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A KNOWLEDGE-BASED APPROACH FOR CIRCUIT ALLOCATION IN SUBTRANSMISSION SUBSTATIONS UNDER MAINTENANCE CONDITIONS

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ABSTRACT

This paper details the development of a knowledge-based system for allocating circuits to duplicate-busbar switching substations under maintenance conditions. The allocation rules in the knowledge bases for the determination of the arrangements of circuit groups and an overall allocation algorithm for combining the group allocation schemes using the strategy of least reduction in power security are developed. The knowledge-based system is applied to a 132 kV substation and the results are presented.

(1) INTRODUCTION

In a duplicate-busbar subtransmission substation [1], groups of incoming and outgoing circuits are connected to the substation busbars such as those in Fig.1 [2]. The arrangement of the circuits is usually determined according to the maximum security of power supply criterion. When one of the circuit breakers or busbars is disconnected for routine inspection, cleaning and maintenance, the configuration of the system will be altered. The circuits have to be re-allocated such that maximum degree of power supply security should be maintained.

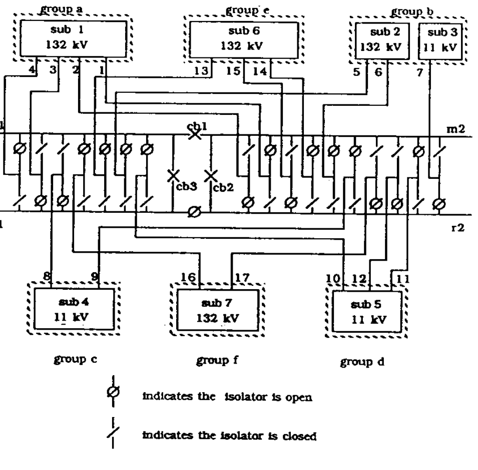

Fig.1 Best overall circuit allocation scheme for 17 circuits in 6 groups

In practice, the re-allocation schemes for the circuits under maintenance situations is determined manually by the operation engineers. The manual process, however, is time-consuming and tedious.

This paper reports the development of a knowledge-based system for re-allocating circuits in switching substations under circuit-breaker and busbar maintenance conditions. The structure of the system is shown in Fig.2. The allocation rules in the knowledge bases and the algorithm for selecting the group circuit allocations for forming the overall allocation schemes are developed. The knowledge-based system is implemented using Prolog [3]. Results obtained by applying the system to determine the re-arrangement of 17 circuits in 6 groups in the substation in Fig.1 under maintenance conditions are presented.

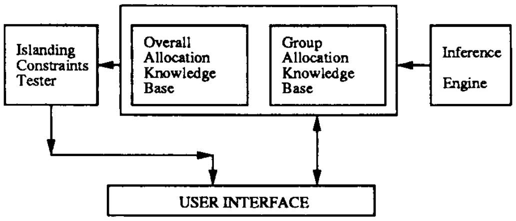

Fig.2 Schematic diagram of knowledge-based system

(2) THE CIRCUIT ALLOCATION PROBLEM

Fig.3 shows the configuration for a 132 kV duplicate busbar substation when circuit-breaker CB3 is taken out of service for maintenance.

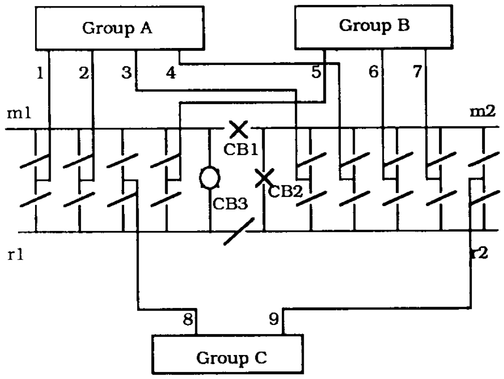

Fig.3 A typical duplicate-busbar substation with circuit-breaker CB3 under maintenance

The circuit groups are to be connected to the main or reserve busbar sections. For the three groups of circuits as shown in Fig.3, there will be 2^9 or 512 overall circuit arrangements. If only the best two arrangements of each group are considered, there will only be 2^3 or 8 best overall circuit arrangements. Therefore, by using the first two best arrangements as the basis to form the overall allocations, the combinatorial problem can be greatly reduced.

To determine the best group allocation schemes, considerations are given to the effects of the busbar and circuit-breaker faults. The power rating loss (PRL) is used to indicate the severity of the power loss for a given circuit arrangement and it is the basis for establishing the allocation rules in the knowledge-bases for determining the best and second best group allocation schemes from a known set of feasible group arrangements. The rules are developed in the next section followed by the development of the rules and algorithm for finding the best overall allocation schemes. The validity of the overall circuit allocation scheme is then checked against the islanding constraints.

(3) GROUP ALLOCATION KNOWLEDGE BASE

(3.1) Derivation of Group Allocation Rules under Circuit-Breakers Maintenance

The preferences of group allocation schemes are to be graded according to the maximum power rating loss due to busbar and circuit-breaker faults. The scheme which provides the least power loss will be the best arrangement. For any scheme, indices MBP and MCP are used to denote the maximum PRL's due to a busbar and a circuit-breaker fault respectively whilst the index TCP is used to denote the sum of the PRL's due to circuit-breaker faults. As the probability of busbar faults is higher than that of the circuit-breaker faults, the priority order of the indices is MBP, MCP and TCP. A scheme with the least MBP is the best group arrangement. If more than one schemes have the same MBP, the MCP's of the schemes are compared and the one with the least MCP is preferred. If more than one schemes have the same MCP's, the TCP's are compared.

The three-circuit group in Fig.4(a) has 8 possible group arrangement schemes as shown in Fig.4(b). Under CB3 maintenance condition, the MBP, MCP and TCP expressions for these schemes are tabulated in Table 1. To determine the best and second best arrangements, the relationships of the circuit power ratings are considered. Let the ratings of the circuits in Fig.4 be a, b and c and a is greater than or equal to b. There are 8 possible relationships as shown in expression set (1). These relationships are termed as the *main relationships*.

(R1)	$a > b > c$	(R2)	$a = b > c$	
(R3)	$a > b = c$	(R4)	$a = b = c$	(1)
(R5)	$a > c > b$	(R6)	$a = c > b$	
(R7)	$c > a > b$	(R8)	$c > a = b$	

Table 1: Fault indices for CB3 under maintenance

Scheme	MBP	MCP	TCP
(1)	(a+b) or c	(a+b+c)	(a+b+2c)
(2)	(a+b) or c	(a+b) or c	(a+b+c)
(3)	a or c	(a+c) or (b+c)	(a+b+2c)
(4)	a or (b+c)	a or (b+c)	(a+b+c)
(5)	a or c	(a+c) or (b+c)	(a+b+2c)
(6)	(a+c)	(a+c)	(a+b+c)
(7)	(a+b) or c	(a+b+c)	(a+b+2c)
(8)	(a+b+c)	(a+b+c)	(a+b+c)

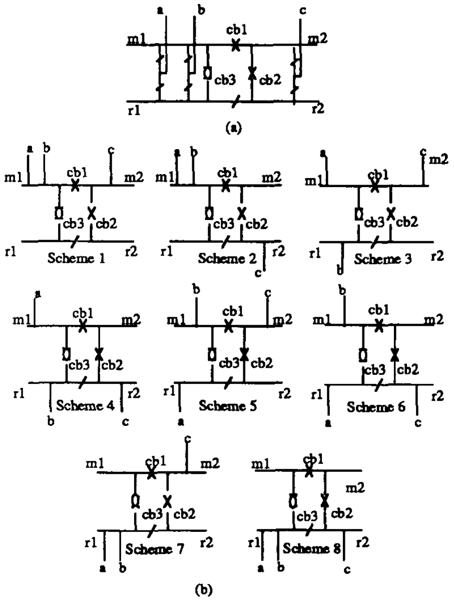

Fig.4 Possible circuit arrangements for a three-circuit group under circuit-breaker maintenance condition

(3.1.1) Fault indices due to main relationships

By applying the main relationships, the expressions in Table 1 can be simplified. For example, when relationship (R4), $a=b=c$, is applied, the expressions in Table 1 become those in Table 2.

Table 2: Fault indices for CB3 maintenance under main relationship, (R4), $a=b=c$

Schemes	1	2	3	4
MBP	(a+b)	(a+b)	a	(b+c)
MCP	(a+b+c)	(a+b)	(a+c)	(b+c)
TCP	a+b+2c	a+b+c	a+b+2c	a+b+c
Schemes	**5**	**6**	**7**	**8**
MBP	a	(a+c)	(a+b)	(a+b+c)
MCP	(a+c)	(a+c)	(a+b+c)	(a+b+c)
TCP	a+b+2c	a+b+c	a+b+2c	a+b+c

From Table 2, since the MBP for scheme 8 and the MCP for schemes 1, 7 and 8 are (a+b+c) showing that all the circuits will be lost, these schemes are not considered further. Based upon the MBP values, it can be determined that schemes 3 and 5 are the best arrangements since minimum power loss will result from busbar failure. Schemes 2, 4 and 6 having identical MBP values are the second best arrangements. Since a = b, schemes 3 and 5 are identical, so are schemes 4 and 6. Under main relationship (R4), therefore, the best arrangement is scheme 3 and the second best is scheme 2 or 4.

(3.1.2) Fault indices due to sub-relationships

Although the main relationships are sufficient to determine the best and the second best arrangements for most cases in expression set (1), situations may arise that there are more than one expressions for the maximum power rating loss in a scheme. For example, under CB3 maintenance and the main relationship (R5), a>c>b is applied, the fault indices will be those summarised in Table 3 below.

Table 3: Fault indices for CB3 maintenance under main relationship, R5 (a>c>b)

	Schemes			
	1	2	3	4
MBP	(a+b)	(a+b)	a	a or (b+c)
MCP	(a+b+c)	(a+b)	(a+c)	a or (b+c)
TCP	a+b+2c	a+b+c	a+b+2c	a+b+c

	Schemes			
	5	6	7	8
MBP	a	(a+c)	(a+b)	(a+b+c)
MCP	(a+c)	(a+c)	(a+b+c)	(a+b+c)
TCP	a+b+2c	a+b+c	a+b+2c	a+b+c

After eliminating schemes 1, 7 and 8 due to their MCP values, the MBP expression in scheme 4 can only be determined by establishing the relationship between a and (b+c). These relationships are referred to as *sub-relationships* and they are a>(b+c), a=(b+c) and (b+c)>a.

For the case that a>(b+c) or a=(b+c), the MBP values for schemes 3, 4 and 5 are a and therefore they are the least. By comparing the MCP and TCP values, it is determined that scheme 4 is the best arrangement and either schemes 3 or 5 is the second best arrangement. Similarly, if (b+c)>a, the best arrangement is scheme 3 or 5 whereas scheme 4 is the second best.

Using the approach in the previous sections, the best and second best group arrangements under the main and sub-relationships for a three-circuit group under CB3 maintenance are shown in Table 4.

Table 4: Summary of best and second best group allocation schemes for a three-circuit group under CB3 maintenance condition

Relationships		Best group arrangement	
Main	Sub	1st	2nd
a>b>c	a>(b+c)	4	3 or 5
a>b>c	a<(b+c)	3 or 5	4
a>b>c	a=(b+c)	4	3 or 5
a=b>c		3	4
a>b=c	a>(b+c)	4	3 or 5
a>b=c	a<(b+c)	3 or 5	4
a>b=c	a=(b+c)	4	3 or 5
a=b=c		3	2 or 4
a>c>b	a>(b+c)	4	3 or 5
a>c>b	a<(b+c)	3 or 5	4
a>c>b	a=(b+c)	4	3 or 5
a=c>b		3 or 5	2 or 4
c>a>b	(a+b)>c	3 or 5	2
c>a>b	(a+b)=c	2	3 or 5
c>a>b	c>(a+b)	2	3 or 5
c>a=b	(a+b)>c	3	2
c>a=b	(a+b)=c	2	3
c>a=b	c>(a+b)	2	3

From the relationships in Table 4, the allocation rules in the knowledge base for the three-circuit group can be found by grouping all the relationships which point to the same scheme. This method can also be applied to form rules for the 2- and 4-circuit groups. The rules derived from Table 4 for the case when CB3 is under maintenance are given below.

1 If [c> =a>b and c> =(a+b)] then
the first best arrangement is scheme 2 and
if (a>b) then
the second best arrangement is scheme 3 or 5 else
the second best arrangement is scheme 3.

2 If [a=b and (a+b)>c] then
the first best arrangement is scheme 3 and
if (a=c) then
the second best arrangement is scheme 2 or 4 else
if (c>a) then
the second best arrangement is scheme 2 else
if (a>c) then
the second best arrangement is scheme 4.

3 If [c> =a>b and (a+b)>c] then
the first best arrangement is scheme 3 or 5 and
if (c>a) then
the second best arrangement is scheme 2 else
the second best arrangement is scheme 2 or 4.

4 If [a>b> =c and (b+c)>a] or
[a>c>b and (b+c)>a] then
the first best arrangement is scheme 3 or 5 and
the second best arrangement is scheme 4.

5 If [a>b> =c and a> =(b+c)] or
[a>c>b and a> =(b+c)] then
the first best arrangement is scheme 4 and
the second best arrangement is scheme 3 or 5.

(3.2) Derivation of Group Allocation Rules for Busbar Maintenance

When one of the busbars is isolated for maintenance purpose, all the circuits have to be transferred to the remaining in-service busbars. For the three-circuit group described previously, the possible circuit allocation schemes during busbar r2 maintenance condition are shown in Fig.5.

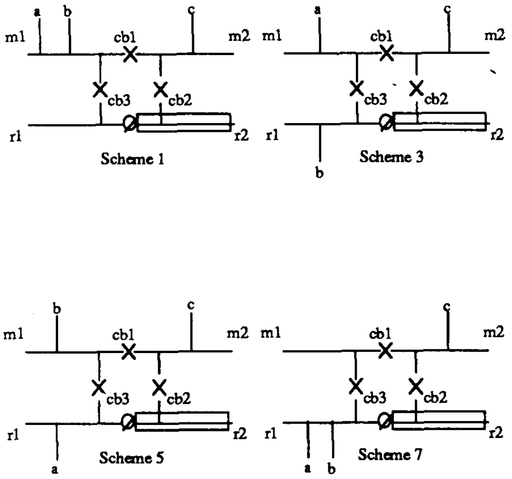

Fig. 5 Possible circuit allocation schemes for a three-circuit group under busbar r2 maintenance condition

The methodology developed in Section 3.1 can be applied to find the best and the second best group circuit arrangements under any busbar maintenance conditions. Whilst all the rules in the knowledge base for the best and the second best group allocation schemes for the three-circuit group in Fig.5 can be formulated, those under busbar r2 maintenance are listed below.

1 If $[(a+b)>c]$ then
the first best arrangement is scheme 5 and
if $[a>b$ and $a> =c]$ then
the second best arrangement is scheme 3, else
if $[c>a>b]$ or $[a=b]$ then
the second best arrangement is scheme 7, else

2 If $[c>a=b]$ then
the first best arrangement is scheme 7 and
the second best arrangement is scheme 5.

(4) OVERALL ALLOCATION KNOWLEDGE BASE

Having determined all the first and second best group circuit schemes for the given groups, the overall allocation arrangements are formed by combining the schemes of all the groups. The first best overall scheme is formed from the combination of all the first best group schemes. The second best overall scheme can be obtained by changing one of the groups to its second best scheme. Out of all the possible changes, the one which leads to the least reduction insecurity in supply is preferred. The same strategy is used for forming overall schemes subsequent to the second best scheme.

(4.1) Formation of the Indices of Reduction in Security

The level of reduction in security when switching from the best group scheme to the second best scheme is given by the differences in the MBP, MCP and TCP indices of the two schemes. These differences are denoted by indices dMBP, dMCP and dTCP which have the same priority order as MBP, MCP and TCP. For the three-circuit group considered previously, when the main relationship R5, $a>c>b$ and sub-relationship $a>(b+c)$ are applied, the MBP, MCP and TCP for the first and second best group arrangements and their differences under CB3 maintenance are listed in Table 5 below.

Table 5 : Fault indices and reduction in security indices for a three-circuit group during CB3 maintenance condition under main and sub relationships $(a>c>b)$, $a>(b+c)$

	MBP	MCP	TCP
First Best	a	a	$(a+b+c)$
Second Best	a	$a+c$	$(a+b+2c)$
Supply Security Reduction	$dMBP=0$	$dMCP=c$	$dTCP=c$

The reduction in security indices in Table 5 are compared between different groups for identifying the group the scheme of which is to be changed. The complete list of these indices when all the main and sub-relationships are considered are given in Table 6. Corresponding indices under busbar maintenance cases can also be obtained in a similar manner.

By grouping all the relationships which lead to identical indices, the rules for finding the expressions for the indices of reduction in security under circuit-breaker CB3 and busbar r2 maintenance conditions are listed.

(a) Circuit-Breaker CB3 under maintenance:

1 If ($a>b$ and $a>c$ and $a> =(b+c)$) then
$dMBP=0$, $dMCP=c$ and $dTCP=c$

2 If ($c>a$ and $a> =b$ and $c> =(a+b)$) then
$dMBP=0$, $dMCP=a$ and $dTCP=c$

3 If ($a=b$ and $b> =c$) then
$dMBP=c$, $dMCP=0$ and $dTCP=-c$

4 If ($a>b$ and $a>c$ and $(b+c)>a$) then
$dMBP=(b+c-a)$, $dMCP=(b-a)$ and $dTCP=-c$

5 If (c>a and a> =b and (a+b)>c) then
dMBP=(a+b-c), dMCP=(b-c) and dTCP=-c

6 If (a=c and c>b) then
dMBP=b, dMCP=(b-c) and dTCP=-c

(b) Busbar r2 under maintenance:

1 If a>b> =c then
dMBP=0, dMCP=0, and dTCP=(a-b)

2 If a>c>b then
dMBP=0, dMCP=(c-b), and dTCP=0

3 If a=b> =c then
dMBP=b, dMCP=0, and dTCP=-b

4 If a=c>b then
dMBP=0, dMCP=(a-b), and dTCP=(a-b)

5 If c>a>b and (a+b)>c then
dMBP=(a+b-c), dMCP=(c-a), and dTCP=b

6 If c>a>b and (a+b)=c then
dMBP=0, dMCP=(c-a), and dTCP=b

7 If c>a>b and c>(a+b) then
dMBP=0, dMCP=b, and dTCP=b

8 If c>a=b and (a+b)>c then
dMBP=(a+b-c), dMCP=(b-c), and dTCP=-b

9 If c>a=b and c> =(a+b) then
dMBP=0, dMCP=a, and dTCP=b

Table 6 : Summary of reduction in power supply security indices for a three-circuit group under circuit-breaker CB3 maintenance conditions

Relationships Main	 Sub	Indices of reduction in security dMBP	 dMCP	 dTCP
a>b>c	a>(b+c)	0	c	c
a>b>c	a<(b+c)	b+c-a	b-a	-c
a>b>c	a=(b+c)	0	c	c
a=b>c		c	0	-c
a>b=c	a>(b+c)	0	c	c
a>b=c	a<(b+c)	b+c-a	b-a	-c
a>b=c	a=(b+c)	0	c	c
a=b=c		c	0	-c
a>c>b	a>(b+c)	0	c	c
a>c>b	a<(b+c)	b+c-a	b-a	-c
a>c>b	a=(b+c)	0	c	c
a=c>b		b	b-c	-c
c>a>b	(a+b)>c	a+b-c	b-c	-c
c>a>b	(a+b)=c	0	a	c
c>a>b	c>(a+b)	0	a	c
c>a=b	(a+b)>c	a+b-c	b-c	-c
c>a=b	(a+b)=c	0	a	c
c>a=b	c>(a+b)	0	a	c

(4.2) Overall Allocation Algorithm

The overall allocation algorithm is best described by considering the allocation of three groups of circuits. Let the reduction in security level be those in Table 7. By comparing these levels between the groups in the order of their priority, the group scheme to be changed is identified. The preferred order of the overall allocation schemes can then be formed accordingly and is summarized in Table 8.

Table 7: Indices of reduction in security for three groups of circuits

Group	dMBP	dMCP	dTCP
1	100	0	-100
2	0	0	35
3	0	65	65

Table 8: Overall allocation schemes for the groups in Table 7

Preference of Overall Allocation	Set identifying change in groups due to dMBP	 dMCP	 dTCP	Preferences in the Group Arrangement 1	 2	 3
1 (best)	{}	{}	{}	1st	1st	1st
2	{}	{}	{2}	1st	2nd	1st
3	{}	{3}	{}	1st	1st	2nd
4	{}	{3}	{2}	1st	2nd	2nd
5	{1}	{}	{}	2nd	1st	1st
6	{1}	{}	{2}	2nd	2nd	1st
7	{1}	{3}	{}	2nd	1st	2nd
8	{1}	{3}	{2}	2nd	2nd	2nd

In Table 8, the empty sets in the first row shows that the best overall allocation scheme is given by the combination of the best individual group arrangements. In the second row, the dTCP set indicates that the scheme for group 2 should be replaced by the second best one to form the second best overall allocation scheme because the dMBP and dMCP sets are empty showing no changes for groups 1 and 3 are required. Rows 3 and 4 show that only group 3 is changed to its second best group arrangement whilst group 2 follows the pattern in rows 1 and 2. Subsequently, the arrangement of group 1 is changed according to the dMBP set and groups 2 and 3 follow the pattern in rows 1 to 4. The changes in the sets due to dMBP, dMCP and dTCP in Table 8 can be expressed by the power sets PB, PC and PT respectively below.

$$PB = \{ \{\}, \{1\} \} ; PC = \{ \{\}, \{3\} \} ; PT = \{ \{\}, \{2\} \}.$$

The general algorithm to form the pattern of the sets for identifying changes in group schemes is to generate the power set PB first. Then for each subset of PB, generate PC and for each subset in PC, generate PT. The union of the generated subsets will give a pattern. This procedure is repeated for the remaining subsets in PB to generate the subsequent patterns.

(4.3) Multiple Overall Allocation Schemes

If some groups are having multiple first or second best group arrangements, the overall allocation algorithm will produce multiple overall allocation schemes. In such circumstances, the multiple overall allocation schemes can be graded according to the overall fault indices OMB, OMC and OTC. These are derived in the same manner as the indices MBP, MCP and TCP of the group arrangements. These overall fault indices indicate the overall effects of the busbar and circuit-breaker faults on the power supply security in the overall schemes.

(4.4) Islanding Constraints Checking

The generated overall allocation schemes using the methods described in the previous sections are checked with the islanding constraints for validity. The checking procedure adopted in the present work is the one reported in Reference [4] by the authors.

(5) APPLICATION EXAMPLES

The developed knowledge-based system is implemented using Prolog and runs on an IBM PC/386 compatible computer. The system has been applied to re-allocate the 6 groups of circuits in the 132 kV substation in Fig.1 under circuit-breaker CB3 maintenance and under busbar r2 maintenance. The load circuits from the 11 kV substations are rated 35 MW and the remaining circuits are rated at 100 MW. The best four overall allocation schemes obtained for each case are summarized in Table 9.

When the allocation schemes for the CB3 maintenance case are compared to those under normal operating condition, nearly all the circuits in r1 have to be transferred to m1 in addition to closing the isolator switch between busbars r1 and r2. In the busbar r2 maintenance case, in addition to the transference of circuits from r2 to m2, most of the circuits in m1 have to be transferred to r1.

(6) CONCLUSIONS

A knowledge-based approach to solve the problem of circuit allocation in duplicate-busbar substations under circuit-breaker and busbar maintenance conditions has been developed and implemented. The allocation rules expressed in constraint form are complete and consistent. An overall allocation scheme generation algorithm based on the minimum reduction in security level strategy has also been developed. From the results of the application examples, it is found that the allocation scheme which provides the maximum degree of security in power supply may not be obtained merely by closing the isolator between two busbar sections under circuit-breaker maintenance conditions and, for busbar maintenance, by simply transferring circuits from the main to the reserve busbar section or vice versa.

Table 9: Best circuit allocation schemes for substation in Fig. 1 under maintenance conditions

Circuits to be allocated to bus-bars

(a) Normal operating condition:

	r1	m1	m2	r2
1st best	4,5,10, 13,16	3,8	2,7,12, 15,17	1,6,9, 11,14
2nd best	4,5,8, 10,13	3,16	2,7,9, 12,15	1,6,11, 14,17
3rd best	4,5,8, 10,13,16	3	2,7,9,12, 15,17	1,6,11, 14
4th best	4,5,10, 13	3,8,16	2,7,12, 15	1,6,9, 11,14,17

(b) Circuit-breaker CB3 under maintenance:

	r1	m1	m2	r2
1st best		3,4,5,8, 10,13,16	7,12, 15	1,2,6,9, 11,14,17
2nd best		3,4,5,8, 10,13,16	2,7, 12,15	1,6,9,11, 14,17
3rd best	4	3,5,8,10, 13,16	2,7, 12,15	1,6,9,11, 14,17
4th best		3,4,5,8, 10,13,16	6,12, 15	1,2,7,9, 11,14,17

(c) Bus-bar r2 under maintenance:

	r1	m1	m2
1st best	3,4,5,8, 10,13,16		1,2,6,7,9, 11,12,14,15,17
2nd best	3,5,8,10, 13,16	4	1,2,6,7,9, 11,12,14,15,17
3rd best	3,4,5,8, 10,13,16	10	1,2,6,7,9, 11,12,14,15,17
4th best	3,4,5,8, 10,13	16	1,2,6,7,9, 11,12,14,15,17

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