A Risk-Based Methodology for Defining the Time of Intentional Controlled Islanding

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Abstract—**Power systems are operated close to their stability limits and this increases the probability of cascading outages leading to large-area blackouts. To mitigate these phenomena, intentional controlled islanding (ICI) has been suggested as an effective corrective strategy that splits the system into sustainable subsystems (islands). There are two primary aspects associated with ICI: *i*) where to island, and *ii*) when to island? This work focuses on the latter and proposes a risk-based methodology that compares in a real-time fashion (i.e., quickly enough) the overall risk of the system without and with islanding (i.e., when an ICI scheme is activated) in order to define a suitable time for system splitting. Simulation results on the IEEE 9-bus system demonstrate the effectiveness of the methodology in determining a suitable time for the creation of islands, which in turn corresponds to the crossing point between the risks of the system without and with islanding.**

Index Terms--**Blackout, intentional controlled islanding, risk assessment, system splitting.**

I. INTRODUCTION

Interconnected power systems are prone to instabilities as they are operated close to their stability limits [1]. This increases the likelihood of cascading outages that typically lead to large-area power system blackouts [1], [2].

To mitigate these cascading outages, intentional controlled islanding (ICI) has been suggested as an effective corrective control action [2]. ICI – also referred in the literature as system islanding or system splitting – is an adaptive control strategy for power systems under emergency and *in extremis* states [2]-[4]. Islanding methods intentionally split the bulk power system into self-sustained subsystems (i.e., electrically separated islands), and they can be used as a last resort after instabilities have been detected, but before the system becomes uncontrollable to avoid blackouts. They can also facilitate the restoration process of the power system [5]-[6].

There are two primary aspects associated with ICI [4], [6]-[8]: *i*) where to island, and *ii*) when to island. While the former aims to find the optimal set of transmission lines that must be disconnected to split the system into islands, the latter seeks to define the optimal time for splitting the electrical network. This work focuses on answering the question of *'when to island'*. To determine the set of lines that optimally splits the system in a real-time fashion (i.e., a few seconds), this work implements the approach presented in [4] (see section II-A for more details).

To address the question *'when to island'*, decision trees and Prony-based methods have been previously proposed [7]-[8]. Although these methods can define a suitable time for splitting the electrical network based on system conditions recorded in a database (i.e., they use previous information to learn how to predict future scenarios), unexpected system changes and unpredictable events may result in incorrect times for splitting, and thus large-area blackouts may occur.

In addition, given that ICI can be classified as System Integrity Protection Schemes (SIPS) [9] and that the interest for assessing their reliability and risk has attracted the interest of several researchers, such as [10]-[12], it is nowadays crucial to perform an adequate risk assessment of ICI schemes.

This work proposes a risk-based methodology to define a suitable time for undertaking system splitting, i.e., to help answer the question '*when to island*'. The proposed methodology assesses in a real-time fashion (i.e., quickly enough, 10ms in this work) the overall risk of the electrical power system without islanding and with islanding, thus avoiding delays. In general, the risk is given by the product of the probability and impact of the electrical event.

In contrast to other approaches, the proposed approach uses data available in real-time, thus avoiding the use of historical data. The suitable time for system splitting is defined as the crossing point between the two curves, i.e., when the risk without islanding becomes higher than the risk with islanding. The simplicity and scalability of the proposed methodology is expected to help operators in the decision-making process of when to split the power system to mitigate cascading outages.

The remainder of this paper is organized as follows. Section II provides the theoretical background on ICI and risk assessment. Section III details the risk-based methodology. Section IV presents a set of simulation results for demonstrating the effectiveness of the proposed methodology. Finally, Section V summarizes and concludes the paper.

II. BACKGROUND: ICI AND RISK ASSESSMENT

This section introduces the main concepts of ICI and risk assessment (i.e., the product of the probability and the impact).

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These concepts are used in section III in the proposed risk-based methodology.

A. Intentional Controlled Islanding

ICI is an effective approach to mitigate cascading outages. This section summarizes the approach presented in [4] that is implemented in this work to determine the optimal set of lines to partition the power system (i.e., to address the '*where to split*', which is not the main focus of this paper). This existing methodology is used in a real-time fashion to evaluate the risk with islanding at every time sample (see section III).

As thoroughly detailed in [4], this approach is based on spectral clustering [13], i.e., a computationally efficient graph theoretic technique that can partition systems using the *eigenvalues* and *eigenvectors* of a (*Laplacian*) matrix associated with the graph that represents the power system. To create electrically separated islands, this approach minimizes the power flow disruption while ensuring that each island contains only coherent generators (generators that oscillated similarly). This significantly enhances the transient stability of the islands, and it is implemented here given its efficiency and scalability to any power system size [4]. The following steps are executed to determine the set of transmission lines that optimally splits the electrical network into k islands [4]:

1. Build a graph G that represents the power flow of the network (with n buses) at the moment of splitting.
2. Compute the *eigenvectors* $\varphi_1, \varphi_2, \ldots, \varphi_k$ associated with the first k *eigenvalues* of $\mathbf{L_N}$, which is given in (1) [13]:

$$\left[\mathbf{L}_\mathbf{N}\right]_{ij} = \begin{cases} 1 & \text{if } i = j; \\ -w_{ij} \big/ \sqrt{d_i d_j} & \text{if } i \neq j \text{ and } ij \text{ is a branch;} \\ 0 & \text{otherwise.} \end{cases} \tag{1}$$

   where w_{ij} is the power flow between buses i and j and $d_i = \sum_{j=1}^{n} w_{ij}$ [13].
3. Place the eigenvectors $\varphi_1, \varphi_2, \ldots, \varphi_k$ as columns to create $\mathbf{X} = [\varphi_1, \varphi_2, \ldots, \varphi_k]$.
4. Normalize each row of $\mathbf{X}$ to obtained $\mathbf{Y}$.
5. Group every load-bus with the nearest generation-bus based on the proximity between the vectors in $\mathbf{Y}$ that were mapped in the *Euclidean space* in point 4.
6. Group the clusters that contain the coherent generators.

The steps mentioned above (detailed in [4]) are implemented every time sample (defined in this work as 10ms) in the proposed risk-based methodology to determine the impact of splitting the power system (the risk of the system with islanding), as further explained in section III.

B. Risk Assessment

The risk of an electrical event is given by the product of the probability of occurrence of the event and its impact on the network (e.g., the total load shedding), as follows:

$$Risk = Probability \times Impact \tag{2}$$

When considering ICI schemes as an available control action to the system operators, then the risk introduced to the network by an undesirable operation of these schemes needs to be taken into account in the risk assessment procedure (similar to the risk assessment of other SIPS). The failure modes of the ICI schemes mainly include: (*i*) the failure to operate following the occurrence of the electrical event, and (*ii*) the incorrect/unnecessary operation of the ICI scheme when there is no event in the network.

An electrical event comprises here a large disturbance and its subsequent consequences that can threaten the network stability (loss of synchronism, etc.). The impact of these failure modes varies and depends on the prevailing system conditions. For instance, if the ICI scheme splits the system into islands when not required during normal electrical conditions, then it may not have a high impact on the system stability. If, on the other hand, it splits it during stressed conditions, then it may trigger a series of cascading outages that may compromise the network stability and lead to customer interruptions, as it happened in the Irish disturbance of 2005 [14].

In order to evaluate the risk of ICI schemes, the probabilities of failure on demand (PFD) and fail-safe (PFS, i.e., the probability of ICI unnecessary operations) are required. Then, the impact of these failure modes on the reliability of the network needs to be assessed. In this study, the amount of load shedding as a result of the ICI failure modes is used as an impact index. Finally, the risk introduced by having the ICI schemes in operation is given by the product of the probability of the ICI failure modes (both the PFD and PFS) and the impact of these undesirable events.

To estimate the PFD and the PFS, fault tree analysis (FTA) is used here. FTA is a systematic method for identifying the events or combination of events that can lead to the top event of the fault tree [15], i.e., ICI undesirable operation in this case. The reliability data of the individual components of the ICI scheme, e.g., logic processor, circuit breakers (CBs), communication links etc., are assumed in this work for illustration purposes. Particularly, the PFD and PFS of the individual ICI components are required, which are then inserted in the fault trees for estimating the overall PFD and PFS of the ICI scheme.

III. PROPOSED RISK-BASED APPROACH FOR DEFINING THE TIME OF ICI

Fig. 1 presents the flowchart of the proposed risk-based methodology for determining the suitable time for applying the ICI scheme. It should be noted that the assessment of the risk of the system without islanding and with islanding is undertaken in parallel, considering that the ICI scheme has been switched in operation by the system operator and it is ready to be activated when required. If the ICI scheme is not implemented, i.e., w/o ICI, then the methodology estimates the impact of the electrical event using the amount of load shedding as an impact index, as discussed earlier. If the ICI scheme is in operation, i.e., with ICI, then the PFD and PFS using FTA, along with the impact of the ICI failure modes, are estimated. The probability of the occurrence of the electrical event threatening the network stability is also taken into account by

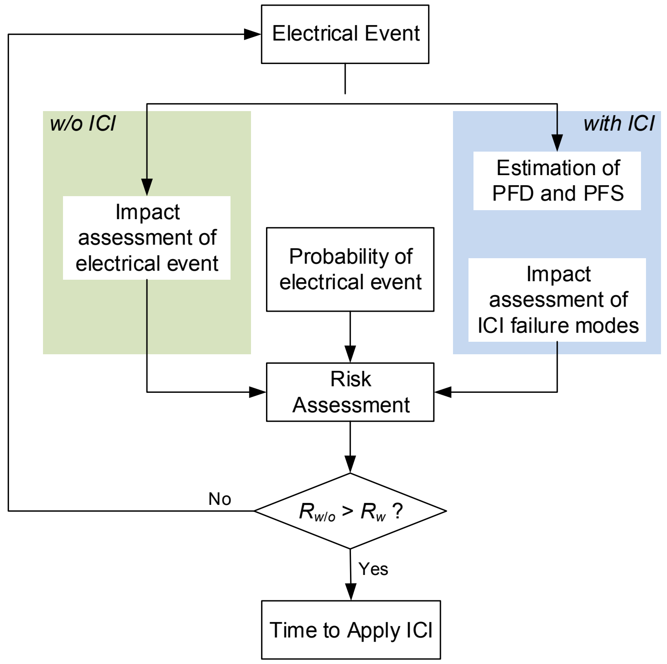

Figure 1. Proposed risk-based methodology for defining the time of ICI

the proposed methodology, which is fed as input to the risk assessment for both w/o the ICI scheme and with the ICI scheme.

Following this, the risk without ($R_{w/o}$) and with (R_w) the ICI scheme is estimated and compared. This procedure is repeated every time sample (10ms in this work) to determine the suitable time to implement the ICI scheme based on the overall system risk, i.e., the risk introduced by the electrical event and the risk by the ICI undesirable operation. If $R_{w/o} < R_w$, then the ICI solution (found using the spectral clustering-based methodology) is not applied. However, if $R_w < R_{w/o}$ then the corresponding time is defined as the suitable time to undertake islanding actions, as the overall system risk with the ICI scheme becomes smaller than the risk without the ICI scheme. This leads to a risk-based approach for deciding when to apply the islanding in order to minimize the risk of the electrical disturbance.

A. Estimation of PFD and PFS

As mentioned earlier, FTA is used to determine the probabilities of the ICI failure modes. The fault trees providing the events that can lead to a PFD and a PFS of ICI scheme are presented in Fig. 2 and Fig. 3, respectively. The reliability data used is shown in Table I.

As it can be seen in Fig. 2, there are several sources of failure errors. If any of the CBs fails, the scheme will fail to open the lines and split the network. It has to be noted though that a failure of the CBs at both ends of a line is required for the scheme not to operate, which is why an AND gate is used. PMUs and PLCs are also possible sources of errors due to lack of information or logic operation respectively. Here, the communications channels play an important role, as the loss of these channels will not allow the activation of the ICI scheme. Also, a problem with the DC power supply can contribute to the scheme absence when required. As noticed in Fig. 2, the failure of an operator to trigger the scheme can also result in the scheme failure to operate.

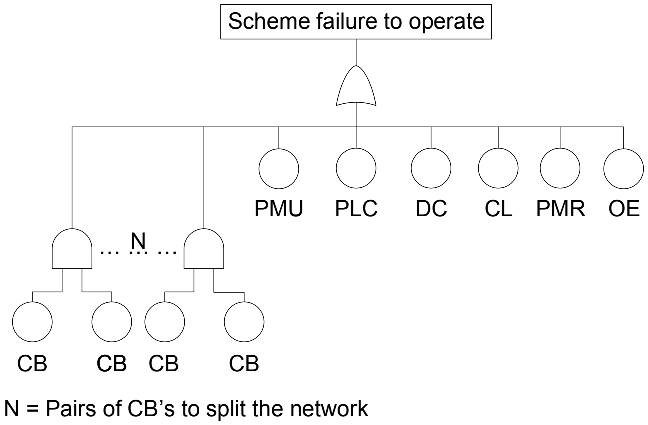

Figure 2. Fault tree for the scheme failure to operate

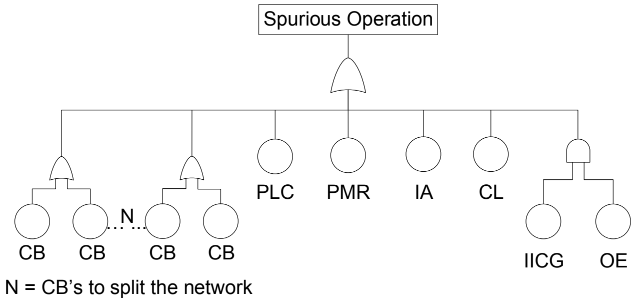

Figure 3. Fault tree for the spurious operation

TABLE I. COMPONENTS RELIABILITY DATA

Component	PFD	PFS
Operating errors (OE)	4.56×10^{-5}	9.12×10^{-5}
Circuit breakers (CBs)	9.11×10^{-4}	1.84×10^{-3}
Phasor measurements units (PMU)	2.61×10^{-4}	5.20×10^{-4}
Power measurements relays (PMR)	2.58×10^{-4}	5.13×10^{-4}
DC power supply (DC)	3.32×10^{-4}	-
Communications lines(CL)	1.01×10^{-4}	-
Incorrect activation (IA)	-	5.20×10^{-4}
Incorrect identification of coherent groups (IICG)	-	2×10^{-4}
Programmable Logic Controller (PLC)	3.36×10^{-4}	6.7×10^{-4}

Similarly, as it can be seen in Fig. 3, if any of the CBs operates unnecessarily, the scheme will operate when is not needed. PMUs and PLCs can also cause an undesired operation by sending incorrect information or carrying out incorrect logic operations respectively. False communication signaling can also trigger the scheme when not required, leading to the creation of unbalanced and undesired islands. Further, an incorrect identification of the islands or an incorrect activation will result in a spurious operation of the scheme, as can be seen in Fig. 3.

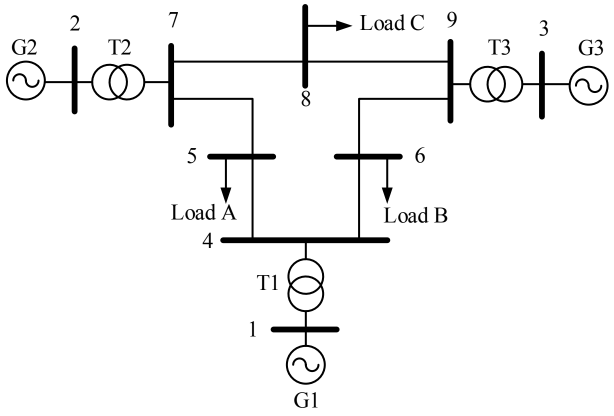

Figure 4. Single-line diagram IEEE 9 bus test system

B. *Impact Assessment of ICI Failure Modes*

The impact is calculated here as the monetary value associated with the load loss due to the activation or not of ICI.

To determine the load loss when islanding is not activated, a load measurement was taken during each sampling time of the simulation (i.e., 10ms). This is then compared with the nominal value assigned to each load (nominal demand at each busbar). The difference between these two values is considered in this work as the load loss.

To determine the load loss when the ICI scheme is active, the net demand is measured a sampling time after (10ms) the creation of each island. As in the case without islanding, this net demand is compared against the nominal value and the difference is considered as the load loss.

It is important to mention that the load loss considered in this work provided useful insights on when to split the analyzed test system (see section IV). In practice, however, other criteria to determine the impact could be considered based on the criteria of the operators. The proposed risk-based methodology is flexible enough to incorporate any impact metric.

IV. SIMULATION RESULTS

This section presents the simulation results. Fig. 4 shows the single-line diagram of the IEEE 9-bus test system [16]-[17]. This test system is used here to demonstrate, with time-domain simulations, the effectiveness of the risk-based methodology in defining the most suitable time to split the electric power system.

As detailed in section II-A, the spectral clustering-based methodology [4]is used at every time sample (i.e., 10ms) to determine the optimal set of lines that splits the power system into self-sustained islands that also satisfy the generator coherency constraint. The actual implementation of the spectral clustering-based methodology is not presented here as this is out of the scope of the paper (see [4]for more details). All time-domain simulations are performed in DIgSILENT PowerFactory [18], and the proposed methodology has been implemented in MATLAB [19].

The overall PFD and PFS of the ICI scheme, as estimated using the fault trees of Fig. 2 and Fig. 3 and the components reliability data of Table I, are 1.3×10^{-3} and 9.0×10^{-3}, respectively. Fig. 6 then shows the risk of the system without and with islanding from the moment that the fault is cleared ($t = 0.25$s). In this case, the risk represents the monetary cost per hour (k\$/h) associated with the load loss if the uncontrolled blackout occurs or if the electrical islands are created in the power system.

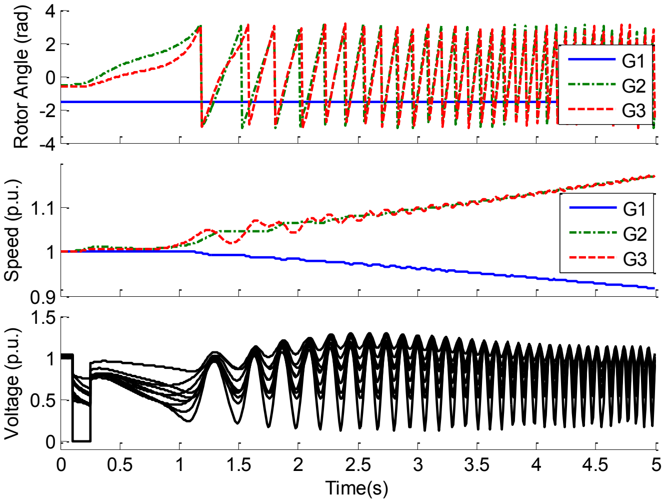

Figure 5. Results for the IEEE 9-bus system without islanding

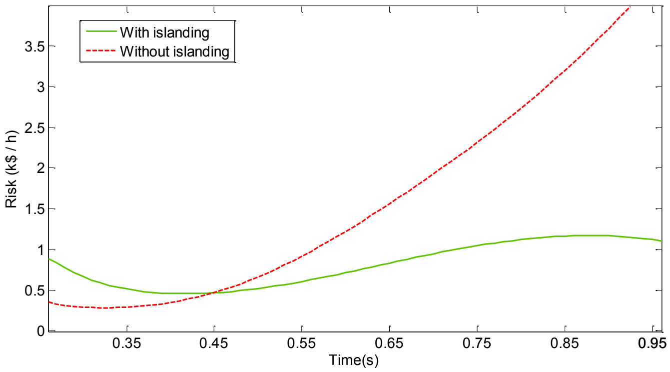

Figure 6. Risk assessment without and with islanding

It can be seen that the risk without islanding increases with time, given that no control action is taken and the system is collapsing. In parallel to the risk without islanding, the risk with islanding (given a solution found by the ICI methodology) is calculated. As it can be observed in Fig. 6, the risk with islanding becomes smaller than the risk without islanding at $t = 0.45$s. Therefore, according to the risk-based methodology (see Fig. 1), this time is considered to be the most suitable one to split the system into two islands (given that two coherent groups of generators were created after the disturbance).

The optimal islanding solution (i.e., for the minimum power flow disruption) found by the spectral clustering-based methodology [4] is shown in Table II. This solution was used to the risk assessment of the system with islanding.

Fig. 7 shows the results of implementing the islanding solution found by the spectral clustering-based methodology at the time found by the risk-based methodology presented in

TABLE II. ISLANDING SOLUTION

Line to be disconnected	Island No.	Buses within island
4-6	1	1,4,5
	2	2,3,6,7,8, 9

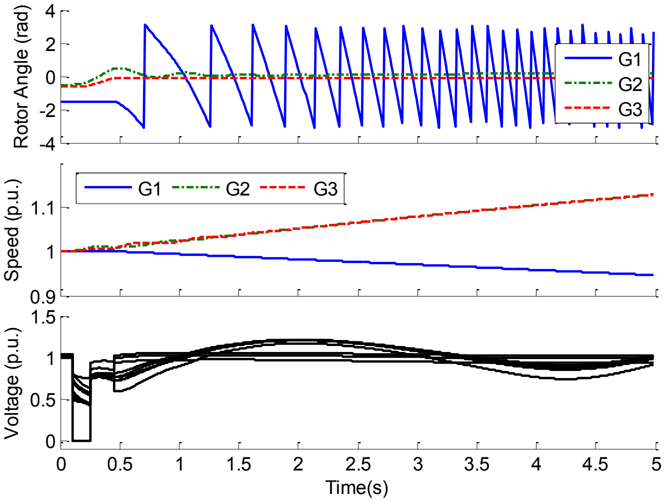

Figure 7. Results for the IEEE 9-bus system with islanding

this paper i.e., at $t = 0.45$s. As it can be observed, the system recovers and two stable islands are created. It is important to mention that this test network has not been equipped with governors; thus, the frequencies shown in Fig. 7 are expected to be stable in the scenario where these controllers are used. Also considering secondary controls, as load shedding, it is possible to restore both frequencies to the nominal value.

V. CONCLUSION AND FUTURE WORK

This paper has proposed a risk-based methodology that compares in a real-time fashion (i.e., quickly enough) the overall risk of the system without and with islanding (i.e., when an ICI scheme is in place) in order to define a suitable time for system splitting. Hence, this work addresses the *"when to island"* aspect in the intentional controlled islanding procedure, which benefits the power system operators in the decision making when to undertake islanding actions.

The proposed risk-based methodology has been tested using the dynamic model of the IEEE 9-bus system. Time-domain simulations have been carried out to demonstrate the effectiveness of the proposed approach. It has been shown that the most suitable time for the creation of islands corresponds to the crossing point between the risks of the system without and with islanding, i.e., when the risk without islanding becomes larger than the risk with islanding.

The proposed risk-based method is a novel and flexible methodology, which can be adapted to any context, without affecting the outline of the procedure. It is also fast enough for defining the time to split the system and it includes a functional method to address all reliability aspects of an ICI scheme.

To quantify the impact without and with islanding, this work has used the load loss (a sampling time after the creation of each island, i.e., 10ms). In practice, however, more accurate metrics can be used given the flexibility of the methodology. Simulations results on the IEEE 9-bus test system demonstrated the effectiveness of the proposed risk-based methodology. Larger test systems (or real ones) can present challenges that may need to be addressed. For instance, a stochastic approach might be required for dealing with the uncertainty associated with the high number of possible electrical events that may occur in a large and complex electric network.

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