Impact of Cascade Disconnection of Distributed Energy Resources on Bulk Power System Stability: Modeling and Mitigation Requirements

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Abstract—**This work presents a new approach to establishing the minimum requirements for anti-islanding protection of distributed energy resources (DERs) with focus on bulk power system stability. The proposed approach aims to avoid cascade disconnection of DERs during major disturbances in the transmission network and to compromise as little as possible the detection of real islanding situations. The proposed approach concentrates on the rate-of-change of frequency (RoCoF) protection function and it is based on the assessment of dynamic security regions with the incorporation of a new and straightforward approach to represent the disconnection of DERs when analyzing the bulk power system stability. Initially, the impact of disconnection of DERs on the Brazilian Interconnected Power System (BIPS) stability is analyzed, highlighting the importance of modeling such disconnection in electromechanical stability studies, even considering low penetration levels of DERs. Then, the proposed approach is applied to the BIPS, evidencing its benefits when specifying the minimum requirements of anti-islanding protection, without overestimating them.**

Index Terms—**Anti-islanding protection, bulk power system, stability, distributed energy resource (DER), dynamic security region (DSR).**

I. Introduction

THE inertia reduction caused by the increase of inverter-based generation is being observed in several power systems over the world. At the same time, the development of distributed energy resources (DERs) connected at the medium- and low-voltage networks represents the decentralization of significant amounts of generation. In this scenario, the discoordination between DER protection and bulk power system requirements may deteriorate the dynamic performance and directly impact the system stability. One important aspect in this regard is the anti-islanding protection, which is essential to avoid dangerous situations for equipment and people in case of distribution network separation from the main grid [1]. As a result, such a condition is generally not allowed by distribution utilities. Moreover, a number of potential technical issues can arise, which include poor power quality, inadequate grounding, loss of protection coordination, and difficulties in automatic reclosing processes [2], [3].

In order to avoid unintentional islanding, anti-islanding protection is required from DERs. Passive strategies can be adopted such as underfrequency/overfrequency functions (81U/O), rate-of-change of frequency (RoCoF) function (81R), and vector shift function (78V) [4]. For inverter-based DERs, active techniques can also be considered such as the negative current injection method and the Sandia frequency shift approach [5].

In order to ensure islanding detection, even in the scenarios with low power exchange with the main grid, distribution utilities generally recommend using very sensitive settings for anti-islanding protection [6]. Nevertheless, a tight setting can lead to maloperation of the anti-islanding protection for the disturbances in the transmission network that cause voltage and frequency variations at the DER connection point. In this scenario, a cascade disconnection of DERs can be observed since their protection would incorrectly interpret the disturbance as an islanding. Depending on the amount of DERs affected, this cascade disconnection can severely impact the dynamic performance and stability of bulk power system. As an example, [7] illustrates two faults that occurred in the California transmission system in 2016 and 2017, which were correctly cleared by the protection system. However, in both cases, the disturbance led to the disconnection of a significant amount of photovoltaic (PV) generation (1200 MW in 2016 and 900 MW in 2017), worsening the dynamic performance of bulk power system. Another actual massive disconnection of DERs after a major disturbance in the transmission system occurred in 2019 when the Great Britain experienced a blackout [8]. In that case, the disconnection of approximately 500 MW embedded generation has contributed to the underfrequency load shedding scheme operation.

The impact of massive disconnection of DERs has recently gained more attention due to the significant increase in the penetration level of these devices in distribution networks. As a result, the way these resources respond to distur-

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bances in the transmission grid has changed from minimally consequential to potentially critical.

In [9], the main impacts of high penetration levels of DERs, particularly PV units, on the operation of bulk power systems are presented. References [10]-[12] focus on illustrating the risks of cascade disconnection of DERs after faults in the transmission system as well as the associated impacts on the bulk power system performance. Reference [13] proposes a grid-tied PV inverter with low-voltage ride-through (LVRT) capability, reactive power support, and islanding protection. In [13], the DER can provide 1.5 s of LVRT and disconnect the inverter within 2 s in case of islanding while satisfying new grid codes. In general, these references analyze the events with severe voltage variations, but do not consider the disturbances with relevant frequency excursions caused by the disconnection of large generation blocks.

In this context, technical standards and grid codes are being modified to incorporate supportability requirements in order to avoid cascade disconnection of DERs after the events in the transmission network, as discussed in [14].

This paper presents a new approach to determining the minimum requirements for anti-islanding protection functions with focus on bulk power system stability. The proposed approach concentrates on the RoCoF and it is based on dynamic security regions (DSRs) with the incorporation of modeling the disconnection of DERs. The anti-islanding function based on the RoCoF has been chosen because, with growing penetration of inverter-based generation and the consequent reduction in the inertia of the power systems, an increase in the RoCoF has been observed. Thus, too sensitive settings for this protection function can increasingly lead to cascade disconnection of DERs, which demands the definition of the minimum requirements not to compromise the bulk power system stability.

The approach is applied to the Brazilian Interconnected Power System (BIPS), which has already experienced unexpected disconnection of DERs, but its grid codes still do not contain any anti-islanding protection requirement.

This paper is organized as follows. Section II presents the background including a brief discussion on anti-islanding protection settings as well as on DER representation in stability analysis. The proposed approach is described in Section III, which also revisits some basic concepts regarding DSRs. Section IV presents the impacts of cascade disconnection of DERs on BIPS stability as well as the results obtained with the proposed approach. The main conclusions and contributions of this work are addressed in Section V.

II. Background

A. Anti-islanding Protection Settings

Islanded operation frequently occurs without prior knowledge or technical support from the distribution operator. As a result, the common practice requires disconnection of DERs either within 2 s after the formation of the island or before the first reclosing attempt [6]. In order to meet those requirements, very sensitive settings are typically employed in anti-islanding protection. In Brazil, distribution companies usually oblige disconnection of DERs for frequencies below 59.5 Hz, since there is no national regulation that requires the coordination between distribution and transmission systems, as recently established in [15] and [16]. In practical situations, it is usual to find settings from 0.1 Hz/s to 1.0 Hz/s for 81R, and 3º to 10º for 78V. These sensitive settings are important to reduce non-detection zones yet they may cause a cascade disconnection of DERs.

B. DER Representation in Stability Analysis

The database adopted by transmission operators for transient stability analysis traditionally contains detailed models of generators, high-voltage DC (HVDC) systems, and flexible AC transmission system (FACTS) devices. Wide area protection systems and special protection schemes (SPSs) are usually fully represented as well. Besides, the distribution network is typically included as an equivalent load at the boundary substations that connect transmission and distribution systems. Consequently, DERs are not modeled in detail and their effect is indirectly considered in the net load, as illustrated by the equivalent model in Fig. 1(a). The net load is the gross load subtracted by the generation values of DERs.

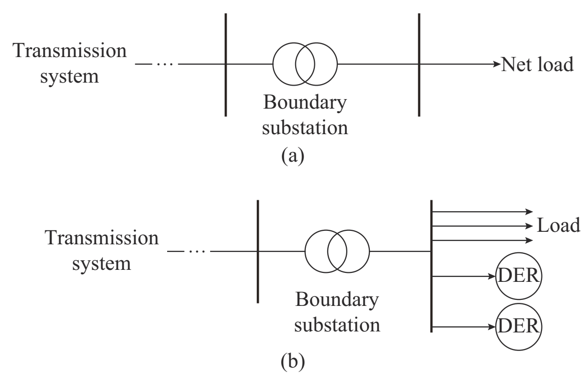

Fig. 1. Equivalent and detailed models of distribution network. (a) Equivalent model. (b) Detailed model.

A detailed model of loads and DERs, as illustrated by Fig. 1(b), is still unusual in transient stability analysis, although it would ease the incorporation of DER protection modeling. Such a representation would be unpractical if one considers the huge amount of required data and the associated simulation burden. Therefore, an alternative modeling strategy is needed which is integrated in the proposed approach, as described in Section III.

III. Proposed Methodology

This section presents a new approach to determining the minimum requirements for DER anti-islanding protection with focus on bulk power system stability. Initially, the proposed approach is presented to represent DER anti-islanding protection in transient stability simulations.

A. Representation of DER Anti-islanding Protection in Stability Analysis of Bulk Power System

In stability analysis, most DERs are incorporated to the load and an equivalent model is adopted, as shown in Fig. 1(a). In order to keep such an equivalent representation, this paper proposes that the DER anti-islanding protection is modeled at the load buses. In this case, if the anti-islanding protection is sensitized, i. e., underfrequency or RoCoF pickup conditions are reached, the protection operation will result in the connection of an additional amount of load at that bus. The additional connected load when the relay operates actually represents the disconnection of DER by the anti-islanding protection. While the underfrequency relay model measures the absolute frequency value, the RoCoF relay model considers the RoCoF over an averaging window of 0.1 s.

In this straightforward approach, the DERs are not modeled in detail, as shown in Fig. 1(b). Instead, only their anti-islanding protection relays are included, whose operation results in a load increase, as seen by the transmission system.

To validate this modeling approach, the disconnection of DERs has been simulated in the BIPS considering both the equivalent and detailed models. The results are shown in Fig. 2 for a typical boundary bus that connects transmission and distribution systems. Three operation points with different load values are analyzed. For each operation point, the generation loss of a certain amount is simulated, as indicated in Fig. 2. The penetration level of DERs is 5% in relation to the amount of the equivalent load in each scenario.

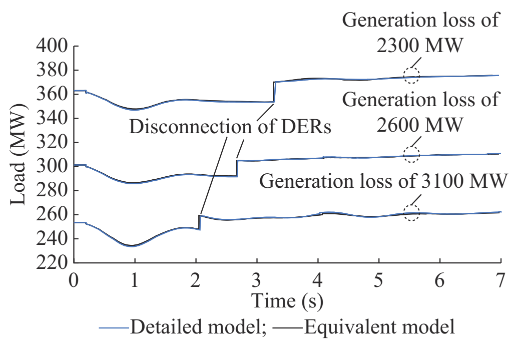

Fig. 2. Load behavior at a typical boundary bus after a generation loss for different operation points.

The simulation with detailed DER model, denoted as the DER_A model [17], has been adopted. The aim of the DER_A model is to represent the aggregate behavior of many small-scale distributed inverter-based generators in the positive-sequence stability analysis. In a nutshell, the DER_A model consists of six building blocks: a reactive power-voltage control, an active power-frequency control, a frequency tripping logic, an active-reactive current priority logic, a fractional tripping, and a voltage source representation. This model is adjusted without considering any DER support to the bulk power system. This is the current practice in the majority of DERs in operation around the world. Besides, in the simulation with equivalent model, the disconnection of DERs is modelled in a simplified way by increasing the amount of load. In both cases, the anti-islanding protection setting is 59.5 Hz with a time delay of 100 ms.

The generation blocks are lost at $t=0.2$ s and, after a few seconds, the anti-islanding protection is sensitized, thus disconnecting the DERs. As shown in Fig. 2, the proposed modeling approach provides an accurate result, indicating the load increase as seen by the transmission system, while preserving the equivalent model usually adopted in transient stability analysis of bulk power systems. The largest difference between the DER disconnection representations is smaller than 1%.

This straightforward approach is a modeling advance since the disconnection of DERs is usually neglected when performing operation planning analysis. In summary, to assess the impacts of cascade disconnection of DERs, especially originated by maloperation of frequency or RoCoF protections, this proposed approach provides good results when analyzing the global impact in the bulk power system. However, for higher penetration levels of DERs and considering that new DERs are able to provide dynamic supports to the bulk power system, more detailed models should be used such as the DER_A model. Also, the techniques based on co-simulation may be the way forward to have a detailed model of the distribution network [18].

B. DSRs

The approach proposed in this paper to determine the minimum requirements for DER anti-islanding protection is based on DSRs. Security regions allow a graphical visualization of redispatch margins of an electrical system for a given set of criteria, as illustrated in Fig. 3. These regions are computed from an operation point considering redispatches in different directions. The redispatches are performed at predefined generation groups (G1, G2, …, Gn) and the security regions are presented in the form of nomograms, which are two-dimensional graphics. It is important to emphasize that each generation group can be composed of several power plants. The choice of generators that will compose each group depends on the characteristics of each electrical system and the nature of the assessments that will be carried out.

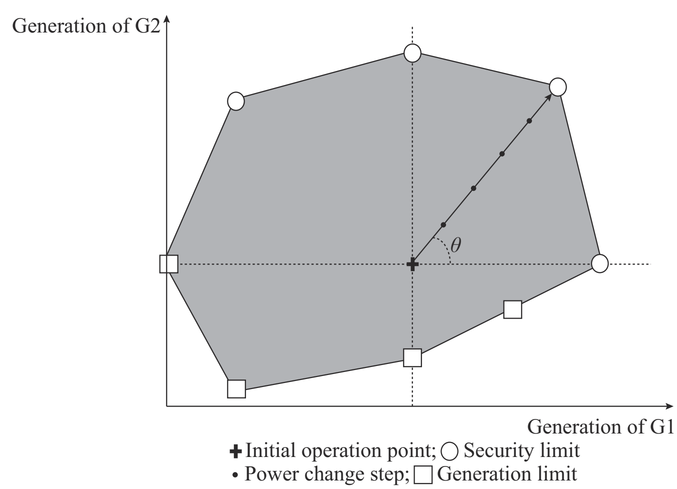

Fig. 3. Illustration of DSR.

For example, in the direction highlighted in Fig. 3, the dispatch of both groups G1 and G2 increases. As a result, the generation of the third group G3 must be reduced. The nomogram illustrated in Fig. 3 shows G1×G2 yet the corresponding graphs G2×G3 and G1×G3 can also be plotted.

Starting from an initial operation point and keeping the system load constant, the redispatch is applied to different directions until either a security criterion is violated or a generation limit is reached. Security criteria may include a dynamic performance index, e.g., a stability limit or even the activation of an SPS. The quantity of directions to be considered defines the angle θ shown in Fig. 3.

For each dispatch configuration, illustrated by the black dots in Fig. 3, the security is assessed for a list of credible contingencies. If all security criteria are met, the redispatch would advance in that direction. Otherwise, a binary search is performed to find the security boundary. After finding all boundaries, the secure area is determined by calculating the area of the irregular polygon of Fig. 3, which can be done by applying the Gauss area formula. Further details on DSR calculation can be found in [19] and [20].

C. The Minimum Requirements for Anti-islanding Protection

In this subsection, an approach to calculating the minimum requirements for DER anti-islanding protection is presented. The proposed approach is applied to 81R, nonetheless the concepts presented here can be extended to other protection philosophies and stability phenomena.

Figure 4 shows a simplified flowchart with the main steps of the proposed approach. Initially, a base case is selected, which corresponds to the initial operation point of the DSR. Since the frequency-based protection is to be evaluated, low inertia scenarios are considered, which generally correspond to light load conditions. Under lower inertia situations, the system will experience greater frequency excursions when a generation block is lost. Besides the base case selection, a list of credible contingencies with critical impact on frequency dynamic performance should also be stipulated.

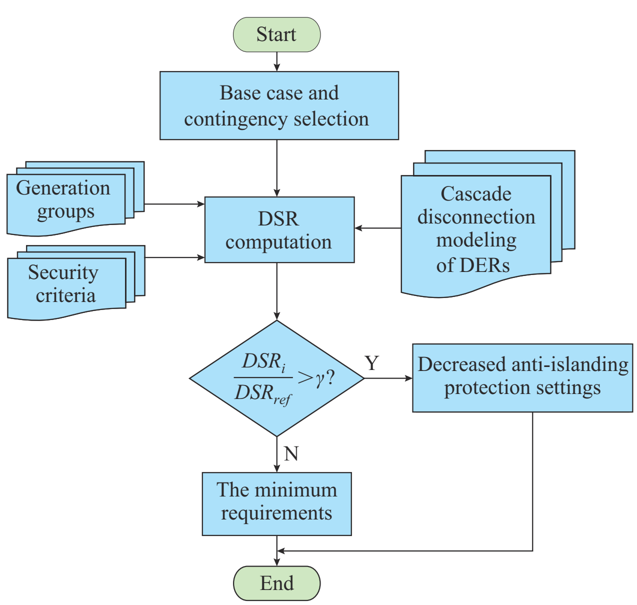

Fig. 4. Simplified flowchart with main steps of proposed approach.

Another relevant input is the definition of the generation groups that will be considered when calculating DSRs. The appropriate choice of those groups depends on the type of problem one wants to observe and on intrinsic characteristics of the studied power system. When the frequency-based anti-islanding protection is to be analyzed, the low inertia scenarios should guide the selection of generation groups.

Following the flowchart of Fig. 4, the DSR is computed without modeling DER anti-islanding protection. The result is called as reference DSR (DSR_{ref}), which provides a picture of the security evaluation at various operation points without any DER disconnection. Indeed, the reference DSR would correspond either to a system without distributed generation or to a system with all distributed generation connected with protection settings reliably and selectively.

After determining the reference DSR, the DER anti-islanding protection is included in the dynamic database and the security region is recalculated. At this stage, both detailed and equivalent modeling approaches discussed in Section III-A can be considered. However, since the focus is on bulk power system, the equivalent model is adopted. Moreover, it is assumed that all DERs in the system have the same and very permissive anti-islanding protection settings, e. g., 3.0 Hz/s (81R).

The secure area of both DSRs computed without and with anti-islanding protection representation, i.e., DSR_{ref} and DSR_i, respectively, are then compared using (1).

$$\frac{DSR_i}{DSR_{ref}} \geq \gamma \tag{1}$$

where γ is the preset threshold, and the parameter γ stablishes the minimum percentage value with respect to the reference DSR that can be accepted when anti-islanding protection is represented. For example, for $\gamma = 97\%$, a maximal reduction of 3% in the security region is tolerated.

An adequate choice of γ should take into account the occurrence probability of a condition that leads to cascade disconnection of DERs during the actual system operation. In extreme cases, where none of security region reduction is accepted, γ should be equal to 100%. In the simulations presented in this work, a 95% threshold is adopted.

A ratio higher than γ means that the settings considered for the DER anti-islanding protection do not have substantial impacts on system security. In other words, the disconnection of DERs does not significantly compromise the bulk power system stability and the anti-islanding protection settings can be more sensitive. Therefore, the iterative process continues and more restrictive pickup values are set for anti-islanding protection. This procedure is repeated while (1) is satisfied. After the first iteration no longer satisfies (1), the minimum requirements are considered to be those set in the previous iteration.

The minimum requirements obtained from the proposed approach are highly dependent of the penetration level of DERs. In fact, the exact amount of DERs connected to the power grid may significantly vary along the day and this information is not straightforward to be obtained. Moreover, future DERs should be taken into account in order to define the connection requisites. Whether reliable information regarding the penetration level of DERs is not available, it is recommended to consider the conservative levels while determining the minimum requirements.

When evaluating future scenarios, the proposed approach can be applied for different penetration levels of DERs. Moreover, DERs already installed in the system should have their protection settings fixed as closer as possible to the actual ones.

IV. RESULTS

The approach proposed in Section III is applied to BIPS. Initially, some fundamental characteristics of BIPS are presented in order to contextualize the developed simulations. In addition, the impact of anti-islanding protection on BIPS dynamic performance is discussed.

A. System Characteristics

The Brazilian electrical matrix is mainly composed of hydraulic generation with an important share of thermal, wind, and PV power plants. Its installed capacity is currently 177.1 GW, of which 61.6% is from hydraulic units. In recent years, a relevant development of wind generation has been observed, exceeding natural gas based power (8.7%), with 12.5% of installed capacity. Although PV generation currently represents a small portion of total capacity (3.1%), a significant growth is expected for the next years [21].

Figure 5 illustrates the BIPS transmission system for 2024 horizon. The system extent should reach 184000 km, which includes six HVDC bipoles with 20 GW of total transfer capacity. One of the most critical contingencies in the system is the loss of one of the two HVDC Xingu bipoles that transfers power from north to southeast regions, where the main load center is located. Xingu bipoles have nominal capacity of 4000 MW each, the transmission lines are about 1500-mile long, and the working voltage is ±800 kV. They are illustrated in Fig. 5 by the dark blue lines.

One particular characteristic of Xingu bipoles is the fact that the rectifier stations at north region are synchronously connected to the rest of BIPS. Consequently, the loss of one bipole may result in severe equipment overload or even stability issues associated to the generators located in the north region.

In order to overcome those potential problems, an SPS has been implemented with two major actions in case of a bipole contingency. The first action is an automatic power run-up on the remaining bipole, and the second one is the generation shed at power plants located in north region. The run-up action increases the power transferred through the remaining bipole, alleviating overloads that may appear in parallel AC lines. On the other hand, the generation cut is important to avoid transient instability and it is mainly performed at Belo Monte, a 11 GW hydro power plant (HPP) located 10-mile away from the rectifier station, which is also highlighted in dark blue in Fig. 5. The number of units to be cut at Belo Monte depends on the amount of DC power lost due to the bipole contingency, but it can reach 4000 MW, resulting in severe underfrequency scenarios.

In the following subsection, the impact of cascade disconnection of DERs on BIPS stability is evaluated. All analyses focus on the loss of one HVDC Xingu bipole. The simulations are developed using the production-grade software Organon [22] considering the full system database provided by the Brazilian Independent System Operator (ISO).

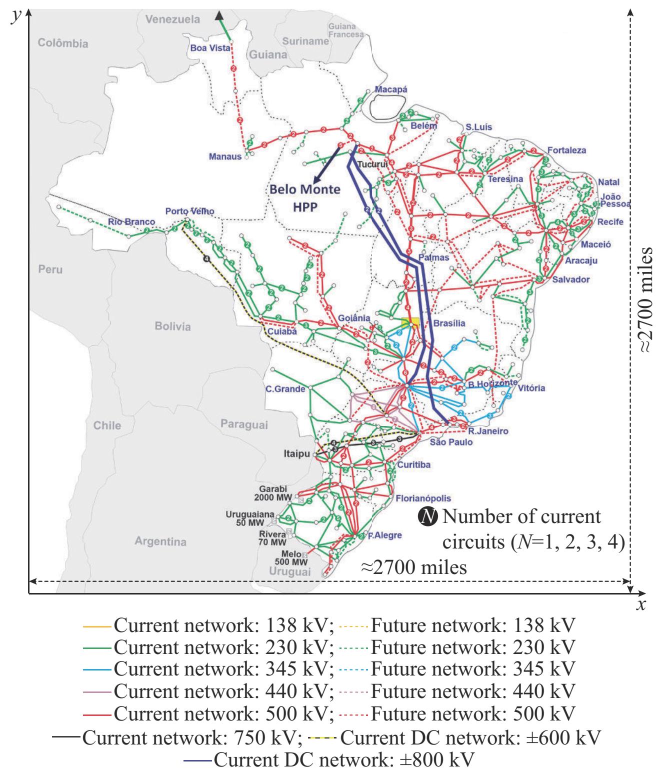

Fig. 5. Main BIPS transmission system.

B. Impact of Cascade Disconnection of DERs on Transient Stability

In order to evaluate the impact of cascade disconnection of DERs on BIPS stability, different penetration levels of DERs have been considered, as indicated in Table I. The penetration level shown in Table I is in relation to the amount of the equivalent load at each bus.

TABLE I
PENETRATION LEVEL OF DER AND PROTECTION SETTING

Penetration level (%)	Total power (MW)	ANSI 81U settings	
		Pickup (Hz)	Time delay (ms)
0	0		
1	570	59.5	100
2	1140	59.5	100
3	1710	59.5	100
4	2280	59.5	100
5	2850	59.5	100

The DER anti-islanding protection has been modeled using 81U settings with 59.5 Hz of pickup and 100 ms of time delay. In addition, this subsection also aims to illustrate the need to adjust DER protection in a coordinated way to underfrequency load shedding (UFLS) settings. This coordination is relevant to avoiding disconnections of DER before the operation of the 1st stage of UFLS.

The analyzed scenario consists of a light load condition expected for the summer 2023 with a demand of 57 GW. The simulated operation point is stressed since the power transferred through the HVDC Xingu bipoles is 8 GW (2× 4000 MW).

The high generation deficit has caused the operation of the 1st stage of the UFLS, even with no DER modelling in the system. In fact, the UFLS has allowed the frequency to recover for 0% and 1% penetration levels. As the penetration level of DERs increases, the frequency performance gets worse. For a penetration level of 2% or higher, the system collapses even after the 2nd stage of UFLS.

The frequency performance is presented in Fig. 6 when one Xingu bipole is lost. This contingency results in the SPS operation, shedding approximately 4000 MW of generation at Belo Monte HPP. The frequency depicted in Fig. 6 is measured at the largest power plant in the southeast region (Ilha Solteira). The UFLS settings are also indicated in Fig. 6. The collapse observed in Fig. 6 is caused by the loss of synchronism between the machines in north region and the rest of the system.

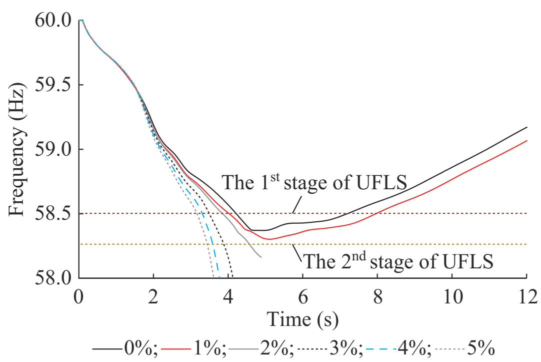

Fig. 6. Loss of Xingu bipole #1: frequency performance for different penetration levels of DERs with sensitive settings (81U: 59.5 Hz, 100 ms).

This loss of synchronism is illustrated in Fig. 7, which shows the rotor angle measured at Belo Monte HPP for different penetration levels of DERs. The loss of synchronism of these specific machines occurs at the penetration level of 3% or higher. For the penetration level of 2%, the system presents several dynamic criterion violations as well as numerical convergence problems. Therefore, 2% is also considered unsafe. We should note that, if the synchronism has not been lost, the frequency would keep falling and additional UFLS stages would be triggered. As a result, additional load would be shed, impacting a more significant number of consumers.

The results show that the cascade disconnection of DERs due to the maloperation of anti-islanding protection can severely impact BIPS stability. The results indicate that, if more than 1140 MW power (penetration level of 2%) is disconnected by the anti-islanding protection, an originally stable scenario turns to be an insecure one, leading to the entire system collapse. In addition, the results clearly show the importance of DER modeling when performing transient stability analysis in the bulk power system, mainly the anti-islanding protection effect. It should be noted that the case of no DER (0%) with sensitive anti-islanding setting corresponds to the usual simulation performed during operation planning studies, since DERs actually exist but their anti-islanding protection is not traditionally considered in the analyses.

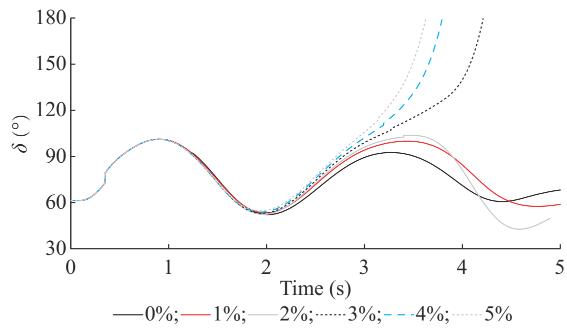

Fig. 7. Loss of Xingu bipole #1: rotor angle at Belo Monte HPP for different penetration levels of DERs with sensitive settings (81U: 59.5 Hz, 100 ms).

C. The Minimum Requirements via DSRs

In this subsection, the proposed approach to determining the minimum requirements for anti-islanding protection is applied to BIPS. Due to the increase of wind power penetration and the installation of new HVDC links with asynchronous operation at their rectifier stations, BIPS has experienced a global inertia reduction in the past years. In this context, the generation groups for DSR calculation are selected as follows: ① Group 1 (G1): HVDC links; ② Group 2 (G2): wind and solar power plants; ③ Group 3 (G3): HPPs.

The above choice is justified since the power provided by the inverter-based generation and HVDC links replaces the power produced by conventional synchronous machines, which results in a reduced resilience to deal with generation loss. The analyzed scenario consists of the same light load condition evaluated in Section IV-B. However, in the base case, the power transferred through the HVDC Xingu bipoles is 6000 MW.

Aiming at a frequency-stable operation, an important security criterion is the frequency threshold of 58.5 Hz that triggers the 1st stage of the UFLS. It means that the approach should indicate the minimum requirements for anti-islanding protection of DERs to avoid any load shedding within the accepted margin stipulated by parameter γ in (1).

Following Fig. 4, the reference DSR for BIPS is computed, as shown in Fig. 8. The simulated contingency is the loss of one HVDC Xingu bipole, which results in a power deficit of 3000 MW due to the consequent generation shed at Belo Monte HPP.

As can be observed in Fig. 8, the power from the HVDC links P_{HVDC} varies from 13800 MW to 18500 MW, while the power from inverter-based generators P_{INV} ranges from 3500 MW to 9500 MW. Moreover, all operation points inside the computed region are secure from both static and dynamic points of view without any load shedding action. In the DSR shown in Fig. 8, the y-axis represents the sum of power provided by all HVDCs, but the power order at Xingu links has been kept fixed at 6000 MW, i.e., the power set at other bipoles is varied to explore multiple scenarios.

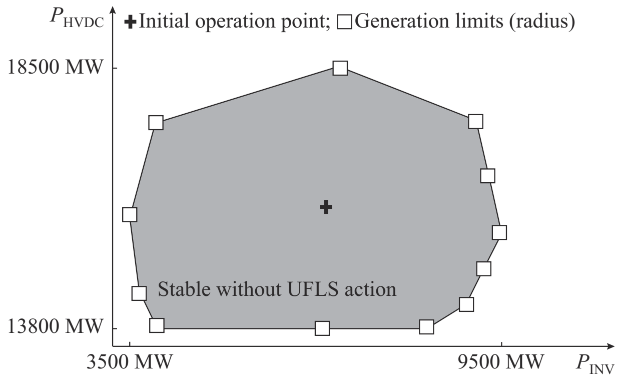

Fig. 8. Reference DSR for BIPS.

The reference DSR does not take into account disconnection of DERs and the next step is to include this effect in the simulation. Therefore, the modeling approach proposed in Section III-A is considered, assuming the penetration levels of DERs are 1% to 5%, with initial 81R protection set with 3 Hz/s. It should be noted that the approach proposed in Section III is applicable for any penetration level of DERs. The range adopted in the study case reflects the actual characteristics of BIPS.

The DSRs computed for penetration levels of 1% and 2% are identical to the reference DSR, which means that the ratio computed by (1) is 100%. This result indicates that, for those penetration levels, the disconnection of the DERs does not compromise any point inside the reference DSR. For penetration levels equal to or higher than 3%, the effect of disconnection of DERs reduces the DSR area, as summarized by Table II.

TABLE II
DSR AREA REDUCTION FOR DIFFERENT PENETRATION LEVELS OF DERS

Penetration level (%)	Total power (MW)	DSR area reduction (%)
1	570	0
2	1140	0
3	1710	15
4	2280	35
5	2850	45

Figure 9 shows the reference DSR and the DSR for a DER penetration level of 3%. Considering the anti-islanding protection is set with 0.4 Hz/s, a 15% reduction is observed in the safe area. In this case, the minimum requirement for the RoCoF function is 0.5 Hz/s. Similar results are shown in Figs. 10 and 11 for penetration levels of 4% and 5%, respectively. As can be observed, the higher the penetration level with uncoordinated settings, the higher the reduction in the safe area.

In all simulated cases, the settings equal to or higher than 0.5 Hz/s can prevent the cascade disconnection of DERs, keeping the safe area equal to the one obtained without any DER representation (reference DSR). In other words, for BIPS, there is no specific need to require RoCoF settings greater than 1 or 2 Hz/s, which can make it difficult to identify real islanding situations in distribution networks.

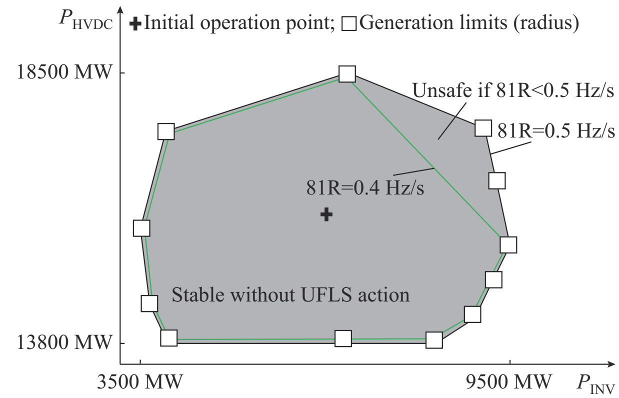

Fig. 9. Reference DSR and DSR for a DER penetration level of 3%.

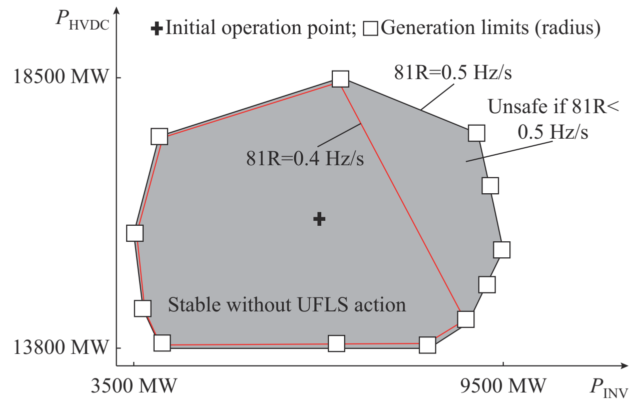

Fig. 10. Reference DSR and DSR for a DER penetration level of 4%.

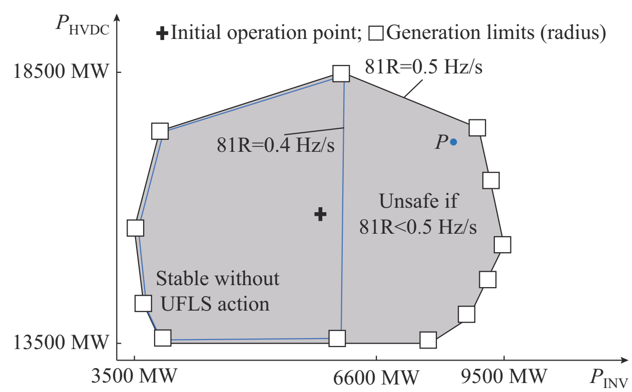

Fig. 11. Reference DSR and DSR for a DER penetration level of 5%.

The results presented in this subsection reinforce that even small penetration levels (3% to 5%) of DERs can significantly impact the stability and the dynamic performance of the bulk power system if the frequency-based protections are extremely sensitive. In this way, the equivalent modeling of cascade disconnection of DERs can be used either to define the minimum requirements for the RoCoF function or to evaluate the impact of this effect on the system behavior. Furthermore, it is evident that modeling the disconnection of

DERs is crucial to provide a more accurate diagnosis of the real system behavior after major disturbances that lead to large frequency deviations.

Regarding the 81U, it is also important to avoid disconnection of DERs before any action of load shedding. In this way, Fig. 12 shows the frequency of the largest power plant connected in the southeast region (Ilha Solteira), when one HVDC Xingu bipole is lost, considering different penetration levels of DERs. These results obtained for the operation point *P* are highlighted in Fig. 11.

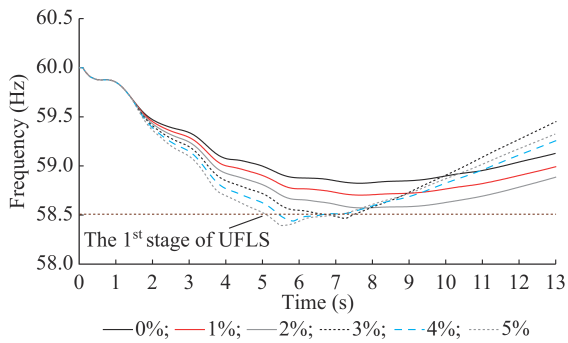

Fig. 12. Frequency of the largest power plant connected in Ilha Solteira considering different penetration levels of DERs in BIPS.

For penetration levels of DERs up to 2%, the system survives without requiring any load shedding. Besides, for penetration levels of DERs equal to and above to 3%, UFLS operation is necessary to guarantee the system stability. In this scenario, the 1st stage of UFLS cuts about 4000 MW of load, which would affect 10 million consumers in Brazil.

V. Conclusion

The inertia reduction caused by the increase of inverted-based generation is observed in several power systems over the world. At the same time, the development of DERs connected at the medium- and low-voltage networks represents the decentralization of significant amounts of generation. In this scenario, the discoordination between the DER protection and the bulk power system requirements may deteriorate the dynamic performance and directly impact the system stability.

One important aspect in this regard is the anti-islanding protection that is essential to avoid dangerous situations for equipment and people in case of distribution network separation from the main grid. The adoption of too sensitive settings for anti-islanding protection functions may cause protection misinterpretation for severe events at the transmission system not related to islanding situation. As a result, cascade disconnection of DERs may occur, worsening the system dynamic conditions.

This paper proposes an approach to calculate the minimum requirements for anti-islanding protection with the focus on the bulk power system security. The proposed approach is based on DSRs that explore low inertia scenarios, which are more susceptible to frequency instability.

In order to include the effect of cascade disconnection of DERs in dynamic simulations of bulk power systems, this paper also proposes a representation inspired on the usual modeling of UFLS protection. However, in the proposed strategy, the DER disconnection is represented by a load increase, corresponding to the penetration level of DERs. Although it is straightforward, this strategy can be considered a modeling advance since DER disconnection is generally neglected by many system operators when performing operation planning analysis, especially for low and moderate penetration levels of DERs.

The impact of anti-islanding protection misinterpretation on the BIPS stability is evaluated. The results show that, depending on the penetration level of DERs, the dynamic performance of BIPS can be severely deteriorated and put the entire system at risk. The impact of DER disconnection can be decisive to assess whether critical contingencies can trigger UFLS. In conclusion, the presence of DERs cannot be neglected when analyzing the bulk power system stability since they can be decisive in the dynamic performance.

The proposed approach to determining the minimum requirements for anti-islanding protection functions has been applied to BIPS. Low inertia scenarios with high inverter-based generation and high power at the HVDC links are explored throughout DSRs. The requirements are obtained for different penetration levels of DERs, matching the dynamic security criteria even under low-inertia situations.

The analyses in this paper are carried out based on the assumption that all DERs have the same adjustments regarding the anti-islanding protection functions. Nevertheless, if DERs in operation do not meet such minimum requirements, they can be disconnected and increase the generation deficit. Therefore, a more precise analysis should require a meticulous survey of the anti-islanding protection adopted in the currently installed DERs since this would impact on future installation requisites as well as on possible retrofit plans.

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