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.

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

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[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.

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, $\Delta(X_{ti}^{E})$, is obtained from

$$\Delta(X_{ti}^{E}) = \alpha_{ti}^{\prime E}(f(\hat{X}_{ti}^{E}, X_{ti}^{E}) - X_{ti}^{E})\Delta t, \quad (1)$$

where X_{ti}^{E} is associated with a negative emotion of agent i at time t. Note that a value of 0 or 1 for X_{ti}^{E} respectively means a low level or a high level of negative emotion. Here, $\alpha_{ti}^{\prime E}$ denotes the pace of the dynamic emotional change; $f(\hat{X}_{ti}^{E}, X_{ti}^{E})$ denotes the level of the effect of the absorption and amplification model on end-user emotion [3], [6]; $\hat{X}_{ti}^{E}$ 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 $\alpha_{ti}^{\prime E}$ is the strength of the connection of consumers/prosumers *i* at time *t* [6]. The latter is expressed as

$$\alpha_{ti}^{\prime E} = \frac{\sum_j \alpha_{ij}^{E} X_{tj}^{E}}{\sum_j \alpha_{ij}^{E}}, \quad (2)$$

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

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

where X_{ti}^{O} denotes how optimistic an agent is. A value of 1 for X_{ti}^{O} 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), $\hat{X}_{ti}^{E}$ is expressed as

$$\hat{X}_{ti}^{E} = w^{EE}\underbrace{(\frac{\sum_j \alpha_{tij}^{E} X_{tj}^{E}}{\sum_j \alpha_{tij}^{E}})}_{Social\ diffusion} + W^{CE}\underbrace{(1-X_{ti}^{C})}_{Cooperation} + W^{PE}\underbrace{(1-X_{ti}^{P})}_{Physical\ health} + W^{QE}\underbrace{(1-Q_{ti}^{e})}_{Power\ systems}. \quad (4)$$

End-users' emotions depend on the levels of emotion of other people (social contagion), cooperation ,X_{ti}^{C}, , physical health,X_{ti}^{P}, , and accessibility to electricity, Q_{ti}^{e}, [3].

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

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

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_{ti}^{e}, [3]. A value of 1 for X_{ti}^{P} 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

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

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, $\Delta(X_{ti}^{C})$, is given by

$$\Delta(X_{ti}^{C}) = \eta^{C}(\frac{1}{1+e^{-\sigma^{C}(X_{ti}^{E}-\phi^{E})}})X_{ti}^{P}(X_{ti}^{O}X_{ti}^{E} - X_{ti}^{C})\Delta t. \quad (7)$$

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_{ti}^{C} 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

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

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

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

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

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

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

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

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.

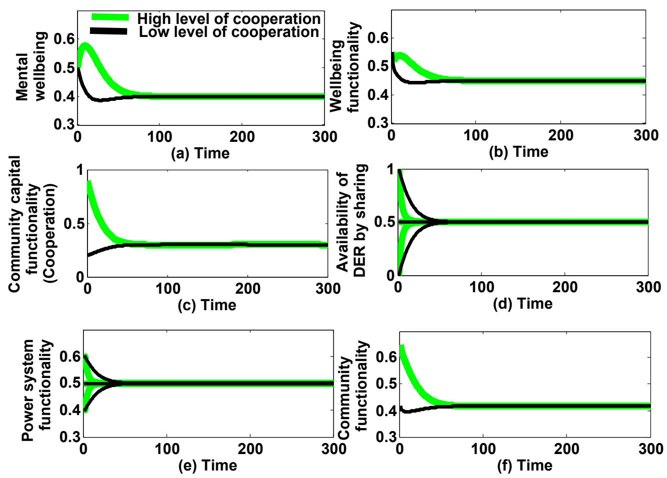

Fig. 1. Dynamical change of the mental well-being, well-being functionality, community capital functionality, the availability of electricity from the DERs, the power system functionality from the end-users' point of view, and the community functionality for two different scenarios, i.e., a high level 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.

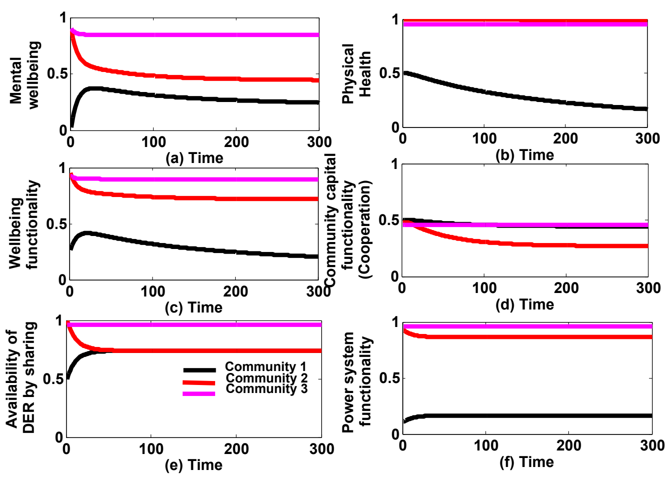

Fig. 2. Dynamical change of the mental well-being, physical well-being, well-being functionality, community capital functionality, the availability of electricity from the DERs, and the power system functionality for the communities 1, 2, and 3. The disaster in Community 1 is very severe so that community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

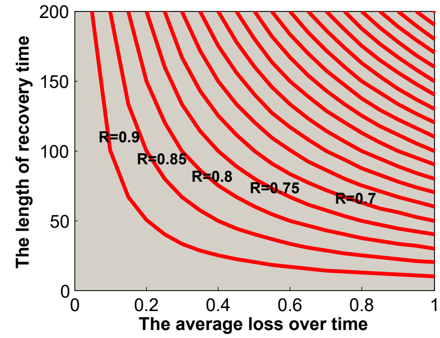

Fig. 3. Resilience curves for the various combinations of the recovery time and average losses

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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