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An ecosystem perspective for the design of sustainable power systems

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Abstract

The evolution of power systems has recently seen a strong increase in renewable energy integration. This evolution has resulted in bi-directional pathways with two-way exchanges between the grid and consumers that is beginning to resemble the cyclic organization of food webs. Ecologically-similar cycling of materials and energy in industrial networks has previously been shown to improve network efficiency and reduce costs. The cyclic organization of food webs is proposed here as a design principle to quantify the effectiveness of two-way connections between the grid and consumers. The presence of ecosystem-like cycling in traditional power grid networks is investigated using the ecological metrics cyclicity and cycling index. Two hypothetical 5-bus grids are modified to replicate the two-way exchanges of real power systems with consumer renewable energy generation. The results show a positive correlation between increased structural cycling in grids and reliability improvements measured by the North American Electric Reliability Corporation (NERC) standard N-1 contingency analysis. These results suggest that the metrics cyclicity and cycling index can play a role in quantifying and improving the sustainability of power grids.

1. Introduction

1.1. Power grid sustainability

Sustainability in the context of power grids is not concretely defined, even though it is a priority for grid design and maintenance. Grid sustainability is defined here as the ability of the grid to survive and sustain in the long term with changing consumer needs and generation technologies [1, 2, 3]. The following factors are identified as critical to enhancing the sustainability of power systems [1, 4]:

- Power source (renewable energy vs fossil fuel)
- Structural longevity of grid components
- Resilience of the grid to disturbances
- The efficiency of generation and transmission
- Profitability for the service providers
- Environmental impact of grid components

Grid evolution has seen the addition of components that help continuously monitor loads, balance generation and usage, and improve reliability and resilience. These changes are referred to as “Grid Modernization” [4]. Despite these many improvements, reliability and resilience is still an active area of research for power systems [4]. The U.S. has suffered from several widespread blackouts in the past, examples include: the New York City blackout of 1977 (a cost of $1.2 billion in 2017 dollars); the Northeast blackout of 2003 (losses estimated at $6 billion) [5] and East coast power outages due to Hurricane Sandy in 2012 (costs estimated at $80 billion) [6]. Grid component failures can lead to cascading failures across the grid while natural disasters can knock down lines and components resulting in grid overloads.

The most sustainable grid scenarios include a high use of renewables and nuclear power along with high network resilience [3]. The increasing affordability of renewable power sources has resulted in strong increases in their prevalence [7]. This increase has not yet replaced traditional fossil fuel based power plants, which have a strong negative impact on the environment [8], however it’s growth is formative: annual US electricity generation from solar and wind energy increased by a factor of 11 from 2006 to 2016 [7].
1.2. Power systems with distributed generation vs ecosystems

Renewable energy systems installed at consumer locations (for example, solar panels on a home or commercial roofs), allow consumers (also referred to as loads) to use their own power and sell back extra. This two-way exchange of power between the grid and the consumer is known as net-metering. Customer participation in net-metering is becoming more popular every year [9] as seen in Figure 1 and public electric utilities in the U.S. are required to offer net metering when requested [10]. These small scale power generating units are known as distributed generation (DG) systems [11] and are changing grid operation. As a result of consumer sell back, the traditionally linear grid is evolving into a complex network with circular pathways reminiscent of the cyclic organization found in ecosystems.

Organisms in a food web are classified as prey and predators (producers and consumers) and the complex interplay between them leads to high amount of cycling [12]. Past research indicates that food webs have evolved to have a highly cyclic organization [13, 14, 15, 16] that results in the efficient use of available resources [17, 18, 19]. Structural cycling in these natural systems exists primarily due to detritus, waste generated by actors, creating feedback from actors that are traditionally only linear grid is evolving into a complex network with circular pathways reminiscent of the cyclic organization found in ecosystems.

An analogy between ecosystems and power grids is made, both are networks of entities - species in food webs and components in power systems - that circulate material and energy. This analogy is the basis for a two-fold approach to sustainability, addressing grid reliability and renewable energy integration into the grid. First, ecological cycling is investigated as a measure to quantify cyclic pathways in grids and second, this cycling is related to the N-1 reliability of the grid.

2. Methods and model

2.1. Power grid test cases

Eight hypothetical grids and two realistic grids are used as test cases. The grids are simulated using the commercial software package PowerWorld Simulator [29]. Nine out of these ten grids are free models included in PowerWorld. The tenth grid is a 37-bus real power grid from [30]. As flow data for real power systems is difficult to obtain, these eight synthetic grids, which closely resemble real grids in their structure and connectivity, are used in the analysis here.

Power delivery from generators to consumers is dependent on the magnitude of transferred power, including real power $P$ and reactive power $Q$. The integral of $P$ over time gives the energy flow within the system. $Q$ supports the system’s voltage, allowing for power flows between actors. The successful operation of a power system must satisfy the real power balance between generation and load plus loss, maintain the system’s voltage rated values, and keep all components functioning within their real and reactive power limits [30]. Real power is taken as primary flow between actors and reactive power is neglected. The real power flow values are obtained by solving the power flow equations. These are a set of nonlinear algebraic equations and depend on the system topology, network parameters, and the system’s initial state. PowerWorld Simulator [29] is used here to ensure that the power flow equations are satisfied for each test case.

2.2. Modelling power grids as food webs

Food webs are complex networks of prey-predator type interactions and are visualized using a digraph, from which the information is quantified in matrices. The food web matrix $[F]$ contains the structural information and the flow matrix $[T]$ contains the flow magnitude information. Each power grid component (buses, generators, transformers, and consumers) is considered equivalent to a species in the food web. These actors are drawn inside the system boundary and the dissipation from transmission lines are considered as losses in the corresponding end buses (terminal bus of a transmission line).

The ecological flow matrix $[T]$ is a $(N+3) \times (N+3)$ matrix, where $N$ is the number of actors in the network, whose elements are the power flows between various components in the system. The element $T_{ij}$ is nonzero if there is a nonzero flow from node $i$ to node $j$. Figure 2 illustrates the flow matrix for the basic 5-bus power grid. The inner light grey section contains the inter-compartmental flows. The inputs, useful outputs, and dissipation that crosses the system boundaries are entered in the cross-hatched top row, the medium grey second to last column, and the dark grey last column respectively. The food web matrix
\([F]\) is a \(N \times N\) matrix made up of ones and zeros, where a one represents an interaction and a zero no interaction. \([F]\) quantifies the presence and direction of the inter-compartmental flows in \([T]\). An element \(F_{ij}\) is equal to 1 if there is a flow from \(i\) to \(j\) and 0 otherwise. The number of non-zero elements of \([F]\) is equal to the number of total links in the network (\(L\)).

\[
[A - \lambda I] = 0 \quad (1)
\]

Cycling index (CI, also known as Finn Cycling Index \(FCI\)) is the ratio of the cycled throughflow \((TSTc)\) to the total internal throughflow \((TSTI)\) in the network \((Eq. 2)\) \([33, 15]\). Cyclicality and \(CI\) quantify the extent of cycling from different perspectives. \(TSTI\), following \(Eq. 3\), is the sum of inputs and all the inter-compartmental exchanges in \([T]\) \([33]\). \(TSTc\) is computed following \(Eq. 4\), where \([L]\) is the Leontief’s inverse matrix whose diagonal elements \((L_{jj})\) indicate the average number of times a quantum of flow passes through the same actor \([12]\).

\[
CI = \frac{TSTc}{TSTI} \quad (2)
\]

\[
TSTI = \sum_{i=0}^{N} \sum_{j=0}^{N} T_{ij} \quad (3)
\]

\[
TSTc = \sum_{j=1}^{N} T_{ij} \left( \frac{L_{jj} - 1}{L_{jj}} \right) \quad (4)
\]

2.4. Grid modifications

Two 5-bus power grids, \(B5_1\) and \(B5_2\) (which have different loads and components), were selected for modification from the set of sample cases available. The three modifications made to each mimic distributed generation that occurs in real power grids. \(B5_1\) and \(B5_2\) are moderately complex with realistic loads and connections, making them ideal for demonstrating the newly transpiring cyclic pathways caused by distributed generation. The distributed generation is created by adding a generator with varying capacities in the place of the load, representing a consumer becoming a small source of power generation, as seen in Fig. 3(b), where a 200 MW generator replaces consumer-1 changes, thereby changing the connections from the original \(B5_1\) grid Fig. 3(a). The addition of a generator changes the phase angles at different buses in the grid leading to change in power flow magnitudes and directions in some of the transmission lines.

Three consumer-1 modifications of increasing generation capacity (50, 150, 250 MW) are made to the \(B5_2\) grid. An assumption is made that the excess generation at consumer-1 is supplied to the grid only during half of its active time period, since renewable energy can be unpredictable. During the non-generation period consumer-1 is assumed to receive power from the grid, and the original grid configuration is active. The sum of the corresponding power flows \((T_{ij})\) in each period are considered as the entries in the flow matrix, representing the average network structure and function. The 4 consumer \(B5_1\) grid is modified with 40MW generating capacities at one, two, and three consumers.

2.5. N-1 contingency analysis

Contingency analyses are critical in power system operation and power market analyses to predict the behavior of the grid during various outage scenarios including a single-element outage, multiple-element outages, and sequential outages \([34]\). The N-1 contingency analysis is considered the primary reliability standard by North American Electric Reliability Corporation (NERC), where ‘N’ stands for the number of major components in the system \([35]\). 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 [30]. An N-1 contingency analysis is performed using PowerWorld on all the grid scenarios to examine whether the added cycling due to distributed generator makes the grid more or less reliable.

3. Results

The $\lambda_{max}$ and $CI$ for the eight original grids and one of the two realistic grids are all zero. The 37-bus realistic grid however has a $\lambda_{max}$ value of 1.0 and a $CI$ of 0.00089. The cyclic pathways in the modified B5_2 grid are highlighted in Fig. 4, showing that a total of three cycles exist in the system when consumer-1 is producing an excess generation of 200 MW.

![Figure 4. The modified B5_2 pathways and connections averaged over an entire day when consumer-1 has an excess generation of 200 MW.](image)

Figure 4. The modified B5_2 pathways and connections averaged over an entire day when consumer-1 has an excess generation of 200 MW. This representation is the combination of the two network scenarios shown in Fig. 3.

Analysis of 104 food web models [36], available in the package enaR for use in the free programming language R, reveals that food webs have a mean $\lambda_{max}$ value of 4.35 and a mean $CI$ of 0.39. The grid modifications are summarized in Table 1 and show that the cycling that is introduced through the consumer generation brings the grid closer to the average cyclic structure and function of food webs. The reliability of the modified networks, as measured by the N-1 contingency analysis, is also shown to increase with these modifications. The number of violations in the N-1 contingency analysis of the original and modified power grids are shown in Table 1. An exponential decrease in the number of violations is observed in the N-1 contingency analysis as the modifications increase the number of cycles in the grid. Increasing cyclicity and $CI$ both show a smooth exponential correlation with decreases in the number of N-1 violations, as seen in Fig. 5 and 6.

![Figure 5. Modifications to both the B5_1 and B5_2 grids show an exponential decay in the number of N-1 violations (y-axis) as cyclicity increases (x-axis).](image)

Figure 5. Modifications to both the B5_1 and B5_2 grids show an exponential decay in the number of N-1 violations (y-axis) as cyclicity increases (x-axis).

![Figure 6. Modifications to both the B5_1 and B5_2 grids show an exponential decay in the number of N-1 violations (y-axis) as cycling index (CI) increases (x-axis).](image)

Figure 6. Modifications to both the B5_1 and B5_2 grids show an exponential decay in the number of N-1 violations (y-axis) as cycling index (CI) increases (x-axis).

4. Discussion

The results suggest that cycles are not present in traditional power grids, all the unmodified grids except for the 37-bus system had $\lambda_{max}$ and $CI$ values of zero. The 37-bus system did demonstrate extremely weak and simple cycling with a $CI$ of 0.00089 and a $\lambda_{max}$ of one. Based on the behavior of the other nine grids this appears to be an exception rather than the rule, however more large grids need to be investigated to further support that traditional power grids have a one-way chain-like structure. The two cycling metrics are used in ecology to identify cyclic energy pathways that influence food web network characteristics such as robustness, organizational efficiency etc.
Table 1. The cycling index (CI), cyclicality ($\lambda_{\text{max}}$), and N-1 contingency analysis violations of the original grids (B5_1 and B5_2), grids modified with excess generation at consumer-2 (B5_1a), consumers 2 and 4 (B5_1b), and consumers 2, 3, and 4 (B5_1c), and consumer 1 (B5_2d, B5_2e, B5_2f). The grid IDs are used for identifying modifications to the original B5_1 and B5_2 grids.

<table>
<thead>
<tr>
<th>Grid ID</th>
<th>Grid Modifications</th>
<th>$\lambda_{\text{max}}$</th>
<th>CI</th>
<th># N-1 violations</th>
</tr>
</thead>
<tbody>
<tr>
<td>B5_1</td>
<td>Sample case - original</td>
<td>0.00089</td>
<td>0.136</td>
<td>12</td>
</tr>
<tr>
<td>B5_1a</td>
<td>40 MW at consumer-2</td>
<td>1.618</td>
<td>0.0878</td>
<td>5</td>
</tr>
<tr>
<td>B5_1c</td>
<td>40 MW at consumer-2 and -4</td>
<td>1.618</td>
<td>0.136</td>
<td>4</td>
</tr>
<tr>
<td>B5_2</td>
<td>Sample case - original</td>
<td>0.00089</td>
<td>0.136</td>
<td>7</td>
</tr>
<tr>
<td>B5_2d</td>
<td>50 MW at consumer-1</td>
<td>1.414</td>
<td>0.0158</td>
<td>1</td>
</tr>
<tr>
<td>B5_2e</td>
<td>50 MW at consumer-1</td>
<td>1.414</td>
<td>0.0347</td>
<td>0</td>
</tr>
<tr>
<td>B5_2f</td>
<td>250 MW at consumer-1</td>
<td>2.06</td>
<td>0.0637</td>
<td>0</td>
</tr>
</tbody>
</table>

The results suggest that they may be useful in the design of robust power systems as well, as the two metrics effectively quantify power cycles and correlate strongly with improved N-1 reliability ratings.

Cycles in power systems at an instant cannot exist because it requires real power to traverse over a loop and come back to its origin that is against Kirchhoff’s laws and dissipates excess power. Considering power flows over longer time periods may vary the magnitudes but will not change the flow directions in the traditional grids. Directional changes do however occur in the consumer sell-back grid scenarios, as seen in Figure 4. It is important to note however that, from a resilience perspective, in the modified configurations not all links are simultaneously active and the intermittent and somewhat unpredictable nature of renewables due to their dependence on weather conditions, unlike traditional fossil-fuel based electricity generation, makes these connections difficult to depend on in critical situations.

Modifications made to the 5-bus grids show increasing improvements to the N-1 reliability measure, with the number of violations in the network exponentially decreasing as the amount of cycling increased. The largest amount of total excess generation that was sold back to the grid saw the highest CI, 120MW total in B5_1c had a CI of 0.136. The highest amount of generation at a single consumer resulted in the highest $\lambda_{\text{max}}$ and the best N-1 rating, 250MW in B5_2f had a $\lambda_{\text{max}}$ of 2.06 and zero N-1 violations. The violations counted by the N-1 analysis can be either overflow in transmission line, voltage exceeding its limit in a bus, or both. A lower number of N-1 violations means more consumers receive the required power without disruptions. Future work will focus on analyzing power grids with more consumers, enabling a higher number of distributed generation systems to be placed in the grid.

4.1. Renewable energy storage

The integration of renewables locally requires a reliable and affordable energy storage system for such distributed generators, especially in scenarios with higher generation values and thus higher cycling. Electricity storage devices can store electricity when production exceeds demand and use the storage during peak-demand periods to ensure a balance for demand and supply [37]. The grid with the highest $\lambda_{\text{max}}$, B5_2f, also has the highest generation of 250MW. The higher cyclicality value in B5_2f is due to the slack generator receiving power, which does not occur for B5_2d and B5_2e where the lower generations of 50 and 150 MW are not enough power to require storage. The unexpected intervals that occur with renewable source require energy storage, a field that is still relatively new. These electricity storage technologies must be robust, reliable and economically competitive [38]. Commercial electricity storage technologies, for example pumped hydro, flywheels, electrical batteries, and compressed air energy storage, are available for large scale renewable energy generation. The problem of optimal placement of storage devices with the objective of maximizing reliability is an area of further work.

4.2. Cyclicality vs cycling index for power systems

Differences in meaning between cyclicity and cycling index gives value to using both metrics, and can be explained using the grids B5_2d and B5_2e. Figure 5 shows that cyclicity for these two grids is the same, whereas the number of violations observed are different (the same is true for B5_1b and B5_1c). CI however varies for all the modified grids. The physical connections in B5_2d are the same as those in B5_2e resulting in $\lambda_{\text{max}}$ remaining the same, however the 150MW excess generation in B5_2e leads to a higher magnitude of power being cycled (higher CI). A larger data set of power grids needs to be investigated to further reveal the relationship between N-1 reliability and cycling.

5. Conclusion

Distributed generation resulting from consumer installed renewable energy generators has seen a steady increase over the years, resulting in a rise in consumer sell-back to the grid. The circular power flow pathways that result from this sell back resemble the cyclic structure and organization characteristic of ecological food webs. Traditional power grids have revealed
that no cyclic structure exists, however when modified to mimic basic consumer sell back the grids showed both cyclic structure and an increasing magnitude of cycled power. The ecological metrics cyclicity and cycling index are able to quantitatively measure the presence and complexity of cyclic pathways in the grid as well as the magnitude of power that is cycled. The results suggest that increasing the prevalence and magnitude of consumer power generation increases the ecosystem-type cycling as well as improves the N-1 reliability rating of the grid. The characteristically cyclic organization of ecosystems may provide a new approach to analyze these emerging sustainable two-way grids.

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