Bio-Inspired Design for Robust Power Networks

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***Abstract*—Extreme events continue to show that existing power grid configurations can be vulnerable to disturbances. Drawing inspiration from naturally robust biological ecosystems presents a potential source of robust design guidelines for modern power grids. The robust network structure of ecosystems is partially derived from a unique balance between pathway efficiency and redundancy. Structural and basic-functional similarities support the application of ecological properties and analysis techniques to power grid design. The work presented here quantitatively investigates the level of similarity between ecosystems and power grids by applying ecological network metrics to a basic, realistic hypothetical 5-bus power system. A comparison between the power grid's performance and average ecosystem performance substantiates the use of the ecological robustness metric for the development of a bio-inspired power grid optimization model. The bio-inspired optimization model re-configures the five bus grid to mimic ecosystem robustness. The results demonstrate the potential of ecosystems to provide new robust design principles for power grids.**

I. INTRODUCTION

Electric power supports everything from the economy to health care, to individual daily activities. Society's widespread dependence on electricity necessitates a robust power network design, one that can effectively supply required power to consumers under a variety of disruption scenarios [1], [2]. Components can be affected, for example, by natural disasters, cyber attacks, physical attacks and internal failures [3]. The costs associated with the resulting interruptions and blackouts can be significant [4]. Quantifying and improving the resilience of the grid is an active research area, with numerous investigations in the last decade. Robustness and redundancy constitute two of the four important features of a resilient system ($robustness$, $redundancy$, $resourcefulness$ and $rapidity$), according to a general framework created by the Multidisciplinary and National Center for Earthquake Engineering Research [5]. How best to quantify and take advantage of redundancy and flexibility in power systems is neither well understood nor has been sufficiently investigated. Grid flexibility and robustness can be addressed in two major ways: short-term *operation* of the grid and long-term grid *design*. Various studies have focused on operational flexibility of the grid to enhance resilience [6]–[8]. These studies address grid flexibility in terms of matching generation capacity and demand to accommodate renewable energy integration. Panteli and Mancarella [5] additionally point out that constructing additional transmission lines can help increase both transmission network capacity and improve operational flexibility. Although the initial investment for redundant lines can be high, the effectiveness of planned redundancy for enhancing resilience has been rated higher than smart/operational measures alone [5]. There also exists some consensus that increasing robustness is important in the creation of a more resilient grid [9]. However, a clear distinction does not exist between the definitions of the terms: resilience, reliability and robustness. The goal of the work presented here is to provide new mechanisms for understanding and achieving the long term robust design of the grid through *increasing system flexibility and redundancy* using biological food webs as inspiration, contributing towards the larger goal of a more resilient grid.

Biological food webs have evolved over millions of years to manage and survive extreme events. These networks have already inspired the redesign of several organizationally analogous human networks: carpet manufacturing networks, water distribution networks, and industrial networks all saw reduced environmental impacts and cost when redesigned to mimic the characteristic structure of food webs [10]–[14]. Similar to these other human networks, the structure of power grids strongly resembles that of food webs, as seen in Figure 1; both are made up of components that exchange, use, and transform energy to meet the needs of the network's actors. A detailed analysis reveals that the quantitative metric $ecosystem\ robustness$ of a dataset of food webs is maximized through a slightly higher preference for flexibility and redundancy over efficiency in interactions [10]. The robustness maximization of these biological networks suggests that they may be a rich source of inspiration for improving power grid design in a way that has not previously been explored.

A biological food web-based approach is proposed here for defining and assessing robustness of power systems. An optimization model is built based on this approach to restructure connections in the grid to maximize $ecosystem\ robustness$ while still satisfying power balance constraints. Robustness is defined here as the ability of a system to survive disturbances, satisfying the needs of consumers despite actors having reduced or total loss of function. The main contributions presented in this paper are (1) the establishment of an analogy between food webs and power systems and (2)

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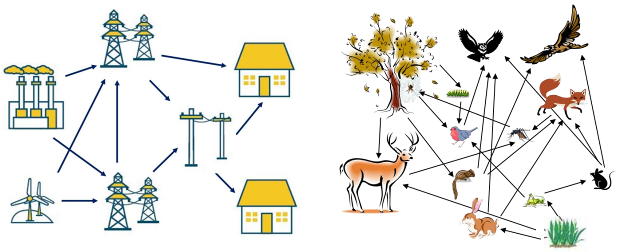


Figure 1. A side-by-side illustration of the structurally similar generic topologies of a power grid (left) and a food web (right), adapted from Layton et al. [13].

the demonstration of a bio-inspired robustness optimization approach for power systems.

II. THE ANALOGY, METHODS AND MODEL

A. *Modeling the Grid as an Ecological Network*

The highly complex interactions of a power system can be modelled after food webs, as a system comprised of prey- and predator-type interactions. Ecological Network Analysis (ENA) is a collection of tools and techniques commonly used by ecologists to analyze ecosystems based on their consumption patterns and interactions [15], [16]. Modeling techniques like input-output modeling, environ analysis, and the ascendency model [16] focus on understanding network characteristics that affect the whole ecosystem functioning. The ascendency model is based on information theory, which emphasizes the role of structure and flow organization on the overall stability and robustness of a system [17]. This model is also applicable to power systems, where the level of organization has significant ramifications on the network's robustness [5], [9].

ENA represents the flows/exchanges between the actors inside and across the chosen system boundaries as a directional graph, or digraph. The actors become nodes and connections between actors are drawn as directed edges. Interactions that cross the self-selected system boundary are broken down into system inputs, useful system exports, and dissipation or non-useful system exports [18]. The power grid actors analogous to species in a food web are taken to be the main grid components: buses, generators, transformers, and consumers. Buses, generators and transformers all perform significant functions in a grid and are therefore treated as actors in ENA: buses aggregate loads, generators provide energy to the system, and transformers bridge loads and generation from low-voltage to high-voltage for efficient energy flow. The power consumers (homes, industries, stores, etc.) are placed outside the system boundary to best represent the $users$ of the useful exported power, mimicking the useful system exports of a food web. The presence and magnitude of interactions between these actors are quantified in two different types of matrices, structural and flow, from where quantitative ENA metrics are calculated to study the structure and functioning of the network.

1) Ecological Flow Matrix: The flow matrix [**T**] is a square $(N+3)$ x $(N+3)$ matrix containing the direction and flow magnitudes of all network interactions [19], where N represents the number of actors in the network. The "extra" three entries in the flow matrix represent the system inputs (first row) and useful and dissipated exports (last two columns). The entries T_{ij} in [**T**] represent the flow magnitude from node i to node j, or from rows (producers or prey) to columns (consumers or predators). Non-zero T_{ij} values represent an interaction and zeros indicate no interaction. The first column ($T_{i,1}$) and the last two rows ($T_{N+2,j}$ and $T_{N+3,j}$) of [**T**], as well as the last two columns of the first row ($T_{1,N+2}$ and $T_{1,N+3}$), are permanently zero as these are impossible interactions in the model: the system inputs cannot output, and the system outputs cannot input.

2) 5-bus test case: PowerWorld Simulator, a power grid modeling and analysis software, provides a number of small training cases that are freely available [20]. These test cases represent realistic grid interactions at a significantly smaller scale than real world power grids. One of these cases, a 5-bus grid, is used here for the application of ENA and the development of a bio-inspired optimization model. The 5-bus case has small but sufficiently representative generation, loads, and connections, making it ideal for demonstrating the analogy and exploring the added connections from the bio-optimization. The 5-bus grid shown in Figure 2 has 2 generators, 5 buses, 1 transformer, and 4 loads.

The corresponding flow matrix [**T**] for the 5-bus grid is shown in Figure 3, with all flow values in units of megawatts (MW). The inter-compartmental exchanges (light-gray in Figure 3) are flows inside the selected system boundary. The boundary was selected such that the loads (consumers) are outside, thus defining their energy consumption as the grid's "useful exports." The medium-gray first row contains inputs to the system from outside the boundary; for the 5-bus power grid these are inputs to the two generators, assuming efficiencies of 90% (448.8MW and 106.6 MW). The medium- and dark-gray last two columns correspond to the energy that leaves each actor in the system that is useful (traveling to consumers, second to last column) and lost (as dissipation to the environment, last column) respectively.

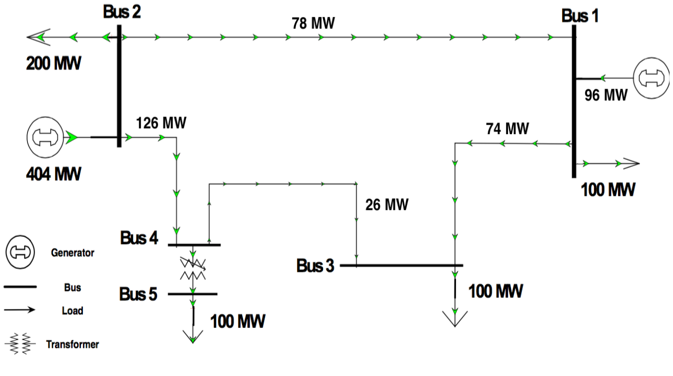
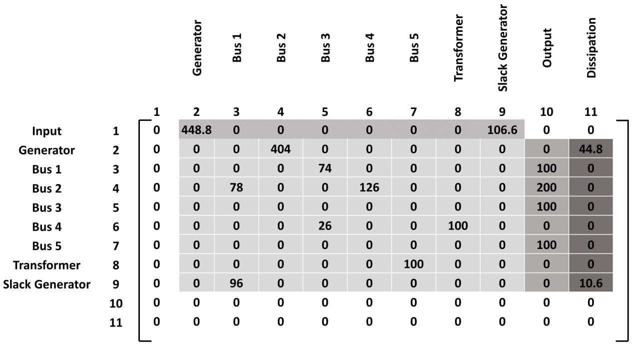


Figure 2. Diagram of the 5-bus power grid [20]. Eight actors are defined as 5 buses, 1 transformer, 2 generators.



			Generator	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Transformer	Slack Generator	Output	Dissipation
		1	2	3	4	5	6	7	8	9	10	11
Input	1	0	448.8	0	0	0	0	0	0	106.6	0	0
Generator	2	0	0	0	404	0	0	0	0	0	0	44.8
Bus 1	3	0	0	0	0	74	0	0	0	0	100	0
Bus 2	4	0	0	78	0	0	126	0	0	0	200	0
Bus 3	5	0	0	0	0	0	0	0	0	0	100	0
Bus 4	6	0	0	0	0	26	0	0	100	0	0	0
Bus 5	7	0	0	0	0	0	0	0	0	0	100	0
Transformer	8	0	0	0	0	0	0	100	0	0	0	0
Slack Generator	9	0	0	96	0	0	0	0	0	0	0	10.6
	10	0	0	0	0	0	0	0	0	0	0	0
	11	0	0	0	0	0	0	0	0	0	0	0

Figure 3. The 5-bus power grid represented as an ecological flow matrix [**T**]. Flow is entered from rows to columns. The first row represents inputs to the grid from outside the system and the last two columns are outputs from inside the system.

The flows T_{ij} from generator/bus/transformer i to j are set here to be the magnitude of the real power (MW), calculated here as P_{ij} in Eq. 1. Real and reactive power flows in power systems, P_{ij} and Q_{ij} respectively, depend on line impedance and state (voltage magnitude V and angle θ) throughout the system:

$$P_{ij} = V_i^2[-G_{ij}] + V_iV_j[G_{ij}cos(\theta_{ij}) + B_{ij}sin(\theta_{ij})] \quad (1)$$

$$Q_{ij} = V_i^2[B_{ij}] + V_iV_j[G_{ij}sin(\theta_{ij}) - B_{ij}cos(\theta_{ij})] \quad (2)$$

where $\mathbf{G}$ is the system conductance matrix, $\mathbf{B}$ is the system susceptance matrix, and $\mathbf{Y_{bus}} = \mathbf{G} + j\mathbf{B}$ is the system admittance matrix [21]. Without loss of generalization and for simplicity of illustration, the power systems in this paper are treated as lossless. This simple, real (non-complex) nodal admittance matrix equation in terms of bus voltage angles and MW injections model is known as "dc" power flow equation [22]. The dc power flows in the system can be obtained by solving the set of linear equations $\mathbf{P} = -\mathbf{B\Theta}$ for bus angles $\mathbf{\Theta}$, where $\mathbf{P}$ is the vector of net real power injections. Traditionally dc models are used in contingency screening, transmission loading relief, transfer analysis, and medium-to-long term transmission planning [22]. The energy produced from generators and consumed by loads is then measured as real power over time. With these power equations in place, ecosystem measures can be applied to describe power flows in a power system to measure and improve the grid's balance between flexibility and efficiency.

The assumptions in this paper's initial application of ENA to power systems are important. A structural analogy is developed in this work between food webs and power grids, and while the general structure of the two networks is similar (components exchanging materials/energy), there are differences in the interaction patterns. Food webs have highly cyclic interactions while power grids tend to be made up of one-directional flows (generators send power to consumers but consumers $usually$ do not send power back to the generators). Biologically-similar interactions do occur within power grids for those components that experience multi-directional flows (buses, transformers). The increasing integration of distributed energy resources to the grid are transitioning power systems towards an even more cyclic state.

ENA is a steady-state network analysis technique, thus requiring steady state assumptions for the energy flows. ENA only considers one flow-type at a time and thus the energy flows are modeled using real power (MW). Two reasons drive this choice: 1) the real power reaching consumers is considered as the essential end goal for power grid networks and 2) redundancy and flexibility can be introduced into the system mostly, or solely, based on the steady-state real power flows (dc power flows). Losses (dissipation) are only included for the generators based on the efficiency assumption of $\eta = 90\%$.

B. Ecological Flow Metrics

The ecological metric **robustness** R was introduced by Ulanowicz et al. to quantitatively measure the potential for food webs to continue functioning in the face of disturbances [17]. Robustness is formulated as a function of two opposing but complementary attributes: unutilized reserve capacity and effective performance. The calculation of R includes **total system throughput** ($TSTp$), **development capacity** (DC), and **ascendency** (ASC). $TSTp$ measures the total units of energy circulated within the system, and is computed by summing *all* directed transactions into, inside, and out of the network, or all elements in [**T**] following Eq. 3 [18]:

$$TSTp = \sum_{i=1}^{N+3}\sum_{j=1}^{N+3} T_{ij} \quad (3)$$

DC (Eq. 4) for a single flow is the dimensionalized maximum amount of uncertainty it can have. Thus for the whole network, it can be calculated by summing individual uncertainties about all events or flows in a system [23].

$$DC = -TSTp\sum_{i=1}^{N+3}\sum_{j=1}^{N+3}\left(\frac{T_{ij}}{TSTp}log\left(\frac{T_{ij}}{TSTp}\right)\right) \quad (4)$$

ASC (Eq. 5) is a dimensionalized aggregate amount of uncertainty accompanying each flow in the network, updated with the knowledge of source and end nodes, and multiplied by the probability that the flow occurs in the first place [24] [25].A higher ASC for two systems of the same size, represents a network that has fewer pathways for flows moving from any one actor to another, resulting in a network with a lower level of uncertainty and a higher efficiency.

$$ASC = -TST_p\sum_{i=1}^{N+3}\sum_{j=1}^{N+3}\left(\frac{T_{ij}}{TSTp}log\left(\frac{T_{ij}TSTp}{T_iT_j}\right)\right) \quad (5)$$

where T_i and T_j are the sum all flows out of i and into j respectively, or $\sum_{m=1}^{N+3} T_{im}$ and $\sum_{n=1}^{N+3} T_{nj}$ respectively.

$$R = -\left(\frac{ASC}{DC}\right)ln\left(\frac{ASC}{DC}\right) \quad (6)$$

Robustness R is a dimensionless metric that is calculated (Eq. 6) as the product of ASC/DC and the natural logarithm of ASC/DC, multiplied by a scaling factor of -1 to ensure that

R will be a positive value [17]. The ratio ASC/DC is known as the **Degree of System Order** and has a value between zero and one, representing the efficiency (closer to one) or redundancy (closer to zero) in a network's connections. A more efficient or organized network corresponds to a smaller number of options for a unit of flow to travel between any two nodes. A more redundant network will generally have a larger number of connections creating more uncertainty in the next step for a unit of flow at any node. This formulation of R allows the quantification of robustness as a function of pathway redundancy and efficiency. Ecosystem robustness is thus directly related to the long-term survival of a network. Ecosystem robustness is maximized when the ratio is balanced at an *ASC/DC* value of 0.367 or 1/e.

III. BIO-INSPIRED OPTIMIZATION FOR POWER SYSTEMS

The formulation of R appears to be a valuable metric that can be applied to power systems, since pathway efficiency and redundancy can be similarly defined for power networks. The metrics in Section II can be used to assess similarities between food webs and power systems, and design the latter to better mimic the former when it comes to structure and robustness. A bio-inspired power network optimization method is presented to convert a power system model into the ENA representation, calculate these metrics, optimize its robustness and design a new network.

The objective of this optimization procedure is to maximize robustness R as a function of $\mathbf{T}$, where $\mathbf{T}$ is the flow matrix of a power system network that also includes generation and load information. The result of the optimization is a new network design for the same generation and loads to maximize robustness R. The problem is formulated as follows (7a)-(7i):

$$\max_{\mathbf{T}} \ R(\mathbf{T}) \tag{7a}$$

$$s.t: \quad T_{ij} \leq P_{ij}^{max}; \ \ (i,j) \in I \tag{7b}$$

$$\sum_{(i,j)\in I} T_{ij} = \sum_{i\in I} P_{Di} \tag{7c}$$

$$\sum_{j\in I} T_{ij} = \sum_{j\in I} T_{ji} \tag{7d}$$

$$T_{i,i} = 0; \ \ i \in I \tag{7e}$$

$$If \ \ T_{ij} \neq 0 \ \ then \ \ T_{ji} = 0; \ \ (i,j) \in I \tag{7f}$$

$$T_{i,g} = P_{Gi}; \ \ i \in I; \ g \in G \tag{7g}$$

$$T_{i,N+2} = P_{Di}; \ \ i \in I \tag{7h}$$

$$T_{i,N+3} = P_{Gi}(1-\eta); \ \ i \in G \tag{7i}$$

where set I represents all buses, sets G and D denote the original system's generators and loads, N is the total number of actors in the system, and T_{ij} represents the power flow from actor i to j as described in the flow matrix.

The constraints in the optimization problem are to ensure the power flow is within limits as well as power balance between generation and loads:

- Eq.(7b) indicates that, during the optimization process, the elements in flow matrix $\mathbf{T}$ are within corresponding power system transmission lines' maximum capabilities.
- Eq.(7c) ensures the total flow within the flow matrix $\mathbf{T}$ equals the net load in power grids.
- Eq.(7d) ensures the total incoming flow to bus i equals the outgoing flow from bus i.
- Eq.(7e) requires there is no flow within bus i itself.
- Eq.(7f) defines the flow direction as only from one bus to another.
- Eq.(7g) - (7i) keep the input flow, output flow and dissipation equal to corresponding generator outputs, loads and generation losses respectively.

Robustness as a function of the ratio (ASC/DC) is nonlinear, and it can be seen graphically in Figure 5. ASC and DC are also nonlinear with respect to the elements of the flow matrix. Thus, the proposed bio-inspired optimization is a continuous and nonlinear optimization problem. The gradient based method is preferable for this kind of problem, and therefore the optimization model is built in MATLAB 2017a [26] and solved by *fmincon* function. Although *fmincon* in MATLAB solves for local optima, global optimum can be easily found by using the function *GlobalSearch* in parallel, with multiple starting points (random flow matrix entries). The resulting optimized power network designs are tested in PowerWorld Simulator [20] to verify and testify their feasibility and reliability.

IV. RESULTS

The ASC/DC and R values for the 5-bus grid system and the averages for a set of 38 food webs are listed in Table I. The various configurations of the 5-bus system are plotted on the R vs. ASC/DC curve in Fig. 5 alongside a set of food webs for comparison. This curve indicates the level of robustness vs. organizational efficiency in a network's pathways. Ecologists refer to the region at the top of the curve as the *window of vitality*. The food webs congregating here suggests their robustness to disturbances is maximized by the incorporation of redundancy [10]. The original 5-bus system has a less than optimal robustness value of 0.2914 suggesting it has more organizational efficiency and less redundancy. However, the bio-inspired optimization is successful in moving the network towards this peak: the robustness of the 5-bus system improves to 0.3472. The ASC/DC decreases from 0.629 to 0.498. Figure 4 shows the optimal network connections contrasted with the original network connections in the 5-bus system.

Reliability is a primary consideration to examine from a power system perspective, for which a N-1 contingency analysis can be used. The N-1 analysis is a standard used by the North American Electric Reliability Corporation (NERC) for transmission line planning [21]. The N-1 contingency analyses are done here for both the original and the optimized 5-bus grids in PowerWorld Simulator. Since a dc model is used, the contingency analysis only considers real power flows. Four violations in the original 5-bus grid and no violations in the bio-optimized grid configuration were observed, suggesting that the bio-optimized network is more reliable than the original during contingencies.

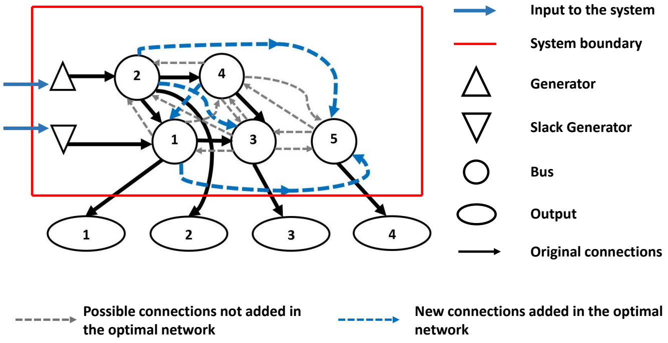


Figure 4. The network of the 5-bus system. The original network is shown in black arrows, possible connections are signified by the dotted arrows in grey and blue. Blue arrows are the new connections added in the optimal network to the original connections for maximizing robustness.

Table I
THE ECOLOGICAL METRICS ASC/DC AND R FOR THE FOOD WEBS (AVERAGES FOR A SET OF 38 FOOD WEBS) AND THE VARIOUS VERSIONS OF THE 5-BUS SYSTEM.

Network	ASC/DC	R
Food webs	0.38	0.36
Original 5-bus	0.629	0.2914
Optimal 5-bus	0.498	0.347
Optimal realized 5-bus	0.53	0.337

V. THE DISCUSSION

Application of the ecological robustness metric R to the 5-bus grid has revealed that organizational efficiency (as measured by an ASC/DC closer to one) is initially higher than redundancy, resulting in a less optimal robustness. The application of and optimization using this robustness metric may allow power system stakeholders to better plan for severe hazard scenarios, similar to ecosystems' ability to withstand disturbances. Mimicking the *window of vitality* robustness is demonstrated in the 5-bus power system by incorporating additional redundancy, bringing the degree of system order closer to that of food webs. The connections in the bio-inspired optimal network contrasted with the connections in the original network can be seen in Fig. 4. The higher robustness value observed in the optimal solution is achieved through added redundant connections. The optimal network adds 4 new connections and achieves a 19% increase in robustness. The new connections added are primarily between different buses. These connections are not necessary during normal operation and thus their presence decreases the organizational efficiency of the network. However, the redundancy added by these new interactions is similar to what is seen in food webs, maximizing robustness. Four new transmission lines are required in the final optimized solution to achieve maximum robustness, and it should be noted that building new transmission lines involves significant capital investment [5]. The exposition in this paper illustrates a proof of concept. Future work will seek to add factors such as transmission line construction cost and outage cost into the optimization.

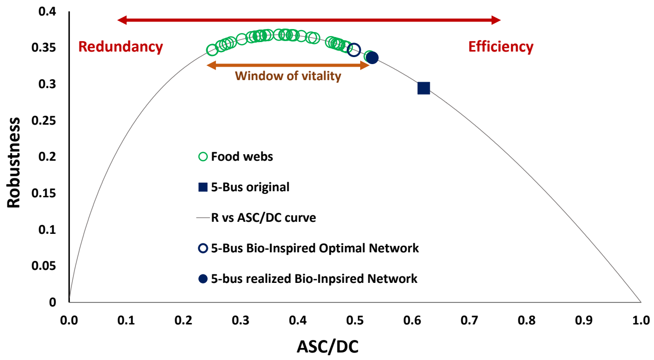


Figure 5. The ecological robustness curve depicting a set of 38 food webs [10], the original and optimized 5-bus system.

The improvement achieved in ecological robustness of the 5-bus system needs to reflect a discernible enhancement in terms of traditional measures of power system performance, to demonstrate the effectiveness of the application of proposed method to power systems. Therefore, N-1 contingency analyses are performed on the original and the bio-inspired optimal network. The N-1 contingency analysis assesses whether the system can withstand the loss of any single major piece of equipment without violating voltage or equipment loading limits while delivering required energy (N stands for number of major components in the system), thus providing a way to compare the original and optimal networks. Although N-1 reliability may not exhaustively manifest all aspects of robustness improvement, it is a good starting point as it is widely adopted and considered the primary reliability standard by NERC. No violations in the N-1 contingency analysis of the bio-inspired optimal network suggests that from the perspective of power system reliability, the bio-inspired design improves power grid reliability.

Reliability, resilience, and robustness are often used interchangeably in describing systems, and the definitions of each for power grids lack a clear consensus in existing literature. Even though they are interrelated, the specific definitions of each should be distinguished to have a clear understanding of what aspect of power system performance they represent and how improving one of them affects the others. Power system *reliability* was historically defined as the ability of a system to supply power to consumers over long periods of time, projecting future performance based on past data [27]. More recently, it has been related to the system's ability to deal with contingencies [21] which is the same as the definition of ecosystem robustness. This makes N-1 reliability analysis a very pertinent assessment of the improved ecological robustness of power systems. Reliability is measured in a variety of ways including with the N-1 reliability, N-1-1 reliability, System Average Interruption Frequency Index (SAIFI), the Customer Average Interruption Duration Index (CAIDI), and the System Average Interruption Duration Index (SAIDI) [28]. *Resilience* under high-impact rare (HR) events has been defined as the ability of the system to (i) gracefully degrade its function by altering its structure in an agile way and (ii) quickly recover once the perturbations cease [5], [29]. This definition renders resilience dependent on dynamics of recovery. Power grid *robustness* currently lacks a well defined measure. It has been vaguely defined based on the spectral properties of the graphs of power grid networks, as the ability of the system to maintain its function when exposed to perturbations [1], [30], [31]. The ecological robustness is different from these metrics in that both network configuration as well as power flow magnitudes are used in defining it. Since resilience includes the planning before and longer-duration recovery in the aftermath of an event, robustness - although a non-dynamic characteristic - is considered a vital feature of a resilient network [5], [32]. Hence the ecological robustness metric, in addition to quantifying power system robustness, has a lot of potential to constitute the redundancy and flexibility aspects in an all-inclusive and generic definition of resilience.

VI. CONCLUSION

Ecology presents an approach to measure and analyze the robustness of power grid systems, and when coupled with the structural properties of biological ecosystems, innovative improvements are suggested as well. The bio-inspired design methodology presented here provides a new mechanism to measure and improve grid robustness by subtly balancing pathway efficiency with redundancy. Although redundancy and reinforcement are known to increase robustness and resilience of engineered systems, the use of redundancy to withstand and respond to threats is not well understood in the context of power systems. The solution presented offers to help bridge that gap by leveraging the success of ecosystems in achieving robustness and sustainability through redundancy. The quantification and use of ecosystem robustness for power systems has the potential to transition to improvements more closely related to grid resilience in the future.

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