Dynamic Transfers: Electrical Distance Test

Applied Innovation
PJM Interconnection

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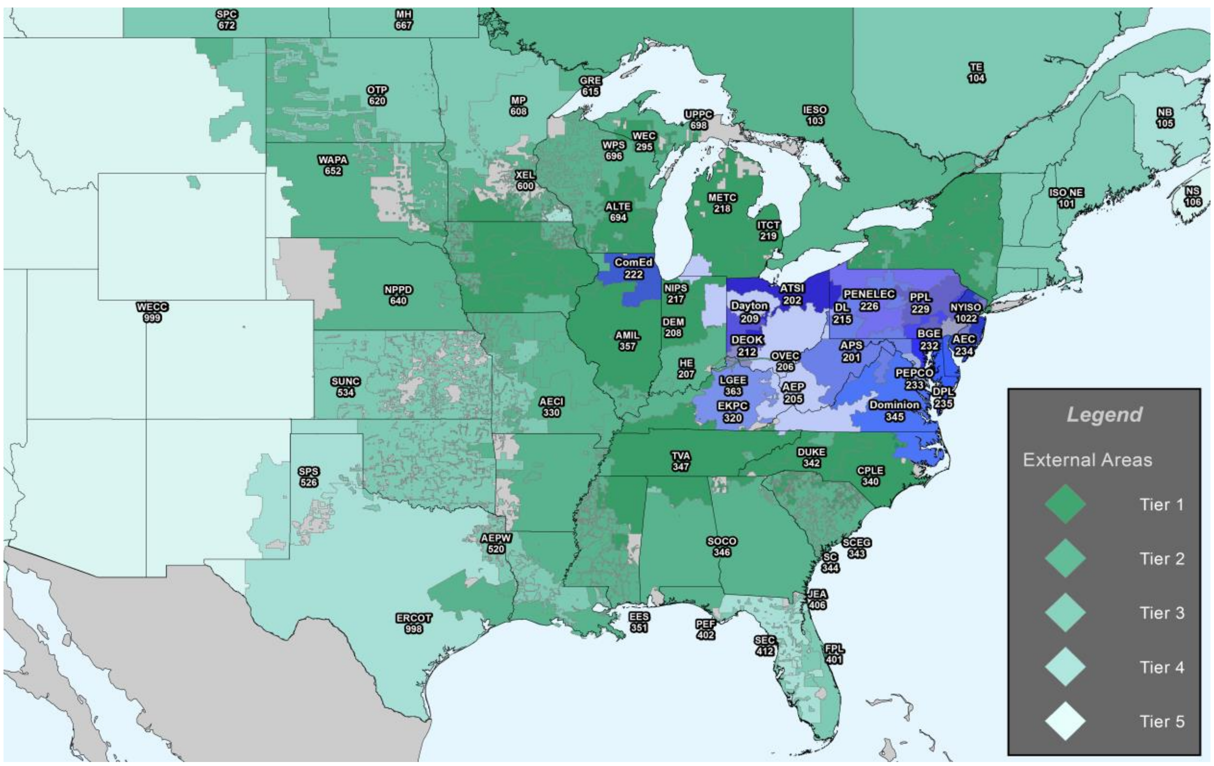
I. Background

Generators geographically located outside the PJM footprint can participate in PJM's markets through a modeling construct referred to as a Pseudo-Tie[1]. PJM is responsible for dispatching these external generators in Day-Ahead and Real-Time markets, and must ensure that reliability and deliverability criteria are met at both PJM and the Native Balancing Authority (BA)[2] where the generator is geographically located.

Incorporating Pseudo-Tie generators entails a certain operational and compliance risk. These resources must be appropriately modeled in EMS and Market models, which bring up numerous challenges, such as external network model expansion, congestion management, telemetry, and state estimator convergence, etc. [2-4].

Historically, in order to determine the eligibility of an external generator for participation as a Pseudo-Tie, PJM relied on criteria based on geographical proximity and Distribution Factors (DFAX). Figure 1 shows the different geographically-derived tiers that were employed to serve as one of the screening criteria. Generators located in Tier-1 automatically met the "geographically close" portion of the criterion. A DFAX analysis was then used to identify facilities that would be impacted by PJM's dispatch of the external resource.

Figure 1. PJM's geographical tiers screening criterion.



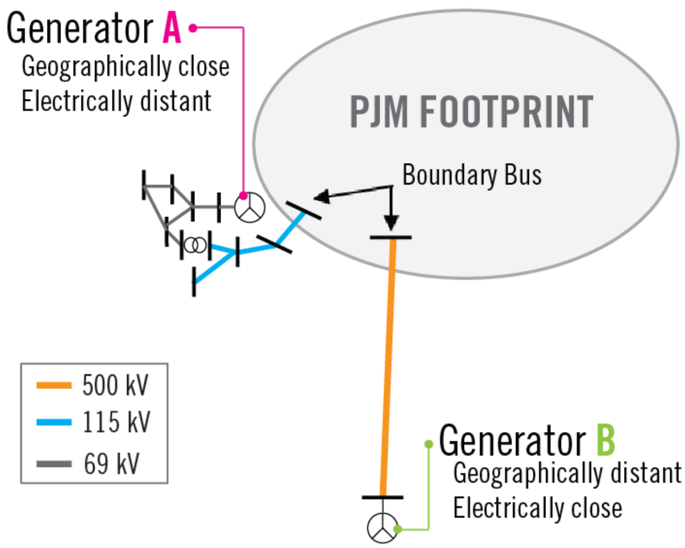
There are several caveats to using geographical distance as a screening criterion. It is well known that geographical distance is not a good proxy for DFAX; i.e., geographical distance disregards the physics that govern power flow in the network [5]. Furthermore, geographical distance does not capture the complexity of the associated model expansion. For example, consider the schematic shown in Figure 2. Generator "A" is geographically close to the PJM footprint, but it is connected to a 69 kV

[1] Pseudo-Tie: A time-varying energy transfer that is updated in real time and included in the Actual Net Interchange term (NIA) in the same manner as a Tie Line in the affected Balancing Authorities' control ACE equations (or alternate control processes). [1]

[2] Native Balancing Authority: A Balancing Authority from which a portion of its physically interconnected generation and/or load is transferred from its effective control boundaries to the Attaining Balancing Authority through a Dynamic Transfer. [1]

network, making it electrically distant from PJM. On the other hand, Generator "B" is geographically far, but it is connected to a 500 kV transmission line; i.e., electrically, it is significantly closer to PJM. The EMS/Market model expansion, which is required to dispatch the Pseudo-Tie generator and to allow for monitoring and control of adjacent facilities impacted by PJM's dispatch, would be riskier for Generator "A".

Figure 2. Schematic showing the advantages of using electrical distance.



The purpose of this paper is to introduce PJM's bright-line eligibility screening criterion based on electrical distance. The objective is to balance:

1. Competitive market access for external generators,
2. Reliability and compliance risks associated with the EMS/Markets model expansion in terms of accuracy, size and complexity, and
3. Effective operational control of Pseudo-Tie generators.

In this paper, **electrical distance** is defined as the per unit (pu) reactance between two buses, and it is calculated using graph theory. It is argued that by selecting an appropriate electrical distance threshold, the proposed methodology facilitates:

- capturing the modeling and operational complexity,
- providing a good proxy for DFAX analysis,
- maintaining competitive market access, and
- providing consistent screening criterion for external resources.

II. Electrical Distance

The Thevenin impedance between two nodes is typically used as an intuitive measurement of electrical distance. The Thevenin impedance between nodes *i* and *j* can be calculated using the following steps:

1. Build admittance matrix *Y* by inspection:
   a. Y_{ii} = sum of admittances connected to bus *i*.
   b. Y_{ij} = **-** (sum of admittances connected between buses *i* and *j*, with *j*≠*i*).
2. $Z = Y^{-1}$
3. Calculate the Thevenin impedance Z_{ij}^{Thev} between nodes *i* and *j*:

$$Z_{ij}^{Thev} = Z_{ii} + Z_{jj} - 2 \cdot Z_{ij} \qquad (1)$$

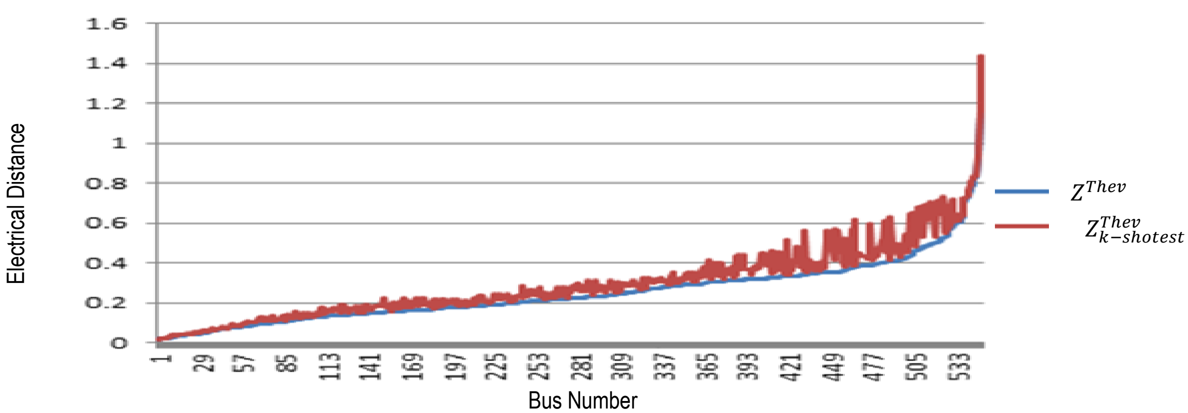
However, equation (1) fails to capture the associated complexity of appropriately modeling the network between buses *i* and *j*. Z_{ij}^{Thev} accounts for all paths between the two nodes; i.e., it considers the entire Eastern Interconnection (including paths through the PJM footprint).

The proposed methodology consists on quantifying the electrical distance by enumerating only the *k-shortest* paths between an external generator that intends to connect as a Pseudo-Tie and a PJM boundary bus. The following steps describe the process:

1. Build a sparse incidence matrix using the pu reactance (line/transformers) as edges.
2. Find the shortest path from the external generator to a PJM boundary bus. In this paper, Dijkstra's algorithm is used.
3. Once the shortest path is determined, find alternative k-shortest paths by:
    a. Removing an edge of the shortest path, one at a time.
    b. Removing all edges of the shortest path.
    c. Removing all edges after/before the first/last edge.
4. Build a new admittance matrix $Y^{k-shortest}$ using only the buses listed in the k-shortest paths.
5. The $Z^{k-shortest}$ matrix can be derived by inverting the $Y^{k-shortest}$ admittance matrix or by inspection.
6. The electrical distance between the external generator and the PJM boundary bus is calculated using equation (1) and $Z^{k-shortest}$.

Fig. 3 shows a comparison between the proposed k-shortest paths electrical distance and the Thevenin impedance (which considers all paths). The figure shows the electrical distance between a particular generator and more than 500 buses in the model. As expected, the proposed electrical distance is, by design, greater than or equal to the Thevenin impedance between any two buses. Note that the difference between Z^{Thev} and $Z_{k-shortest}^{Thev}$ tends to grow as the electrical distance between the buses increases; a desirable feature, since using k-shortest paths inherently accounts for the potential modeling complexity of integrating the external resource. Intuitively, integrating electrically "close" generators would require a simpler, less risky, network model expansion.

Figure 3. Comparison between Thevenin impedance $\boldsymbol{Z^{Thev}}$ (all paths) and the k-shortest electrical distance $\boldsymbol{Z_{k-shortest}^{Thev}}$. As expected, $\boldsymbol{Z_{k-shortest}^{Thev}}$ is greater than or equal to $\boldsymbol{Z^{Thev}}$.



In general, the calculated electrical distance is assumed to be independent of system loading [5, 6]. However, active elements like Phase Angle Regulators (PAR) need to be treated differently.

PARs are replaced by an equivalent reactance that maintains the real power flow in the line. For example, for a particular system state in which two parallel 345 kV phase-shifters are carrying 160 MW/each, the equivalent reactance is comparable to 145 miles of a 345 kV transmission line. Note that despite being geographically close, buses separated by phase-shifters can be quite distant from an electrical distance point of view. Previous research highlights a similar conclusion regarding voltage levels [5]; the reactance of transformers also creates a noteworthy separation between voltage levels.

If a PAR is allowed to regulate, the derived equivalent reactance would change as a function of the power flowing in the network. For the purpose of this paper, the controllers of PARs are fixed (i.e., the equivalent reactance is fixed).

For simplicity, High-Voltage Direct Current (HVDC) lines and Variable Frequency Transformers (VFTs) are treated as open circuits (i.e., electrically distant). There are less than a handful of HVDCs and VFTs in the PJM footprint. Therefore, the simplifying assumption does not significantly impact the final results.

III. Electrical Distance Test

III.1. Electrical Distance Test in PJM

The Electrical Distance Test is one of the FERC approved eligibility requirements that an external resource must satisfy in order to become a Pseudo-Tie within the PJM Balancing Authority Area (BAA). This requirement is as follows:

- Each external resource requesting to Pseudo-Tie into PJM will be evaluated by calculating the electrical distance, which is the equivalent Thevenin impedance from the highest connected voltage from the station the unit is inter-connected to a PJM border bus. If determined to be feasible, meaning the resulting equivalent impedance is determined to be less than or equal to 0.065 pu plus one adjacent bus, the cost of the EMS model upgrade will be borne by the Market Participant requesting to Pseudo-Tie. [7]

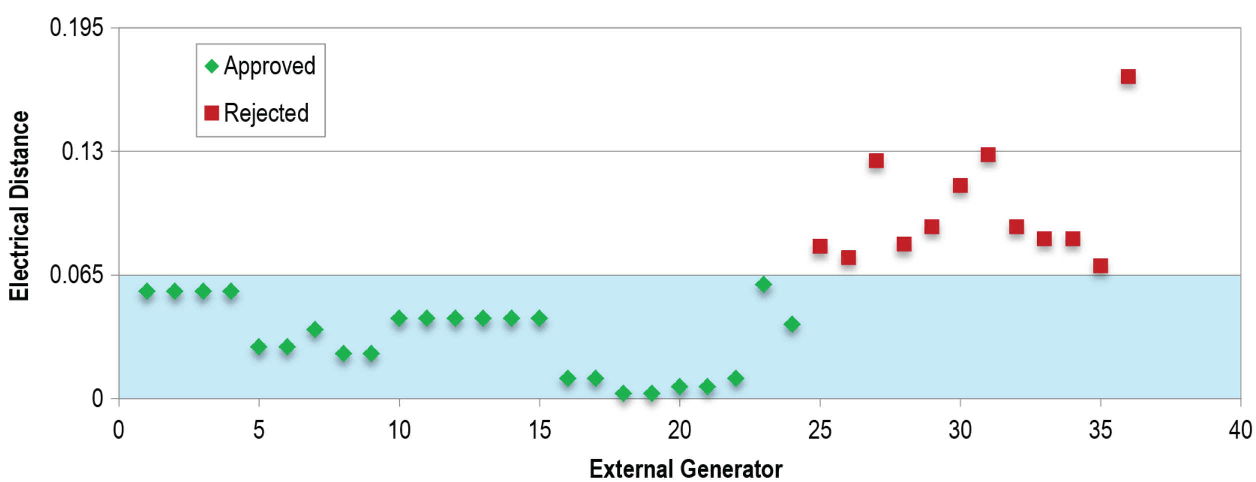
III.2. Threshold of 0.065 pu

An electrical distance threshold of 0.065 pu, albeit arbitrary, was selected as a good compromise between maintaining competitive market access for Pseudo-Tie generators and bounding operational and modeling risks. The simulation results are based on the Eastern Interconnection power flow model created by the Multiregional Modeling Working Group (MMWG) [8].

As described in Section II, the methodology with k-shortest paths is used to calculate the electrical distance between an external generator and a PJM boundary bus. If the electrical distance to any boundary bus is less than the 0.065 pu threshold, then the external generator passes this eligibility criterion.

Fig. 4 shows a comparison between the proposed threshold, 0.065 pu, and previously approved/rejected Pseudo-Tie requests. Recall that the eligibility of an external generator to Pseudo-Tie into PJM was previously based on a combination of geographical tiers, DFAX analysis, and engineering judgment regarding the feasibility of expanding and maintaining the external model. Note that all previously approved requests in this representative sample fall within the proposed threshold, while all rejected requests exceed it.

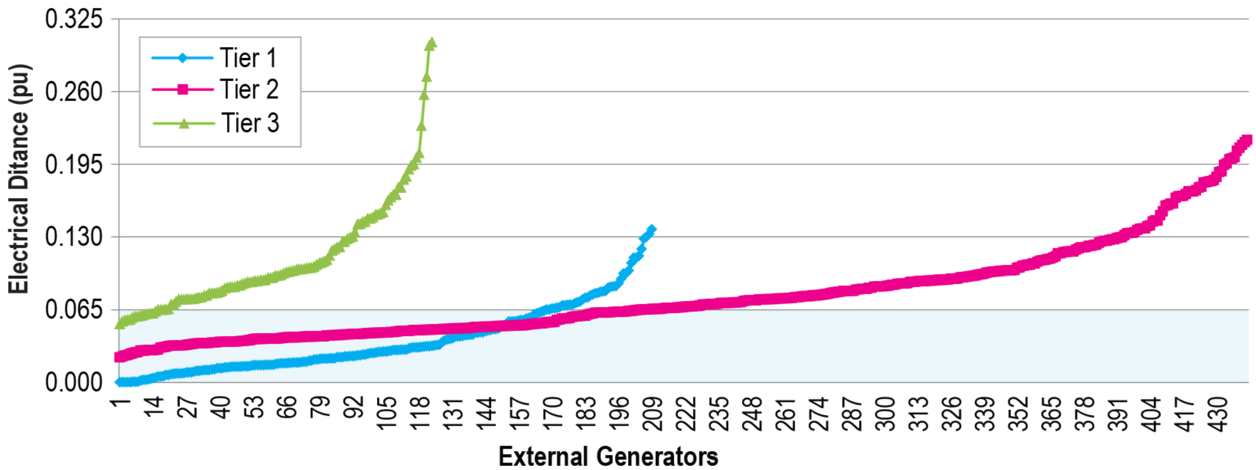
Figure 4. Comparison between electrical distance and previously approved/rejected Pseudo-Tie requests.



III.3. Geographical Tiers vs. Electrical Distance

A comparison between the geographical tiers (see Fig. 1) and the proposed electrical distance is shown in Fig. 5. Tier-1 generators, considered to be geographically close, were eligible for participation as Pseudo-Ties, while tier-2 and tier-3 generators were further scrutinized, requiring time-consuming analysis.

Figure 5. Comparison of electrical distance threshold (0.065 pu) and geographical tiers.



Note that some tier-2 and tier-3 external generators pass the criteria. Similarly, some previously defined tier-1 resources are actually electrically distant from PJM.

Note that, as expected, the geographical distance is not a good proxy for electrical distance. Approximately 80% of generators previously classified as tier-1 are below the 0.065 pu threshold (see **Error! Reference source not found.**); the remainder do not pass the electrical distance criterion. Interestingly, 47% of tier-2 and 13% of tier-3 generators would be eligible to participate as Pseudo-Ties. Therefore, the electrical distance provides a screening criterion that is more consistent with the complexity of the associated model expansion.

Table 1. Geographical vs. Electrical Distance

	Pass	Fail
Tier 1	80%	20%
Tier 2	47%	53%
Tier 3	13%	87%

III.4. Operational & Modeling Risks

Pseudo-Tie generators with Capacity Performance (CP) commitments in the PJM Capacity Market are meant to be comparable substitutes for internal resources. PJM is responsible for committing and dispatching these resources in both Day-Ahead and Real-Time Markets. In other words, the Native BA is no longer able to use these resources to meet its load, reserves, or any other requirements.

EMS and Market models must be expanded to ensure reliability at both PJM and the Native BA. DFAX analysis is used to identify external facilities that would be impacted by PJM's dispatch of the Pseudo-Tie generators. A DFAX threshold of ≥5% is typically used in the industry [9, 10]. The actual DFAX used for a final implementation can vary based on the specific requirements of coordinated flowgate agreements with the external parties involved.

The DFAX threshold serves itself as a screening tool; engineering judgment is then used to assess the feasibility of the model enhancements. For example, the electrical distance of a particular external generator was calculated to be 0.431; i.e., it does not pass the electrical distance screening criterion. The DFAX analysis for that generator, on the other hand, identified more than 700 buses that would be impacted by PJM's dispatch [11]. In other words, in order to properly model this particular generator, a prohibitively large number of buses would have had to be added to the EMS and Market models.

Assuming a high X/R ratio, electrical distance is a good proxy for DFAX analysis [6] (the distance is correlated with the angle required to transfer real power from bus *i* to *j*). One of the main advantages of calculating electrical distance using k-shortest paths is that it intrinsically captures the modeling complexity. Intuitively, a generator that fails to pass the 0.065 pu screening criterion would require a larger and riskier model expansion (even after contemplating k-paths, the generator still appears to be electrically distant from PJM).

The reliability risk associated with maintaining large EMS models is well documented in [12]. A recent analysis of EMS outages presented at the NERC Monitoring and Situation Awareness Technical Conference noted that 65% of EMS outage reports over the year from October 2017 to September 2018 were related to State Estimator or Contingency Analysis (SE/CA), and 57% of the SE/CA events were attributed to modeling.

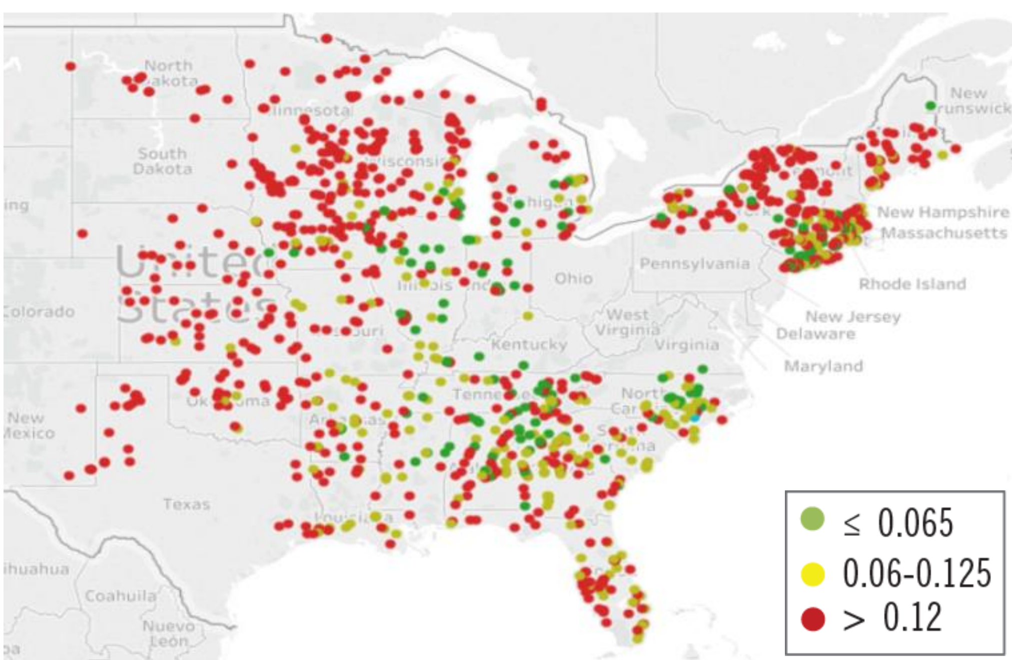
III.5. Competitive Market Access

Fig. 6 shows a map with generators in the Eastern Interconnection and the associated electrical distance. Green dots represent generators closer than 0.065 pu (i.e., generators that would pass the screening criterion). Yellow and red dots represent generators that do not meet PJM's criterion.

The total generation eligible to participate as Pseudo-Ties shown in Fig. 6 is over 130 GW. To put this in perspective, this is equivalent to 70% of PJM's internal installed capacity. The proposed electrical distance threshold clearly preserves competitive market access. As of the writing of this paper, more than 5000 MW of external generation participate as Pseudo-Ties.

As a final remark, Figure 6 is included for illustration purposes only; requests to connect as Pseudo-Ties are studied on a case by case basis.

Figure 6. Electrical distance to PJM of generators in the Eastern interconnection. Eligible Pseudo-Tie resources encompass over 130 GW of generation.



III.6. Markets Eligibility Criteria

Other criteria, beyond electrical distance, must be met before a generator can participate as a Pseudo-Tie. Those include:

1. Model consistency between the Native BA and PJM. DFAX of coordinated flowgates must be within 2% of each other's model.
2. Market-to-Market flowgate test. At least one flexible[3] generator internal to the PJM BA has a DFAX of at least 1.5% on each eligible or existing flowgate.
3. PJM must be able to include firm flows associated with the Pseudo-Tie generator in the Day-ahead market on all coordinated facilities.

Further details on the PJM eligibility criteria can be found in [7].

IV. References

[1] NERC. Available: https://www.nerc.com/files/glossary_of_terms.pdf
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[4] PJM, "PJM Manual 3A: Energy Management System (EMS) Model Updates and Quality Assurance (QA)," vol. Revision 16, September 27, 2018.
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[8] PJM. Available: https://www.pjm.com/planning/rtep-development/powerflow-cases/mmwg-base-cases.aspx
[9] NERC, "Standard MOD-030-3 Flowgate Methodology," November 13, 2014.
[10] NERC, "Standard MOD-028-2 Area Interchange Methodology," July 24, 2013.
[11] PJM, "Response to Deficiency Letter re: Proposed External Capacity Response to Deficiency Letter re: Proposed External Capacity," Docket No. ER17-1138-000, 2017.
[12] NERC, "Analysis of EMS Outages," October 2, 2018.

[3] A generator is considered flexible if the economic minimum is less than the economic maximum.