Transmission Hosting Capacity of Distributed Energy Resources

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***Abstract*—Distributed energy resources (DERs) are transforming the operation and planning of both distribution and transmission grids. Stability impacts from the increasing generation contribution of DERs have been widely recognized in distribution systems and are emerging in transmission systems. There is a need for the development of transmission hosting capacity studies of DERs so utilities will be able to predict and prevent instabilities, reductions in reliability on the electrical grid, and create planning methodologies that enable the continued growth of DERs. This paper evaluates the impact of different modeling considerations for assessing hosting capacity of DERs in transmission systems through analysis on a 2,000-bus synthetic grid test system. The modeling considerations include transient and steady state contingencies, use of dynamic load and DER models with voltage support control, dynamic load composition, and seasonal and loading scenarios. The results demonstrate that transient stability evaluations are more limiting than steady state analysis, the use of voltage support control in DERs can increase hosting capacity in the system, and large variations in hosting capacity can be found when assessing between seasonal variations. From comparing system factors the amount of wind generation in the system was a critical factor for hosting capacity in this study.**

I. Introduction

The increasing generation contribution of distributed energy resources (DERs) has created challenges on both the distribution and transmission grid. It is important to characterize these impacts to be able to predict and prevent instabilities and reductions in reliability on the electrical grid. Also to create adequate practices and planning methodologies that enable DERs' continued growth.

Currently, DERs are a salient part of power system planning with the U.S. market penetration forecasted to increase from 4.7% in 2015 to 6.7% in 2040 [1]. Numerous factors drive this increase, including: environmental drivers such as limiting green house gas emissions and avoidance of new transmission and generation construction [2]–[5], or national/regulatory drivers such as energy security through diversification [2]. The impacts of high DER contribution on the distribution grid have been heavily studied and numerous optimal placement and sizing methods–as well as hosting capacity methods–have been developed to avoid negative technical impacts while maximizing DER penetration. The technical impacts include overvoltage, power harmonic distortion, thermal overloading of equipment, exceeding equipment short circuit capacity, and maloperation of protection equipment [6], [7]. Hosting capacity (HC) methods determine the maximum amount of DERs that can be integrated into the power system while maintaining the required system performance, such as the technical impacts just mentioned. Optimal placement and sizing methodologies aim to increase HC through leveraging topology and system connectivity properties.

A key component of the HC and optimal placement and sizing methods is the inclusion of uncertainty in the system and DERs. The uncertainty is accounted for with either probabilistic or both probabilistic and deterministic strategies, often completed with Monte Carlo assessments. In [8]–[10], Monte Carlo based methods are used to assess the impact of either distributed generation (DG) placement and size uncertainty, load or generation uncertainty, or network topology variability in overall HC of DGs. These studies constrain the HC via technical and economic limits. These studies highlight the importance and need to include uncertainty assessments or at a minimum deterministic variations when evaluating HC. They also all solely evaluate steady state technical constraints and do not consider transient stability limits.

Transient stability is an important consideration, especially in light of new regulations in the U.S.A. allowing DERs to participate in ancillary service markets of the transmission grid [11]. The type and operating strategies of distributed wind generators can improve the reactive power savings and impact steady state and transient voltage stability as shown in [12]. In [13], the dynamic and steady state voltage stability is evaluated under a moving cloud scenario with solar PV, demonstrating how the dynamic characteristics can be more limiting than the static snapshots.

Another consideration and variability in HC is load types models, which can be modeled as either dynamic or steady state. In [14], [15], voltage dependent load models are considered with DER placement and sizing, demonstrating how load composition impacts optimal DER portfolios. The effect of time-varying load models and solar PV size and placement is studied in [16]. HC of solar PV in the distribution grid is compared between distribution systems with residential, industrial, commercial, and a mix of time-varying load types. This work demonstrates how the variation in the hourly load profiles impacts the solar PV HC, with the smallest HC found

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with residential systems which have the greatest mismatch in solar PV generation and load demand throughout the day. [17] also notes the importance of considering different periods of time and the lack of HC studies that address this, while introducing a dynamic HC study that considers hourly time frames on numerous days. These studies highlight the effects of load models, however none included dynamic load models in transient stability simulations.

The impacts of DERs in the transmission systems have been less studied than in the distribution system. Transmission expansion planning studies have identified significant impacts on their analysis due to the introduction of DERs [18]–[24]. These techno-economical transmission planning methods have been developed in a similar vein to distribution system DER HC studies to ensure stable and cost effective planning for higher DER contributions on the transmission grid. However, a need has been identified for development of specific transmission grid DER HC methods as impacts on transmission transient stability have been noted due to high DER contributions in [25], [26]. A study investigating the impacts of increasing DG penetration on the transient stability of a transmission system showed that certain contributions of DG can improve the transient stability by reducing large power flows, which detrimentally affect the damping of oscillations in the system [25]. This work provides additional argument for encouraging the growth of DERs. However, also similar to distribution systems, high contributions of DERs do have the potential to negatively impact both the steady state and transient stability of transmission systems and it is important to be able to identify the HC as well as other advanced metrics that provide more accurate representation of the current state of the system.

This work addresses HC of DERs in the transmission grid and evaluates the impacts and importance of different modeling strategies. There are numerous modeling setup considerations to scope when developing a DER HC method for transmission systems. These considerations include timeframe and scenarios, uncertainty, steady state and/or transient stability constraints, and scope of models to include such as dynamic load and DER transient models. It is accepted that these factors can impact the results of a HC study as shown in the literature reviewed, however the importance and magnitude of impact of these factors is not known. This study addresses the questions of the relative importance of these considerations and their impacts on HC results. The HC of DERs on the 2,000-bus synthetic grid overlaid on the Texas Interconnect [27] is evaluated using different modeling considerations. The contribution of this work is the evaluation of DER HC on transmission systems with assessment of the impacts on HC due to the following modeling considerations:

- Transient contingencies with dynamic load models, dynamic DER models, and steady state contingencies
- Dynamic load composition variation
- Impact of seasonal and loading variations

The remainder of this paper is organized as follows. Section II discusses the impacts of model fidelity on transmission HC evaluated with transient contingencies with dynamic load models and dynamic DER models and steady state contingencies. In Section III, we compare the transmission HC with seasonal and loading variations. Section IV details the impact of variation in dynamic load composition on Transmission HC. In conclusion, Section V discusses the implication of the results found in this study.

II. Steady State Contingencies and Transient Contingencies with Dynamic Load Model and Dynamic DER Model Impacts on Transmission HC

This study determines the HC of DERs in transmission systems using the 2,000-bus synthetic grid overlaid on the geographical footprint of Texas Interconnect [27]. This section evaluates the impacts of modeling differences using a Fall low loading seasonal scenario on the 2,000-bus system.

A. Experimental Setup

The modeling scenarios evaluated in this section are:

A : Transient contingency with dynamic load models and dynamic DER models with high voltage support

B : Transient contingency with dynamic load models and dynamic DER models with low voltage support

C : Transient contingency with dynamic DER models with high voltage support and no dynamic load models

D : Transient contingency with dynamic DER models with low voltage support and no dynamic load models

E : Transient contingency with dynamic load models and no dynamic DER models

F : Transient contingency without dynamic DER or load models

G : Steady state contingency

The HC is defined as the maximum amount of DERs in the system while maintaining stability, as determined by stability limits. The stability limits include load loss, steady state and transient under and over voltage limits, under and over frequency limits, and rotor angle deviation. A set amount of limit violations are allowed per each contingency and the HC is determined when the amount of violations per contingency surpasses the allowed amount of limit violations. The amount of load loss allowed per contingency was 5% of the total load. A total of 100 individual violations were allowed per contingency. The transient contingency violations were determined with transient limit monitors as specified in Table I, based on the Electric Reliability Council of Texas (ERCOT) standards. The steady state contingency violations were also determined with limit monitors, set by minimum and maximum bus voltages and overloading of branches. Similarly, 100 violations are allowed with steady state contingencies for determination of the HC.

A set of contingencies are used to evaluate the HC. A subset of critical contingencies were used instead of $N-1$ to reduce the computation time. The set of contingencies included a contingency from each of the areas in the system. The contingency chosen in each area corresponded to a line loss whose line had the highest power transfer distribution factor (PTDF) [28] linear sensitivity with power transfers between the different areas and the slack bus. The PTDF represents what percent of a transfer would appear on each

TABLE I: Transient Limit Monitors for Determining Violations in Transient Stability Contingencies

Violation Type	Limit Value	Limit Duration (s)
Voltage Dip Load Bus	± 0.25 pu	0
Voltage Dip Load Bus Duration	± 0.2 pu	0.33
Voltage Dip All Bus	± 0.2 pu	0.33
Voltage Dip Non-Load Bus	± 0.2 pu	0
Frequency	<59.6 Hz	0.1
Rotor Angle	$\pm 90°$	0

transmission line. Therefore the line with the highest PTDF is one of the most critical lines if not the most critical line, depending on the engineering application. This selection method of contingencies is designed to capture the most severe contingencies that will limit the HC more drastically.

These contingencies were analyzed both as a steady state and transient contingency as specified in the modeling scenarios. The steady state contingencies calculate the power flow due to the loss of a line. The transient contingencies simulate a fault on a line at 1 second with both ends of the lines opening six cycles after the fault.

B. Load Modeling

All loads in power systems are inherently dynamic depending on the time scale. It is this timescale that determines which load models are required for accurate representation of load behavior. Daily or hourly load profiles capture the steady state load changes throughout the day. Typical load models for steady state loads are either static MW or voltage dependent [16]. These load models are used when evaluating steady state contingencies in this study. To evaluate transient contingencies the load can still be simulated with static load models, however, dynamic load models, which include static and dynamic components, are more representative of the behavior of real loads connected to the grid. These dynamic components have substantial impact on the transient voltage stability and rotor angle stability of the grid, and the importance of their inclusion when evaluating stability has been widely recognized [29]–[31]. Therefore, dynamic load models are included in this section when evaluating HC with transient simulations. The dynamic load model used in this study is the composite load model which includes models of four types of motors, power electronics, and static load. The parameters of the composite load model for each of the loads were generated with the Load Model Data Tool (LMDT) [32], and set to an assortment of residential, agricultural, industrial, and commercial feeders.

C. DER Modeling

DERs have typically been modeled as load reductions on the transmission system, which is accurate when considering steady state contingencies. For evaluating steady state contingencies in this study DER contributions are modeled as load reductions. When DERs are modeled as a load reduction their sensitivity to tripping during transient contingencies is not captured, which can detrimentally affect the stability of the grid. This was witnessed in California when 900 MW of rooftop solar tripped due to over-voltage transients [33]. Due to concerns from events such as this, fault ride through capabilities have been required in California [34]. This behavior will only be captured if DERs are modeled with trip settings. Additionally, with FERC order 841 states DERs can provide ancillary services such as voltage support to the grid and be compensated through ancillary markets [11]. These DER capabilities will impact stability on the transmission grid and therefore must be represented when modeling transient simulations to accurately represent DERs. This study includes the DER_A model in PowerWorld to enable simulation of DER trip settings and voltage support [35]. The voltage support settings are created with the gain constant in the reactive power priority control loop in the model. The high voltage support setting has a gain constant of 50, and the low voltage support is modeled by setting the gain constant to zero and therefore is only based on the reference reactive power input as explained in [35].

The amount of DERs in the system is based as a percentage of the load at the load bus. The percentage of DERs at each load bus is increased uniformly, meaning the percentage of DERs at each bus is the same throughout the system. In a system as geographically large as the Texas Interconnect it is unrealistic that the percentage of DERs at each load bus would be the same, as most DERs are rooftop solar PV and the dispersion of rooftop solar PV is neither likely to be present evenly throughout the system nor generating the same amount of power at the same time. However, this study considers total HC and not the likely DER generation scenario. Therefore, this section considers uniformly increasing DER percentages across the system to identify the maximum system hosting capacity.

D. Results

The HC is evaluated for the modeling scenarios specified earlier as A-G. The resulting DER HC for each of these scenarios are illustrated in Figure 1. The HC evaluated with steady state contingencies is significantly greater than all of the evaluations using transient contingencies. This finding confirms the earlier study result in [13] that HC evaluated with steady state conditions and contingencies will result in inflated results due to transient conditions being more limiting. To further investigate the scenarios involving transient contingencies, the load behavior at load bus 7051 is examined and the time-series results from the line fault between buses 7304 and 7059 are presented in Figure 2. The time-series plots are separated in scenarios that included dynamic load models (A,B,E) and those that did not include dynamic load models (C,D,F).

The time-series results are separated by those scenarios with dynamic load models and those without dynamic load models because the dynamic load model behavior dominates the behavior of the load, this is seen by comparing Figure 2 [a] to [b]. It is important to note that the current, load MW and Mvar, and DER MW and Mvar time-series output is not included in Figure 2 when no dynamic DER models are included. This is because when no dynamic DER models are

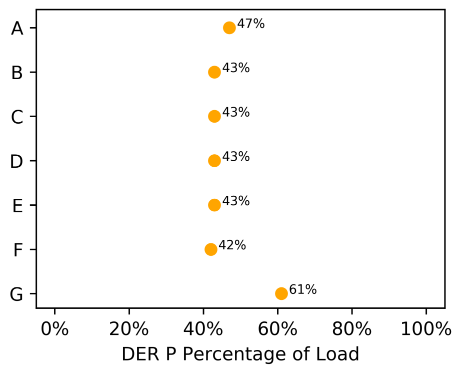
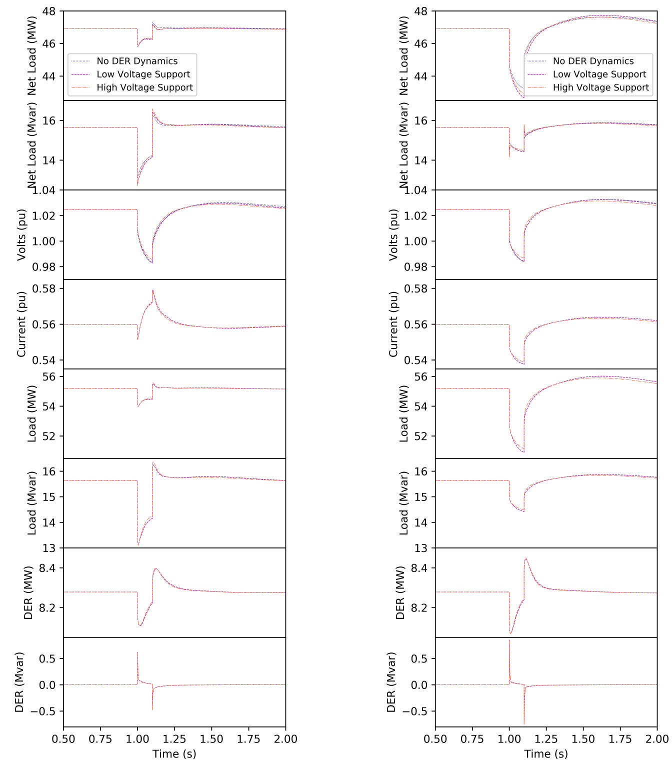


Fig. 1: Comparison of hosting capacity of DERs on the 2,000-bus synthetic grid with different modeling scenarios: A) Transient Contingency with Dynamic Load Models and Dynamic DER Models with high voltage support, B) Transient Contingency with Dynamic Load Models and Dynamic DER Models with low voltage support, C) Transient Contingency with Dynamic DER Models with high voltage support and no dynamic load models, D) Transient Contingency with Dynamic DER Models with low voltage support and no dynamic load models, E) Transient Contingency with Dynamic Load Models and no dynamic DER models, F) Transient Contingency without Dynamic DER or Load Models, G) Steady State Contingency.



(a) (b)

Fig. 2: Time-series output from load bus 7051 for [a] scenarios with dynamic load models (A,B,E) and [b] scenarios without dynamic load models (C,D,F)

included the DER contribution is taken directly out of the load and only the net load behavior exists as an output. In a transient contingency, a load without a dynamic load model exhibits constant impedance behavior. With a dynamic load model the load behavior includes induction motor components and other voltage dependent components. These differences result in a large active power and current dip in the load without dynamic loads and a large reactive power dip and current increase with dynamic load models. The active power dip without dynamic loads is representative of constant impedance behavior. The induction motor behavior with dynamic load models results in a high current draw and reactive power dip due to the deceleration of the induction motors [29]. The active power also has less swing when the dynamic loads are included due to less of the load having constant impedance behavior. Since the only additional behaviors that dynamic DER models bring are trip settings and voltage or frequency support controls, the dominant behavior between the two models is the dynamic load model. In both [a] and [b] one can see that the inclusion of voltage support reduces the voltage dip from the reactive power input provided by the DER. The reduction of this voltage dip between scenarios A and B explains the increase in HC. The reduction of the voltage dip between scenario C and D, without dynamic load models, does not increase the HC. It is possible that the voltage support plays less of a crucial role when dynamic load models are not present, and therefore does not have an impact on HC. When dynamic DER models are not included, as in the scenarios E and F, the DER contribution is taken directly from the load, so the net load behavior is based on the load model whether that be a static or voltage dependent model or a dynamic load model. Therefore when the dynamic DER model is not included what is missing is voltage support and the voltage dip is greater, which explains why in scenario F the HC is decreased.

The findings from this section demonstrate how the inclusion of voltage support controls on DERs can have a systemwide increase in HC, specifically when dynamic loads are considered in the system. There is around a 15% difference in HC between evaluations with steady state contingencies and transient contingencies. Whereas there is a maximum of a 5% difference between transient contingency scenarios. Though higher fidelity modeling included in transient contingencies provides greater insight into the provided system stability benefits due to DER controls and impacts from dynamic loads in the system, in general it is of greater importance to perform transient contingency evaluations over steady state contingencies as transient contingency conditions are more limiting and representative of the system's actual capabilities. If steady state contingencies or conditions are used to evaluate the HC of the system it is necessary for it to be understood that the reported HC is likely inflated or optimistic.

III. Dynamic Load Model Variation in Transmission HC

The experimental setup of this section is similar to Section II, but with transient contingencies with both dynamic load and DER models. This section analyzes the parameters in the dynamic load models to evaluate how variability in the dynamic load behavior impacts HC. The parameters varied are the percentages of each type of load within the composite load model. These parameters were gathered with the LMDT with settings set to the shoulder season in the Texas regions, as the a Fall loading scenario is used for this section. The parameters were calculated for every hour of the day. An example of the parameters for one load at load bus 7051, which is set as a rural/agricultural feeder, are shown in Figure 3.

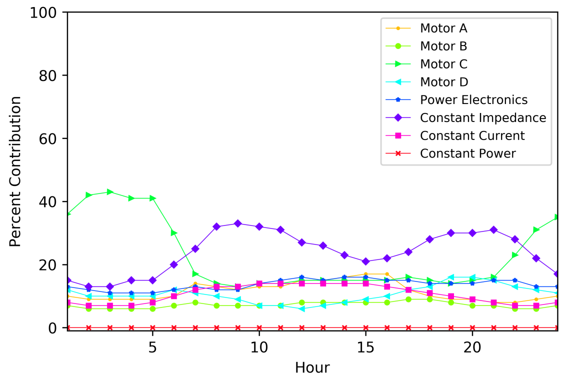


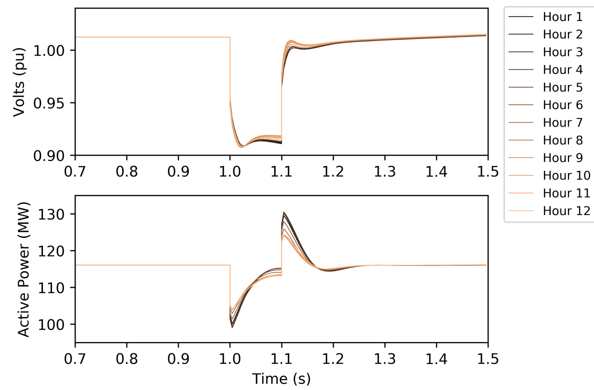
Fig. 3: Hourly composite load model parameters for load bus 7051, a rural/agricultural load, during the shoulder season generated with the Load Model Data Tool Comparison.

The main shift in load behavior over the course of the day is between the constant impedance load and the motor c load which is representative of low inertia pump type motors.

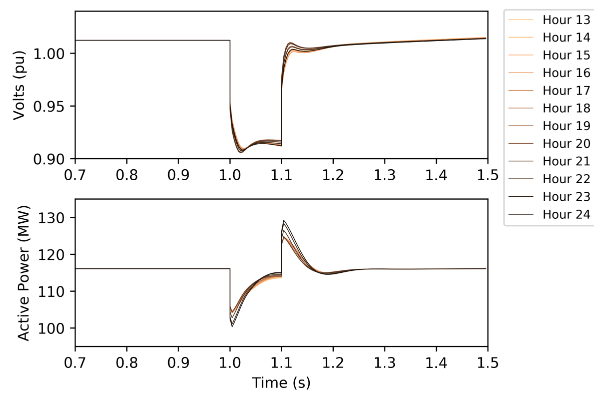
A. Results

The variation in the load types throughout the day impacts the responses of the load. The impact of this shifting load profile on transient stability is demonstrated with the line fault on the line between buses 7304 and 7095 and shown in Figure 4. The figures show the time-series output from load 7051 with the hourly load parameters for (a) hours 1-12 and (b) hours 13-24.

One can see that as the load type shifts from majority motor based at hour 0 to majority constant impedance based at hour 12 the active power dip increases to represent more constant impedance behavior and the voltage recovery is a little higher. The HC was evaluated at each hour with the hourly load parameters and there was no change in HC. The change in dynamic load parameters are designed to be characteristic of the load types in Texas and this suggests that the variation in load behavior has a negligible impact on HC in this system. The variation in load behavior in other systems with different load profiles could impact the HC, especially in systems with diverse load behaviors or a high presence of induction motors which can negatively impact transient voltage stability. However, the finding for this system is that variation in dynamic load behavior is not critical for evaluating HC.



(a)



(b)

Fig. 4: Time-series outputs from load 7051 with hourly composite load model parameters for [a] hours 1-12 and [b] hours 13-24

IV. Impact of Seasonal and Loading Variations on Transmission HC

This section evaluates HC of the 2,000-bus synthetic system for different seasonal and loading scenarios. The seasonal and loading scenarios were developed in [27]. The evaluation of conditions, stability, and capability of systems throughout numerous seasons and loading is critical for operations and planning in transmission systems. For example, the Bonneville Power Administration incorporates seasonal base cases into their short-term available transfer capability (ATC) methodology [36]. The goal of the evaluation of HC across the seasonal and loading scenarios in this study is to highlight the impact that season and loading can have on HC and also to identify specific system conditions or factors that limit the HC.

The HC in this section was determined using $N-1$ line loss steady state contingencies. Steady state contingencies are used here instead of transient contingencies to reduce the computational burden of evaluating $N-1$ line loss contingencies, which total 3,206 contingencies. The same number of allowed violations per contingency used in Section II are used to determine the HC in this section. In addition to the limits used in Section II, 32 unsolved contingencies out of the 3,206 are also allowed before the limit of the HC is reached.

A. Results

A total of eight scenarios are evaluated in this section, a high (peak) and low loading for Spring, Summer, Fall, and Winter where each season has a different generation profile. These scenarios are generated from yearly time series data taken at the lowest and highest load time periods for each season. The resulting HC for each scenario is illustrated in Figure 5.

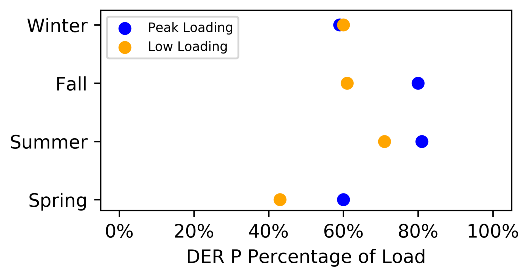


Fig. 5: Seasonal hosting capacity results for high and low loading scenarios for each season. The hosting capacity is the DER active power (P) as a percentage of load at each load bus. The high or peak loading is in blue and the low loading is shown in orange.

The resulting HC across all seasons and loading scenarios varies greatly between seasons with a total range of 20%. Additionally, all but one season, winter, has high HC in the peak loading scenario in comparison to the low loading scenario. For explanation of these results the HC values were compared to several system level factors. The system level factors included reserve amount, generation amount, and linear sensitivity factors such as weighted transmission loading relief (WTLR). The system level factors considered were:

1) Generation Amount (MW and Mvar)
2) Generation Downward Capability (MW and Mvar)
3) Generation Upward Capability (MW and Mvar)
4) Wind Generation (MW)
5) Generation Outage Capacity (MW)
6) Transmission Outage Capacity (MVA)
7) Percent of Branches over 50% loaded

The generation amount, downward and upward capability, generation outage capacity, and transmission outage capacity all relate and can act as a system reserve. Numerous studies have shown that system reserves impact the amount of wind generation that can be stably integrated in transmission systems [37], whose impact in terms of uncertainty and variability is similar to DERs. Since this test system has a high presence of wind generation both the wind generation and system reserves could be a limiting factor in HC. Additionally, in these test cases the dispatch of wind generation is not curtailed or determined by unit commitment. The percent of branches over 50% loaded is in reference to their pre-contingency state. Therefore, this percentage is likely impacted by wind generation amount, and could also be a potential limiting factor.

Each of these factors were compared against the HC for all scenarios to determine if trends arose to suggest if certain factors were key limiting or dominant factors. Of the factors evaluated, only three showed strong trends: reactive power generation amount, active power wind generation amount, and percent of branches over 50% loaded. These data and their corresponding trend-lines are shown in Figure 6.

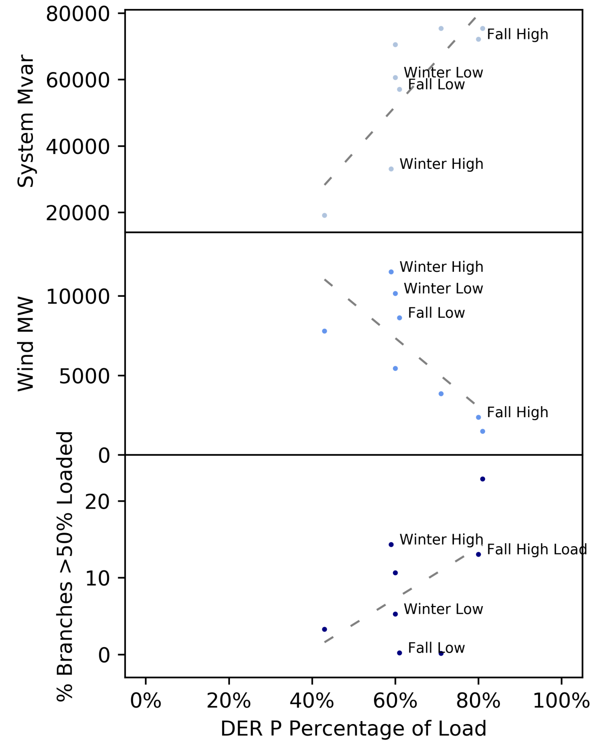


Fig. 6: Trends between system conditions and hosting capacity

Since the trend between peak and low loading for each season was flipped for the winter season, the peak and low loading scenarios for the Fall and Winter months are annotated in Figure 6. This is to show how the flip between peak and low loading also appears in the trend between the HC and system level factors.

As the amount of reactive power in the system increases and the HC increases, this trend is seen throughout all scenarios. The amount of reactive power in the system contributes to the voltage stability. In distribution systems, increasing DER generation causes a reduction in voltage stability by causing over-voltage within a feeder. The trend seen here suggests that reactive power supply is also a limiting factor for HC in transmission systems as well. The increase in wind active power generation results in a decrease in HC. It is likely due to this shift in generation, specifically in the areas where wind generation is present, that causes greater stresses in the system as seen by the increase in percent of branches over 50% loaded that cause a decrease in HC. The effective reduction in load, due to an increase in DER contribution in these steady state contingencies, reduces the loading on the branches. Therefore, the greater the initial loading on branches present in the high loading seasonal scenarios the more room to accommodate DERs and greater the HC.

The HC trends were then compared to where the violations in the system occurred at the HC limit for each scenario.

TABLE II: R-values for correlation relationship between area location of limiting contingency elements and the violation elements of the contingency for against the amount of reactive power generation, active power wind generation, and percent of branches over 50% loaded in each area.

	Reactive Power Generation by Area	**Active Power Wind Generation by Area**	**Percent of Branches over 50% Loaded by Area**
Contingency Element Area	-0.014	0.511	0.480
Violation Element Area	0.106	0.604	0.396

The contingency elements that caused more than 100 violation limits and the elements that reached a violation were binned into each of the areas of the system. The area locations of the contingency elements and the violation elements were then compared to the amount of reactive power generation, active power wind generation, and percent of branches over 50% loaded in each area. The test system has eight areas which combined with the eight seasonal and loading scenarios created 64 data points to compare to determine a correlation. The correlation r-values were calculated for these three factors and are shown in Table II.

A strong correlation relationship exists with a r-value of 0.5 or greater for a strong positive relationship and -0.5 or lesser for a strong negative relationship. Strong relationships are seen between both contingency element area and violation element area and wind generation confirming the relationship between hosting capacity and wind generation. The greater the amount of wind generation the lower the hosting capacity. The relationship with branch loading is almost strong, and weak relationships exist with reactive power generation by area. It is also likely that the branch loading is a result from wind generation amount. We also note that the wind generation trend is the only one where the trend between high and low loading scenarios between Fall and Winter scenarios switches. There is greater wind generation during the winter high loading scenario than the winter low loading scenario. This flips for the Fall season where there is more wind generation in the Fall low loading scenario than the high loading scenario. This is the only factor where this flip in the trend between Winter and Fall low and high loading scenarios of hosting capacity and the system factor exists. This implies that the greatest determining factor in these scenarios is wind generation amount as it is the only factor whose trend applies to all high and low seasonal scenarios, including the flipped low and high loading scenarios in the Winter season. These results suggest that the most limiting factor toward HC of DERs in this test system is the amount of wind generation. In the setup of these scenarios wind generators do not participate in any curtailment or unit commitment and they are located in select areas, located in five out of the eight areas, versus throughout all areas of the system. This study also does not include DERs in unit commitment or dispatch or curtailment. This lack of dispatch control of wind generation and DERs from the utility reduces the stability of the system in the case of high penetration of DERs. Strategic curtailment of DERs and wind generation has the potential to increase the overall hosting capacity of DERs and is an area of future work. A key takeaway from these results is unit commitment and dispatch of all generation in the system plays an important role in the ability of the system to host DERs.

V. Conclusion

This paper outlines the increasing need to assess DER HC on the transmission grid as the generation contribution of DERs increases. This study investigates the impact of modeling factors on transmission HC results on the 2,000-bus synthetic grid overlaid on the Texas Interconnect. The modeling factors assessed include transient versus steady state contingencies, dynamic load and DER models including voltage support control, variation in dynamic load model composition, and seasonal and loading scenarios. The results demonstrate transient stability conditions are more limiting to HC than steady state stability conditions. Within transient contingency evaluations of HC the results vary between only 5% of DER contribution versus near 20% between transient and steady state evaluations. The use of voltage support controls within the DER dynamic model are proven to increase the HC in the system by 4%. The dynamic load composition variation assessed for this system makes no impact on the HC, however it is not guaranteed to be insignificant for all transmission systems. The seasonal and loading variations illustrate great differences between the resulting HC and highlight the need to assess the HC for numerous system scenarios to confirm system capabilities, as is similarly done in utility operation and planning methods. The impact of wind generation in this system also becomes a critical factor to HC. This is likely due to dispatch strategy employed in this system and indicates the need for inclusion and evaluation of dispatch of all resources if DERs are going to be integrated in transmission systems at high contributions.

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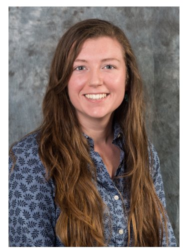

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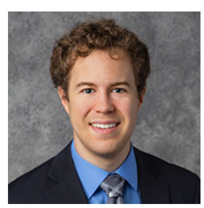

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