SPP Grid Strength Study with High Inverter-Based Resource Penetration

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Abstract- **As inverter-based resource (IBR) capacity and penetration increase in today's electric power systems, there is increasing concern with respect to system stability and security. Southwest Power Pool (SPP) is aggressively pursuing security certainty as its footprint experiences remarkably high penetration levels of IBR. Recent studies performed by the Electric Power Research Institute (EPRI) and SPP were conducted to determine the stability margin of SPP's system when high levels of renewables are present. This paper discusses the impact of inverter-based resources with respect to system strength and provides study results showing areas in the SPP footprint that could experience power electronic inverter instability due to large disturbances.**

Index Terms— **Critical clearing time, inverter based resources, inverter instability, short circuit ratio, solar, wind**

I. INTRODUCTION

ELECTRIC POWER systems around the world are changing from systems of the past that were owned by siloed, regulated utilities with one-way power flows and slow controls to those that are unregulated with bi-directional power flows, dynamic power electronic based fast controls, and more prosumer oriented customers. These changes have ushered in the era of the smart grid. Smart transmission systems such as time synchronized phasor measurements can now give operators wide-area, dynamic insight into system conditions. Power electronic devices are increasingly being used for power flow and voltage control. The operation of existing grids is becoming more efficient through technologies such as optimized switching algorithms and dynamic line rating. Distribution systems are becoming highly automated with smart meters and solid state micro-electronic fast acting protection schemes.

Generation has also undergone tremendous change. Over the last 25 years, the world has seen remarkable growth in renewable resources. Figure 1 shows recent wind and solar penetration records for selected worldwide locations [1]. This graphic shows the Southwest Power Pool instantaneous IBR penetration record was set in 2017 at 52%; however, SPP has since attained an instantaneous wind penetration of 67.3%, with an additional 1.5 GW of market-based curtailments. Expected IBR capacity in SPP is 23 GW by 2020 and 28-33 GW by 2025. As more renewable capacity is brought on line, competitive and environmental pressures are forcing many coal plants into retirement. Studies are now being performed to determine the impact of 80 - 100% inverter-based generation [2], something that would never have been considered ten years ago.

table 1. The wind and solar penetration level records for various regions.

Region	Country	Instantaneous Penetration of Asynchronous Generation as a Percentage of Load	Annual Penetration of Asynchronous Generation as a Percentage of Load	Peak Load (MW)
CAISO	United States	49% (2017)	27% (2016)	46,232 (2016)
Denmark	Denmark	140% (2015)	42% (2015)	6,000 (2013)
EirGrid	Ireland	60% (2017)	22% (2016)	4,700 (2016)
Electric Reliability Council of Texas	United States	50% (2017)	15% (2016)	71,000 (2016)
MISO	United States	22% (2016)	8% (2016)	120,700 (2016)
Portugal	Portugal	105% (2016)	23% (2015)	8,300 (2015)
South Australia Grid	Australia	119% (2016)	35% (2016)	2,895 (2016)
Southwest Power Pool	United States	52% (2017)	14% (2015)	50,083 (2016)

Fig. 1. Wind and solar penetration [1]

Growth in renewable generation does not come without its challenges. Forecasting wind and solar availability has long been difficult due to its stochastic nature, leading to wind and solar generation dispatching and ramping challenges. The so-called "duck curve" [3] has garnered attention due to increased solar causing a misalignment of peak solar capacity and demand. Degraded frequency response due to decreased inertia is certainly a topic of worldwide discussion as increased renewables displace conventional generation. The impact on system frequency due to behind-the-meter distributed generation (mainly solar) is also a topic of great interest. A large number of power system transient stability studies with large wind and/or solar penetration levels have been performed to determine the electro-mechanical response of synchronous generation. As generation shifts to more renewables, flow patterns change and voltage instability can occur.

The question of how inverter-based controls can affect the system and other inverter controls has recently become a very pertinent question and topic of interest. There have been numerous isolated events wherein inverter controls have not operated as expected by traditional bulk power system operating standards. With hundreds of MW of IBR coming into the generation interconnection queues, the growing intensity of occurrence of such events can be a cause of concern to a transmission planner. Thus, metrics to identify possibility of occurrence of inverter control instability in a large bulk power system is the topic of this paper.

Part II provides a brief dialogue on types of inverter-based renewable generation and Part III discusses the present industry understanding of the impact of the power electronic converters used in IBR on the bulk electric power system. Part IV discusses the potential stability impact of IBR on weak grids. Part V provides the background and assumptions for the SPP study to determine potential problematic areas on the SPP system, if any, as a result of IBR installed at weak points on the grid. Part VI provides study results and conclusions are drawn in Part VII.

II. TYPES OF INVERTER-BASED RENEWABLE GENERATION

Wind and solar generation differ from conventional generation in that there is no rotating mass cycling in synchronism with the system electrical frequency. The voltages and currents produced interact with a decoupling dc bus and must be converted to ac for grid interconnection. Newer wind turbines, mostly Type 3 and 4, utilize power electronic converters to provide power and voltage control. Solar PV installations have no moving parts at all and require converters as well. These converter interfaces are constructed at the wind turbine or solar PV array to convert the generated variables, i.e. voltage, current, power, etc., to 60 Hz ac power frequency values.

A. Wind Generation

There are generally four utility-scale wind turbine technologies in use today. These are shown in figure 2 and are briefly described below.

1. Type I – Squirrel Cage Induction Generator

This older type of wind generator is considered fixed speed and has no power electronics. It cannot control voltage, thus requires external shunt capacitors for power factor correction.

2. Type 2– Wound Rotor Induction Generator

This generator has a variable external rotor resistance with power electronics driven by pitch regulated blades for constant power output. This WTG cannot control voltage, thus also requires external shunt capacitors for power factor correction.

3. Type 3 – Doubly Fed Induction Generator

This generator is driven by variable speed, pitch regulated turbine blades. The variable frequency supply is fed into the rotor windings through a back-to-back converter, achieving variable speed operation. Independent control of active and reactive power is achieved through rotor-side converter control.

4. Type 4 – Full Converter Synchronous Generator

The generator is driven by variable speed, pitch regulated turbine blades. The generator variable output is directly coupled to the network through a full power back-to-back converter, provided voltage and power control.

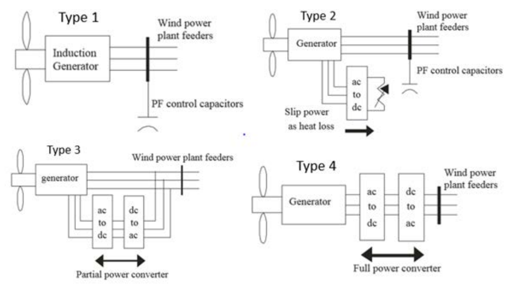

Fig. 2. Wind turbine technologies.

B. Solar PV Generation

The dc output of solar PV generation is interfaced with the power system through a power electronic based converter system as shown in figure 3. Whether the system is single phase as in rooftop solar or three phase utility scale, the operation is similar. There is a myriad of multi-level conversion topologies in use today for solar PV. These inverters can control both real and reactive power and can achieve voltage control as required.

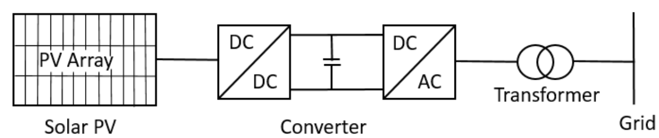

Fig. 3. Solar PV technology.

III. IMPACT OF INVERTER TECHNOLOGY ON BULK POWER SYSTEMS

As the percentage of wind and solar has increased, there has been increased interest in potential impacts to grid security for major disturbances.

Inverters can enter what has been termed "momentary cessation", an operating mode used by inverters where they momentarily cease current injection into the grid when voltages fall outside their predetermined threshold values. Momentary cessation is a mode of operation that was considered to be admissible in distribution systems due to the unique nature of voltage control equipment and power flow direction in distribution systems. Its use in bulk power system connected IBR was not expected. However, inadvertent use of momentary cessation in bulk power system IBR has recently been brought to the attention of solar manufacturers, utilities, and researchers alike due to the outages associated with the 2017 Blue Cut and Canyon 2 fires in the western U.S. where wildfires caused momentary cessation of 900MW and 1200MW of solar power output respectively [4][5]. Among the issues found were:

- slow wind plant ramp rate limiter interactions preventing the fast resumption of pre-disturbance active current injection levels,
- susceptibility of inverters to tripping due to instantaneous transient overvoltages,
- inverter tripping due to phase-lock loop fault codes de-synchronizing the plant to the grid,

- inverter tripping due to dc reverse current fault codes in the plant control systems,
- apparent inter-relationship between in-plant shunt compensation, sub-cycle transient overvoltage, and momentary cessation that results in inverter tripping,
- erroneous plant tripping based on near instantaneous frequency measurements due to system fault generated transients.

The Australia blackout of 2016 is also of interest to the industry as over 450MW of wind generation went off-line due to system faults during a severe weather event. An investigation determined that hard coded lockout schemes within inverter controls were a primary contributor to the loss of wind power [6].

Interactions between adjacent wind farm controls or adjacent HVDC controls can also occur as noted in [7].

In [8] it is shown that increasing the levels of inverter-based renewables can cause destabilization of inter-area modes of oscillation. Small signal stability studies can be used for analysis and can be accomplished through state space methods using a linearized model of the system as shown in equations (1) and (2),

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{1}$$

$$y(t) = Cx(t) + Du(t) \tag{2}$$

where x is the state vector, u is the control vector, y is the output vector, A is the state matrix, B is the input matrix which includes the forced oscillation input, C is the output matrix, and D the transition matrix. The authors show that increased IBRs could potentially destabilize the inter-area mode, particularly when the IBR is installed in an importing area, producing a destabilizing effect that is attributed to the reactive power control of the wind turbine generator.

Lastly, an electrically weak bus or area can have an adverse impact on the inverter-based generator performance [9]. Grid strength can be described as the degree of power system "stiffness" with respect to voltage and frequency. A strong bus would experience relatively small voltage changes due to a disturbance and larger changes would occur at a weak bus. Grid strength is location specific and can be defined at a particular bus or group of buses and largely depends on generation mix and grid topology.

When connecting an inverter-based resource, the relative strength or weakness is normally measured at the point of interconnection (POI) using the conventional Short Circuit Ratio as shown in equation (3).

$$SCR = \frac{SCMVA}{MW} \tag{3}$$

where the numerator SCMVA is the available short circuit power at the point of interconnection and the denominator is the MW capacity of the resource being connected.

In [9] and [10], ERCOT and GE have provided insight into grid strength by providing methods to calculate the strength where multiple inverter based resources are connected to the power system electrically close to one another, taking into account the effect of control interactions between wind plants. The Weighted Short Circuit Ratio (WSCR) and the Composite Short Circuit Ratio (CSCR) are defined in equations (4) and (5).

$$WSCR = \frac{\sum_i^N SCMVA * MWi}{\sum_i^N MWi} \tag{4}$$

$$CSCR = \frac{MVA}{MW} \tag{5}$$

There is no consensus on the ratio value that defines "weak" and "strong"; however, research shows that weakness seems to be associated with values from less than 3 to less than 6. For instance, in [11] it is proposed that an SCR between 5 and 3 at the POI should be considered weak and an SCR less than 3 is very weak. Where multiple windfarms are electrically close, the minimum value of the SCR, WSCR, or the CSCR should be used. In this paper we will note an SCR less than 6 as weak.

It should be noted that these ratios should only be used to screen the system under study. Low ratios are not a true indicator of system stability issues when studying the fault response of systems with high levels of IBR. Additional analysis with transient stability software is sometimes used; however, present state of the art positive sequence dynamic models do not adequately capture the response of the fast control loops within an IBR control system such as the Phase Lock Loop (PLL) under weak grid conditions. A transmission planning engineer must then rely on additional tools such as an Electromagnetic Transient (EMT) software to provide a trustworthy representation of the response [11] [12].

IV. IBR AND SYSTEM STRENGTH DURING A SEVERE FAULT

In [13], phase lock loop stability has been defined as the ability of an IBR to remain synchronized to the grid subsequent to a large disturbance. The PLL in the IBR controller is the mechanism that tracks the angle of the grid to maintain synchronism with the grid.

It is described in [14] that during a severe disturbance, the impedance as seen from the IBR POI can be high, hence a low SCR and a weak grid connection can exist during the duration of the fault. The weakness of the connection will cause larger excursions of terminal voltage during the Low-Voltage-Ride-Through (LVRT) period than would not otherwise occur for conventional resources. Since, as shown in figure 4, the terminal voltage V_T is input to the PLL, which determines the angle of the IBR injected currents and thus the voltage, the high impedance condition causes the output PLL frequency ω_{pll} to move away from the nominal grid frequency.

Even if the pre-fault grid at the wind farm is strong, it can become weak during the fault, and also after a fault due to outages of lines. Regardless, PLL stability should be taken into consideration when studying the stability of IBR due to large disturbances.

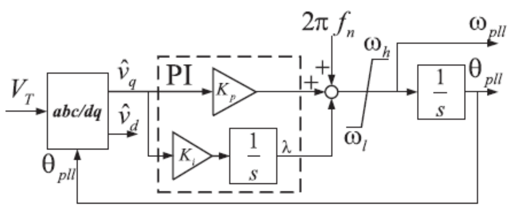

Fig. 4. PLL control block diagram.

The evaluation of the inverter PLL to maintain synchronism during power system disturbances (i.e., fault conditions) is an active area of investigation by researchers ([17]-[19]). In the most standard PLL configuration as shown in Fig. 4, measurements of the inverter output voltage in *abc*-variable are transformed to the *dq* synchronously rotating reference frame using the PLL estimated value of the phase angle θ_{pll}. The resulting value for $\hat{v}_q$ thus fulfills the role of the phase-error signal in a classical PLL. The gains K_p and K_i are selected in a manner such that the error between the estimated and actual voltage angles of the grid interface $\varepsilon = \theta_g - \theta_{pll}$ goes to zero. A general large-signal stability requirement can be stated in terms of the grid impedance Z_g between the IBR voltage V_g and the POI in terms of the injected current I_{IBR}. Stated as an inequality for PLL stability [19], it can be shown that it is necessary for

$$I_{IBR} < \frac{V_g}{|Z_g \sin \varepsilon|}. \quad (6)$$

Consequently in order to maintain PLL stability for a given grid voltage V_g, an increase in either the grid impedance or the PLL error requires a reduction in the amount of IBR output current.

V. SCOPE OF STUDY FOR SPP'S SYSTEM

Southwest Power Pool is a Regional Transmission Organization having members in 14 states in the Midwest U.S. The SPP system consists of approximately 5000 substations, 66,000 miles of transmission, and 800 generating plants with a generating capacity of 90GW, 20GW of which wind. As previously mentioned, SPP has recently experienced a record 71% instantaneous wind penetration. With another 8GW of wind under construction and 5GW of signed interconnection agreements as of this writing, wind growth within SPP's footprint is continuing to exceed expectations. The generation interconnection queue has grown exponentially with over 70GW of Wind and 25GW of Solar presently being queued for study.

These developments are the genesis of SPP's recent initiation of the Inverter-Based Integration Study (IBIS) study, which will determine the impact of high levels of IBR with respect to the stability and security of the system. One aspect of this study was a collaboration between SPP and the Electric Power Research Institute (EPRI) on the issue of system strength. The goal of this phase of the project was to determine the existence (if any), the cause, and the impact of inverter controls interactions due to grid weakness and high levels of IBR on system stability and security within its footprint. Initial work, which is the subject of this paper, consisted of determining weak buses and weak areas in the SPP footprint by calculating the short circuit ratios as SPP desired to understand the relative strength and weakness at system buses with interconnected IBR.

A 2018 Light Load model with 23.6 GW of load (42% of peak load) was chosen as the study case with wind penetration set at 62.5%. Transmission branch outages were introduced to replicate actual SPP Operations outages during the light load period.

One hundred and sixty (160) existing wind plant locations along with sixty (60) in the generation interconnection queue were selected for study. EPRI's Grid Strength Assessment Tool (GSAT) [15] was used to study the selected locations. The GSAT software screens hundreds of buses based on short circuit current to evaluate SCR, WSCR, and CSCR. Additionally, it also provides insights into possible controller instability for those locations deemed to be of low SCR. It further determines locations where possible controller interactions among plants electrically close to one another may exist.

VI. SCR STUDY RESULTS

Figure 5 is a depiction of a typical wind farm connected to the SPP grid. The POI bus is delineated from the IBR terminal bus to show the two are separated by an impedance that will, depending on the complexity of the wind plant/feeder network, result in a range of differing SCRs at the IBR terminal bus when compared to the POI.

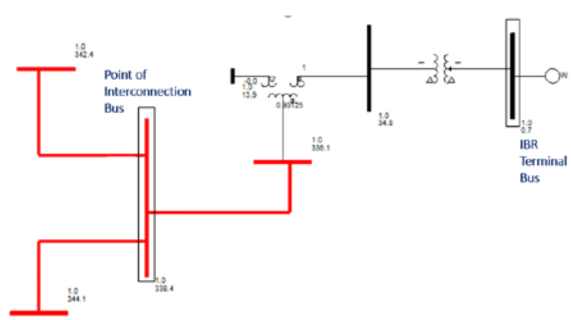

Fig. 5. Typical IBR connection to SPP grid.

Using EPRI's GSAT software, SCRs at both the POI and the IBR terminals were determined for the 220 locations in the study. The histograms in figure 6 show that there is a wide range of SCR values, particularly when measured at the POI. It is clear that the SCRs are higher, meaning stronger conditions, at the POIs. Five (5) POI SCRs were found below 6.0, which was the threshold used for weakness.

It should be noted that even though the resulting SCRs were lower at the IBR terminal in every instance, the measurements at the POI more adequately described the strength. This is because the IBR terminal bus is not the physical bus at the turbine controls, but is a single imaginary collective bus used to model the entire wind farm with its controls.

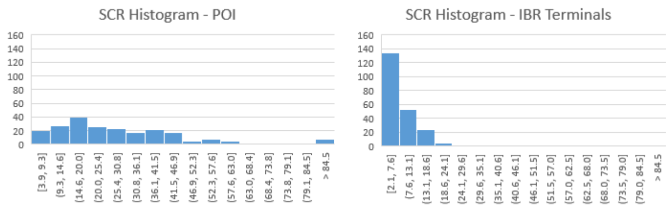

Fig. 6. SCR histograms for POI and IBR terminals.

It is shown in [16] that low or high ratios do not necessarily indicate inverter instability. Since the total picture isn't revealed with the ratio alone, a new metric designated as Critical Clearing Time (CCT) developed by EPRI was used [16]. In the context of this study, the critical clearing time is the maximum time for which a fault can remain on the system before the occurrence of inverter controller instability. EPRI's GSAT software calculates this value at every IBR location specified by the user. The calculated CCTs are shown in figure 7 plotted on a logarithmic y-axis. The figure shows most CCTs were above 9 cycles, which is SPP's threshold to determine if further study is required. Four (4) locations were however found with CCT below 9.0 cycles as denoted by the red squares in the figure.

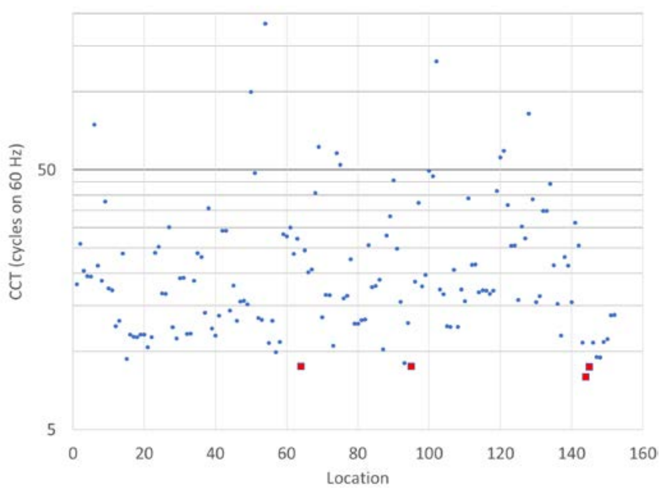

Fig. 7. Critical clearing times.

Based upon both the SCR thresholds and the CCT thresholds, it was possible to use EPRI's GSAT to screen through all 220 locations in a quick and efficient manner. The locations with a higher probability of inverter instability were then filtered as tabulated in tables 1 and 2. Table 1 shows the locations with SCRs below 6 with corresponding CCTs and the table 2 shows the locations with CCTs less than 9 cycles with corresponding SCRs. For locations 183 and 163, the CCT could not be evaluated as the corresponding locations were part of the generation interconnection queue and thus in this analysis were either out of service or at 0 MW. In order to evaluate CCT, the corresponding inverter plant has to be generating MWs in the system snapshot considered as the MW output level of the plant plays a crucial role in the value of the CCT. A lower value of MW output would result in a higher CCT and vice versa for a higher value of MW output.

The entirety of SCR and CCT data for the IBR 220 locations shows there is a low correlation between the two metrics, meaning a low SCR does not imply a low CCT and a high CCT doesn't imply a high SCR. In selecting the location for EMT analysis, the location with both low SCR and CCT was desired; however, tables 1 and 2 show there is no location that violates both the SCR and the CCT thresholds. Location 149 however was selected for further study based on engineering judgment.

Table 1: SCRs < 6.0

Location	SCR (POI)	CCT (cycles)
136	3.9	15.2
183	4.8	
90	5.0	45.6
163	5.5	
149	5.5	10.9

Table 2: CCTs < 9.0 Cycles

Location	SCR (POI)	CCT (cycles)
144	17.5	8.0
145	23.2	8.7
64	20.6	8.8
95	26.3	8.8

The impact of contingencies on the SCR and CCT was also considered. SPP's contingency screening process was used to determine the contingencies that would be used for this analysis. This process screens all buses in the system above 100 kV to determine the locations that are most vulnerable to transient instability and ranks them in order using a ranking index. Eight (8) contingencies (FFS1 through FFS8), three (3) N-1 and five (5) N-1-1, were selected and included in the power flow analysis to determine the impact of each on both SCR and CCT. The graphs in figure 8 compare the change in SCR from the base (N-0) value for each of the eight contingencies, measured at the POI and the IBR terminals. It is concluded that the SCRs are not adversely impacted due to these contingencies. FFS6, FFS7, and FFS8 appear to cause significant changes; however these differences are expected as the SCRs are relatively large in the base case, hence these changes do not provide additional information regarding the strength of the network for these contingencies.

Figure 9 shows the CCT at each POI bus for all eight contingencies compared to the base case, again plotted on a logarithmic y-axis. The results show the CCTs change very little. While it appears that all the contingencies are not shown in the figure, closer examination reveals all eight contingency cases, along with the base case are clustered together for each bus, meaning no significant difference. These results reveal there is no impact on CCT due to these contingencies.

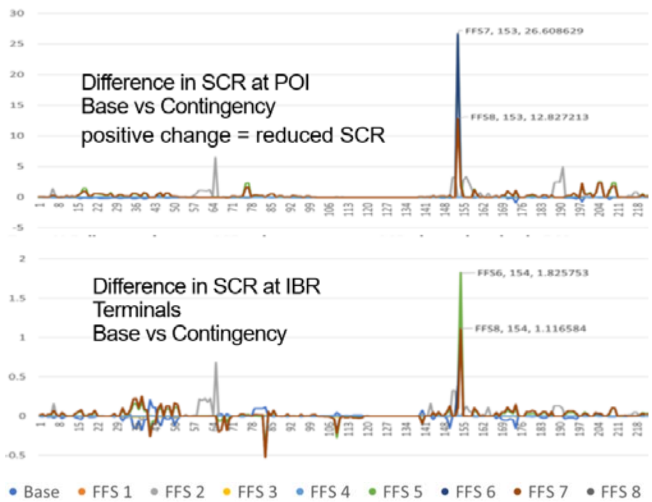

Fig. 8. Impact of contingencies on SCRs.

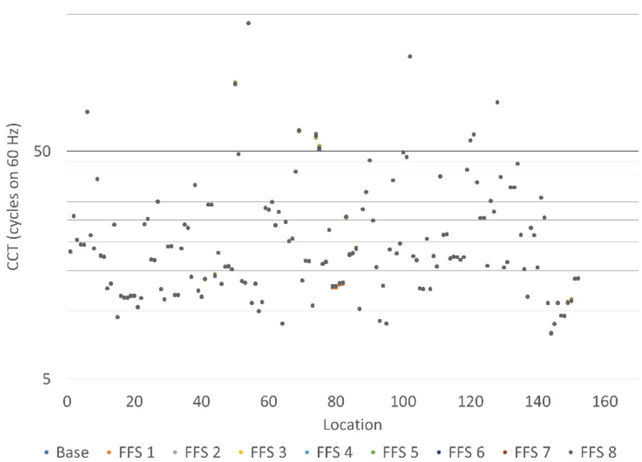

Fig. 9. Impact of contingencies on CCTs.

VII. CONCLUSION

In this paper, the various types of IBR interactions that can be of concern while planning for the increase in percentage of IBR in a large bulk power system are first reviewed. As the percentage of IBR increases, correspondingly synchronous generation must be de-committed to maintain steady state power balance across the system. This, in combination with the large geographical distance between new IBR plants and the transmission system, can result in a reduction of available system short circuit strength at IBR locations. A low short circuit strength can result in fast IBR controls becoming unstable. Thus, prior knowledge of locations with possibility of instablity must be identified, especially if the location is in an existing generator interconnection queue. The results of such a screening analysis across SPP's footprint have been shown in this paper.

Ongoing work by EPRI and SPP will include the analysis of location 149 using EMT analysis since location 149, along with IBR locations in its electrical vicinity, could experience inverter instability. It is worthwhile noting that selecting location 149 does not necessarily imply that inverter instability exists at the wind plant, but that among the 220 locations analyzed in this study, it is has a higher likelihood for inverter instability since it has the lowest SCR/CCT combination.

VIII. ACKNOWLEDGEMENT

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