Selectively Modeling Generator Capability Curves Based on Critical Generator Parameter Rankings

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***Abstract*—This paper presents a methodology to selectively model critical generators with generator capability curves. The proposed methodology determines top critical generator parameters including generator real and reactive power output that heavily influence bus voltages, line loading, and LMP results through OPF sensitivity analysis. Various cases with different renewable generation dispatch levels are used to decide the ranking of the most significant generators. Specific generators are modified using reactive capability "D-curves" based on the ranking results. The appropriateness of the presented approach for selectively updating generators is validated through OPF solution analysis, contingency analysis, and computations time measurement. The evaluation results of the selectively updated case are compared with those of original and fully updated cases.**

***Index Terms*—Generator capability curve, critical generator parameter ranking, sensitivity analysis, optimal power flow**

I. Introduction

SELECTING a good compromise for system modeling is a difficult problem since it involves multiple conflicting objectives, various decision-makers, and huge uncertainties [1]. Power system engineers and researchers always face trade-off issues between complex and simplified models when designing or selecting electric grid models for their studies. They sometimes prefer to use simpler models instead of including every modeling detail into the system due to the computational burden from the added complexity. For example, many engineers use the simplified DC power flow model rather than the full AC power flow equations. In [2], it is shown that the DC locational marginal price (LMP) model has reasonably good performance in revealing the congestion patterns, and it is considerably faster than the full AC model. On the other hand, some research results show that using simpler models is not enough to get accurate power flow solutions and represent the current power system properly because of the integration of the large amounts of new types of generators and electronic devices at both transmission and distribution levels [3]–[5].

While many efforts have been made to create good infrastructure for power system model decisions [6]–[10], there is no general approach that tells us which details should and should not be included, based on trade-off characteristics (e.g. accuracy, computation time, accessibility, etc.), for power system planning studies. In this regard, this paper aims to focus on providing a modeling approach for generators using reactive capability "D-curves", which is a boundary of active and reactive power operating points by armature current limit, field current limit, and end-region heating limit [11], [12].

Generators' capabilities are often designed with rectangular constraints that do not consider the impact of maximum and minimum real power limits on active and reactive power output. This approximate model is employed to avoid issues of optimization complexity although it is less precise [13]. Another issue of using generator capability curve is some generator D-curves are not readily available [14]. To provide more accurate generator models with given limited engineering resources, this paper presents a methodology to select specific generators that need an accurate modeling approach by finding the most significant generators that heavily influence the optimal power flow (OPF) solution through sensitivity analysis. Based on the ranking results, the related generators are updated with D-curves. After selectively modifying critical generators, OPF solution analysis, contingency analysis, and computation time are conducted to evaluate the model performance. These results are then compared with the original and fully updated cases. The original case does not include any D-curves while the fully updated case involves D-curves for all generators of the system.

Section II presents the OPF sensitivity analysis using various scenarios with different renewable generation dispatch levels. It explains how to determine the top critical parameters including generator real and reactive power output in the large-scale grid and presents the ranking result. Section III updates specific generator models with generator capability curves based on the critical generator parameter ranking result. It also evaluates the performance of the selectively updated case through OPF solution analysis, contingency analysis, and computational time measurement. Section IV includes the conclusion and future work.

II. Ranking Critical Generator Parameters

This paper introduces a methodology to selectively update significant generator elements based on parameter ranking results using the OPF sensitivity analysis. Three scenarios with

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different renewable generation dispatch levels are created for the study. The most impactful generator active and reactive power output parameters that affected bus voltage, line MVA, and LMP results are determined using the generated scenarios. The overall flow chart of this work is shown in Fig. 1.

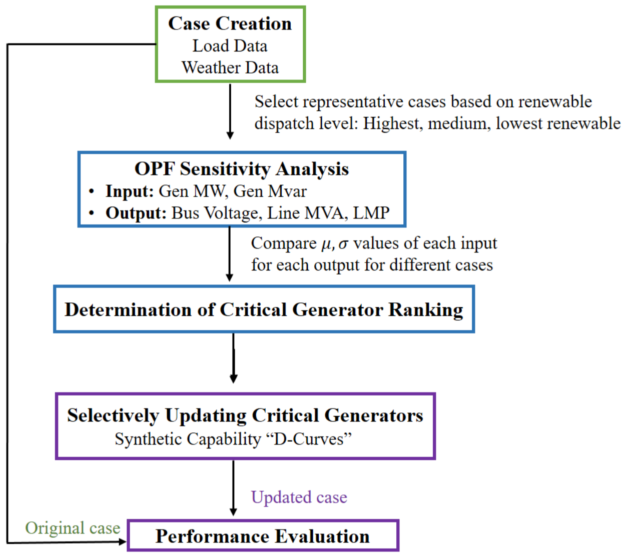


Fig. 1: Flow chart of selectively updating generator capability curves.

A. Scenarios with Load and Weather Variation Data

Texas A&M University has generated synthetic electric grids that are fictitious but functionally and statistically realistic compared to the actual grid [15], [16]. The synthetic power system cases including geographic loads, generators, transmission lines, and other power system elements are publicly available unlike the real grid whose access is limited due to security constraints [17]. Different cases have different sizes ranging from 200 buses to 70,000 buses and they represent different regions' footprints in the United States.

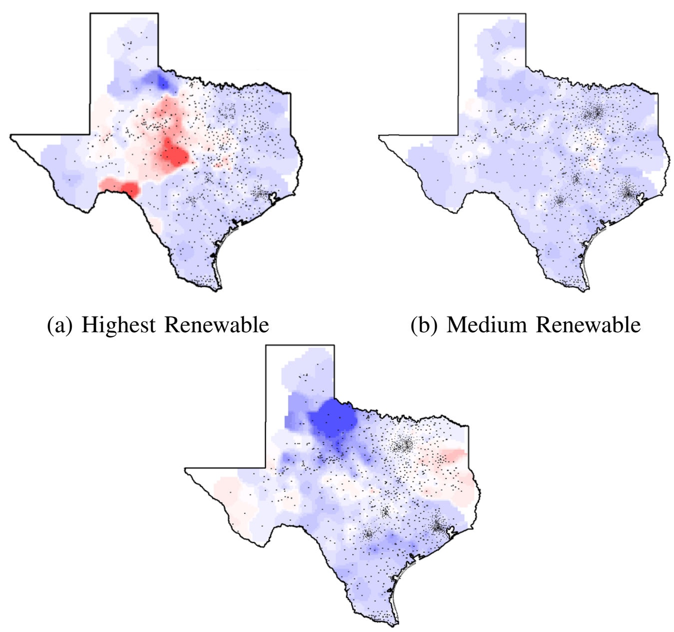
For this study, a 2000 bus synthetic electric network is used, which embodies the geographic footprint of Texas. The synthetic 2000 bus case involves 2,000 buses, 1,350 loads, 544 generators, 2,345 transmission lines, two load tap changers (LTCs), one phase shifter, and 1,250 substations. The unique variation of bus-level hourly load time series for the synthetic Texas case is created based on the methodology explained in [18]. The realism of the synthetic load time series is verified through the comprehensive validation metrics [19]. Additionally, synthetic hourly weather data that includes temperature, dew point, wind speed, wind direction, and cloud cover percentage is interpolated to the associated electric grid elements using their geographic coordinates using strategy presented in [20]. Based on the weather data, the hourly real power output and the maximum limit of each generator are determined. Wind outputs have been generated considering wind speed and turbine power curve models and solar outputs have been created using cloud percentage and date and time

TABLE I: Description of 2000 Bus Cases with Different Renewable Dispatch Levels

Case Description	Load (GW)	Renewable Generation (GW)	Total Generation (GW)	Generation Capacity (GW)
Highest Renewable	30.8	12.3	33.0	99.7
Medium Renewable	31.7	6.2	31.8	93.3
Lowest Renewable	24.2	0.265	24.5	87.1

information. Other generators' maximum active power limits are decided considering temperature inputs.

After simulating synthetic scenarios with the hourly load and weather variation data for a specific year, particular scenarios with feasible OPF solutions are selected for this study considering their renewable generation dispatch level; the lowest generation has 1.08% of the total generation as renewable, while the middle case has 19.5% and the highest case has 37.4%. The detailed information of the scenarios is presented in Table I. Different solution results by different renewable generation dispatch levels are described in Fig. 2 as an example. The voltage ranges from 0.86 p.u. to 1.18 p.u.. Red color indicates low voltage issues and dark blue color represents high voltage issues. It presents that the highest and lowest renewable cases involve low and high voltage issues in some regions of Texas as shown in Fig. 2a and Fig. 2c while the medium renewable case has overall normal voltage profiles in Fig. 2b.



(a) Highest Renewable (b) Medium Renewable

(c) Lowest Renewable

Fig. 2: Bus voltage magnitudes for the highest, medium, lowest renewable 2000 bus cases.

B. OPF Sensitivity Analysis

In order to rank the critical generators of the system, this paper utilizes sensitivity analysis to measure the impact of changes in component values on various output parameters in the system. For this work, the two primary inputs tested are generator real and reactive power output. The output parameters that are used to determine the impact of changing the aforementioned inputs are from the OPF. In particular, the bus voltages across the system, the line loading on all the different lines in the system, and the LMP of the buses in the system are observed.

The OPF sensitivity analysis is conducted to measure how changing each of the inputs independently impacts the three output parameters of interest. Inputs that have a higher impact are considered to be more critical and necessitate a more careful look, or a higher fidelity model.

This paper's main contribution is to demonstrate an overall methodology to selectively update significant generators with D-curves. The paper's purpose is not to present any new approaches for the sensitivity analysis itself. Instead, a one-at-a-time (OAT) method, widely known as the Morris method is used here to perform the actual sensitivity analysis [21]. OAT methods are sensitivity analysis tools where changes in the input values are defined by discrete and finite levels within some range. Mathematically, for any system $y(x)$, the Morris method defines the elementary effect for any given input x_i in (1). Here, k refers to the size of the input space for any input, and Δ is any multiple of $\frac{1}{p-1}$ for a chosen $p \geq 2$. It is important to note that one of the primary benefits of the Morris method is that instead of measuring the impact of every element within the k-dimensional input space, it randomly samples the input space for each element being tested thus it aids in saving time, especially for the large-scale system but still provides accurate results.

$$EE_i = \frac{\begin{aligned}[y(x_1, x_2, \ldots, &x_{i-1}, x_i + \Delta, \ldots, x_k) - \\ &y(x_1, x_2, \ldots, x_{i-1}, x_i, \ldots, x_k)]\end{aligned}}{\Delta} \quad (1)$$

In order to quantify and rank the elementary effects of various inputs, the Morris method utilizes two statistical measurements; the mean, denoted as μ, and the standard deviation, denoted as σ. For any individual input i, there is an associated mean μ_i and standard deviation σ_i. The mean is simply a measure of impact; the higher a mean is, the larger the impact of an input value on the measured outputs. The standard deviation, however, is a measure of non-linearity. Inputs with large standard deviations are generally considered to have non-linear impacts on the outputs, while lower standard deviations imply linear impacts.

Bringing all of this information together, the methodology is as follows. Each case study has a given OPF solution for the base case without any adjustments. This is taken as the reference state of the system. Then, each input element undergoes the Morris method, and its value is varied based on a random sampling of given input space. The OPF for the case is solved again, and the output parameters of interests are again measured. This is compared against the reference state of the system, and the mean and standard deviation of all the input changes is calculated. This is done for every element in the system, and the results are then plotted to determine which elements have the largest impact.

C. *Results on Critical Generator Parameter Ranking*

The ranking of critical generator parameters (generator real and reactive power output) is determined by considering each parameter's mean and standard deviation values from the OPF sensitivity analysis results for different outputs (bus voltage magnitudes, line MVA flow, and bus LMP values) for various cases with different renewable generation dispatch levels (the highest, medium, and lowest renewable MW outputs). A parameter that includes the highest mean and standard deviation is considered the most important parameter.

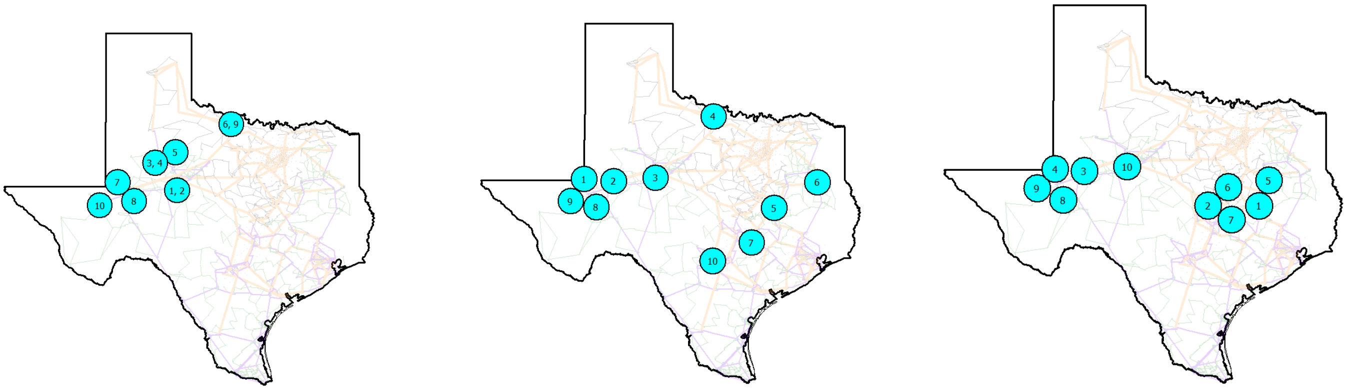
It is observed that the ranking results are varied depending on the renewable variations and the type of outputs. For example, for the voltage magnitude results, a generator MW parameter (Bus 3044) is ranked first in the highest renewable case and ranked 9th in the medium renewable cases while the generator did not make the top critical generator parameter list for the lowest renewable case. Furthermore, in singular case studies, the ranking of the critical generator parameters can also vary between different outputs. For instance, with the medium renewable case, a generator MW parameter (Bus 3133) is 7th for the voltage magnitude result but it was not able to be included in the top critical generator parameter list for the line MVA and LMP results.

To determine the overall top significant parameters for each output, the different ranking results from the various renewable variation cases are comprehensively analyzed. If a specific parameter is ranked higher based on its mean and standard deviation values for multiple cases, it is considered a more important factor than other parameters. But if different parameters are placed in the same ranking for the different cases, their mean and standard deviation values are compared to each other. A parameter that contains the highest mean and the highest standard deviation is ranked higher. However, in a situation where parameter A has a higher mean but lower standard deviation and parameter B has a lower mean but higher standard deviation, parameter A is ranked higher than parameter B since it is assumed that the mean value has a higher priority for the critical generator parameter decision.

Based on this ranking approach, the overall top critical generator parameter ranking results have been determined. The results are described in Table II. It includes the type of element/parameter, bus number, and ID. The geographic locations of the highest impact generators in the system by different outputs are depicted in a one-line diagram using Geographic Data Views (GDVs) in Fig. 3 [22]. The blue color represents generators. Each generator's ranking is displayed as a string.

III. Selectively Updating Significant Generators

This paper proposes the use of a more accurate modeling strategy for the specific generators determined to have the most impact on a system's OPF sensitivity analysis. Since they greatly affect the system's solution, adding detailed model designs to the system should aid in having more accurate and



(a) Voltage Magnitude (b) Line MVA (c) LMP

Fig. 3: Geographic locations of overall top 10 significant generators by different output results in 2,000 bus case.

TABLE II: Overall Ranking of Top Critical Generator Parameters in 2000 bus system

Ranking	**Overall Top Critical Generator Parameters**	**Top Critical Generator Parameters by Output Results**		
		V p.u.	**Line MVA**	**LMP**
1	3044(1), Gen MW	3044(1), Gen MW	1053(1), Gen Mvar	8087(1), Gen Mvar
2	1053(1), Gen Mvar	3044(1), Gen Mvar	1081(1), Gen Mvar	5281(1), Gen MW
-	1081(1), Gen Mvar	3133(1), Gen MW	3044(1), Gen MW	1081(1), Gen Mvar
4	2085(1), Gen MW	3133(1), Gen Mvar	2085(1), Gen MW	1053(1),Gen Mvar
5	8087(1), Gen Mvar	3133(2), Gen Mvar	8087(1), Gen MW	8070(1), Gen Mvar
6	3044(1), Gen Mvar	2085(1), Gen MW	8116(1), Gen MW	5282(1), Gen MW
-	5281(1), Gen MW	1080(1), Gen Mvar	6007(1), Gen MW	5283(1), Gen MW
8	3133(1), Gen MW	1078(1), Gen Mvar	1049(1), Gen Mvar	1049(1), Gen Mvar
9	3133(1), Gen Mvar	2085(1), Gen Mvar	1048(1), Gen Mvar	1048(1), Gen Mvar
10	3133(2), Gen Mvar	1051(1), Gen Mvar	6052(1), Gen Mvar	3045(1), Gen MW
-	8087(1), Gen MW	1073(1), Gen Mvar	3045(1), Gen MW	5360(1), Gen MW
-	1049(1), Gen Mvar	1050(1), Gen Mvar	1053(1), Gen MW	1050(1), Gen MW
-	8070(1), Gen Mvar	3045(1), Gen MW	2004(1), Gen MW	3133(1), Gen Mvar

reliable results. For the synthetic Texas 2000 bus case, 11 out of 544 generators are updated based on the result of the overall top critical generator parameters as presented in Table II.

A. *Generator D-Curve*

Generator capability curves for 11 significant generators are modeled considering three assumptions.

1) The capability curve is the intersection of three circles including armature current limit, field current limit, and end-region heating limit.
2) The minimum and maximum real and reactive power limits that are given create a rectangular capability "box" that fits completely within the actual generator capability curve.
3) The maximum rated apparent power output is greater than the maximum apparent power output as calculated from the maximum real and reactive power output as defined in the synthetic case.

Since the purpose of this paper is to introduce an overall algorithm to select significant generators in the system and update them with generator D-curves rather than presenting any methods to create reactive capability curves, a general method is used for the creation of the synthetic D-curves for the most impactful generators. To obtain realistic maximum and minimum values of reactive power for generators in the synthetic grid, (2a) to (2c) is used [23]–[25]. An example of a generator capability curve is shown in Fig. 4.

$$Q_{max,t} = \sqrt{S_{rated}^2 - P_{max}^2} \tag{2a}$$

$$Q_{min,t} = \sqrt{S_{rated}^2 - (pf_{leading} \cdot S_{max})^2} \tag{2b}$$

$$pf_{leading} = \frac{P_{max}}{\sqrt{P_{max}^2 + Q_{min}^2}} \tag{2c}$$

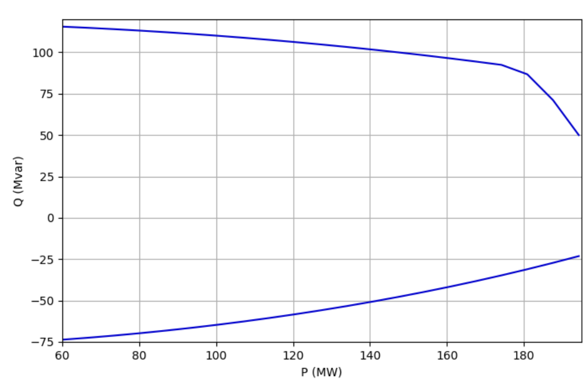


Fig. 4: An example of generator capability curve: Bus 1053 in 2000 bus case.

B. Performance Evaluation

The performance of the selectively updated case that involves D-curves for the most impactful generators in the system is tested through OPF solution analysis, contingency analysis, and computation time measurement. For the comparison, the same tests are conducted for a fully updated case that includes D-curves for all generators as well as the original case that does not have any D-curves. Note that selectively updated and fully updated cases are called SU case and FU case, respectively, in this paper.

The OPF solution results are analyzed to see if the SU case provides more accurate and reliable solutions compared to the two other cases. Difference contouring for the LMP and voltage magnitude results are depicted in Fig. 5 and Fig. 6. It clearly presents the LMP differences between the SU and original cases; the SU case has higher LMPs in the west and high plains regions of Texas while it has lower LMPs in the northwest region of Texas compared to the original case. It can be seen that the locations where the main differences were found are identical to the overall top significant generators' locations in the system. Voltage magnitudes less change by the generator D-curves but it still reveals some changes in the west region of Texas. However, it is noted that the FU case even did not converge to a solution and a blackout occurred. Thus, the OPF result was not able to be obtained for the FU case. These results exhibit that including D-curves for the significant generators provides a more accurate and reliable OPF solution than two other cases.

Computation time for each case is measured 10 times by checking the taken time to solve the OPF and its average computation time is described in Table III. Like mentioned above, the FU case's computation time was not able to be checked due to the divergence. The result shows that the original case solves OPF quicker than the SU case. But the difference between the two cases is only 0.0012 second.

TABLE III: Average Computation Time to Obtain OPF Solution for Original, Selectively Updated, and Fully Updated 2000 Bus Cases

	Original Case	**SU Case**	**FU Case**
Computation Time (sec.)	0.0711	0.0723	N/A
Note	-	-	Not Converge

Contingency analysis is then conducted for original, SU, and FU cases to see how different model designs can result in different power system operating results when facing unexpected failures. The total number of potential contingencies is 3875 including generator, branch, and substation failures. Table IV presents overloading line, low voltage, high voltage, and unsolvable violation results for three different cases. Note that multiple violations occurred per a single contingency. The SU case has a lower number of violations for line MVA, low voltage, and unsolvable compared to the original case while it has more violations for high voltage. The largest number of violations for a single contingency is 53 for the original case and 49 for the SU case. Average number of violations for a single contingency is 24 and 22 for the original and the SU cases, respectively. However, the contingency results for the FU case was not able to be assessed because of the converging issue. In total, the SU case shows a lower number of violations and more reliable results compared to the two other cases.

TABLE IV: Number of Violations for Original, Selectively Updated, and Fully Updated 2000 Bus Cases

Violations		**Original Case**	**SU Case**	**FU Case**
Line MVA		65976	65959	N/A
Voltage	Low	27004	15778	N/A
	High	157	3808	N/A
Unsolvable		16	9	N/A
Total Violations		93153	85554	N/A
Note		-	-	Not Converge

IV. Conclusion

Given limited engineering resources for generator D-curves, this paper presents a methodology to selectively update some important generators with generator capability curves instead of putting every modeling detail into the system or making the system too simple. To select the most impactful generators in the large-scale system, it determines the ranking of generator real and reactive power that heavily influence the bus voltage, line loading, and LMP through the OPF sensitivity analysis. Various cases with different renewable generation dispatch levels are used to conduct the sensitivity analysis and determine the overall ranking of the top critical generator parameters.

Based on the critical generator parameter ranking results, some specific generators are updated using generator D-curves. Then, this paper evaluates this new approach's appropriateness by testing OPF solution analysis, contingency analysis, and computation time measurement. The results show that it presents a more accurate and reliable solution than original and fully updated cases. Although the selectively updated case provides the OPF solution slower than the original case, since the computation time difference between the two cases is only 0.0012 second, it is negligible. Therefore, it is concluded that the proposed methodology should be applied to the power system when designing generator models more efficiently. This paper can guide power system researchers and engineers on how to address conflicts in the generator model design and make systematic model choices. Future work includes ranking and modeling critical transformers and lines as well as generators. Model decision metrics can be developed to validate the modeling approaches.

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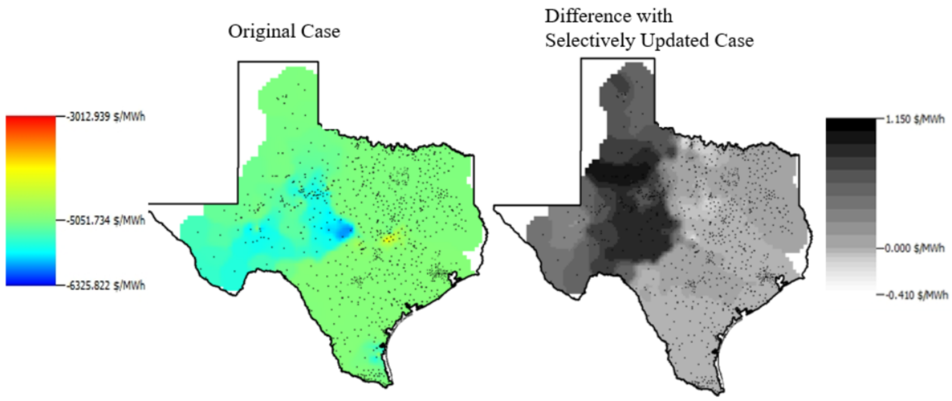

Fig. 5: Bus LMPs in OPF solution for original 2,000 bus base case (left). Difference contours with comparison to base for selectively updated case (right).

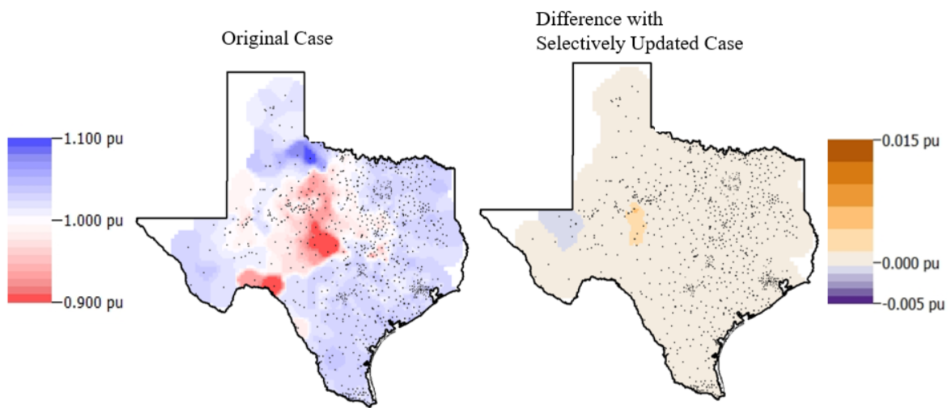

Fig. 6: Bus voltage magnitudes in OPF solution for original 2,000 bus base case (left). Difference contours with comparison to base for selectively updated case (right).

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