defined as

$$f(\hat{X}^E_{ti}, X^E_{ti}) = \eta^E \underbrace{[X^O_{ti}\overbrace{(1-(1-X^E_{ti})(1-\hat{X}^E_{ti}))}^{upwards\ spirals} + (1-X^O_{ti})\overbrace{(\hat{X}^E_{ti}X^E_{ti})}^{downward\ spirals}]}_{amplification\ model} + (1-\eta^E)\underbrace{\hat{X}^E_{ti}}_{absorption\ model}, \quad (3)$$

where X^O_{ti} denotes how optimistic an agent is. A value of 1 for X^O_{ti} indicates that the consumer/prosumer is optimistic. The first grouping of terms represents the amplification model, while the last term denotes the absorption model. The amplification model is developed based on Fredrickson's broaden-and-build theory, including upwards and downwards spirals [6]. If there is no external disaster within the group, the absorption model based on a bottom-up architecture may be used. On the other hand, when a sudden occurrence happens, the amplification model should also be employed. The combination of both models is appropriate for disaster resilience and planning. In (3), $\hat{X}^E_{ti}$ is expressed as

$$\hat{X}^E_{ti} = w^{EE}\underbrace{(\frac{\sum_j \alpha^E_{tij} X^E_{tj}}{\sum_j \alpha^E_{tij}})}_{Social\ diffusion} + W^{CE}\underbrace{(1-X^C_{ti})}_{Cooperation} + W^{PE}\underbrace{(1-X^P_{ti})}_{Physical\ health} + W^{QE}\underbrace{(1-Q^e_{ti})}_{Power\ systems}. \quad (4)$$

End-users' emotions depend on the levels of emotion of other people (social contagion), cooperation ,X^C_{ti}, , physical health,X^P_{ti}, , and accessibility to electricity, Q^e_{ti}, [3].

2) Dynamical Physical Health Modeling: The dynamical change of the physical health, $\Delta(X^P_{ti})$, is obtained with

$$\Delta(X^P_{ti}) = \eta^P(\frac{1}{1+e^{-\sigma^P(X^E_{ti}-\phi^E)}}) ((1-X^E_{ti})(1-(1-Q^e_{ti}))Z_{ti}) - P_{ti})\Delta t. \quad (5)$$

where η^P is the physical health dynamical coefficient. Physical health is affected by the level of mental health [3], [7], the hazard injury factor, i.e., Z_{ti}, and accessibility to electricity, Q^e_{ti}, [3]. A value of 1 for X^P_{ti} means the consumer/prosumer is at a high level of physical health.

3) Well-Being Functionality: Social well-being, S_t, consists of the physical and mental well-being of the community. It is found from

$$S_t = \frac{1}{N}(\beta^E \underbrace{\sum_i(1-X^E_{ti})}_{Community\ Mental\ health} + (1-\beta^E)\underbrace{\sum_i X^P_{ti}}_{Community\ Physical\ health}). \quad (6)$$

where N consists of the total number of power system end-users and β^M is a coefficient of mental health.

B. Community Capital Functionality

We use cooperation as a metric of community capital. The dynamical change of the level of cooperation of consumers and prosumers, $\Delta(X^C_{ti})$, is given by

$$\Delta(X^C_{ti}) = \eta^C(\frac{1}{1+e^{-\sigma^C(X^E_{ti}-\phi^E)}})X^P_{ti}(X^O_{ti}X^E_{ti} - X^C_{ti})\Delta t. \quad (7)$$

where ϕ^E is the fear threshold. The level of cooperation is a function of the positive or negative emotional level based on the narrowing hypothesis of Fredrickson's broaden-and-build theory [8]. Indeed, the level of cooperation depends on the emotional intensity , the physical health , and the level of optimism of the end-users [3]. A value of 1 for X^C_{ti} means a high level of cooperation the consumer/prosumer has.

C. Role of Distributed Energy Resources

There are two main sources of electricity that supply the consumers, i.e., utilities and distributed energy resources (DERs). Utilities supply the demand as the primary source. However, during disasters some communities may lose the electricity supplied by utilities. In this situation, depending on their level of cooperation, the end-users who own DERs, namely, the prosumers, may wish to share their electricity with the consumers without electricity. By doing so, they contribute to the improvement of the degraded community's functionality during a disaster.

1) Sharing Electricity Produced by DERs: The dynamical change of accessibility to the electricity generated by DERs, $\Delta(Q_{ti}^{DER})$, is expressed as

$$\Delta(Q_{ti}^{DER}) = \alpha_{ti}^{DER}(\alpha_{ti}^{DER} - Q_{ti}^{DER})\Delta t, \qquad (8)$$

A value of 1 for Q_{ti}^{DER} means the consumer/prosumer uses the whole DERs' capacity to supply its demand. The normalized amount of electricity shared with agent *i*, α_{ti}^{DER}, is given by

$$\alpha_{ti}^{DER} = \frac{\sum_j \alpha_{ij}^{E} X_{tj}^{C} Q_{tj}^{DER}}{\sum_j \alpha_{ij}^{E} X_{tj}^{C}}. \qquad (9)$$

2) Available Electricity During a Disaster: During a disaster, the available electricity, Q_{ti}^{e}, is the total electricity supplied from utilities and prosumers, which is written as

$$Q_{ti}^{e} = W_i^{DER} \underbrace{Q_{ti}^{DER}}_{Distributed\ energy\ resources} + (1 - W_i^{DER}) \underbrace{Q_{ti}^{U}}_{Utilities}. \qquad (10)$$

where Q_{ti}^{U} is the electricity generated by the utilities. a Value of 1 for Q_{ti}^{U} means that the utilities use the whole of their capacities to supply the consumers/prosumers' demand. In addition, W_{DER} is The fraction of the total amount of electricity consumed by an end-user that comes from DERs

D. Power System and Community Functionality

During an emergency and in an extremis state as well as during a disaster, an active demand-side management system and DERs responding to frequency changes contribute to the improvement of the degraded power system functionality.

This paper considers the average of the well-being of the community, the community capital, and power system functionality as community functionality. Hence, community functionality, CF_t, is expressed as

$$CF_t = \frac{1}{3}\Big(\underbrace{S_t}_{Social\ well-being} + \underbrace{\frac{1}{N}\sum_i X_{ti}^{C}}_{Community\ capital} + \underbrace{\frac{1}{N}\sum_i Q_{ti}^{e}}_{Power\ system\ functionality}\Big) \qquad (11)$$

V. Community of Nine End-Users Facing a Hurricane

We validated our model with the case study I of [9]. We develop an artificial society by considering the dependence between well-being, community capital, and power systems. In this section, we implement the proposed model for a simple case study, i.e., a community of nine end-users facing a hurricane. This community is divided into 3 groups, each of them includes 3 end-users. We assume that each group's end-users have no contact with the end-users of another group. Note that in practice, an end-user may consist of many consumers and prosumers. In this case study, we consider X_{ti}^{E}, X_{ti}^{C}, X_{ti}^{O} and Q_{ti}^{e} be equal to 0.5. The supply of electricity for each agent is estimated to be 2 MWh. The power system supplies 0.8 MWh while the DERs, e.g., photovoltaics and wind turbines, supply 0.2 MWh. Other variables are equal to 1.

Figure 1 displays multi-dimensional outputs of the case study for two different scenarios: 1) when the level of cooperation is 0.9, and 2) when the initial level of cooperation is 0.2. We display the well-being, community capital, and power system functionality during a disaster. The disaster occurs at time 0. When the cooperation level is high, the prosumers share their electricity sooner than when the level of cooperation is low. Therefore, having electricity and a high level of cooperation increases the community's well-being and community capital. The well-being and the community capital resilience increase by 9% and 13%, respectively. In addition, the community experiences a higher level of community functionality and community resilience. Note that various types of functionalities can cover each others' drawbacks when a disaster happens. According to this figure, since the cooperation is high at the beginning stages, the mental well-being initially increases but then decreases with the continuation of the disaster. To sum up, the more community capital, the more the power system is resilient.

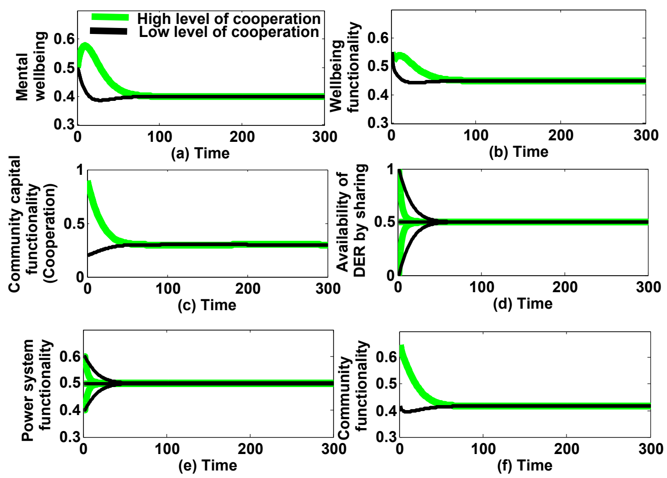

Fig. 1. Dynamical change of the mental well-being, well-being functionality, community capital functionality, the availability of electricity from the DERs, the power system functionality from the end-users' point of view, and the community functionality for two different scenarios, i.e., a high level of cooperation and a low level of cooperation. the disaster happens at time 0. A high level of cooperation between the consumers and the prosumers increases community functionality and resilience.

VI. Society of Six Separate Communities

This case study demonstrates the impact of diversified populations and power system functionality on community functionality and the resilience of the different communities. Case study 2 includes a society with six separate communities. Community 1 includes 150 end-users. X_{ti}^{E} and X_{ti}^{P} follow the Gaussian distribution $N(0.98, 0.02^2)$ and $N(0.5, 0.1^2)$, respectively. The electricity supplied from the utility is wholly disconnected in this community. Community 2 includes 250 end-users. X_{ti}^{E} follows the Gaussian distribution $N(0.1, 0.1^2)$. Communities 1 and 2 are extremely close-knit. Hence, the strength connection between the two communities follows the Gaussian distribution $N(0.9, 0.1^2)$. Communities 3, 4, 5, and 6 include 135, 450, 500, and 120 end-users, respectively. For these communities, X_{ti}^{E} follows the Gaussian distribution $N(0.1, 0.1^2)$. (X_{ti}^{P}), and (X_{ti}^{C}) for all communities follow the Gaussian distribution $N(0.98, 0.02^2)$ and $N(0.5, 0.1^2)$, respectively. Additionally, there is no link between other communities. The intra-connection strengths of all communities follow the Gaussian distribution $N(0.9, 0.1^2)$.

Figure 2 provides the multidimensional output-oriented measure of community resilience for the six communities. Community resilience is conditioned on the basis of the well-being resilience, the power system resilience, and the community capital resilience. Since Communities 1 and 2 are close to each other, Community 2 supplies electricity to cover some parts of the electricity outage of Community 1. Hence, power system functionality and resilience in Community 1 increases. The power system resilience of these six communities are equal to 0.14, 0.87, 0.96, 0.96, 0.96, and 0.96, respectively. In addition, because of the support provided by Community 2 to Community 1, the mental well-being of the latter increases. That increase lasts as long as the socio-infrastructure capacity of Community 2 allows it to provide that support. On the other hand, because Community 2 provides mental and electric support to Community 1, its well-being decreases. Understandably, the physical well-being of Community 2 does not change since the disaster happens in Community 1. The well-being resilience of these six communities is equal to 0.28, 0.73, 0.95, 0.95, 0.95, and 0.95, respectively. The community capital in both Communities 1 and 2 decreases over time. Community 2 experiences a higher decrease in community capital because it always provides service and support to Community 1. The community capital resilience of these six communities is equal to 0.41, 0.31, 0.49, 0.49, 0.49, and 0.49, respectively.

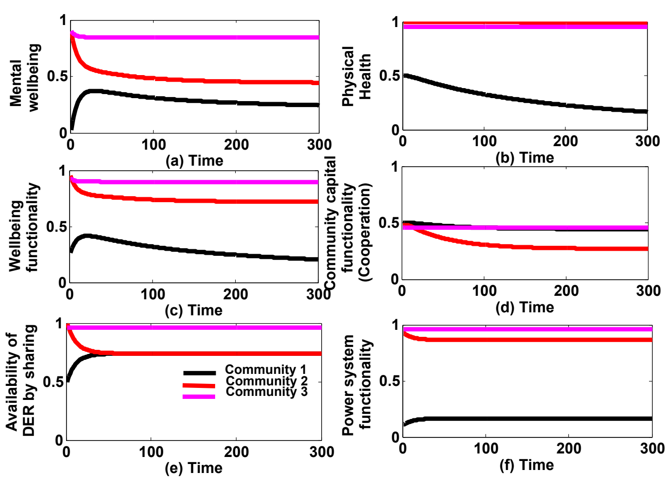

Fig. 2. Dynamical change of the mental well-being, physical well-being, well-being functionality, community capital functionality, the availability of electricity from the DERs, and the power system functionality for the communities 1, 2, and 3. The disaster in Community 1 is very severe so that community 1 faces an outage of electricity.

Community 1 experiences a lower level of losses because of the support of Community 2. In other words, if Community 2 does not support Community 1, the losses in Community 1 increase. The community resilience of these six communities is equal to 0.29, 0.63, 0.82, 0.82, 0.82, and 0.82, respectively.

Figure 3 presents the resilience curve related to Community 1 for combinations of the average losses and recovery time. As is clear, there is a trade-off between average losses and recovery time. To sum up, the disaster-prone community can increase its power system and community resilience by receiving support from other communities.

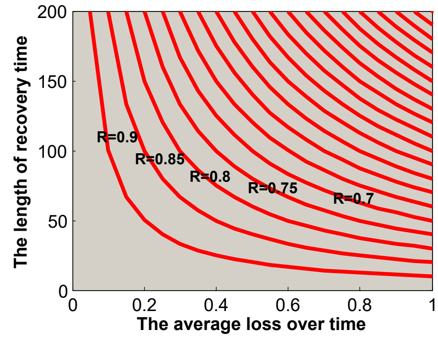

Fig. 3. Resilience curves for the various combinations of the recovery time and average losses

VII. Conclusions

In this paper, we model the complex collective behavior of consumers and prosumers during a disaster to study power system and community resilience. The proposed stochastic, multi-agent-based model in this paper is useful for emergent processes and for finding new hypotheses that can be tested in real-world scenarios. It is assumed that some of the end-users have distributed energy resources (DERs) because of the importance of on-site generation on power system and community resilience. We considered the interdependence between community well-being, community capital, and power system functionality by developing an artificial society based on neuroscience and social science theories. Although this paper is an essential forward step in modeling complex collective behavior for resiliency planning, some additional ideas and challenges need to be considered in future work. For example, it has been suggested to specify the critical electrical loads in each society to enhance community resilience. Supplying critical loads during a disaster is of grave importance. Consequently, there is a need to distinguish among various kinds of loads in this model.

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January 18, 2021

Thank you for the thorough review of the articles entitled "Multi-Dimensional Output-Oriented Power System Resilience based on Degraded Functionality". Your review has been of great help for us to understand the weak points of this paper as well as to spot other minor mistakes, and has resulted in an enhanced version of the original paper. The authors wish to thank the reviewers for their in-depth comments. Restructuring the manuscript allowed for the context to be enhanced accordingly. The response to each reviewer is given per his/her numbering or using key-words from his/her comments. All major and minor updates (most of them are referred to in the following response) are highlighted in the revised manuscript. We wish to thank Reviewers for their positive and productive contribution to the improvement of the presentation and content of our manuscript. Authors are glad to note that the reviewer appreciates the work and finds the topic important and interesting. Thank you for your valuable comments. We have dedicated our time to systematically address each comment raised by the reviewers. We believe that each comment was instrumental in drastically upgrading the quality of the paper and hope that the manuscript in its current state has answered all the comments raised by the reviewers in the best possible way.

- **Reviewer #1**

  > *The topic of this paper is timely and demonstrated a good incorporation of social science concepts. Overall, the authors did a good job explaining the social science terminology used, and was an interesting and novel application of artificial societies. There are two suggestions for revision:*

  Authors are glad to note that the reviewer appreciates the work.

  - ***C#1:*** *Explain why communities 3-6 were included in the second case study, or remove them all together, as they didn't seem to contribute much to the results and made figure 2 too busy to view the interactions between communities 1 and 2 properly.*

    Thanks for the reviewers comment. In the revised version of the paper, we only consider community 3. We remove communities 4-6.

  - ***C#2:*** *Both case studies were taken from other papers. It would be beneficial to include a short description of what the specific impact on the power system would be for the disaster used in each case.*

    Thanks for the reviewers comment. We added a short description of the result at the end of each case study.

    Case study 1:

    In the first case study, when the cooperation level is high, the prosumers share their electricity sooner than when the level of cooperation is low. Hence, the power system functionality increases, leading to an increase in power system resilience. In other words, the more community capital, the more power system resilience.

    Case study 2:

When a community (C_B) based on its the socio-infrastructure capacity support other Community facing disaster (C_A), it increases the power system resilience of C_A. In addition, it increases Community capital, the wellbeing of C_A, leading to a further increase in power system and community resilience of C_A.

- **Reviewer #2**

Although the model presented in section IV could be of interest, it is currently not understandable:

Authors would like to thank the reviewer for the very helpful comments and suggestions. In this paper, we proposed a multi-dimensional output-oriented method to measure resilience. In the proposed model, the effect of the social community on the power system resilience is considered. Currently the role of social community on power system resilience and effect of power system resilience on community resilience are not considered. Our work intends to address this gap in the research and stimulate others to follow up this research. Specifically, in our simulations we assumed that some of the agents have distributed energy resources because of the importance of on-site generation on community resilience. This model accounts for the fact that the social well-being of a community is influenced by both the mental and the physical well-being of its individuals. we also considered critical psychological features such as fear, anxiety and cooperation, experience during a disaster. Each of these features for a given community were assumed to be based on normal distribution. The most important results inferred from the two case studies are as follows. When the level of cooperation is increased, the agents show a lower level of fear. Furthermore, they share their electricity sooner than when they have a low level of cooperation. In addition, the positive features of the agents may rectify their behavioral drawbacks. Consequently, we may say that the society has a different amount of power system and community resilience under different disasters.

The strength of our work comes from the computational social science approach, where we create artificial societies from the bottom up, to gain more understanding of a collective behavior, through structured simulations. Meaning, starting the modeling process from the scientific evidence in the literature, creating individual agent rules, representing the relations found in the literature. Through the agent interactions in the model, our simulation results show emergent patterns - collective behaviors - that cannot be predicted from the individual agent rules. These emergent effects give us understanding of which communities and power systems are more or less vulnerable during disasters, based on which combinations of factors. They help us understand the power system and community resilience better and help us to derive new hypotheses that can be tested in real-world scenarios. Another strength is that the model provides the option of modeling many different effects, which would be costly and difficult to carry out with only experiments or surveys.

- **C#4:** *the authors introduce a lot of quantities without defining properly which ones are parameters and which ones are variables, notations are not always consistent, some quantities are not explained (e.g. phi*$^{\mathrm{E}}$, $\mathrm{eta}^{\mathrm{P}}$, etc.).

  We went through the text and checked that. In the revised version, we defined the potential parameters which were not defined in the previous version of the paper. η^P *is the physical health dynamical coefficient.* ϕ^E *is the emotion threshold.*

- **C#5:** *Furthermore, the use of the model is strange: when a set of differential equations is used to simulate the response of a system to a disturbance, the steady state before the disturbance is* *usually first computed and then something is changed in the differential equations to simulate the disturbance. In this case, nothing changes, the authors claim that the disaster occurs at time 0, but as it is not in a steady state before, I am not sure what they compute.*

Thanks for the reviewers comment. We predict the dynamic change of the power system's functionality and social Community when a disaster happens. Although the disturbance in the system is a disaster, various features are affected and can be considered as a disturbance of dynamic systems. In other words, it depends on how you define the disaster. We can also have both static and dynamic disturbance during a disaster. Here, we face a dynamic system consist of both social behavior and power systems. This is a little different from power system dynamics. Different people have their own behavior and social features specific to various types of disaster. End users can be categorized into communities based on their own profiles, e.g., nationality, culture, or spatial region. [1].

[1] C. Gao and J. Liu, "Uncovering spatiotemporal characteristics of human online behaviors during extreme events," PLoS ONE, vol. 10, no. 10, 2015, Art. no. e0138673.

Such groups have different social initial values and responses to the same events. South Asia is more sensitive to the tsunami (because of the tragic memory of the Indian Ocean tsunami 2004) and the nuclear crisis (because of the geographical influences of potential radioactive leaks). Hence, the initial human behavior for the same community is different for various types of disasters. According to each type of disaster and spatial-temporal situation, we should set them. Please see the following papers for more information:

(2) Valinejad, J. and Mili, L., 2020. Community Resilience Optimization Subject to Power Flow Constraints in Cyber-Physical-Social Systems in Power Engineering. arXiv preprint arXiv:2004.00772.
(3) P. Ye, S. Wang, and F.-Y. Wang, "A general cognitive architecture for agent-based modeling in artificial societies," IEEE Transactions on Computational Social Systems, vol. 5, no. 1, pp. 176–185, 2017.
(4) T. Bosse, M. Hoogendoorn, M. C. A. Klein, J. Treur, N. van der Wal, and A. van Wissen, "Modelling collective decision making in groups and crowds: Integrating social contagion and interacting emotions, beliefs and intentions," Autonomous Agents and Multi-Agent Systems, vol. 27, no. 1, pp. 52–84, 2013.
(5) S. Barsade and D. E. Gibson, "Group emotion: A view from top and bottom," Research on Managing Groups and Teams, vol. 1, pp. 81–102, 1998.
(6) T. Bosse, R. Duel, Z. A. Memon1, J. Treur, and N. van der Wal1, "A multi-agent model for mutual absorption of emotions," International Conference on Principles and Practice of Multi-Agent Systems, pp. 48– 67, 2009.

In this paper, our focus is the only disaster. As we showed that during a disaster, that various types of functionalities can cover each others' drawbacks when a disaster happens.
The aim of the paper is :
1) Conceptualizing the problem and provide a discussion on the effect of community resilience on power system resilience and vice versa
2) Predict and measuring the functionality and resilience of both social Community and power system.
3) In the first case study, when the cooperation level is high, the prosumers share their electricity sooner than when the level of cooperation is low. Hence, the power system functionality

increases, leading to an increase in power system resilience. In other words, the more community capital, the more power system resilience.
4) When a community (C_B) based on its the socio-infrastructure capacity support other Community facing disaster (C_A), it increases the power system resilience of C_A. In addition, it increases Community capital, the wellbeing of C_A, leading to a further increase in power system and community resilience.

– **C#6:** *Results in figure 1 show that the final state of the system does not depend on the initialization of the differential equations (for the two cases studied).*

Thanks for the reviewers comment. This statement is not correct. For figure 2, this is clear that the final state of the system for community 1 and 3 are entirely different. The reason is the features of these communities. Please see the description of case study 2 in the paper. Not only does the final state of the system depend on the initial value of cooperation, but also it depends on the initial value and the effect of dynamic change of other features. In figure 1, only the initial value of the level of cooperation is different. The initial value and social behavior of all other features are the same. The reason is to see the effect of only cooperation on dynamic change (not for the general conclusion or any other conclusion). When the cooperation level is high, the prosumers share their electricity sooner than when the level of cooperation is low. Here, time is important. When the system responses sooner, the average functionality and hence resilience increase. Having electricity and a high level of cooperation increases the community's well-being and community capital—the well-being and the community capital resilience increase by 9% and 13%, respectively. In addition, the community experiences a higher level of community functionality and community resilience.

– **C#7:** *This unclarity can be due to the fact that the paper is badly balanced: the first 2 pages (over a total of 5) are devoted to general considerations.*
Thanks for the reviewer's comment. We devoted the two first pages to conceptualizing the problem, which was of high importance for us. There is a need for sufficient explanation and conceptualizing the dependence of power system resilience and community resilience, definitions, and disaster losses that the literature lacks.

– **C#8:** *The authors are thus encouraged to clarify their model, the use of the model and to demonstrate the interest of their model.*

We understand the reviewer's concern. For understanding the equations better, please see the following reference.

(1) Valinejad, J. and Mili, L., 2020. Community Resilience Optimization Subject to Power Flow Constraints in Cyber-Physical-Social Systems in Power Engineering. arXiv preprint arXiv:2004.00772.

In addition, the following references are useful:

(1) L. Mili, K. Triantis, and A. Greer, "Integrating community resilience in power system planning," Power Engineering: Advances and Challenges Part B: Electrical Power, 2018.
(2) P. Ye, S. Wang, and F.-Y. Wang, "A general cognitive architecture for agent-based modeling in artificial societies," IEEE Transactions on Computational Social Systems, vol. 5, no. 1, pp. 176–185, 2017.
(3) T. Bosse, M. Hoogendoorn, M. C. A. Klein, J. Treur, N. van der Wal, and A. van Wissen,

"Modelling collective decision making in groups and crowds: Integrating social contagion and interacting emotions, beliefs and intentions," Autonomous Agents and Multi-Agent Systems, vol. 27, no. 1, pp. 52–84, 2013.
(4) B. L. Fredrickson and T. Joiner, "Positive emotions trigger upward spirals toward emotional well-being," American psychological society, vol. 13, no. 2, 2002.
(5) S. Barsade and D. E. Gibson, "Group emotion: A view from top and bottom," Research on Managing Groups and Teams, vol. 1, pp. 81–102, 1998.
(6) T. Bosse, R. Duel, Z. A. Memon1, J. Treur, and N. van der Wal1, "A multi-agent model for mutual absorption of emotions," International Conference on Principles and Practice of Multi-Agent Systems, pp. 48– 67, 2009.
(7) S. Tan, Y. Wang, Y. Chen, and Z. Wang, "Evolutionary dynamics of collective behavior selection and drift: Flocking, collapse, and oscillation," IEEE Transactions on Cybernetics, vol. 47, no. 7, pp. 1694–1705, July 2017.

Discussion on the social science theories and the basics are out of the scope of this paper. In this paper, our focus is on our contribution, the concept of resilience, the effect of social community on the power system, and vice versa. The current model has given us more understanding of the power system resilience and community resilience. It is essential to predict the resilience to a disaster of various communities with different features and see how one community is prepared to face an upcoming one.

- **Reviewer #3**

  This paper address an important topic - power system resilience. It models the complex collective behavior of consumers and prosumers. This reviewer has a few comments:

  Authors are glad to note that the reviewer appreciates the work.

  - ***C#9:*** *the authors need to further elaborate the meaning of each index, e.g., how much it is different for power system functionality being 0.4 and 0.5.*

    Thanks for the reviewers comment. All of the features takes values within the interval [0 1]. In the revised version of the paper, we added a description of the meaning of the value of each variable. For the power system, all of the variables are in per-unit. We assume that in scenario 1, utilities can supply 40 MW demand. We assume that in scenario 2, utilities can supply 50 MW demand. We consider 100 MW as the base value. Hence, the per-unit MW generated by utilities in scenarios 1 and 2 are equal to 0.4 and 0.5. The difference between 0.4 and 0.5 can be different for various power systems with various features. Please see the table below as well:
  - ***C#10:*** *the typos need to be corrected, e.g., in the paragraph following equation (1), subscript 'ti' is not written properly.*

    Thanks for the reviewers comment. According to the reviewer's comment, we went through the text and modified writing mistakes.

Table 1: Definition of the mental features and the meaning of their numerical values. These features are assumed to follow a Gaussian distribution with a mean taking a value in the interval [0 1].

Characteristic	definition	Value (between [0,1])
Mental health	negative feelings, fear, and anxiety as indexes	0 means the consumers/prosumers does not have any fear, anxiety and depression, 1 means the highest level of fear,and anxiety
α^{E}_{ti}	the strength of the connection of consumers/prosumers	0 means there is no connection/communication between two agents, 1 means the highest level of connection/communication exist
Cooperation	Willingness to work unitedly on a particular number of task and sharing resources, information, and experience that aimed to common goal and objective	0 means the consumers/prosumers does not have any willingness to cooperate, 1 means the highest level of cooperation the consumers/prosumers has
Personal characteristic	Level of being optimistic during a disaster	0 means the consumers/prosumers is pessimistic, 1 means the consumers/prosumers is optimistic
Physical health	The level of physical health of an individual	0 means the consumers/prosumers is at the lowest level of physical health, 1 means the consumers/prosumers is at the highest level of physical health
Q^{U}_{ti}	The fraction of electricity that is available from utilities to a costumer	0 means utilities do not supply the demand of the consumers/prosumers , 1 means utilities use the whole of their capacities to supply the consumers/prosumers' demand
Q^{DER}_{ti}	The fraction of electricity that is available from DERs to an individual	0 means the consumers/prosumers do not have access to any type of DERs , 1 means a consumer/prosumer uses the whole its DERs' capacity to supply its demand.
W_{DER}	The fraction of the total amount of electricity consumed by an individual that comes from DERs	0 means that only utilities supply the whole demand of the consumers/prosumers, 1 means only DERs supply the whole demand of the consumers/prosumers