IMPACT OF INCREASING DISTRIBUTED ENERGY RESOURCE PENETRATION ON THE SYSTEM STRENGTH OF ISLANDED GRIDS

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CONTENTS

SUMMARY

As renewable penetration increases, it becomes more challenging to integrate inverted-based resources into the existing power grid because it negatively impacts the system strength. The system strength is associated with the inverted-based resources' terminal voltage's sensitivity to its current injection variations. This sensitivity is low in a "strong" system but is high in a "weak" system.

Short Circuit Ratio (SCR) is a common index used to evaluate the system strength at the point of interconnection (POI) of a grid with renewable energy resources. However, the SCR cannot be easily applied to understand the system strength when several renewable resources are connected electrically close. To overcome this limitation, the Composite Short

Circuit Ratio (CSCR) approach developed by GE11 2 and the Weighted Short Circuit Ratio (WSCR) method developed by ERCOT3 have been widely applied by NERC1 and other utilities.

These methods have been proposed to determine the system strength for groups of inverted-based resources near each other. In this contribution, the CSCR and WSCR methods were applied to determine the impact on the actual system strength when future phases of energy resources are added to a grid with a peak load of ~200 MW with already high renewable penetration in the system.

The main objective was to evaluate the impact on the existing system strength of the future Phase 2 of renewable energy resources and the need for conventional generation connected to the system to meet the grid code requirement (both the CSCR and the WSCR metrics above 2.0). Finally, while the results discussed in this contribution were obtained at an islanded grid, we believe our findings are similarly applicable to non-islanded power systems with renewable resources in close proximity.

INTRODUCTION

In recent years, the scale of inverted-based resources (IBRs), such as wind, solar, and battery energy storage systems (BESS), has been increasing rapidly in many areas. The connection of distributed energy resources (DERs) to the power grid could bring great challenges to the voltage stability since the DERs are usually located in remote areas, and they could potentially be connected to weaker points of the existing power grid, which could be far away from load centers.

DER integration into a weak power grid can cause undesired system stability issues, particularly related to voltage stability. Therefore, examining the system strength for increased renewable penetration is significant given instability is more likely to occur at the weakest points. In addition, to further increase the penetration of renewable resources, evaluating the system strength is necessary. The system strength can be defined as the power grid's ability to maintain or restore voltage stability at the interconnection points of the renewable energy plants.

1 "Integrating Inverter-Based Resources into Low Short Circuit Strength Systems. Reliability Guideline," NERC. December 2017.

2 "Stable Renewable Plant Voltage and Reactive Power Control," NERC ERSTF. June 11-12, 2014. GE Consulting.

3 "Modeling Inverter-Based Resources in Short-Circuit Programs," EPRI. October 2020.

The SCR is the most basic and easily applied index to evaluate the system strength at the POI of a renewable power plant. The SCR has traditionally represented the voltage stiffness of a grid. The system strength evaluation using the SCR method only considers the connection capacity at the POI for a single renewable plant. However, the SCR method may provide an overly optimistic estimation of the system strength because this method does not take account the interaction between the renewable energy resources located nearby. The CSCR and WSCR methods were developed to take into consideration the effect of interactions between the adjacent renewable plants on the system strength.

The CSCR method assesses the system strength for a group of renewable plants connected to the same POI through the formation of a common medium-voltage bus. The WSCR method can define the system strength for a group of renewable plants connected to different POIs by assuming all DERs are connected to a virtual common bus. These two advanced methods can represent a better evaluation of system strength with high penetration of renewables in an islanded grid when additional renewable phases are added.

This paper aims to accurately determine the system strength for a power system that includes conventional generators, photovoltaic (PV) systems, and BESS to provide energy services on an island. The study focused on the impact of increased renewable plant penetration on the system strength by determining the system's CSCR and WSCR values. In addition, the impact of increased renewable resources on the system strength was evaluated. Both CSCR and WSCR were determined to assess the system strength under different system operating conditions, considering future load growth and increased renewable resources.

The remainder of this paper is organized as follows:

- In Section II, the mathematical expressions of the SCR, CSCR, and WSCR metrics are elaborated.
- In Section III, the system description, the CSCR-WSCR results, and a summary of results are presented. The impact of increasing renewable resources on the overall system strength also is analyzed.
- In Sections IV and V respectively, conclusions and future work are presented.

SYSTEM STRENGTH METRICS DESCRIPTION

In this section, the definition of the three system strength evaluation methods is provided.

Short Circuit Ratio

SCR is defined as the ratio of the short-circuit apparent power at the POI without current contribution from the IBRs, SC_{MVA}, to the nominal power rating of the IBRs being connected to the POI, MW_{IBRS}. Based on this definition, SCR is given by:

$$SCR = \frac{SC_{MVA}}{MW_{IBRs}}$$

A low SCR ("weak system") indicates high sensitivity of voltage to change in the IBRs' current contribution. High SCR ("strong system") indicates a low sensitivity and predominantly is unaffected by changes in the IBRs' current contribution. The SCR index is the commonly used calculation method when considering a single IBR operating into a power system. When electrical distances between IBRs are small, they may interact with each other and oscillate together. In such cases, the SCR-based system strength calculation method gives overly optimistic results.

Composite Short Circuit Ratio

To consider the effect of interaction between adjacent IBRs and, therefore, to get a better estimate of the system strength, a more appropriate quantity is the CSCR. This method ties all IBRs of interest together by creating a common medium-voltage bus.

The CSCR is defined as the ratio of the composite short-circuit MVA at the common bus without current contribution from the IBRs, CSC_MVA, to the sum of the nominal power rating of all IBRs connected at the common bus, MW_{VER}

$$CSCR = \frac{CSC_{MVA}}{MW_{VER}}$$

This method calculates an aggregate SCR for multiple inverter-based resources instead of each resource, as occurs with the conventional SCR approach. The CSCR is difficult to apply when a common medium-voltage level cannot be derived because the IBRs of interest are not connected to the same POI.

Weighted Short Circuit Ratio

To overcome the CSCR operational limit mentioned above, the WSCR method is proposed. The WSCR method assumes all IBRs are connected to a virtual bus. WSCR is defined as

$$WSCR = \frac{\sum_i^N SCMVA_i * P_{RMWi}}{\left(\sum_i^N P_{RMWi}\right)^2}$$

The CSCR and WSCR methods are typically used when a more accurate estimate of the system strength is required compared to the conventional SCR method when there are several IBRs connected in the vicinity.

SYSTEM DESCRIPTION AND CSCR- WSCR RESULTS

Power System Model Description

Power flow scenarios were prepared to conduct short-circuit studies to determine the system strength of the islanded grid under different operating conditions. CSCR and WSCR metrics were calculated using the approaches described1[4 5] assuming all existing conventional generation units available in the islanded grid are in service (regardless of the dispatching levels). Four additional conventional “main units” will be dispatched to provide additional system inertia to increase the system strength. The peak load of the islanded grid is about 200 MW.

The future renewable plants in Phase 2 were represented in the power-flow model as generators, and their corresponding impedances were set to limit their short-circuit contribution to 1.1 p.u. of their rated current. The power-flow model was configured and the short-circuit study was conducted, both using the Positive Sequence Load Flow (PSLF) software.

The following scenarios were implemented in the power-flow model:

- Phase 1 (existing)—320 MW of renewable energy resources in service (including PVs and BESS)
- Phase 2 (future)—Additional 400 MW renewable energy resources in service for a total of 720 MW (a 125% increase of renewable energy resources)

For each of the cases listed above, the power-flow cases were adjusted to reflect the following generation dispatch conditions:

a. All four main conventional generation units are out of service. All power was supplied by Phase 1 renewable plants (PV plants and existing energy-shifting batteries) connected to the system, including an existing 75-MW BESS.

b. Same as (a) with three main conventional generation units rated at 40 MW each, in addition to all existing conventional generation units available in the islanded grid (dispatched at their minimum output) and all the existing BESS are being charged by the excess of generation from conventional generators in the system.

c. Same as (a) with four main conventional generation units dispatched, in addition to all existing conventional generation units available in the islanded grid (dispatched at their minimum output) and all the existing BESS are being charged by the excess of generation from conventional generators in the system.

4 “Integrating Inverter-Based Resources into Low Short Circuit Strength Systems. Reliability Guideline,” NERC. December 2017.

5 “Stable Renewable Plant Voltage and Reactive Power Control,” NERC ERSTF. June 11-12, 2014. GE Consulting.

Table 1 lists the six power-flow scenarios implemented in the power-flow model to conduct the system strength analysis on the islanded grid. The dispatch conditions of the main conventional generation units are also shown in the table.

Composite and Weighted Short Circuit Ratio Results

Power-flow models were implemented for all six scenarios listed in **Table 1**. Automation scripts were developed to execute short-circuit studies for three-phase faults applied at relevant buses in the system. These scripts were executed after solving each of the power-flow cases while the fault current and pre-fault voltages at buses of interest were monitored. The CSCR and WSCR values were calculated using the methods and the equations described in the "System Strength Metrics Description" section **on page 3**.

TABLE 1. Summary of Power-Flow Scenarios Used for the System Strength Calculations for Renewable Phase 1 (Existing) and Renewable Phases 1 & 2 (Future)

Scenario	Renewable Phases	Main Unit 1	Main Unit 2	Main Unit 3	Main Unit 4
1	Phase 1 (existing)	no	no	no	no
2	Phase 1 (existing)	**yes**	**yes**	**yes**	no
3	Phase 1 (existing)	**yes**	**yes**	**yes**	**yes**
4	Phases 1 &2 (future)	no	no	no	no
5	Phases 1 &2 (future)	**yes**	**yes**	**yes**	no
6	Phases 1 &2 (future)	**yes**	**yes**	**yes**	**yes**

Table 2 shows CSCR and WSCR results for all six scenarios. In addition to having Phase 1 and Phase 2 existing and future renewable plants in service (scenarios 4, 5, and 6), scenarios 5 and 6 include the main units dispatched at 135 MW (scenario 5) and at ~200 MW (scenario 6). All existing conventional generators were dispatched at their minimum output, and all the existing BESS were being charged by the excess of generation from conventional generators in the system.

Representative CSCR and WSCR results for scenarios 3 (Phase 1—existing) and 6 (Phases 1 & 2—existing and future) renewable plants are shown in **Table 3 on page 8** and **Table 4 on page 9**. Results for the short-circuit MVA (SCMVA) obtained at the conventional generator terminals as well as the composite SCMVA and the SCMVA* PRMW product are listed in the tables, where PRMW is the MW output of IBRs to be connected at a particular bus. CSCR and WSCR results for those scenarios are indicated at the bottom of the tables.

TABLE 2. Summary of CSCR and WSCR Results (values<2.0 in bold)

Scenario	Renewable Phases	Main Units in Service	CSCR	WSCR
1	Phase 1 (existing)	none	2.40	**1.55**
2	Phase 1 (existing)	three	3.43	2.18
3	Phase 1 (existing)	four	3.62	2.28
4	Phase 1 & 2 (future)	none	**1.55**	**1.21**
5	Phase 1 & 2 (future)	three	**1.91**	**1.95**
6	Phase 1 & 2 (future)	four	2.02	2.04

TABLE 3. Representative CSCR and WSCR Results for Renewable and Conventional Generation Dispatch Scenario 3

Phase 1:

IBR	Rating (MW)	SCMVA*PRMW	Composite SCMVA
PV 1	25	6,201	1438
PV 2	30	20,747	1438
PV 3	30	20,747	1438
PV 4	30	7,629	1438
PV 5	30	7,149	1438
BESS 1	25	57,198	1438
BESS 2	16.2	17,714	1438
BESS 3	23.8	17,300	1438
BESS 4	24	31,380	1438
BESS 5	16	5,942	1438
BESS 6	16	11,065	1438
BESS 7	16	11,065	1438
BESS 8	20	5,086	1438
BESS 9	20	4,766	1438
75 MW BESS	75	135,948	1438

Summary:

Summary	Total
Total WSC MVA	359,936
Total Renewable MW	397
CSCR	3.62
WSCR	2.28

TABLE 4. Representative CSCR and WSCR Results for Renewable and Conventional Generation Dispatch Scenario 6

Phase 1:

IBR	Rating (MW)	SCMVA*PRMW	Composite SCMVA
PV 1	25	6,228	1446
PV 2	30	21,261	1446
PV 3	30	21,261	1446
PV 4	30	7,890	1446
PV 5	30	7,246	1446
BESS 1	25	62,607	1446
BESS 2	16.2	19,759	1446
BESS 3	23.8	17,667	1446
BESS 4	24	33,302	1446
BESS 5	16	5,984	1446
BESS 6	16	11,339	1446
BESS 7	16	11,339	1446
BESS 8	20	5,260	1446
BESS 9	20	4,831	1446
75 MW BESS	75	160,319	1446

Phase 2:

IBR	Rating (MW)	SCMVA*PRMW
BESS 10	80	325,250
BESS 11	80	108,247
BESS 12	80	108,247
BESS 13	80	108,247

TABLE 4. CONTINUED Conventional Generation Dispatch Scenario 3 Summary

Conventional Generation

Unit	MW (Max)	SCMVA
Main Unit 1	45	149
Main Unit 2	45	149
Main Unit 3	45	149
Main Unit 4	68	192
Unit 1 (x2)	10	34
Unit 2 (x2)	9	23
Unit 3 (x6)	26	58
Unit 4 (x3)	19	89
Unit 5	40	110
Unit 6	44	70
Unit 7	44	70
Unit 8	20	77
Unit 9	21	49
Unit 10	40	75
Total SC MVA		1,293

Summary of Phase 1 & Phase 2

Summary	Total
Total WSC MVA	1,046,285
Total Renewable MW	717
CSCR	2.02
WSCR	2.04

SUMMARY OF RESULTS AND DISCUSSIONS

The system strength of an islanded grid with a peak load of 200 MW and a total installed capacity of renewable resources of 320 MW was analyzed for different operating conditions, particularly to determine the impact of increasing the penetration of DERs on the grid. Composite and Weighted Short Circuit Ratio results for all scenarios indicate:

- Phase 1 (Scenarios 1, 2 and 3): CSCR and WSCR calculation results for Scenario 1 indicate the system strength is weak (WSCR=1.55 <2.0) when existing Phase 1 of renewable plants is connected to the system. However, it can be observed in Scenarios 2 and 3 that, as long as at least three main conventional generation units are dispatched (in addition to all the existing conventional generation units), the system strength remains above the minimum 2.0 grid requirement.
- Phases 1 & 2 (Scenarios 4, 5, and 6): Adding future Phase 2 of renewable plants has a negative impact on the overall system strength. It can be observed the CSCR values decrease between 35% to 44% (depending on the scenario) and the WCSR values decrease between 11% to 22% (depending on the scenario) when future Phase 2 is added. However, both CSCR and WSCR results meet the minimum 2.0 criteria if all four main conventional generation units are dispatched (in addition to all the existing conventional generation units).
- However, if there are not sufficient conventional generators in service because of retirement or maintenance, the system strength will degrade to an unacceptable level (CSCR or WSCR < 2.0). Thus, we recommend future studies to determine options to enhance the system strength, including installing synchronous condensers in appropriate locations.

CONCLUSIONS

This paper has discussed the impact of increased renewable energy resources in the system strength, particularly on an islanded grid. Composite and Weighted Short Circuit ratio calculation results on a system model with Phase 1 (existing) and Phase 2 (future) renewable plants support the following claims:

- WSCR calculation results for Scenario 1 indicate the grid does not meet the system strength criteria (WSCR = 1.55 < 2.0) when existing Phase 1 is connected, and the main conventional units are out of service. CSCR and WSCR calculation results for Scenarios 2 and 3 indicate the grid meets the system strength criteria (CSCR and WSCR >=2.0) when existing Phase 1 is connected as long as three of the main conventional units are in service. Thus, the main conventional units play an important role in the system strength when the existing Phase 1 of renewable plants is connected.

- CSCR and WSCR results show adding future Phase 2 also has a negative impact on the overall system strength. It can be observed that CSCR values decrease between 35% to 44% (depending on the scenario) and the WSCR values decrease between 11% to 22% (depending on the scenario) when future Phase 2 is added.
- CSCR and WSCR calculation results for Scenarios 4 and 5 indicate the grid does not meet the system strength criteria (i.e., both CSCR and WSCR < 2.0) when both existing Phase 1 and future Phase 2 are connected and there is fewer than three main conventional units in service. In general, it can be observed the system strength increases if the number of conventional generating units (including the main units) in service increases when both existing and future Phases 1 and 2 of the renewable generation projects are connected.
- Based on these results, it is recommended to perform studies to determine necessary measures to enhance the system strength in the future. One potential solution is to add synchronous condensers with proper size and locations to meet the CSCR and WSCR >=2.0 criteria because of the addition of the new renewable Phase 2, particularly when the main conventional units are out of service.

FUTURE WORK

Short-circuit study results for all six scenarios (see **Table 2 on page 7**) indicate the worst-case condition for CSCR and WSCR is observed in Scenario 4 when future Phase 2 is added and all the main conventional generator units are out of service. Based on this, it is recommended to conduct a synchronous condenser sizing study to determine its appropriate location and rating to meet the CSCR and WSCR >=2.0 criteria because of the addition of the new renewable Phases 2 and lack of conventional generators in the system. Another possibility to be considered is to convert some of the existing conventional generation units into synchronous condensers to meet the minimum CSCR and WSCR requirement.

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