A Novel Technology for Determining the Controlled Islanding Boundaries

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***Abstract*-- The power system is operated closer to the stability limit than ever before and is vulnerable to catastrophic failure. When a power system encounters a series of large disturbances that may eventually lead to catastrophic blackouts, only rely on the traditional relay protection schemes to isolate the fault may not be sufficient to mitigate the consequences and ensure the stability of the system. Therefore, other pre-determined controlled protections, such as intelligent controlled islanding, need to be applied as well. Intelligent controlled islanding serves as the last resort of remedial action to prevent the collapse of a power system. This paper proposed a strategy to determine the boundaries of the intelligent islanding scheme. This research intends to search the load more efficiently and determine the islanding boundaries quickly in a large power system. This admittance matrix based approach aims to provide a general solution for determining the cut set. For a speedy recovery of intelligent control islanding, where to implement the controlled islanding is the main issues needs to be discussed. After the coherent groups of generations are detected, the location of intelligent islanding in this paper is determined in two steps. The first step of this method is finding the loads within the island. The load selection of the controlled islanding is based on electrical closeness instead of physical distance. The loads are selected relying on Relative Electrical Distance (RED) between each generator and load bus. Ranking the magnitude of relative electrical distance from smallest to largest, we could determine which buses would be more influential on the dynamic performance of the generators, and could preliminarily select the loads within each island. The second step is determining the boundary lines for islanding by the non-zero element of the "mutual admittance matrix". The simplicity of load detection and boundary determination makes this method very attractive. The 29-machine, 128-bus WECC system is used to validate the proposed controlled islanding scheme. With this method, it enables the generators in the same island to stay in synchronism and the imbalance between the generators and load demand is minimized.**

***Keywords*-- Islanding, Boundaries Determination, Relative Electrical Distance, Transient Stability**

1. INTRODUCTION

Intentional controlled islanding scheme is considered as a final defense of the power system to maintain the stability of individual separated island. The prediction results of the transient stability [1-3] can be used as the online instability alarms and local control. If the system is predicted to be unstable, and the coherent groups of generation are detected followed by the prediction, then the controlled islanding scheme is considered as a feasible and valid measurement to restore the stability of system.

The idea of controlled islanding based on slow coherency was first proposed in reference [4]. If the relay protection does not stabilize the system and different coherent groups are recognized, then it is necessary for the system take the controlled islanding measures to separate the system to several subsystems before the perturbation travels from one part of the system to another. This avoids the cascading consequence of the power system. The controlled islanding is considered self-healing and can effectively constrain the disturbance within a small region.

In an n buses power system, all the possible splitting lines combination number is calculated by $2^n - 1$. This is time consuming to find the combination of tripping line to split the system into islands. Therefore, it is necessary to develop a feasible controlled islanding scheme to determine the islanding boundaries in real time. Currently, the methods developed for controlled islanding are few. One popular islanding scheme is studying the power flows on the critical lines. The intersection lines for controlled islanding are determined by observing the change rate of active power on both ends of the line in the system [5]. The main disadvantages of the pre-determined boundary method are that the generators in the same island may be not coherent and it may also result in the imbalance between the load demand and generation output, which results in undesirable generation dropping and load shedding [6]. Another feasible islanding scheme is performed by studying the electrical center or the active power in transmission lines in the system. These two methods mentioned above require exhaustive offline simulation to select the critical buses as the potential electrical center. The electrical center is formed when the phasor angle difference between both ends of the transmission line is 180°, which is detected by the R-Rdot Out of Step relay. However, the electrical center will shift to other locations when the system topology changes. Another prevalent islanding scheme is graphical based islanding, called Ordered Boundary Decision Diagram (OBDD) [7]. This scheme is a graphical search theory for the possible islanding boundaries while meeting the static state loading balance and the static stability limit. The disadvantage of the OBDD method is the large computer resources that are required for its huge searching space. The slow coherency based controlled islanding method is deployed to split the generators into different coherent groups. Within each island, the imbalance between the generators' output and the load demand is minimized. Reference [6] further refined the searching of the islanding boundaries by a maximum flow with minimum cut, using a graph based scheme. Reference [7] implements the load shedding that takes into account the declining frequency to avoid frequency instability in the load rich system. Combining with the graphical approach, reference [8] studied the controlled islanding in the large scale system by the network simplification algorithm.

Furthermore, the generators that belonged to the same coherent group are represented by a fake node, and the islands are split by resorting to the prebuilt graph partition library. The advantage of slow coherency criterion is that it takes into account the dynamic behavior of the generators. The result of the slowly coherent grouping is independent to the disturbance, which reveals the intrinsic trends of the generators' behavior after disturbance.

The rest of the paper is structured as follows. Section 2 introduces two critical factors for controlled islanding. Three steps of controlled islanding scheme are provided in Section 3. The load selection based on electric distance and boundaries determination during islanding is illustrated. Section 4 presents the controlled islanding analysis results on a 10-Machine, 39-Bus system and a 29-Machine, 128-Bus model of the Western Electricity Coordinating Council (WECC) system. The conclusion is provided in Section 5.

2. Key factors for control islanding

Two key factors in the controlled islanding strategy are to determine the initiated time and the boundaries of the intelligent islanding scheme. This research intends to search the load more effectively and determine the islanding boundary quickly in a large power system. The proposed method is coherency based controlled islanding which is different from reference [4, 5], this approach aims to provide a general solution for determining the cut set.

For a speedy recovery of the intelligent control islanding, two main issues needs to be addressed:

- When to implement the controlled islanding.
- Where to split the system.

When: Assuming the coherency of the generators is detected at an early stage by some advanced techniques, the intelligent islanding would be considered as a possible remedial measure to restore the stability of the power system after a large disturbance when the transient instability has been predicted and the traditional contingency protections, such as relay tripping, is not likely to restore the system stability. The instability can be predicted by an innovative method using 12-cycle apparent impedance trajectories that mentioned in [1].

Where: The location of intelligent islanding is determined in two steps. The first step of this method is finding the loads within the island. The load selection of the controlled islanding is based on electrical closeness instead of physical distance. The loads are selected relying on Relative Electrical Distance (RED) [9] between each generator and load bus. Ranking the magnitude of relative electrical distance from smallest to largest, we could determine which buses would be more influential on the dynamic performance of the generators, and could preliminarily select the loads within each island. The second step is determining the boundary lines for islanding by the non-zero element of the "mutual admittance matrix". The simplicity of load detection and boundaries determination makes this method very attractive.

In this paper, "where" to implement the controlled islanding is focused. The proposed intelligent controlled islanding scheme is based on two assumptions:

1) The coherency of different generators is recognized by the advanced coherency identification technology after the contingency.
2) The buses with larger electrical distance must be connected by at least one bus with smaller electrical distance.

The intelligent controlled islanding scheme proposed in this paper can be explained by the flow chart in Figure 1.

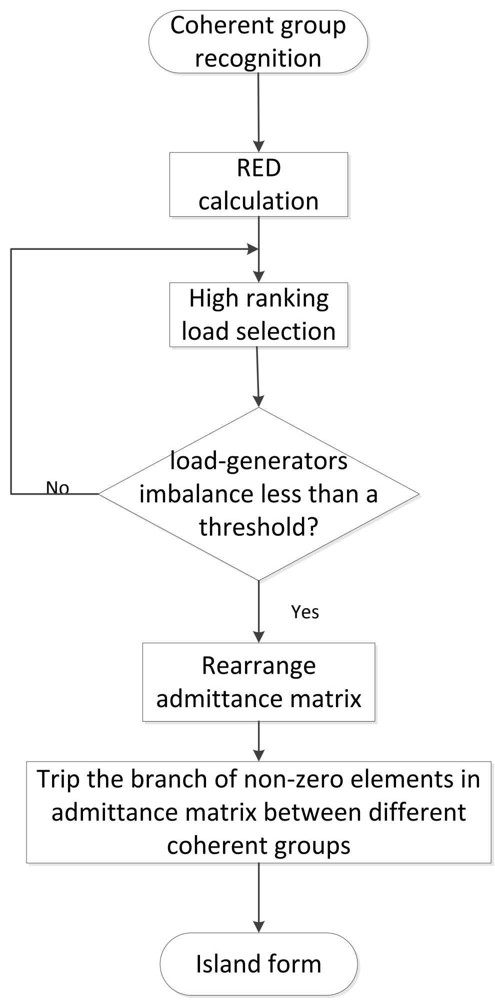

Figure 1: Flow chart of intelligent islanding

3. METHODOLOGY FOR CONTROL ISLANDING

A. Coherent Group Recognition

Before initiating the intelligent islanding, the coherent groups of the generators need to be recognized. Generators belonging to the same group should remain in the same island. Suppose all the buses in a system are expressed as $B = B_G \cup B_L$; where B stands for all the buses in the system, B_G stands for the generator buses; and B_L stands for the other buses remaining in the system. Suppose n groups of coherent generators have been recognized, such that $\sum_{i=1}^{n} B_{Gi} = B_G$, B_{Gi} is the i$^{\text{th}}$ coherent group of generators. The generator buses in a different coherent group (the j$^{\text{th}}$coherent groups for example) belongs to the different island $B_{Gi} \cap B_{Gj} = \phi, i \neq j$

B. Load Selection by Relative Electrical Distance (RED)

The first step of the proposed controlled islanding method is to find out the loads within each island in order to minimize the mismatch of generation output and load demand. Loads are selected by the relative electrical distance (RED) [9] ranking to balance the active power of the generators. The concept of the relative electrical distance was first proposed by Vishaka K. el. to estimate the relative electrical locations of the generators buses with respect to the load buses.

Ranking the RED index from smallest to largest, the loads with higher RED ranking with respect to the generator will have larger impacts on the generator rotor angle behavior compared to the lower ranking ones. Based on the topology of the network, the admittance matrix is constructed:

$$\mathbf{Y_b} = \begin{bmatrix} \mathbf{Y_{gg}} & \mathbf{Y_{gl}} \\ \mathbf{Y_{lg}} & \mathbf{Y_{ll}} \end{bmatrix} \tag{1}$$

in which, the subscript g stands for the generator buses and the subscript l stands for the other buses in the system. The voltages of all the buses can be obtained by (2)

$$\begin{bmatrix} \mathbf{E_g} \\ \mathbf{V_l} \end{bmatrix} = \begin{bmatrix} \mathbf{Y_{gg}} & \mathbf{Y_{gl}} \\ \mathbf{Y_{lg}} & \mathbf{Y_{ll}} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{I_g} \\ \mathbf{0} \end{bmatrix} \tag{2}$$

in which, $\mathbf{I_g}$ is the injection current of the generators. The voltage of the buses without generators can be expressed as:

$$\mathbf{V_l} = -(\mathbf{Y_{ll}})^{-1} \mathbf{Y_{lg}} \mathbf{E_g} \tag{3}$$

If we let $\mathbf{F_{lg}} = -(\mathbf{Y_{ll}})^{-1}\mathbf{Y_{lg}}$, we get a complex matrix that gives the relation between load bus and source bus voltages. The rows of $\mathbf{F_{lg}}$ correspond to the load buses, while the columns correspond to the generator buses.

Relative electrical distance (RED) is defined as:

$$RED = \mathbf{I} - abs(\mathbf{F_{lg}}) \tag{4}$$

$\mathbf{I}$ is a unity matrix.

In each coherent group of generators, the loads with shorter relative electrical distance should be selected to remain in the island. A ranking table of the RED therefore can be listed for load selection reference.

The load searching will terminate when the following three requirements are met.

1. The next load in the ranking table is the terminal bus of a generator that belongs to other coherent groups.
2. The power imbalance between the generator-load is less than a threshold.
3. Bus/load selection of each generator via the RED ranking table must have at least one bus duplicated to guarantee the connection within the island.

According to the operation experience of the power system, the Out of Step relay trips one after another, which indicates that multiple coherent groups do not develop simultaneously. Any contingencies resulting in multiple groups of coherency are initiated by two coherent groups at the first stage. Therefore, the controlled islanding in this paper only focuses on two groups of contingency. One coherent group with fewer generators will be chosen to select the load based on the RED method since it will make the speed of load searching faster. The other coherent group will take over the rest of the buses, which means one of the islands can guarantee the generator-load balance, and the remaining island may need proper load shedding or a generator curtailment scheme to restore the generator-load balance.

Since the basic configuration of the islands does not change dramatically within a short period of time when different lines are removed, the RED index table is prebuilt prior to the disturbance and can be applied as a reference during the contingency.

C. Islanding Boundary Determination

The second step of the proposed islanding method is to determine the boundary for controlled islanding in a short period of time using the admittance matrix. This is done by tripping the connecting lines between the two islands indicated by the non-zero elements of the “mutual-admittance matrix”. The concept of the “mutual-admittance matrix” is explained later.

Take a simple 3-generator 5-bus system with two coherent groups for example,

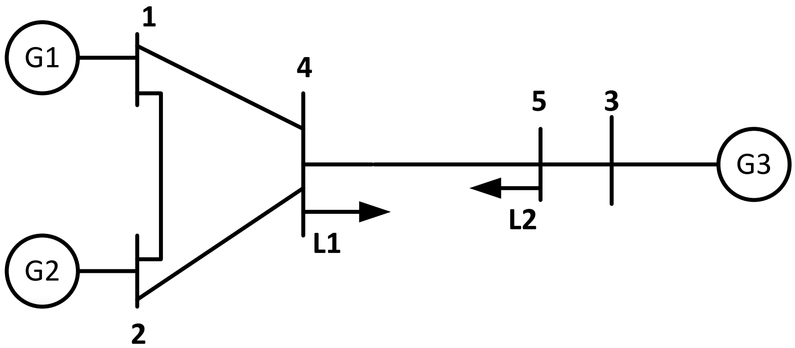

Figure 1: Five buses illustration system

The admittance matrix is:

$$\mathbf{Y} = \begin{bmatrix} Y_{11} & Y_{12} & 0 & Y_{14} & 0 \\ Y_{21} & Y_{22} & 0 & Y_{24} & 0 \\ 0 & 0 & Y_{33} & 0 & Y_{35} \\ Y_{41} & Y_{42} & 0 & Y_{44} & Y_{45} \\ 0 & 0 & Y_{53} & Y_{54} & Y_{55} \end{bmatrix} \tag{5}$$

Only when there is connection between bus i and bus j, does $Y_{ij} \neq 0$

$$Y_{ij} = \begin{cases} c\,(c \neq 0) & \text{connected} \\ 0 & \text{disconnected} \end{cases} \tag{6}$$

The concept of the islanding boundaries is illustrated in Figure 3

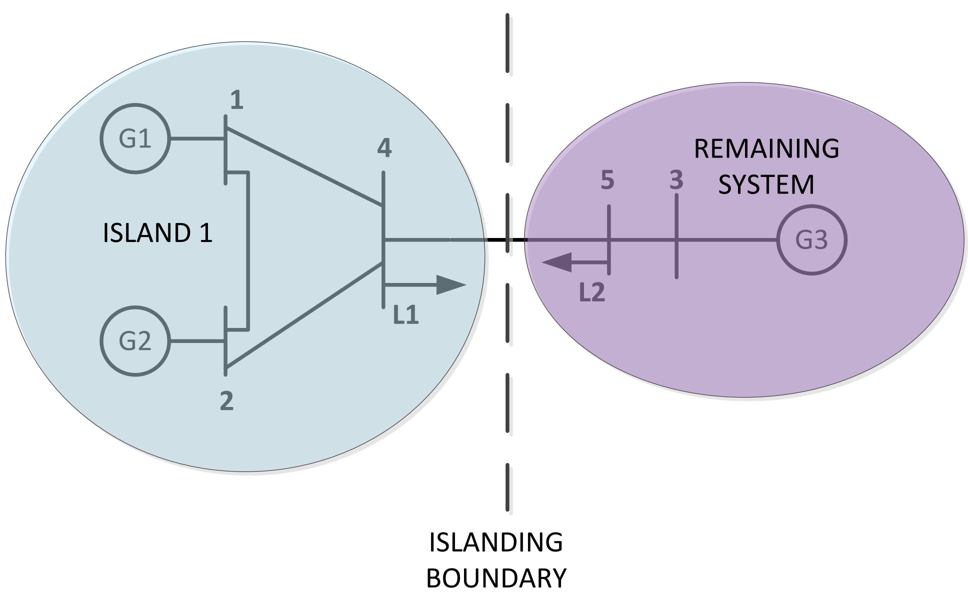

Figure 2: Concept of intelligent islanding

Suppose generator G1 and G2 are identified in a coherent group, oscillating against generator G3, and load L1 is selected to balance the power output of G1 and G2 by the RED method. Therefore island1 includes G1, G2 and L1, while the remaining system, island2, which consists of G3 and L2. $\mathbf{G1, G2, L1} \in \mathbf{Y_{island1}}$, $\mathbf{L2, G3} \in \mathbf{Y_{island2}}$. The admittance matrix of each island is:

$$\mathbf{Y_{island1}} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{14} \\ Y_{21} & Y_{22} & Y_{24} \\ Y_{41} & Y_{42} & Y_{44} \end{bmatrix}, \mathbf{Y_{island2}} = \begin{bmatrix} Y_{55} & Y_{53} \\ Y_{35} & Y_{33} \end{bmatrix} \tag{7}$$

Therefore, the structure of the admittance matrix can be rearranged and expressed as (8)

$$\mathbf{Y} = \begin{bmatrix} \mathbf{Y_{island1}} & \mathbf{Y_B} \\ \mathbf{Y_B}^T & \mathbf{Y_{island2}} \end{bmatrix} \tag{8}$$

Here, define $\mathbf{Y_{island1}}, \mathbf{Y_{island2}}$ as the "self-admittance matrix" of island 1 and island 2; $\mathbf{Y_B}$ is defined as the "mutual-admittance matrix" between the two islands in this paper. Rearranging the admittance matrix according to the sequence of islands as given in (7), the admittance matrix of (5) is rearranged to (9).

$$\mathbf{Y} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{14} & 0 & 0 \\ Y_{21} & Y_{22} & Y_{24} & 0 & 0 \\ Y_{41} & Y_{42} & Y_{44} & Y_{45} & 0 \\ 0 & 0 & Y_{54} & Y_{55} & Y_{53} \\ 0 & 0 & 0 & Y_{35} & Y_{33} \end{bmatrix} \tag{9}$$

In this case, the "mutual-admittance matrix": $$\mathbf{Y_B} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ Y_{45} & 0 \end{bmatrix} \tag{10}$$

The non-zero elements in the "mutual-admittance matrix" $\mathbf{Y_B}$ denote the lines that connect between island1 and island2. $\mathbf{Y_B} = \mathbf{0}$ means that the island 1 and island 2 are completely separated. Therefore, by tripping the intersection line 4-5 ($Y_{45} = 0$), island 1 and island 2 can be formed.

4. SIMULATION RESULTS

The proposed controlled islanding scheme can be applied to both of the steady state and the transient conditions. In this section, the IEEE-39 bus system is tested in the steady state to illustrate the proposed controlled islanding scheme, while the WECC 128-bus system is tested under transient conditions to validate the feasibility of the proposed controlled islanding scheme.

4.1 IEEE-39 bus system

During the normal operation, at any given time, it is possible to partition the system into desirable parts [10]. The locations selected to be tripped should minimize the imbalance between the load and generation within the island, which will result in the least disturbance of operation. The IEEE-39 buses system is tested for the controlled islanding method in the steady state. The topology of the system is shown in Figure 4

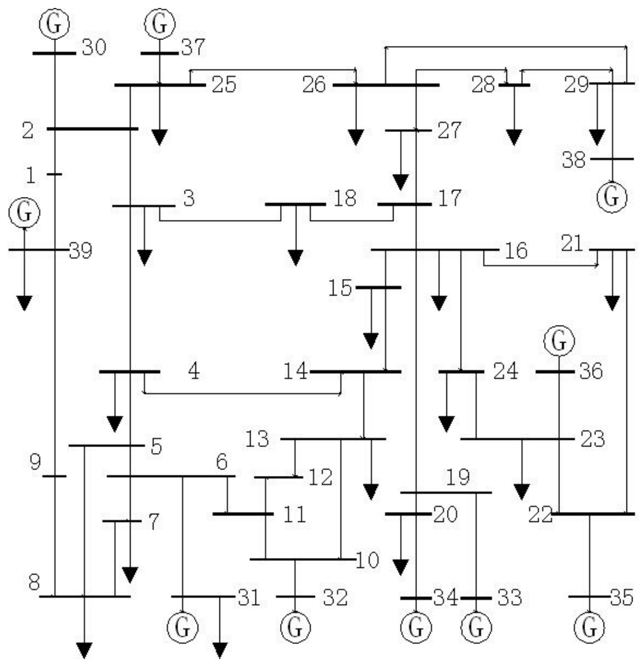

Figure 3: IEEE-39 buses system

Suppose Gen 31 and Gen 32 are chosen to form a new island isolated from the other generators in the system. Following the flow chart of intelligent islanding in Figure 1, the steps are as follows.

Step 1: Calculate the relative electrical distance (RED) of every load bus with respect to every generator and build the load index table. Sorting the load bus by the RED from smallest to largest, the top 3 rankings with respect to GEN 31 and GEN 32 are shown in Table I:

TABLE I

THE TOP 3 RANKING OF LOAD WITH RESPECT TO GEN 31 AND GEN32

RANKING	GEN 31	GEN32
1	load 7	load 12
2	load 8	load 7
3	load 12	load 4

The load searching scheme is implemented according to the load sorting. For example, load 7 and load 12 are selected in the first depth of the load searching, since they are the loads with the smallest electrical distance with respect to GEN 31 and GEN 32 respectively. At the second depth of load searching, load 8 and load 7 are selected. Therefore, after two depths of load searching scheme, loads 7, 8, and 12 are chosen to match the generation output of GEN 31 and GEN 32. At t=2s, the generation output of Gen31 and Gen 32 is 1161.97MW, loads with high RED ranking should be accumulated in the island until the power imbalance between the generators and the load is minimized or less than a set threshold. In this case, only three depths of load searching are needed, shown as Table II

TABLE II

THREE DEPTHS OF LOAD SEARCHING TO BALANCE THE CAPACITY OF GEN 31 AND GEN32

DEPTH	Load selected	Load demand (MW)
1st	7,12	242.3
2nd	7,12,8	764.3
3rd	7,12,8,4	1264.3

From Table II, the 3rd depth of load demand (1264.3 MW) is closer to generator capacity (1161.97 MW) than the 2nd depth of load demand (764.3 MW). Therefore, the load searching stops at the 3rd depth. In total, loads 7, 4, 8, and 12 are chosen in the three depths of RED load searching. The total load demand of these buses is 1264.3MW.

During the load searching, the buses with smaller RED value with respect to GEN 31 and GEN 32 than the selected load buses should also be included in the island. This is because the selected load buses must be reached by some of those buses according to the second assumption mentioned in section 2. Based on Table III and Table IV, the buses with smaller RED selected from the two generators to the load in these three depths searching are buses 6, 5, and 11 for GEN31; while buses 10, 13, 11, 14, 6, and 5 are for GEN32. Therefore, buses 5, 6, 10, 11, 13 and 14 should also be included in the island.

TABLE III

THE RED OF BUSES WITH RESPECT TO GEN 31

GEN 31		
DEPTH	BUS NO.	RED
	BUS6	0.636197
	BUS5	0.66219
1st	LOAD7	0.666766
2nd	LOAD8	0.682141
	BUS11	0.730154
3rd	LOAD12	0.754517

TABLE IV

THE RED OF BUSES WITH RESPECT TO GEN 32

GEN 32		
DEPTH	BUS NO.	RED
	BUS10	0.531236
	BUS13	0.57995
1st	LOAD 12	0.585514
	BUS11	0.596021
	BUS14	0.692729
	BUS6	0.721147
	BUS5	0.729942
2nd	LOAD 7	0.740853
3rd	LOAD 4	0.749654

Step 2: Rearrange the admittance matrix with the sequence of $(\mathbf{Y}_{\text{island1}}, \mathbf{Y}_{\text{island2}})$

$(31,32,4,5,6,7,8,10,11,12,13,14) \in \mathbf{Y}_{\text{island1}}$
$(1,2,3,9,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,33,34,35,36,37,38,39) \in \mathbf{Y}_{\text{island2}}$

The admittance matrix rearranged with the new sequence can be seen in Appendix A. The non-zero elements of $\mathbf{Y}_\mathbf{B}$ are $Y_{3,4}$, $Y_{8,9}$ and $Y_{14,15}$. Therefore, to partition island 1 and island 2, lines 3-4, 8-9, and 14-15 need to be tripped.

4.2 WECC 128-bus system

The proposed controlled islanding scheme is also tested in the WECC 128-bus system for transient application.

A three phase fault is created at bus 68 at 0.2 seconds that the fault lasts for 300 milliseconds. The fault is cleared by tripping all the lines connected to bus 68. At t=0.8s, generator 72 is already out of step. At t=1.0s, two coherent groups are oscillating against each other:

Coherent group1: generator at bus 1, 5, 8, 13, 19, 26, 28, 88, 91, 96,102

Coherent group2: generator at bus 33, 38, 44, 46, 47, 49, 53, 60, 62, 65, 67, 76, 81, 113, 119, 126, 5699

The rotor angle plots for all generators without intelligent islanding are shown as Figure 5.

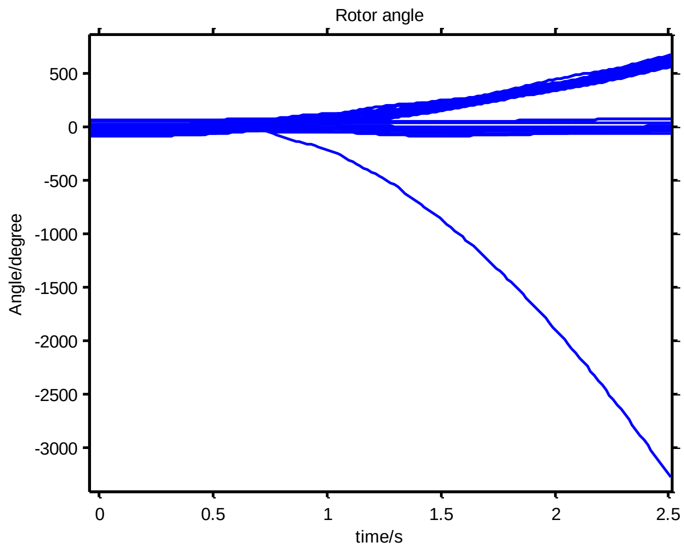

Figure 4: Rotor angles without controlled islanding

The flow chart process of intelligent islanding shown in Figure 1 is thus followed.

Step 1: Calculate the relative electrical distance (RED) of every load bus with respect to the generators in coherent group 1. At t=1.0s, the generators' capacity in island 1 is 36726.7 MW. Based on the RED index, Table V lists the top loads to match the generators' capacity in island 1.

TABLE V

THE TOP RANKING OF LOAD WITH RESPECT TO THE GENERATORS IN ISLAND 1

GEN in island 1	RED Ranking													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
GEN1	2	6	7	9	25	11	12	14	18	20	17	15	23	93
GEN 5	6	3	7	9	25	11	2	12	14	18	20	17	15	23
GEN 8	7	9	25	11	12	14	18	20	17	15	2	6	93	24
GEN 13	12	14	18	20	17	25	11	15	9	23	93	92	94	7
GEN 19	20	17	18	14	12	25	11	15	9	23	93	92	94	22
GEN 26	24	9	25	11	7	12	14	18	20	17	15	23	93	92
GEN 28	29	27	22	30										
GEN 88	87	83	89	85	86	84	68							
GEN 91	90	92	94	93	101	23	100	98	99	97	95	89	15	85
GEN 96	95	97	99	98	100	93	94	23	92	101	15	90	22	27
GEN 102	101	100	98	99	97	90	95	94	92	23	15	89	85	86

As mentioned in the second requirement of the load searching in Section B, the accumulation of load with respect to the generators in one island will stop when the next load/bus is the terminal buses of the generators which belong to the other coherent group. Therefore the load searching of GEN 28 is stopped at bus 30, which is the terminal bus of generator 29. The load searching with respect to GEN 88 stops at bus 84 because the next ranked bus is 68, which has been tripped during the contingency. Next, loads with high ranking in the island are accumulated until the imbalance between generation output of coherent group 1 and the load demand is minimized. In this case, fourteen depths are needed for the load selection, which are shown in Table VI.

TABLE VI

FOURTEEN DEPTHS OF LOAD SEARCHING TO BALANCE THE CAPACITY OF ISLAND 1

Depth	Load selected	Load demand (MW)
1st	2,6,7,12,20,24,29,87,90,95,101	27163.45
2nd	2,6,7,12,20,24,29,87,90,95,101,3,9,14,17,27,83,92,97,100	31720.18
3rd	2,6,7,12,20,24,29,87,90,95,101,3,9,14,17,27,83,92,97,100, 25,18,22,89,94,99,98	33812.15
4th	2,6,7,12,20,24,29,87,90,95,101,3,9,14,17,27,83,92,97,100, 25,18,22,89,94,99,98,11,20,85,93,	35972.50
5th	2,6,7,12,20,24,29,87,90,95,101,3,9,14,17,27,83,92,97,100, 25,18,22,89,94,99,98,11,20,85,93,86	36015.76
6th	2,6,7,12,20,24,29,87,90,95,101,3,9,14,17,27,83,92,97,100, 25,18,22,89,94,99,98,11,20,85,93,86,84,23	36679.50
…		
14th	2,6,7,12,20,24,29,87,90,95,101,3,9,14,17,27,83,92,97,100, 25,18,22,89,94,99,98,11,20,85,93,86,84,23,15,19	36709.38

The load searching stops at depth 14th when the load demand (36709.38MW) is maximally match the generator capacity (36726.7MW) in island1. Also the connection between the generators in the island is guaranteed by:

$$L_i, L_j \subset island\ ,\ load_i \in L_i, load_j \in L_j$$

$$\forall load_i \cap load_j \neq \phi, i \neq j$$

in which, L_i, L_j stand for the loads set selected by RED method with respect to generator GEN_i and generator GEN_j respectively.

Step 2: Rearrange the admittance matrix with the sequence of $(\mathbf{Y}_{\mathbf{island1}}, \mathbf{Y}_{\mathbf{island2}})$.

$(1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,83,84,85,86,87,88,89,90,91,92,93,95,96,97,98,99,100,101,102) \in \mathbf{Y}_{\mathbf{island1}}$

$(\textit{remaining buses in system}) \in \mathbf{Y}_{\mathbf{island2}}$

The non-zero elements of the mutual admittance matrix $\mathbf{Y_B}$ are $Y_{29,30}$ and $Y_{77,78}$ therefore, to isolate island 1 and island 2, both line 29-30 and line 77-84 need to be tripped. The islanding boundaries of transient 2 are shown in Figure 6.

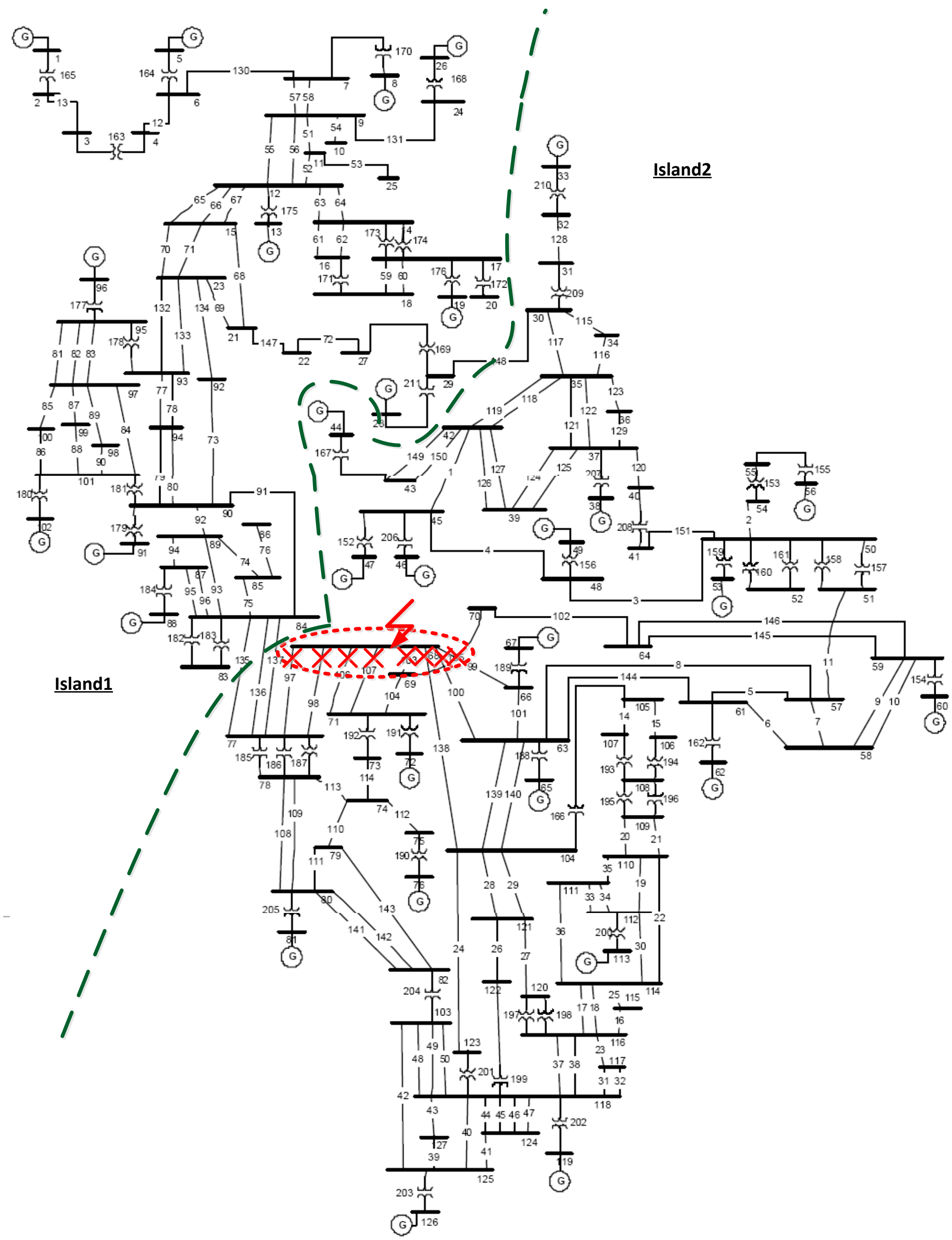

Figure 6: Controlled islanding of WECC 128 buses system

It can be seen from Figure 7 and Figure 8 that the oscillations of the rotor angles in island 1 and island 2 are within the stable boundary (less than 180 degrees) and all the angles are damping along with time. All the buses' voltages are within the $\pm 5\%$, the frequencies are within 0.5Hz deviation from 60Hz.

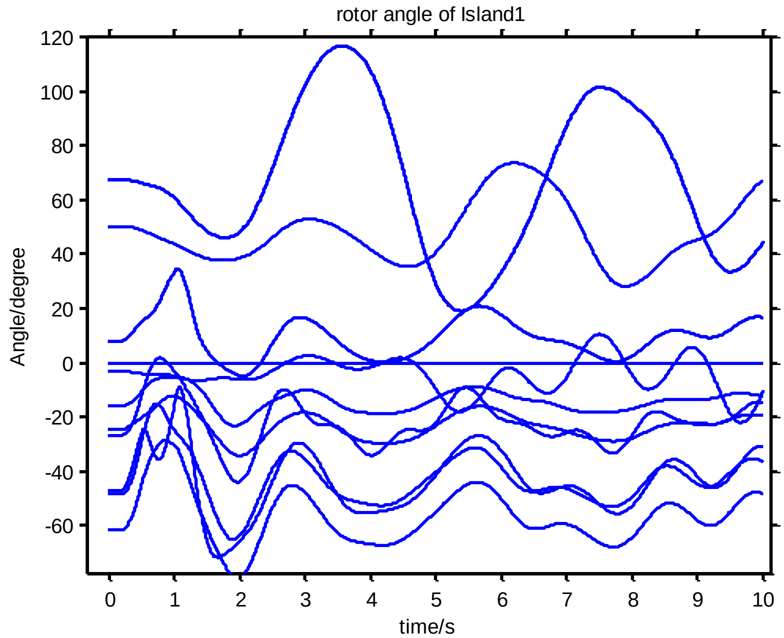

Figure 7: Rotor angles of island 1

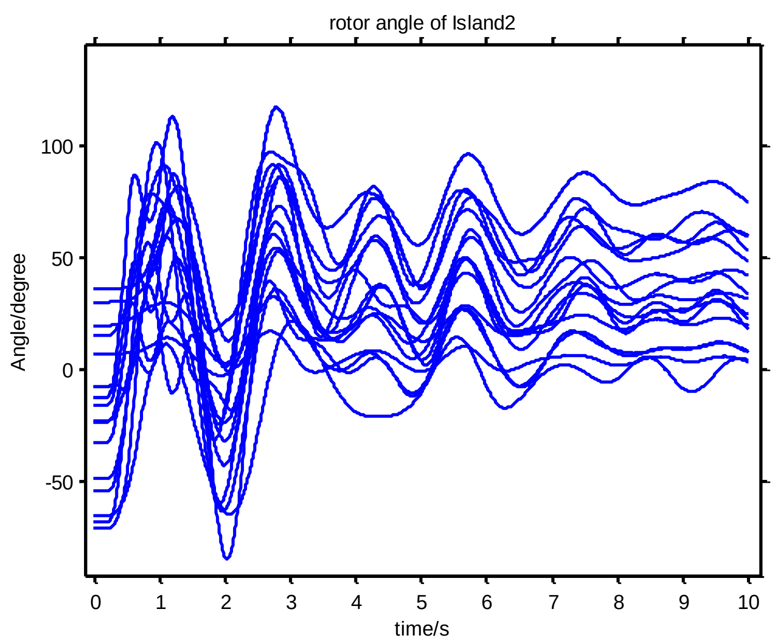

Figure 8: Rotor angles of island 2

To validate the feasibility of this method, the active power of the boundary lines are simulated without the controlled islanding. The active power of line 29-30, line 77-84 are shown as below:

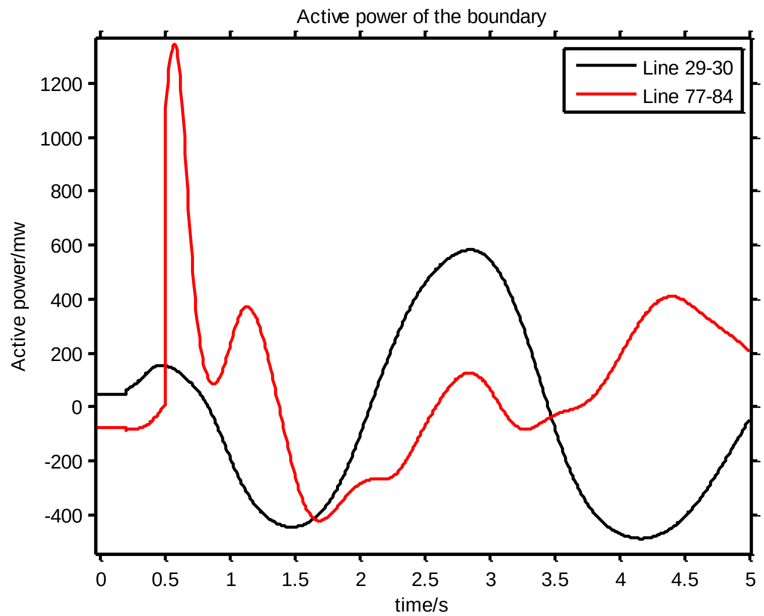

Figure 9: Active power of Line 29-30 and Line 77-84

It can be seen from Figure 9, the active power of line 29-30 and line 77-78 fluctuate remarkably during the contingency, which are identical with the current criteria of islanding boundary detection [5] in the power system.

5. Conclusion and Discussion

This paper proposed a novel intelligent controlled islanding method. This method has been tested in the IEEE-39 bus system and WECC 128 bus system, which verified its practicability and validity in the steady state and the transient simulation.

The proposed algebraic calculation based method, is fast and easy to be implemented. There are mainly two steps in the intelligent controlled islanding. Step1: After the recognition of coherent groups, the load can be chosen within the island based on the RED load index table. Step 2: Detect the islanding boundaries based on the mutual admittance matrix. The advantage of the proposed method is saving large initial searching space of the islanding strategies, which is more feasible for online application. The RED index table is pre-built prior to the disturbance and applicable during contingency, since the basic configuration of the islands does not change dramatically in a short time frame when some lines are removed during contingency. The loads ranked higher on the list have greater impact on the generator angle performance and should be chosen as the loads to match the generator capacity in the island. Furthermore, the load ranking in this method that based on electrical distance is insensitive to the random load changes.

Considering multiple coherent groups oscillation, based on the conjecture 3 in reference [10], it is believed that the loss of synchronism does not occur simultaneously according to the experience that the Out of Step relay operates one after another. The proposed islanding scheme allows the stability to be restored within the two islands at the early stage before successive new islands occurrence.

It can be concluded that the proposed method is a very efficient and remarkably high speed method that can be applied to a power system for real time splitting. It not only helps to seek the boundaries of different generator groups in the steady state, but also rapidly detects the controlled islanding boundaries for the operators when the system splitting is unavoidable during the contingencies.

6. References

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Appendix A

For display convenience, the nonzero elements in the matrix have been replaced with ones while rearranging the admittance matrix. The sub-square matrix in the lower right corner, colored purpled, indicates island 1, the sub-square-matrix in top left corner indicates island 2. The red colored nonzero elements shown in the matrix is the intersection lines between island 1 and island 2. Those lines (Line 3-4,Line 14-15,and Line 8-9) will be tripped in order to isolate island 1 and island 2.

Island 2 Island 1

BUS	1	2	3	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	33	34	35	36	37	38	39	9	14	4	5	6	7	8	10	11	12	13	31	32
1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
15	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	1	1	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

33	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1	0	0	0	0	0	0
14	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	0	0
4	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	1	0	0	1	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	1	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1	0	1
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	1	0	0
31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1

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