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# Power Systems Performance Evaluation on High Renewable Penetration Levels ⋆

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**Abstract:** The paper proposes a novel approach for system performance measurement and evaluation on asynchronous generation high penetration levels scenarios. The concept of the Multi-Infeed Interaction Short Circuit Ratio (MISCR) is extended for multiple asynchronous sources. Different scenarios combining wind power penetration levels and capability factors are analyzed, considering the IEEE benchmark 39-Bus system modified and a simplified full converter (FC) wind generation model. The results suggests that the traditional approaches from the Short Circuit Ratio (SCR) be more conservative than the proposed methodology.

*Keywords:* System Performance, Renewable High Penetration, IEEE 39-Bus benchmark System, Multi-Infeed Interaction Short Circuit Ratio (MISCR)

## 1. INTRODUCTION

The raise of renewable sources penetration levels into electrical power systems experienced along the last few decades have been arousing a wide range of discussions about its operational security, efficiency, supplying reliability and operation economic aspects.

Currently, the renewable penetration levels reaches from 30% up to 40% of the annual amount of the energy supplying, as seen in Denmark and Ireland (ECREEE, 2016; EERE, 2018), with recent studies pointing to 70% in 2022 (IEA, 2017). The Brazilian electrical power system is expected to reach about 16% of renewable sources penetration up to 2029 (PDE, 2019), highlighting the wind power plants in its northeast region.

Its characteristic active generation variability due to weather conditions as the wind direction and speed, rainfalls and shading, figures out as one of the main challenges for its large scale integration within the conventional generation network. Some of its most imminent consequences are the decreasing of the system inertia and the voltage stability (Mohandes et al., 2019), which also takes place in the distribution network (Anju and Mampilly, 2018) and may be potentially increased with the popularization of the distributed generation plants. Such variability may even exceed the support capability of the ancillary services (Waite and Modi, 2019), raising the network operation complexity (Holttinen et al., 2009; Dudurych et al., 2016) and its planning of the expansion and operational costs.

The power systems strength measurement is usually addressed from the Short-Circuit Ratio (SCR). However, it does not provide a perception of the renewable penetration levels influence over the system reliability regarding the multiple interaction effects between the AC/DC power converters on the network performance. Therefore, the SCR index may offer a more conservative perspective for the renewable power plants performance in high penetration scenarios.

The paper addresses the application of the Multi-Infeed Interaction Short-Circuit Ratio (MISCR), proposed by Cigré (2008) for High Voltage Direct Current (HVDC) multiple infeeding systems performance measurement, instead, for renewable high penetration levels. From the Anatem™ software, different wind power penetration scenarios are explored for a simplified full converter (FC) model within the modified benchmark IEEE 39-bus system. A comparison between the system performance measurement from SCR and MISCR is addressed. The capability factor influence on the system performance measurement is also explored trough two wind conditions (WC) sets. The second section brings a general review about the MISCR index concept; a brief description about the 39-bus test system and the simplified FC model are presented in the third section. The results are discussed in the fourth section and, finally, the paper main contributions and conclusions.

## 2. THE MISCR INDEX

According to NERC (2018), the SCR index,

$$SCR_i = \frac{S_{CC_i}}{P_i}, \tag{1}$$

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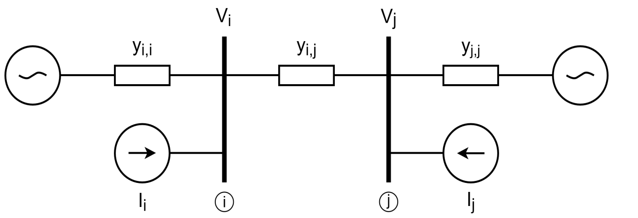


Figure 1. A generic two-bus test system representing any pair of buses of a real network.

dimensionless, is suitable for single-infeed systems or in those which the *i-esimal* HVDC link may be assumed isolated and there are no external influences on its performance, where $S_{CC_i}$ means its short-circuit level and $P_i$, its rated power. For multiple-infeed systems, although, the mutual interactions between the converter stations in the fed area must to be retained in order to improve the performance measuring.

The Multi-Infeed Interaction Factor (MIIF), proposed by Cigré (2008), provides a dimensionless electrical coupling measuring tool from the ratio between the application of a voltage step $\Delta V_i$ of 1% in a bus and the voltage magnitude variation $\Delta V_j$ per unit observed for a remote one after the power flow calculation, given by

$$MIIF_{j,i} = \frac{\Delta V_j}{\Delta V_i}. \quad (2)$$

Such definition have also been reviewed and new formulations proposed and discussed in recent works as seen in Aik and Andersson (2013); Zhou et al. (2016); Chen et al. (2017). According to Lirio et al. (2013) and Zhou et al. (2015), the electrical coupling can be measured from the bus impedances if neglected the network non-linearities. Assuming the system depicted in Figure 1, according the definition, the $\mathrm{MIIF}_{j,i}$ index can be expressed for any of system buses in terms of the network admitances from the voltage variation

$$\Delta V_j = \Delta I_{i,j} \frac{1}{y_{j,j}},$$

and once

$$\Delta I_{i,j} = \frac{y_{i,j} y_{j,j}}{y_{i,j} + y_{j,j}} \Delta V_i,$$

thus

$$\Delta V_j = \frac{y_{i,j} y_{j,j}}{y_{i,j} + y_{j,j}} \Delta V_j \frac{1}{y_{j,j}},$$

and finally, (2) can be rewritten as

$$\mathrm{MIIF}_{j,i} = \frac{y_{i,j}}{y_{i,j} + y_{j,j}}. \quad (3)$$

From the network topology, the bus admitances array can be expressed as

$$Y = \begin{bmatrix} y_{i,i} + y_{i,j} & -y_{i,j} \\ -y_{i,j} & y_{j,j} + y_{i,j} \end{bmatrix},$$

and, once inverted, yields to the bus impedances array,

$$Z = \frac{1}{(y_{i,i} + y_{i,j})(y_{j,j} + y_{i,j}) - {y_{i,j}}^2} \begin{bmatrix} y_{i,i} + y_{i,j} & y_{i,j} \\ y_{i,j} & y_{j,j} + y_{i,j} \end{bmatrix},$$

from which the MIIF index can be rewritten as a function of the network bus admitances and impedances arrays entries as

$$\mathrm{MIIF}_{j,i} = \frac{Y_{i,j}}{Y_{j,j}} = \frac{Z_{i,j}}{Z_{i,i}}. \quad (4)$$

The SCR definition, according to Cigré (2008), thus, can be extent to a multi-infeed scenario trough the MISCR index, given as

$$\mathrm{MISCR}_i = \frac{S_{CC_i}}{P_i + \sum_{j=1}^{N}(\mathrm{MIIF}_{j,i} P_i)}, \quad (5)$$

where the short-circuit level is given by

$$S_{CC_i} = \frac{1}{Z_{i,i}} = y_{i,i} + \frac{y_{i,j} y_{j,j}}{y_{i,j} + y_{j,j}}. \quad (6)$$

dimensionless, regards the *i-esimal* HVDC link considering its mutual contributions with each one of the $N$ existent DC links electrically close. Replacing (6) and (4) in (5) comes

$$\mathrm{MISCR}_i = \frac{1}{P_i Z_{i,i} + \sum_{j=1}^{N} P_j Z_{i,j}}, \quad (7)$$

as proposed first by de Toledo et al. (2005).

## 3. ANALYSIS MODELS

### *3.1 The Test System*

The original IEEE 39-bus test system (New England system), for small signal transient stability studies, found on Benchmark Systems for Stability Controls (2019), owns 10 synchronous generators to which identical voltage regulators (AVR) and stabilizers (PSS) controllers are associated. There are no voltage control equipment as tap changers transformers, synchronous or static condensers or overexciting limiters. All the system loads are modeled as constant power.

The machine in the bus 39 is assumed to represent the USA electrical power system dynamic equivalent. For the proposed analysis, such equivalent synchronous machine is replaced by a infinite bus model, being its AVR and PSS controllers removed in order to improve the system dynamical response leading, thus, to the referred modified test system.

### *3.2 The Simplified FC*

The device dynamics is provided by a current controlled source model in the Anatem™ software. As depicted in Figure 2, the User Defined Controllers (CDU) acts over a current controlled source in order to provide a certain amount of current injected in the system. The analysis

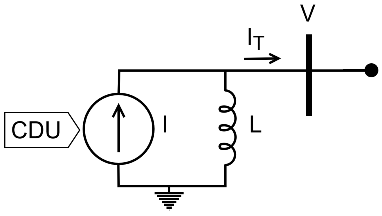


Figure 2. The Anatem™controlled current source schematic model.

assumes the typical wind farms models susceptance ($L$) found in the Brazilian stability simulations database about 2.3% (BDE, 2019). The unitary rated power is assumed, for convenience, as $100MVA$, with the minimum and maximum reactive power generation limits set as a function of the active dispatch, respectively, $-0.3pu$ and $0.3pu$ in the machine base. The simplified wind FC generation CDU design is presented in the Figure 3.

## 4. METHODOLOGY OF ANALYSIS

The points of common coupling (PCC's) for the wind power farms are arbitrarily set as a way to provide the different penetration levels. The number of units in each plant is set from the active generation ($P_g$) in the PCC in order to achieve a specific range of values for capability factors which characterize the WC scenarios. The first WC is assumed such that provides the plants capability factors about the typical Brazilian wind power plants value of 60% PDE (2019). Additional analysis are also carried out considering WC for capability factors about 40%. The Table 1 gathers the PCC's and capability factors obtained for each WC.

Actually, the number of operating machines is constant; the delivered power depends on the wind conditions. However, for the proposed analysis, to avoid major changes in the steady state scenario available, the capability factors are changed by increasing the number of machines in the PCC's.

Table 1. The 39-bus Test System Sets

| Bus | $P_g[MW]$ | $Q_g[MVar]$ | $1^{st}$ WC | | $2^{nd}$ WC | |
|---|---|---|---|---|---|---|
| | | | $N_{mach_1}$ | $F_{cap_1}$[%] | $N_{mach_2}$ | $F_{cap_2}$[%] |
| 33 | 632 | 109.60 | 10 | 63.20 | 15 | 42.13 |
| 35 | 650 | 210.60 | 11 | 59.09 | 16 | 40.63 |
| 36 | 560 | 102.90 | 9 | 62.22 | 14 | 40.00 |
| 37 | 540 | 0.21 | 9 | 60.00 | 13 | 41.54 |
| 38 | 830 | 23.21 | 14 | 59.29 | 20 | 41.50 |

From (7) and (3), the renewable high penetration problem can be assumed similar to a multi-infeed scenario, once there is a known mutual influence between the wind farms control. According to Palsson et al. (2002), the wind high penetration levels yields to a transient stability problem, once the active power generation varies with the wind speed changes in the order of seconds. The phenomena is better seen from the test system dynamic power-voltage (PV) relation shapes, as proposed by Corsi and Taranto (2007), depicted in Figure 4 for the bus 15 from different wind power penetration scenarios in the test system and the base case.

The results assumes a total increment about 110% along a simulation time of $600s$, for a constant impedance load. The voltage stability is clearly reduced as the wind penetration percentages increases, except for a penetration about 24%. Such result can be related with the higher reactive power dispatch by the plant in the bus 38 in comparison with that in the bus 35 combined with its the capability factor. The total reactive power amount dispatch is similar in the 19% and 24% of wind penetration scenarios, what is reflected in the PV curve shapes.

The highest penetration levels also provides PV curves shapes with less points in comparison with the base case, pointing to its mutual influence on the system dynamics once there are no other equipment able to act on such time scale.

## 5. RESULTS AND DISCUSSION

### *5.1 First Wind Condition*

The MIIF indexes between the wind farms PCC's computed from Anatem™software for each penetration scenario in the first WC are presented in the Table 2. The SCR and MISCR indexes regards a wind farm to be connected to the bus 33 are related in the Table 3 for the different penetration levels analyzed and the assumed PCC's, considering the active dispatch.

Table 2. $1^{st}$ WC MIIF Indexes for Bus 33

| Penetration [%] | MIIF to the PCC | | | |
|---|---|---|---|---|
| | Bus 35 | Bus 36 | Bus 37 | Bus 38 |
| 10 | 0.133 | 0.110 | 0.074 | 0.060 |
| 19 | 0.133 | 0.111 | 0.104 | 0.062 |
| 21 | 0.242 | 0.140 | 0.062 | 0.062 |
| 24 | 0.135 | 0.112 | 0.063 | 0.097 |
| 39 | 0.294 | 0.274 | 0.127 | 0.077 |
| 52 | 0.302 | 0.292 | 0.124 | 0.127 |

Table 3. $1^{st}$ WC PCC, SCR and MISCR

| Penetration [%] | PCC | $P[MW]$ | $Q[MVar]$ | MISCR | SCR |
|---|---|---|---|---|---|
| 10 | 33 | 632 | 109.60 | 3.74 | 3.74 |
| 19 | 33 e 37 | 1172 | 109.81 | 3.42 | 3.72 |
| 21 | 33 e 35 | 1282 | 320.20 | 2.87 | 3.58 |
| 24 | 33 e 38 | 1462 | 132.81 | 3.29 | 3.71 |
| 39 | 33,35,36 e 37 | 2382 | 423.31 | 1.99 | 3.29 |
| 52 | 33,35,36,37 e 38 | 3212 | 446.52 | 1.73 | 3.19 |

As expected, the penetration level increasing is followed by a SCR and MISCR decreasing, what points that the system becomes weaker as so as higher the wind generation percentage is. The performance of the wind farm placed in the bus 33 would be compromised anyway, but the MISCR reveals the mutual wind generation control influence effects on the system behavior, suggesting an evaluation more critical than that provided by the SCR .

The SCR and MISCR indexes values increase observed from the wind penetration percentage of 21% to the 24% one can be related, in the first, exclusively with the higher $S_{CC}$ but, in the second, both with it and the lower MIIF index, as seen from Table 2, respectively, about 0.242

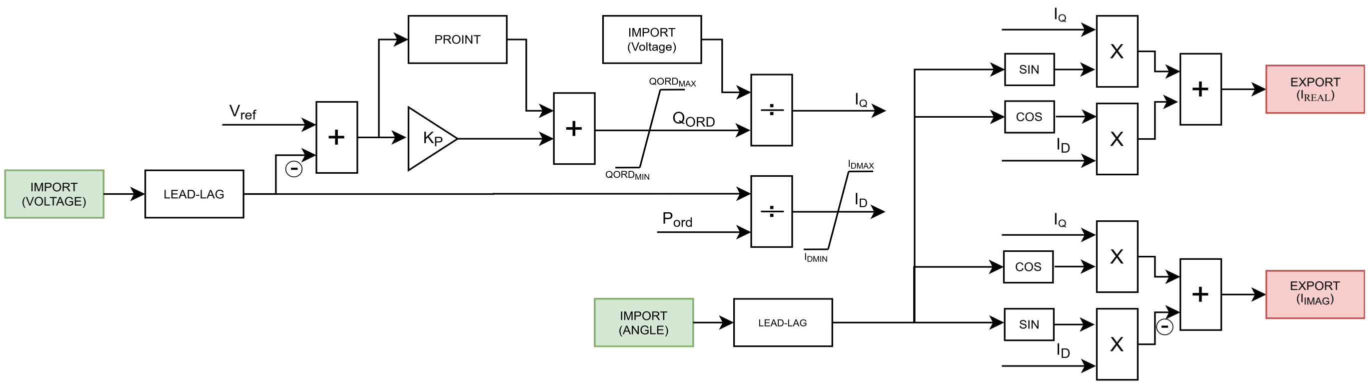


Figure 3. The wind simplified FC generation CDU diagram.

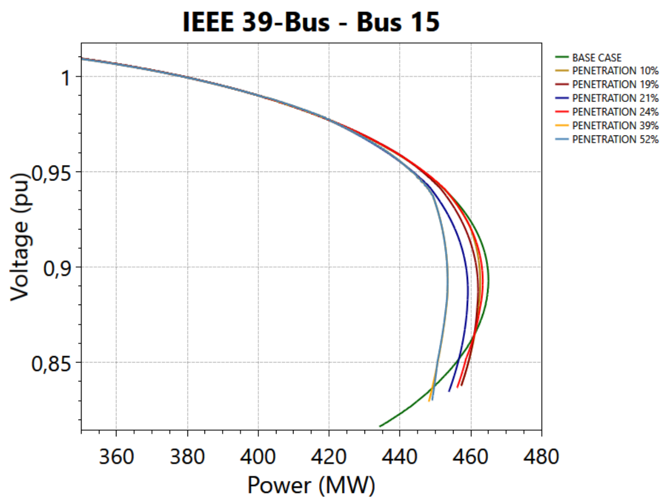


Figure 4. The IEEE 39-bus test system PV curves for the bus 15 from different wind power penetration levels considering the first WC.

from the bus 33 to the bus 35 and 0.097, to the bus 37, despite of the higher rated power of the wind farm in the bus 38 in comparison with that in the bus 35. Such results suggests the influence of the electrical coupling in the system performance measuring.

### *5.2 Second Wind Condition*

The computed MIIF indexes, as in the previous case, are presented in the Table 4. The SCR and MISCR indexes are related in the Table 5 for the different penetration levels analyzed.

Table 4. $2^{nd}$ WC MIIF Indexes for Bus 33

| Penetration [%] | MIIF to the PCC | | | |
|---|---|---|---|---|
| | Bus 35 | Bus 36 | Bus 37 | Bus 38 |
| 10 | 0.133 | 0.110 | 0.074 | 0.060 |
| 19 | 0.133 | 0.111 | 0.104 | 0.062 |
| 21 | 0.241 | 0.139 | 0.062 | 0.062 |
| 24 | 0.134 | 0.111 | 0.063 | 0.118 |
| 39 | 0.305 | 0.294 | 0.123 | 0.074 |
| 52 | 0.065 | 0.011 | 0.160 | 0.063 |

The both indexes still decreases as the penetration level increases. The results corroborates those observed for the

Table 5. $2^{nd}$ WC PCC, SCR and MISCR

| Penetration [%] | PCC | $P[MW]$ | $Q[MVar]$ | MISCR | SCR |
|---|---|---|---|---|---|
| 10 | 33 | 632 | 109.60 | 3.74 | 3.74 |
| 19 | 33 e 37 | 1172 | 109.81 | 3.42 | 3.72 |
| 21 | 33 e 35 | 1282 | 320.20 | 2.87 | 3.58 |
| 24 | 33 e 38 | 1462 | 132.81 | 3.21 | 3.71 |
| 39 | 33,35,36 e 37 | 2382 | 423.31 | 1.96 | 3.29 |
| 52 | 33,35,36,37 e 38 | 3212 | 446.52 | 2.46 | 3.19 |

first WC when comparing the penetration scenarios of 21% and 24%. However, the electrical coupling influence in the system performance measurement from MISCR index is clearly identified from the comparison with the previous result for a penetration of 52%, once the $S_{CC}$ is the same for both WC despite of the MIIF indexes are not.

The indexes magnitudes smooth reduction regards the first WC points to the influence of the parallel susceptance from the current controlled source model. The increase of the number of units leads to the wind farm parallel equivalent susceptance reduction, thus, the MIIF between the PCC's reduction, once it is a function of the network impedances, as shown in the section 2. Such results suggests that the system performance measurement can be also influenced by the wind farms active dispatch.

## CONCLUSIONS

The paper analyzed the effects of the renewable generation mutual influence on the system performance measuring by proposing the application of the multi-infeed MISCR index instead of the traditional approaches based on the SCR. As an illustrative case, different wind power penetration and two WC scenarios are evaluated for the test system. The results points that the SCR provides a more conservative measurement than the MISCR index in terms of the system performance, once the mutual influence is not considered in the first. The results analysis also reveals the system performance evaluation susceptibility to the wind farms active dispatch. In future works, authors intent to investigate the renewable high penetration issues in the Brazilian electrical power grid 10-year forecast scenarios, tracing a system performance profile.

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