High Penetration of Inverter Based Resources Assessment on Stability and System Strength

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***Abstract*— In order to reach global objectives of minimizing environmental impacts attributed to power systems, further implementation of renewable energy sources is necessary. However, planning high penetration of renewables presents new control challenges for current power systems since most new technologies are power electronics based. This paper presents a methodology to evaluate possible control issues and solutions to guarantee system wide stability and identify weak points under high penetration of IBRs. The methodology uses both transient stability and system strength assessment of existing and planned IBR installations. Several system strength metrics are computed considering N-0 and N-1 contingencies. For the transient stability analysis, key parameters of the IBR dynamic model are adjusted to identify possible stability issues by the simulation of selected contingencies. The methodology identifies weak points in the power grid and control settings in the power plant and inverter controllers that negatively affect system stability. This methodology was evaluated with information from a utility company. The results suggest future points that require additional studies and a list of recommendations to include in stability guidelines for the secure interconnection of new IBRs in the Bulk Power System.**

Keywords*— *Inverter-based resource (IBR), Short Circuit Ratio, System Strength, Transient Stability, System Wide Stability, Local Stability.

I. Introduction

Stability evaluation is a well-known issue [1] in the operation and planning of traditional power systems, where synchronous generators predominate. However, with the penetration of renewable resources, the proportion of power generation from inverter-based resources (IBR) is increasing. It is expected that 36% of global energy demand will be met with renewable energy sources (RES) by 2030 [2]. As a result of further integration of IBRs, new planning procedures [3] have been proposed for stability [4], [5], as well as system strength evaluation [6], [7].

In this paper, a methodology for the evaluation of the stability and system strength of the system during network planning is proposed. The methodology assesses control and protection problems at the systemic level and identifies possible weak points at the local level, which could appear with the increase in the number of IBRs. The methodology is composed of two different analyses: the first analysis involves the evaluation of the system strength based on short circuit metrics and voltage stability [8] [9]. The second analysis involves the analysis of the transient responses of the system considering a set of contingencies. The methodology was evaluated using a network from a Transmission Owner (TO) and is illustrated using two scenarios: one with existing IBRs and another with high penetration of IBRs in the transmission network. As a result, the possible weak points of the network were observed, unstable responses of some plants were found, and recommendations were made to be included in the planning and operation criteria of this type of resource. In general, some alternatives to improve the system strength in weak areas are synchronous condensers, network upgrades or active power curtailment from the IBRs.

To show the methodology and its results, this paper is organized as follows: Section II presents the methodology for evaluating the systemic and local stability of the power system. In section III, a real network is presented as a case study. Section IV presents the results of the analysis. Finally, section V shows the conclusions.

II. Proposed Methodology

This paper proposes a methodology for the evaluation of systemic and local stability facing up a high penetration of IBRs. The proposal includes the location of weak points in the network to indicate possible plants or groups of plants that may present unstable responses at the local level, and the verification of the systemic response using transient simulations. Potential local problems were identified using system strength metrics, while systemic response was assessed through transient responses.

A. System Strength

System strength is defined as the ability of a power system to maintain a sinusoidal voltage wave with an established frequency and magnitude at a certain point in the network after a disturbance. Various metrics in the literature aid in the identification of weak points in the network and thus quantify voltage response stability at certain points. The metric magnitudes provide insight into whether or not a more detailed analysis is necessary to avoid possible control and protection problems at the local level. The common system strength metrics used are short circuit ratio (SCR), compound short-circuit ratio (CSCR), and location-dependent short-circuit ratio (SDSCR). Further analysis including benefits and drawbacks of every metric are discussed in [6] and [10].

Short Circuit Ratio (SCR): The most common metric used to determine the relative strength of a power system, the SCR is defined as the ratio between the short circuit apparent power of a three-phase fault at a given location in the power system to the rating of the IBR connected to that location, as shown in (1).

$$SCR_{POI} = \frac{SCMVA_{POI}}{MW_{IBR}} \tag{1}$$

where, $SCMVA_{POI}$ is the short circuit level in MVA at the point of interconnection (POI) without the current contribution from the IBR and MW_{IBR} is the rated power of the IBR that is connected at the POI. A low SCR (weak system) indicates high voltage sensitivity (magnitude and phase angle) to changes in active and reactive power injections or consumption. High SCR systems have low sensitivity and are predominantly unaffected by changes in power injection.

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Compound Short Circuit Ratio (CSCR): Commonly used when multiple IBRs are connected at the same POI, CSCR estimates the equivalent system impedance seen by multiple IBRs by creating a common medium voltage node and connecting all IBRs at that common node. The CSCR is defined according to (2).

$$CSCR_{POI} = \frac{CSC_{MVA}}{MW_{IBR}} \quad (2)$$

Where CSC_{MVA} is the compound short circuit in the common node without current contribution from the IBRs and MW_{IBR} is the sum of the nominal power of all the IBRs considered. Therefore, this method calculates an aggregate SCR for multiple IBRs. CSCR evaluation will provide a more accurate estimate of system strength compared to SCR values when more than one IBR is available.

Site Dependent Short Circuit Ratio (SDSCR): This method quantifies the power system strength with a single IBR in terms of the distance to the voltage stability limit [6]. The SDSCR is given by (3).

$$SDSCR_i = \frac{\left|V_{R,i}\right|^2}{\left(P_{R,i} + \sum_{j \in R, j \neq i} P_{R,j} w_{ij}\right)\left|Z_{RR,ii}\right|} \quad (3)$$

Where, $V_{R,i}$ is the voltage of the IBR at bus *i*, $P_{R,i}$ is the nominal power of the IBR at bus *i* connected in the POI, $P_{R,j}$ is the nominal power of the IBR at bus *j* in the power system, $Z_{RR,ii}$ represents the Thevenin impedance at node *i* in the equivalent two-node system, and w_{ij} is calculated according to (4).

$$w_{ij} = \frac{Z_{RR,ij}}{Z_{RR,ii}} \left(\frac{V_{R,i}}{V_{R,j}}\right)^* \quad (4)$$

SDSCR takes into account interactions between multiple IBRs at different sites by modeling the electrical connection between all IBRs. This allows for evaluation of the system strength in terms of the static voltage stability limits.

For the SCR, CSCR and SDSCR metrics, the range of values shown in TABLE I is commonly used for system strength assessment [6].

B. Transient Stability

Transient stability analysis identifies stable and unstable responses of a system after a disturbance. To perform this analysis, the following procedure is proposed: First, a load flow is performed for the base case scenario. This guarantees the convergence of the load flow and that the output power of each generator is within its capacity curves. Next, the dynamic simulation is carried out, including the dynamic models and the configuration of the protections of each plant and of the entire interconnection. Different representative contingencies of the system are selected for evaluation. The execution of the dynamic simulation shows the tripping of the protections together with the states of lines, generators and loads as results. This simulation is taken as the base case.

TABLE I. SHORT CIRCUIT STRENGTH ASSESSMENT

System	SCR	CSCR	SDSCR
Very Weak	$SCR < 2$	$CSCR < 1$	$SDSCR < 2$
Weak	$2 \leq SCR < 3$	$1 \leq CSCR < 2.5$	$2 \leq SDSCR < 3$
Strong	$SCR \geq 3$	$CSCR \geq 2.5$	$SDSCR \geq 3$

Subsequently, an evaluation of sensitivity is carried out by changing the control parameters at a systemic level of the base case. For this, the parameters of the dynamic model are selected and modified in accordance with the experience in IBR studies and with common industry standards such as NERC [11] and IEEE [12]. Parameters selected for sensitivity analysis include voltage droop, frequency droop, P and Q ramp limits, and fast voltage response gain. Finally, based on the simulation results, the base case is compared with the modified cases in order to identify the parameters associated with the dynamic model of the IBRs that influence the stability of the system.

III. STUDY CASE AND ASSUMPTIONS

A. System Description

The proposed methodology is evaluated using an IBR database from a TO, the data is adapted (location and operators/substations name) to avoid confidential property violations. The technical information is described in TABLE II. The evaluation of the stability and strength of the system was carried out for the conditions projected for the summer of 2026 using the light load scenario (50%) at full solar power, since this is the scenario that considers the least number of connected synchronous units and, therefore, represents one of the weakest conditions regarding a high number of IBRs.

For the analysis of the system strength, two scenarios are considered: a reference scenario with an expected penetration of IBRs and a scenario with high penetration of IBRs, both cases for the year 2026. On the other hand, for the evaluation of the transient stability, two scenarios are analyzed: the first considering the parameters provided of the IBRs by the future interconnections and the second modifying the key parameters of the IBRs to determine the possible impacts on stability performance.

1) *Baseline and High Penetration Scenarios:*

The baseline scenario used the most recent short-circuit and stability cases. 148 contingencies were selected and simulated in the areas close to the IBR projects. TABLE III shows the total number of conventional plants and IBRs of all network operators in the power system (Area A to I) for the stability and short-circuit simulation of both cases. For the base case, 10,683 MW of generation with IBRs, 14,964 MW of conventional generation. For the high penetration scenario, an IBR penetration of 16,561MW was assumed.

Fig. 1 shows the geographical location of the IBRs included in this study, where the blue points are the projects considered in the base case and the green points are the IBRs included in the high penetration scenario.

TABLE II. DESCRIPTION OF THE NETWORK

Network	Buses	Lines	Loads	Shunt	Generators
69	1156	1328	736	157	-
115	484	562	286	42	-
138	589	695	415	57	-
230	661	876	293	47	-
Total	**2890**	**3461**	**1730**	**303**	**428**

TABLE III. GENERATORS FOR CONVENTIONAL, BASELINE. AND HIGH IBR PENETRATION SCENARIONS, GROUPED BY AREA DISPATCH

Area	**IBR Base Case**		**High IBR Penetration**		**Conv. Plants**	
A to I	**No**	**[MW]**	**No**	**[MW]**	**No**	**[MW]**
Total	149	10,683	229	16,561	81	14,964

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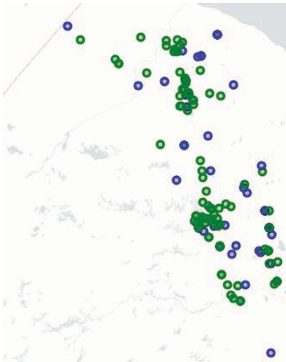

Fig. 1. IBR location, blue points are the IBR for the baseline and green points are the IBR for high penetration scenario

System Strength modeling considerations: First, a reference scenario is simulated assuming a WECC model [13] for each IBR project, considering the short-circuit cases that require a redispatch to accommodate all the additional power produced by the IBRs. The dispatch will be adjusted to the minimum and maximum power limits of each plant, as well as the generation limits of the combined cycle turbines with steam turbines and combustion turbines.

After obtaining the base case synchronous generation dispatch, additional IBRs are included to create a high penetration scenario. The settings for the Automatic Sequence fault Calculation (ASCC) module in the PSS/E software must be defined according to the operator's criteria. Finally, the short circuit calculation is performed for the high penetration scenario using PSSE, from which the system strength metrics are obtained. This calculation is made considering the contingencies N-0 and N-1 of the lines connected to the POI of each IBR. The SCR and SDSCR are calculated at the POI of each IBR. CSCR is calculated at POIs that are shared by multiple IBRs.

Dynamic modeling considerations: Dynamic simulations were run using PSS/E and automated with Python for results management. The following data was used to evaluate the transient stability: frequency deviation, voltage, and angles at the POI where the IBRs are connected, rotor angles of the synchronous generators, and active and reactive power of the IBR plants.

Operation criteria and sensitivity in control parameters: The operation criteria included the recommendations in [12], [14], and [15], the following recommendations were considered for the IBRs: after fault clearing, the active power ramp returns to pre-fault active current injection within 1 s. The generator controller's low voltage power logic (LVPL) ramp limit (Rrpwr) must be set to a value greater than or equal to 1.0 p.u./s. The plant must remain interconnected during a fault if the voltage levels and time remain within the no-trip zone of the NERC requirements [14]. Likewise, it is recommended to reduce momentary cessation through active power injection as equipment limitations allow. However, momentary cessation can be implemented in IBR models either in the inverter model (Zerox parameter) or by using the VDL1 and VDL2 features in the inverter models (REECA1 and REECCU1). Frequency relay models must avoid instantaneous tripping and include a time delay for signal filtering; it is recommended to set the pickup time to more than 0.1s. The dynamic models and their associated parameters can be consulted in [13].

Considering the above, for the sensitivity scenarios, the model parameters were modified as shown in TABLE IV (columns 'Value 1' to 'Value 3') according to the NERC recommendations. Only one parameter is changed in a scenario to evaluate its impact on the system. TABLE IV also shows the most frequent values for the provided dynamic models and the number of IBRs with this setting (e.g. "f droop up = 4% → 70" indicates that 70 IBRs have a droop of 4%)

IV. Results

The results of the simulations showed various points that may present stability problems at the local level and list the impacts of the control variables at the systemic level.

A. Stability Assesment

Several types of contingencies were simulated, including normally cleared faults, extreme contingencies with delay cleared faults, loss of substations, and loss of transmission right-of-way in accordance with NERC [16]. Frequency and voltage protections for generators, line relay protections and Special Protection Schemes were simulated. Fig. 2 to Fig. 4 show the total generation lost by disconnected machines, the active power curtailment of the generators, the frequency nadir and, finally, the damping of voltage, output power, rotor angles and frequency signals (following the definition in [12]).

According to the results, the following can be observed: The frequency loop parameters in the PPC model (REPCA1) do not have a significant impact on the transient behavior. Active power curtailment and machine tripping are not affected by changes in frequency droop or deadband.

The adjustment of the voltage droop in the PPC model to 5% or more improves the general performance of the system considering the decrease in the active power curtailment in the group of IBRs that present an active power block in comparison with the base case.

Droop values of 10% show a reduction in the voltage damping for most of the contingencies evaluated.

TABLE IV. Parameters Considered for Sensitivity analysis

Variable	Model	Value 1	Value 2	Value 3	Settings
Frequency Droop	REPCA1	5%	10%	-	f droop up = 4% → 70, f droop up= 5% → 50 f droop dn = 4% → 70, f droop dn= 5% → 46
Frequency deadband		0.0006	0.0003	-	fdbd = 0.006 → 91, fdbd = 0 → 25
Voltage Droop		5%	10%	-	Vdroop = 3% → 74. Vdroop = 0% → 25
Voltage dead band		0	0.001	-	Vdb = 0 → 122, Vdb = 0.001 → 24
PQ Priority	REECA1/ REECB1/ REECCU1	P	Q	-	P → 18, Q → 130
OVRT		1.2	1.15	-	Vup = 1.1 → 48, Vup = 1.2 → 44
LVRT		0.9	0.85	-	Vdip = 0.9 → 65, Vdip = 0.85 → 33
LVPL)	REGCA1	LVPLsw: 0	LVPLsw: 1 Brkpt = 0.8 Zerox = 0.79	LVPLsw: 1 Brkpt = 0.8 Zerox = 0	LVPLsw = 0 → 15, LVPLsw = 1 → 133 Brkpt = 0.8 → 105, Brkpt = 0.75 → 15 Zerox = 0.79 → 72, Zerox = 0.2 → 33
Rrpwr		1 pu/s	10 pu/s	0.5 pu/s	Rrpwr = 10 pu/s → 42, Rrpwr = 0.5 pu/s → 28

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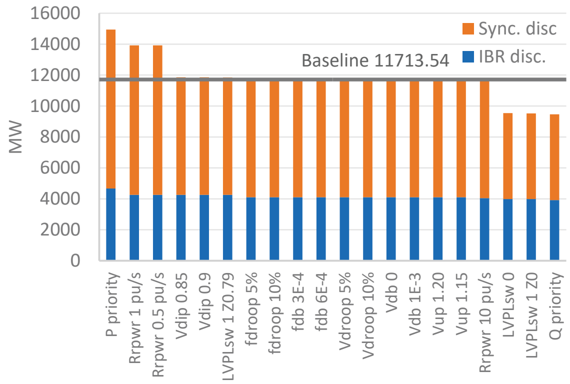

Fig. 2. Total generation disconnected per case

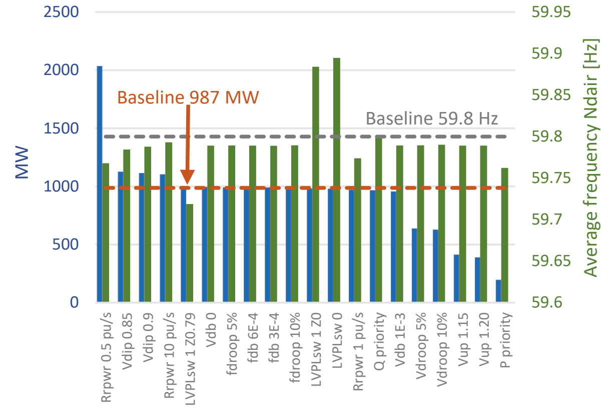

Fig. 3. Total active power curtailment and avg. frequency Nadir per case

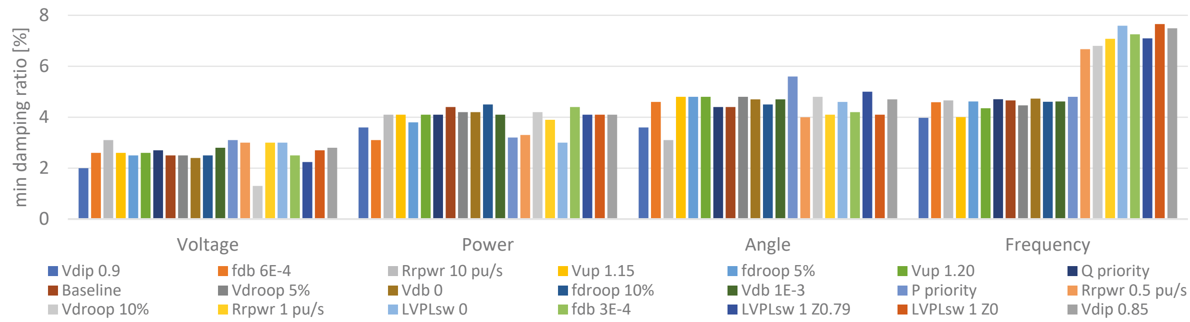

Fig. 4. Minimum damping ratio per signal

Changing the PQ priority in the electrical model gives opposite results as explained below: Enabling Q priority on all IBRs (19 out of 149 with P priority) avoids disconnection of the largest plant during a contingency; and considering all contingencies, there are fewer contingencies with machine disconnection and, therefore, a lower value of the total generation lost. On the other hand, enabling priority P on all IBRs decreases the total value of active power curtailment present on some inverters.

The change in the maximum limit to activate the injection of reactive power (Vup) does not affect the disconnection of the machines. However, there is a small increase in the total generation lost by modifying the minimum limit to activate reactive injection (Vdip). Regarding the active power curtailment, the change of the Vup solves the problems with some IBRs that enter this zone after clearing the contingency. For this reason, the amount of active power curtailment and the number of contingencies with curtailment is much lower when setting Vup higher than 1.15pu. Changing the minimum limit (Vdip) to 0.85 or 0.9 pu deteriorates the transient response due to increased active power curtailment.

The change in low voltage power logic (LVPL) does not affect the MW curtailment of the IBRs. However, there is an improvement in the number of contingencies with machine disconnection and the total generation lost by disabling this logic, or by changing the Zerox parameter to disable the momentary cessation on the generator.

The change in the power ramp in the generator model to 0.5 pu / s results in an increase in the active power curtailment and in the disconnected generation units. After fault clearing, active power ramping has no impact on disconnected generation in some areas, while other areas exhibit lower generation disconnection with active power ramps greater than 1 pu/s. Further analysis in additional geographic areas is required to determine specific ramp requirements to increase system safety. The total generation lost can be greatly improved by imposing Q priority on all IBRs and ensuring that the Active Ramp Limit (Rrpwr) parameter is greater than 1.0 p.u./s. Finally, the worst dampings appeared in the voltage signals. Keeping the voltage droop at 5% or less on the IBRs will help avoid any poor voltage damping issues.

Fig. 3 shows that the cases with lower value of average frequency nadir corresponds to where LVPL is enabled and momentary cessation is implemented in the generator.

B. System Strength Assesment

TABLE V shows the lowest system strength metrics for each voltage level for base case and high penetration scenario, these last values are shown in parenthesis. Since there are not multiple IBRs in the same POI for voltages below 500 kV the CSCR was not calculated for those buses in the baseline.

From the base case, the SCR and CSCR show that the system is considerably strong because there are no levels below 3, even for N-1 contingencies. Instead, the SDSCR shows that, for an area B contingency, the number of connected IBRs is creating weak zones in the power system.

TABLE V. LOWEST RATIOS PER VOLTAGE LEVEL BASE CASE AND HIGH PENETRATION (PARENTHESIS)

Volt	SCR		SDSCR		CSCR	
kV	Area	Val	Area	Val	Area	Val
69	B	1.8 (2)	B	1.2 (0.9)	B	(7.3)
115	A	5.4 (5.4)	A	1.7 (1.2)	A	(2.8)
138	A	5.1 (5.1)	A	2.2 (1.8)	A	(7.8)
230	B (E)	7.1 (3.7)	B	1.6 (1.1)	B	4.1 (1.8)

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For the 69kV network, the minimum SCR metric is slightly higher for the high penetration case due to the dispatch of the new generation and the power flow solution.

Fig. 5 shows the heat map for the SDSCR with all nodes of 115 kV or higher with or without IBRs for the N-0 contingency.

Fig. 6 shows the percentage decrease in SCR levels for the maximum load case compared to the light load case. As shown in Fig. 6, the light load case gives the worst possible scenario due to the decrease in synchronous generation. For the high penetration scenario, the SCR and CSCR do not show levels lower than 1, which suggests that the system is stable under the tested conditions. Finally, the SDSCR shows that there are 3 contingencies that could present unstable behavior due to the increase in IBRs. Furthermore, for this scenario, all the metrics suggest that there are several weak areas in the system considering N-1 contingencies.

V. Conclusions and Recommendations

In this paper, a methodology is presented to evaluate the stability of power systems under high penetration levels of IBRs in order to guarantee a stable and safe response.

This evaluation considers transient simulations to guarantee the stability of the entire transmission network. The simulations include sensitivity to changes in the control parameters of the IBRs that allow evaluation of generation disconnection, active power curtailment, frequency nadir and system damping after the appearance of an event.

The results show that the frequency parameters do not have a significant impact in the system stability. On the other hand, voltage droop, PQ priority, ramp rate limit, and momentary cessation play an important role for system stability. NERC recommendations shall be followed to guarantee a stable response.

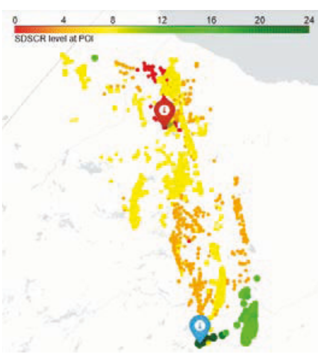

Fig. 5. SDSCR Heat-Map baseline case N-0 contingency

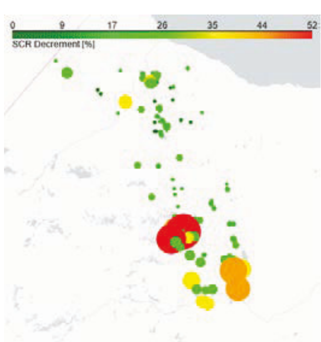

Fig. 6. Percentage decrement of the SCR levels of the peak case in comparison with the light case

On the other hand, the strength of specific points of the network is evaluated from short-circuit metrics and voltage stability at specific points. Analyses are performed under (N-0) and (N-1) conditions to identify weak points that suggest possible transient interaction or voltage instability of the IBRs.

The methodology was successfully applied in the interconnection of the power system and will allow defining the criteria for the adjustment of IBRs controls in the system and the planning and operation criteria facing a high penetration of IBRs. The methodology is applicable to any network that wishes to observe and create planning and operation criteria facing a high penetration of renewables.

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