Ranking the Radial Configurations for Minimum Losses Distribution System Reconfiguration. Part 1: Benchmark Results

RANKING THE RADIAL CONFIGURATIONS FOR MINIMUM LOSSES DISTRIBUTION SYSTEM RECONFIGURATION. PART 1: BENCHMARK RESULTS

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Abstract ***In electricity distribution systems with weakly meshed structure and radial operation, the determination of the optimal radial configuration for a given objective function (e.g., minimum losses) is a challenging task because of lack of regularity of the system topology. This paper provides benchmark results on the determination of the configuration with minimum losses for five test networks commonly used in the literature. The analysis is carried out for a single set of data representing the system loading. Further results considering a multiple reconfigurations run at successive time intervals are included in the companion paper (Part 2).***

Keywords: distribution system, radial network, minimum losses, reconfiguration.

1. INTRODUCTION

The choice of the best radial configuration from the weakly meshed structure of an electrical distribution system is an optimization problem depending on the system topology, loads and generations, and can be solved by using different objectives for distribution system reconfiguration. Minimum losses reconfiguration is a classical optimization problem taken into account by the electricity distributors and is considered in this paper.

The *number* of radial configurations that can be extracted out of the weakly-meshed structure can be calculated by resorting to the Kirchhoff's theorem [1], but the *generation* of the radial configurations is a challenging task because of lack of regularity of the system topology, and has to be addressed by resorting to specific tools. These tools exploit graph theory concepts in the formation of the spanning trees [2]–[12].

In real-size distribution systems the number of radial configurations could be so high to prevent the operators making exhaustive search of all the possible combinations. However, the current evolution of the distribution systems is emphasizing the role of *microgrids* interconnecting local resources and loads in specific districts [13][14]. The interest in calculating the entire set of radial configurations can be revamped by the perspective of addressing relatively small microgrids, determining the true global optimum corresponding to the predefined objective function.

When performing exhaustive search is practically intractable in terms of computational burden, a reduced number of configurations can be analyzed by using various reconfiguration methods. A detailed review on these techniques is outside the scope of this paper. Information can be found from recent reviews [15][16].

This paper is based on the determination of the number of radial configurations and determines the corresponding set of open branches starting from weakly meshed network structures through network reduction [10] and on the comprehensive approach to compute the distribution network losses for all network configurations, indicated in [17] and applied in a structured form in Section 2.3 of [18], determining the global optimum from exhaustive search and showing a systematic assessment of the best configurations obtained for five test networks commonly used in the literature. The use of the proposed approach to study the persistence of the optimal configurations and to discuss the possibility of applying intra-day reconfigurations in distribution systems with time-dependent generation and load patterns is addressed in the companion paper [19].

Figure 1 shows the overall structure of the approach implemented for loss calculations. With respect to the scheme presented in [18], there is the additional calculation of a *performance index*, activated if the interval power flow computation has been executed, to calculate the performance index of the various configurations obtained. The related formulation and details are shown in [19].

2. BEST CONFIGURATIONS AND GLOBAL OPTIMA FOR THE TEST SYSTEMS

The generation and analysis of the entire set of radial configurations enables us to show the global optimal solutions to the optimization problems run on a set of test systems widely used in the literature. Five test systems have been used in [10] and [20] to generate the radial configurations through the formation of the reduced network. These test systems are denoted as *System A* [21], *System B* [22], *System C* [23], *System D* [24] and *System E* [25], and their reduced networks are drawn in [10]. In order to use a common reference, for all networks the supply node voltage(s) are set to 1 per unit (pu) and the base power used is 1 MVA[1].

This section shows the global optima (with minimum losses) for the test networks considered, as well as the list of the best 10 configurations found for each network.

[1] Different base power values and supply node voltages have been generally used to study these networks in the papers in which the networks have been first introduced and in successive papers.

Graphical representations showing the best network configurations are included for the sake of visual representation and for creating a common reference, as various authors used different node numbering for the same network.

The number of radial configurations for the initial and reduced networks considered in this paper is indicated in Table 1. These numbers of radial configurations[2] make it possible to run exhaustive search and loss calculation for the test systems in reasonable computation times with today's personal computers. The same test systems are then used in the following sections of this paper to investigate the characteristics of the optimal solutions for the classical problem of optimal reconfiguration with minimum losses.

The cumulative distribution function (CDF) of the total losses is shown as well. The CDF is constructed by considering all the possible configurations that can be extracted out of the initial networks. Since the radial configurations leading to non-acceptable power flow results have been discarded, the CDF of the losses does not always reach unity on the vertical axis; the difference between unity and the maximum CDF value represented corresponds to the portion of discarded solutions.

Concerning the five test systems used:

- *System A*: no branch current limit is indicated in the reference paper [21]. The lower and upper voltage limits are set to 0.9 pu and 1.1 pu, respectively. The best 10 configurations are reported in Table 2, and the CDF of the total losses is shown in Figure 2. The number of acceptable configurations is 159, that is, 83.7% of the total. The best configuration[3] is shown in Figure 3. The percentage of occurrence of the open branches in the best 10, 30 and 50 configurations is shown in Figure 4.
- *System B*: the branch limits are taken from [22]. The lower and upper voltage limits are 0.9 pu and 1.1 pu, respectively. The best 10 configurations are indicated in Table 3, and the CDF of the total losses is shown in Figure 5. The number of acceptable configurations is 128 (59.8% of the total). The best configuration is shown in Figure 6. The percentage of occurrence of the open branches in the best 10, 30 and 50 configurations is shown in Figure 7.
- *System C*: this system is widely used for spanning tree assessment (e.g., [7][10]). The branch limits are taken from [23]. The lower and upper voltage limits are 0.8 pu and 1.1 pu, respectively. The best 10 configurations are indicated in Table 4, and the CDF of the total losses is shown in Figure 8. The number of acceptable configurations is 27,203 (53.6% of the total)[4]. The best configuration is shown in Figure 9. The percentage of occurrence of the open branches in the best 10, 30 and 50 configurations is shown in Figure 10.
- *System D*: no branch limits are reported in [24]. The solutions refer to the network data in the base case. The other two cases considered in [24] for optimization, with light loading (load scaling factor 0.5) and heavy loading (load scaling factor 1.2) are not addressed here. The lower and upper voltage limits are 0.9 pu and 1.1 pu, respectively. The best 10 configurations are indicated in Table 5. The best solution appears in four configurations, as in the initial data the load in the nodes 41, 42 and 43 is null, so opening the branch 43-44 is equivalent to opening the branch 28-41, 41-42 or 42-43. The same results with equal total losses are then repeated for the successive blocks of 4 solutions. The CDF of the total losses is shown in Figure 11. All configurations are acceptable, as no thermal limit is indicated for the branches and the system loading is relatively low. The best configuration is shown in Figure 12. The percentage of occurrence of the open branches in the best 10, 30 and 50 configurations is shown in Figure 13.
- *System E*: the branch limits are taken from [25]. The root node voltage is 1 pu. The lower and upper voltage limits are 0.9 pu and 1.1 pu, respectively. The best 10 configurations are indicated in Table 6, and the CDF of the total losses is shown in Figure 14. The number of acceptable configurations is 752,922 (14% of the total). The best configuration is shown in Figure 15 [5]. The percentage of occurrence of the open branches in the best 10, 30 and 50 configurations is shown in Figure 16.

3. CONCLUSIONS

This paper has presented some benchmark results referring to the ranking of the radial configurations for five test networks, taking into account loss minimization. The ranking has been made by combining the results of exhaustive search of the radial configurations with the calculation of the network losses and the ranking of the solutions obtained. Methods based on graph theory have been successfully used on relatively small networks such as the one tested, and are used inside generalized optimization procedures, also with recent contributions on customized heuristic [29].

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[2] For *System D*, a correction has been made in the values reported in the last column of Table VIII in [24], according with the indications reported in section 6.2 of [18].

[3] In some papers (e.g., [26]–[28]) the branch data have been considered in ohm rather than in per units. In these cases, the losses reported in the best configuration found are different with respect to the ones indicated here.

[4] Different values of the supply voltage have been used in literature papers (e.g., 1.05 pu in various cases), resulting in different total losses with respect to the ones reported here (obtained with 1 pu supply voltage). Furthermore, the loads at node 29 are set to the values indicated in the original paper [23], with active power 0.2 pu and reactive power 0.6 pu (modified values for the power loads have been reported in various other papers; the equality of the load values at that node have to be checked before comparing the results).

[5] In this paper, all branches have been considered as potentially redundant branches, while in [25] branch 17-18 cannot be open. The best configuration shown here differs with respect to the one shown in [25]. In particular, in the optimal solution shown in [25] branch 17-18 is replaced by branch 18-23, while all the other branches in the best configuration are the same. The optimal solution shown in [25] is the 36th solution obtained here in ascending order of total losses.

Table 1. Number of radial configurations for the initial and reduced networks of test and real systems

System	reference	rated voltage [kV]	*N*	*B*	*S*	*Q*	N_R	B_R	K_R	K_{tot}
A	[21]	23	16	16	3	3	4	6	16	190
B	[22]	10	10	13	1	4	5	8	45	214
C	[23]	12.66	33	37	1	5	9	13	463	50,751
D	[24]	12.66	70	74	1	5	9	13	463	407,924
E	[25]	20	44	47	4	7	11	17	5,544	5,363,333

Table 2. The best 10 configurations for *System A*

No.	open branches			total losses [pu]
1	09-11	07-16	08-10	0.908967
2	09-11	07-16	10-14	0.936488
3	09-11	06-07	08-10	0.937195
4	05-11	07-16	08-10	0.949285
5	09-11	06-07	10-14	0.958235
6	09-11	15-16	08-10	0.960400
7	05-11	07-16	10-14	0.979960
8	05-11	06-07	08-10	0.980353
9	05-11	15-16	08-10	0.995549
10	09-11	15-16	10-14	0.998738

Table 3. The best 10 configurations for *System B*

No.	open branches				total losses [pu]
1	03-05	06-09	08-09	02-10	0.268271
2	03-05	06-09	04-08	02-10	0.276391
3	02-05	06-09	03-09	04-10	0.277111
4	02-05	06-09	03-09	02-10	0.278942
5	03-05	06-09	03-09	02-10	0.279057
6	03-05	06-09	03-09	04-10	0.281306
7	03-05	06-09	08-09	04-10	0.281579
8	02-05	06-09	08-09	02-10	0.281748
9	02-05	06-09	08-09	04-10	0.290975
10	03-05	06-09	04-08	04-10	0.290976

Table 4. The best 10 configurations for *System C*

No.	open branches					total losses [pu]
1	24-28	06-07	08-09	13-14	31-32	0.13955
2	06-07	27-28	08-09	13-14	31-32	0.13997
3	24-28	06-07	09-10	13-14	31-32	0.14028
4	06-07	27-28	09-10	13-14	31-32	0.14070
5	24-28	06-07	10-11	13-14	31-32	0.14120
6	06-07	27-28	10-11	13-14	31-32	0.14163
7	06-07	27-28	08-09	13-14	17-32	0.14191
8	24-28	06-07	08-09	13-14	17-32	0.14216
9	06-07	27-28	09-10	13-14	17-32	0.14242
10	24-28	06-07	08-09	13-14	30-31	0.14260

Table 5. The best 10 configurations for *System D*

No.	open branches					total losses [pu]
1	43-44	07-20	10-11	08-14	30-31	0.009142
2	42-43	07-20	10-11	08-14	30-31	0.009142
3	28-41	07-20	10-11	08-14	30-31	0.009142
4	41-42	07-20	10-11	08-14	30-31	0.009142
5	43-44	07-20	08-10	08-14	30-31	0.009150
6	42-43	07-20	08-10	08-14	30-31	0.009150
7	28-41	07-20	08-10	08-14	30-31	0.009150
8	41-42	07-20	08-10	08-14	30-31	0.009150
9	43-44	07-20	08-09	08-14	30-31	0.009158
10	42-43	07-20	08-09	08-14	30-31	0.009158

Table 6. The best 10 configurations for *System E*

No.	open branches							total losses [pu]
1	7-8	34-35	20-21	6-15	19-22	25-28	17-18	0.117243
2	7-8	35-36	20-21	6-15	19-22	25-28	17-18	0.117409
3	7-8	34-35	20-21	6-15	19-22	28-36	17-18	0.118555
4	8-9	34-35	20-21	6-15	19-22	25-28	17-18	0.118936
5	6-7	34-35	20-21	6-15	19-22	25-28	17-18	0.118965
6	8-9	35-36	20-21	6-15	19-22	25-28	17-18	0.119102
7	6-7	35-36	20-21	6-15	19-22	25-28	17-18	0.119131
8	7-8	34-35	20-21	6-15	15-19	25-28	17-18	0.119161
9	7-8	35-36	20-21	6-15	22-25	25-28	17-18	0.119462
10	6-7	34-35	20-21	15-17	19-22	25-28	17-18	0.119496

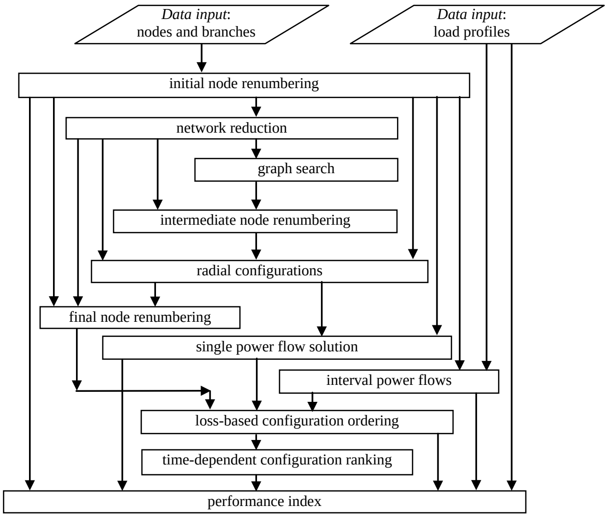

Figure 1. Structure of the approach implemented for loss calculations. The arrows represent the information flow among the modules.

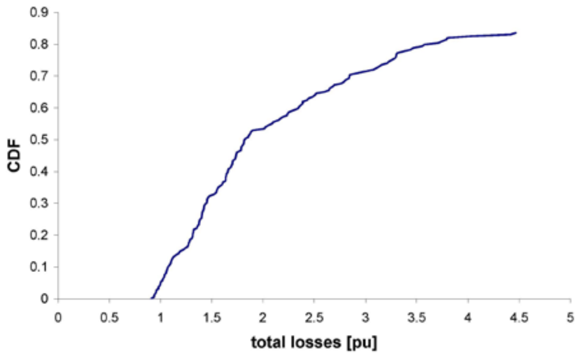

Figure 2. Cumulative distribution function of the total losses for *System A*.

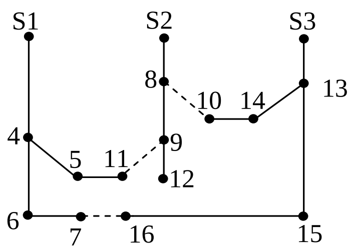

Figure 3. Globally optimal configuration with minimum losses for *System A* (dashed lines: open branches).

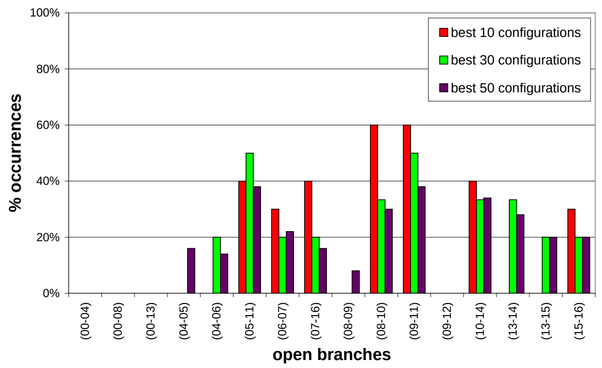

Figure 4. Percentage of occurrence of the open branches in best 10, 30 and 50 configurations for *System A*.

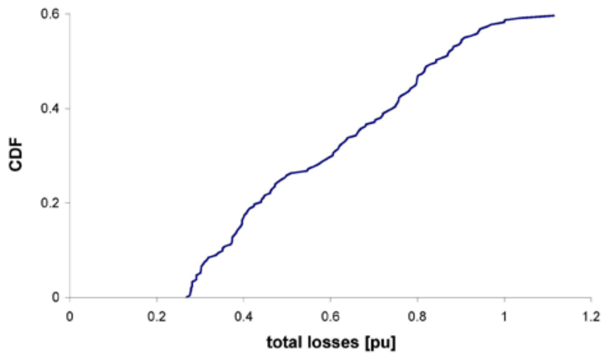

Figure 5. Cumulative distribution function of the total losses for *System B*.

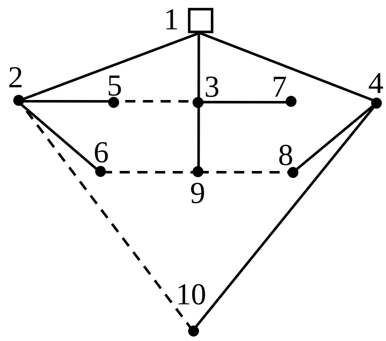

Figure 6. Globally optimal configuration with minimum losses for *System B* (dashed lines: open branches).

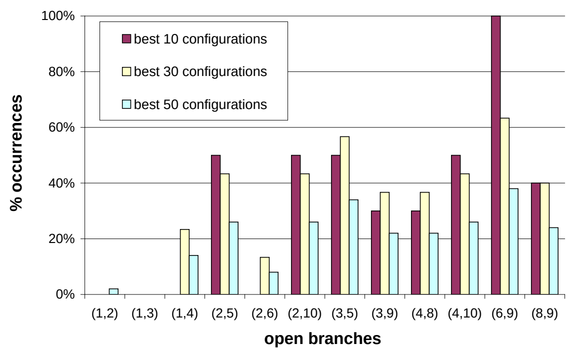

Figure 7. Percentage of occurrence of the open branches in best 10, 30 and 50 configurations for *System B*.

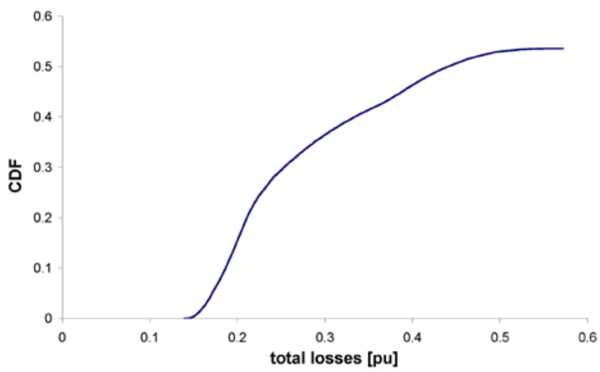

Figure 8. Cumulative distribution function of the total losses for *System C*.

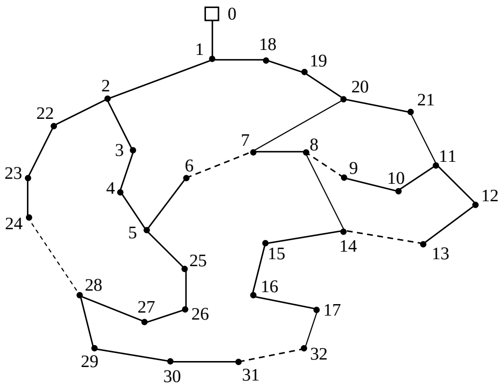

Figure 9. Globally optimal configuration with minimum losses for *System C* (dashed lines: open branches).

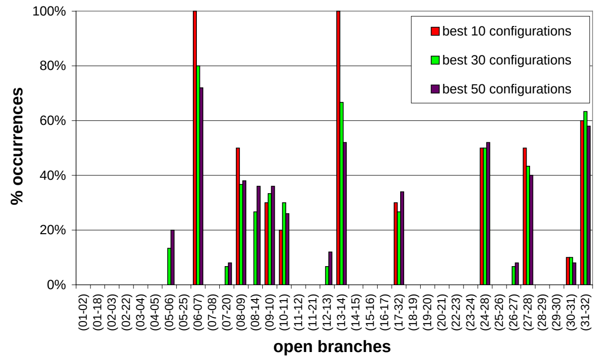

Figure 10. Percentage of occurrence of the open branches in best 10, 30 and 50 configurations for *System C*.

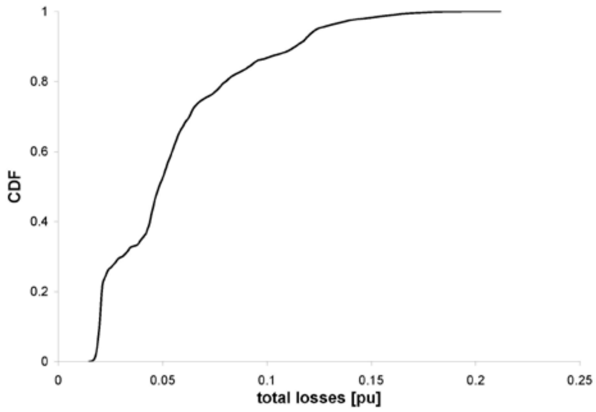

Figure 11. Cumulative distribution function of the total losses for *System D* (all configurations are acceptable).

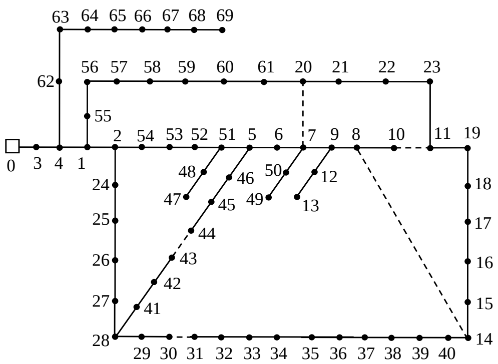

Figure 12. Globally optimal configuration with minimum losses for *System D* (dashed lines: open branches).

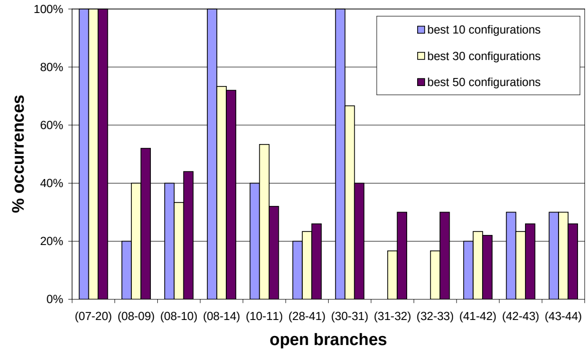

Figure 13. Percentage of occurrence of the open branches in best 10, 30 and 50 configurations for *System D*. The branches with no occurrence in the best 50 configurations are not indicated.

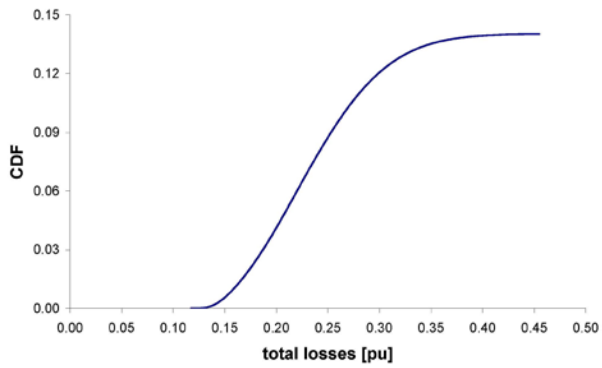

Figure 14. Cumulative distribution function of the total losses for *System E*.

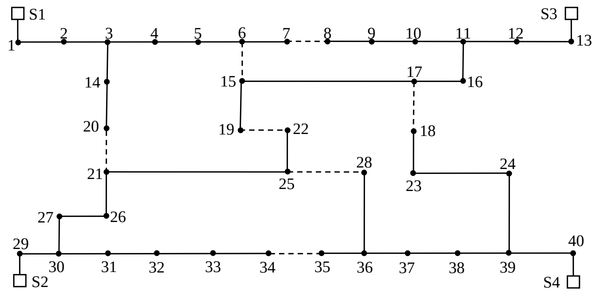

Figure 15. Globally optimal configuration with minimum losses for *System E* (dashed lines: open branches).

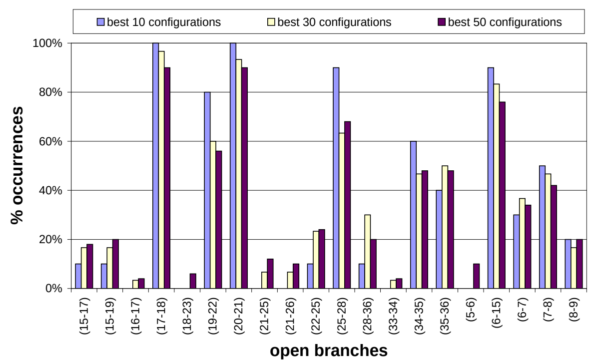

Figure 16. Percentage of occurrence of the open branches in best 10, 30 and 50 configurations for *System E*. The branches with no occurrence in the best 50 configurations are not indicated.

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