Ranking the Radial Configurations for Minimum Losses Distribution System Reconfiguration. Part 2: Intra-day Time-domain Assessment

RANKING THE RADIAL CONFIGURATIONS FOR MINIMUM LOSSES DISTRIBUTION SYSTEM RECONFIGURATION. PART 2: INTRA-DAY TIME-DOMAIN ASSESSMENT

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Abstract ***This paper applies the approach indicated in the companion paper (Part 1) to study the persistence of the optimal configurations in distribution systems with time-dependent generation and load patterns. The solution ranking is carried out at each time step, then a comparison among the solutions is made in the perspective of dividing the time period during the day to apply intra-day reconfiguration separately for the daylight and the night periods. The related savings in the energy losses with respect to maintaining the same globally optimal configuration during the day are illustrated and discussed on a test network example. Three performance indices are defined to obtain and compare the corresponding ranking of the configurations during the time period considered.***

Keywords: distribution system, radial network, minimum losses, reconfiguration, ranking, intra-day, performance indices.

1. INTRODUCTION

The calculation and ranking of the radial configurations on the basis of the energy losses carried out in Part 1 of this paper [1] has considered a single setting of the loads at every node. This solution can either correspond to a snapshot in time for a system with evolving loads during time, or to a conventional solution in which the network loads are assumed to represent a specific condition, for example the maximum loading of the network or a reference case used for off-line studies. In this case, the *time* variable is not specified.

In the present situation of the electrical distribution systems, characterized by the increasing diffusion of distributed generation [2], distributed storage and demand response (all together forming the Distributed Energy Resources – DER), the calculation of a single solution for the entire network is rather limitative with respect to the variety of loading conditions that may occur. In particular, the variability in time and the uncertainty with which the *net* load (formed by loads and local generations) at each node of the network appear in the distribution networks call for more detailed analyses at different time periods.

Indeed, the net load may change during time to a large extent, especially because of the evolution in time of the local generation, making it difficult to establish the conditions to be used for minimum losses reconfiguration. The analysis can be carried out in a *deterministic* way, e.g., using the forecast values of loads and generations, or in a *probabilistic* way by modeling the uncertainties, or in a *multi-scenario* analysis context in which a number of scenarios, possibly with different characteristics, are assessed and the solution is found by applying decision-making criteria [3]–[5].

On the one hand, the presence of variable net load patterns during time, together with the advances in distribution automation that make it possible to perform remote configuration changes, provide the rationale for considering intra-day reconfiguration as a potentially convenient option. On the other hand, there are some issues to be considered. For example, the configuration changes are associated to a cost of the switching actions needed to activate the changes [6][7]. Furthermore, the uncertainty on the real behavior of the net load introduces a question on whether the optimal or pseudo-optimal configuration that can be calculated is actually the best one in actual operating conditions. These issues generally suggest to limit the number of intra-day reconfigurations during the day. The identification of the best conditions for changing configuration (i.e., how many times and when during a given period of observation) is one of the current research challenges. Specific details can be found in recent references [8]–[11].

This paper considers the case in which the intra-day reconfigurations may occur in a limited number during the day in a static (i.e., predefined and fixed) way [5], namely, by partitioning the day into two time intervals corresponding to a daylight period and a complementary night period. This case corresponds to a system in which there is a significant difference between the net load in the two time intervals. This may occur when the local generation is composed in a significant way of photovoltaic systems and cogeneration systems in on-off operation (switched off during the night), in the absence of a practically significant storage. Other cases of static intra-day reconfiguration have been considered by assuming time intervals of 4 hours [12], considering the days of the year [13], or applying seasonal reconfigurations [14].

Other static procedures define in advance the time periods on the basis of the determination of different loading levels [15][16].

Without loss of generality, in this paper the relevant time step for the analysis is assumed to be one hour. In this case, the numerical values of the average power and of the hourly energy are coincident. If different time steps are used, the duration of the time step has to be explicitly introduced in the calculations in order to properly represent the values of power and energy in the context in which they are used.

The ranking of the hourly-based configurations is taken as the starting point for developing a procedure aimed at selecting the most appropriate configurations to be used in the time intervals considered, taking into account that in the power flow solutions calculated at each hour there could be situations such as constraint violations, requiring a suitable treatment in the definition of the objective function to be used for the overall ranking of the system configurations.
Once the interval power flow has been executed for all the time steps in the period of analysis, suitable performance indices can be calculated to rank the results obtained from the various configurations at the various time steps.
The remainder of this paper is organized as follows. Section 2 introduces the framework for multi-hour solution ranking. Section 3 addresses the formulation of two performance indices. Section 4 shows the results obtained on a case study application. The last section contains the concluding remarks.

2. MULTI-HOUR SOLUTION RANKING

In order to calculate the behavior of the distribution system along successive time intervals, at each node of the system the net load pattern is defined by combining the effect of the representative load patterns for different types of consumers (e.g., residential, commercial, industrial, and local generation). For this purpose, a typical day is defined, for which the hourly load patterns of the different consumers are defined for a period of observation with H = 24 hours.
The load patterns are calculated starting from the normalized load profiles of the various types of consumers (reported in Figure 1 for nodes with prevailingly residential, industrial or commercial load, respectively), by multiplying these profiles by the reference power for each type of consumer at each node.

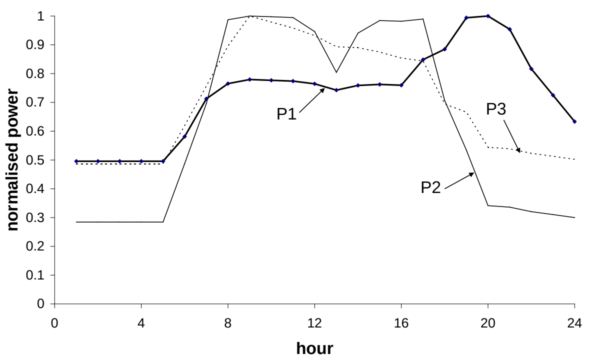

Figure 1. Conventional hourly loads for a typical weekday in Autumn: prevailingly residential load (P1), prevailingly industrial load (P2) and prevailingly commercial load (P3).

Considering hourly loads, the interval power flow calculation procedure indicated in Figure 1 of [1] is run H times to get H sets containing K_{tot} radial configurations each. For each hour $h = 1,\dots, H$, the radial configurations are then ranked in ascending order of the total losses.

A possible way to choose the best configuration to be maintained for a given time period is to start from the results of the hourly-based ranking and take into account the *persistence* in time of the best configurations. Generally the characteristics of the net power patterns are such that there is no configuration resulting at the top of the ranking for all the hours of the day. In these conditions, it is relevant to identify the configurations that can remain at high positions of the ranking for relatively high number of hours. Then, the choice on how to manage the presence of multiple optional configurations providing relatively good results depends on the distribution system operator (DSO), e.g., with the following options [8]:

- The selected configuration has to be maintained for the entire day (no intra-day reconfiguration).
- A given partitioning of the day is defined in advance (e.g., considering daylight and night periods).
- The presence of different tariff periods is taken into account[1] to study the best configuration for each tariff period separately. It has to be noted that multiple tariff periods may be present in the same day, so that the option of performing multiple switching during the day has to be acceptable for the DSO.
- The DSO intends to assess the convenience of resorting to dynamic reconfiguration, in which the partitioning of the time periods is not fixed, but the timeline of the configuration changes is determined from suitable algorithms [8]–[11].

The option considered in this paper is that the partitioning of the day is known in advance, with the definition of a daylight period and of a complementary night period.

3. PERFORMANCE INDICES

Starting from the results obtained from the hour-by-hour power flow calculations, the *daily losses* obtained by maintaining each radial configuration are calculated for the entire day or for the period of interest. The use of a fixed configuration minimizing the daily losses as objective function has been addressed in [7].
In the assessment presented in this paper, the configurations in which the power flow solutions lead to violations at one or more hours should be identified and treated appropriately.
In order to allow automatic calculations, the solutions with violations at a given hour $h = 1,\dots, H$ are not eliminated, but are penalized by introducing a (relatively high[2]) penalty factor ρ.
Each configuration is then assessed through two performance indices introduced here. Let us denote with $L_X^{(h)}$ the losses calculated at hour $h = 1,\dots, H$, and introduce the binary flag $u_X^{(h)} = 0$ if no violation occurs in

[1] For instance, according to the Italian Authority for Electricity and Gas the conventional low-load hours range from hour 11 pm to hour 6 am (night period) for weekdays and include the entire day for weekends or bank holidays occurring during the week. The remaining hours (daylight period) are partitioned into intermediate and peak-load hours.
[2] For each network, here the penalty factor has been set to 100 times the maximum active power load taken from the load pattern data.

the power flow calculation of configuration X at hour h = 1,…, H, otherwise $u_X^{(h)}$ = 1. The performance indices are defined as follows:

a) the *penalized loss-based performance index*

$$\Psi_X = \frac{1}{\sum_{h=1}^{H} L_X^{(h)} \left(1 + \rho\, u_X^{(h)}\right)} \quad (1)$$

For this performance index, if no violation occurs during the day, the performance index becomes the inverse of the daily losses [17]. In this case, the index provides a quantitative value referring the performance to the (inverse) total losses.

b) the *rank-weighted penalized loss-based performance index*, in which $r_X^{(h)}$ is the position of the configuration X in the ranking of the configurations referring to hour h, and $S_X^{(h)}$ is the total apparent node net power:

$$\Xi_X = \sum_{h=1}^{H} \frac{1}{r_X^{(h)} \frac{100 \cdot L_X^{(h)}}{S_X^{(h)}} \left(1 + \rho\, u_X^{(h)}\right)} \quad (2)$$

This performance index is qualitative, as it introduces the numerical weight given by the ranking.

c) a variant of the index (2) in which the sum of the lower-side terms of the fraction is calculated before the inversion:

$$\Theta_X = \frac{1}{\sum_{h=1}^{H} r_X^{(h)} \frac{100 \cdot L_X^{(h)}}{S_X^{(h)}} \left(1 + \rho\, u_X^{(h)}\right)} \quad (3)$$

All these indicators take into account what happens in the entire period of observation (e.g., one day) and include the penalty term for taking into account possible constraint violations. However, there is a structural difference among these indices. In the performance index (1) the sum is located at the lower side of the fraction, as the meaningful term is given by the total (penalized) losses, and the inverse of the total result is then calculated in order to express higher performance by means of higher numbers. The indicator (3) has a similar general structure concerning the calculation of the sum of the entries. Conversely, in the performance index (2) the sum is not located at the lower side of the fraction. Using different structures for the indices (2) and (3) leads to different results, as discussed below by giving a practical explanation of the difference between the two structures with illustrative numbers not strictly related to the number of hours considered in the daily analysis and to the system used in the case study application.

Let us consider a simplified case in which the time steps are three, the system has many radial configurations but the configurations visualized here are four (denoted with the letters A, B, C and D) and the ranking of the solutions at each time step is the one indicated in Table 1. Let us also consider indicative values for the losses and for the total load (Table 2).

Table 1. Hourly ranking (position $r_X^{(h)}$) of the three configurations in the simplified case.

configuration X	time step h		
	1	2	3
A	100	80	1
B	1	1	70
C	200	20	2
D	4	3	30

Table 2. Network losses (pu) and total load (pu) of the three configurations in the simplified case.

configuration X	time step h		
	1	2	3
A	0.125	0.131	0.120
B	0.105	0.110	0.140
C	0.136	0.119	0.121
D	0.110	0.112	0.131
total load	5.25	5.29	6.12

Let us now take into account the various configurations and assume that no violation occurred in the time steps of analysis, so that $u_X^{(h)}$ = 0 for h = 1, 2, 3. Table 3 shows the ranking based on the performance indicator (1). In the specific case, two solutions have the same value of total losses and are both positioned in the third position.

Table 3. Ranking using the performance index (1).

configuration X	total losses	performance index Ψ_X	final ranking
A	0.3760	2.6596	3
B	0.3550	2.8169	2
C	0.3760	2.6596	3
D	0.3530	2.8329	1

Table 4 shows the lower-side terms of the fraction in equation (2), namely, the terms $100 \cdot r_X^{(h)} L_X^{(h)} / S_X^{(h)}$ for h = 1, 2, 3. Table 5 shows the inverse of the terms of Table 4, highlighting that the effect of the position $r_X^{(h)}$ of the configuration X in the ranking at hour h, is such that the entries with low ranking (and high values of $r_X^{(h)}$) lead to very small contributions to the performance index (2), whose values are reported in Table 6.

If the terms of Table 4 are summed up together before calculating the inverse of the sum, to calculate the performance index (3), the results are shown in Table 7.

Table 4. Lower-side terms of the fraction in (2)

configuration X	time step h		
	1	2	3
A	238.1	198.1	1.96
B	2.00	2.08	160.1
C	518.1	45.0	3.95
D	8.38	6.35	64.2

Table 5. Individual terms of the sum in (2)

configuration	time step *h*		
	1	2	3
A	0.0042	0.0050	0.5100
B	0.5000	0.4809	0.0062
C	0.0019	0.0222	0.2529
D	0.1193	0.1574	0.0156

Table 6. Ranking by using the performance index (2)

configuration	performance index Ξ_X	final ranking
A	0.5192	2
B	0.9872	1
C	0.2770	4
D	0.2923	3

Table 7. Ranking by using the performance index (3)

configuration	sum from Table 3	inverse of the sum	final ranking
A	438.17	0.002282	3
B	164.21	0.00609	2
C	567.04	0.001764	4
D	78.95	0.012667	1

These result highlight some specific features of the performance indices. The index (1) is related to the actual losses, and the values may be relatively similar when the configurations are assessed for different loading conditions. As such, the ranking may depend on the data uncertainty. The index (2) privileges the positions in the ranking. The index (3) provides a result in which the contribution of the top ranked positions is masked by possible low-ranked entries, so that it privileges the cases in which the number of low-ranked positions is low. In the example shown here, the ranking obtained from the indicators (1) and (3) looks consistent, however this result cannot be assumed as a general conclusion.

4. APPLICATION EXAMPLE ON A TEST SYSTEM

The loads in the nodes of *System C* (introduced in part 1 [1]) have been defined in terms of the three load profiles indicated in Figure 1. The slack voltage has been set to 1 pu, as uniformly used in the tests run in [1], even though the original reference [18] used the slack voltage equal to 1.05 pu.

Table 8 reports the ranking of the hourly solutions in ascending order of total losses (the solution with the lowest losses is indicated with 1). The results show that no configuration emerges in the top position of the hourly loss ranking, so that a specific search for the best configuration to be maintained for the entire day has to be carried out.

Considering the whole day, as well as the night period and the daylight period separately, Table 9 shows for each period the five configurations leading to the lower daily losses (ordered in ascending order of losses). In the solutions reported, no violation occurred during the 24 hours, so that the daily losses in the relevant period are equal to the inverse of the performance index.

By assuming the whole day as the relevant period, the five ordered configurations correspond to the configurations ranked in the order 2, 1, 4, 3 and 7 in Table 4 of [1].

Taking into account as relevant period the daylight period, the five ordered configurations correspond to the configurations ranked in the order 1, 3, 2, 5 and 4 in Table 4 of [1]. Considering as relevant period the night period, the five ordered configurations correspond to the configurations respectively ranked in the order 882, 899, 857, 1258 and 1168 in the analysis of Section 2 of [1].

The results from Table 9 indicate that the configurations presenting the lowest values of daily losses in the same period exhibit a low number of switching operations to pass from one of them to another one. This fact ensures operational flexibility to the distributor without reducing the network performance significantly.

In the specific case shown, the daily losses in the best configuration during the day period are 2.8702 pu. If the distributor intends to change configuration passing from the night period to the daylight period and vice versa by using the best configurations found, the daily losses can be reduced to 2.4680 + 0.1236 = 2.5916 pu. Hence, in the example shown this kind of two-period reconfiguration can produce an interesting 10% further loss reduction.

The values indicated in this paper clearly depend on the load profiles, but are useful to explain (also in quantitative terms) that configuration changes can be helpful for loss reduction purposes. Making configuration changes in the night period with respect to the daylight hours is further motivated by the fact that the system loading during the night exhibits low variation. As such, the night period is well suited to identify a dedicated distribution system configuration.

If the ranking is carried out by using the performance indicator (2), the solutions are indicated in Table 10. It can be observed that the top ranked configuration from the ranking with (2) is the second solution obtained in the ranking performed with the index (1), while the top-ranked configuration from (1) is in the third position when using the index (2). With the indicator (3), four of the first 10 solutions are in common with the solutions appearing in the other indices. Overall, being the three indicators structurally different, the converging information is that a few configurations, i.e., #2, 4, 7 and 9 in the ranking with the index (1), are located in the first ten places of the ranking in the three cases, so that these configurations can be considered as viable solutions to define the single daily configuration to be used. More generally, in the presence of different solutions, the solution can be found by resorting to suitable decision-making techniques, e.g., decision theory [3][5] applied to the overall set of performance indicators defined, provided that all indicators are considered to be equally meaningful, and in case applying different weights to the indicators to reflect possible DSO's acceptability preferences.

Table 8. Hourly ranking (position $r_X^{(h)}$) of some configurations for *System C*

open branches					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
24-28	06-07	08-09	13-14	31-32	175	175	175	175	175	17	3	**1**	2	2	**1**	**1**	3	**1**	**1**	**1**	**1**	4	74	405	384	295	255	214
06-07	27-28	08-09	13-14	31-32	**1**	**1**	**1**	**1**	**1**	**1**	**1**	22	8	11	13	7	**1**	9	26	27	15	**1**	5	60	50	21	8	3
24-28	06-07	09-10	13-14	31-32	229	229	229	229	229	24	5	2	3	3	3	3	6	2	2	2	2	6	115	494	468	390	317	276
06-07	27-28	09-10	13-14	31-32	4	4	4	4	4	2	2	28	13	14	18	10	2	17	32	35	22	3	10	101	82	41	19	9
24-28	06-07	10-11	13-14	31-32	279	279	279	279	279	40	8	4	5	5	4	4	8	4	3	3	3	12	171	649	620	506	435	363
06-07	27-28	10-11	13-14	31-32	6	6	6	6	6	4	4	35	20	23	26	18	5	24	40	42	31	7	28	181	150	77	44	21
06-07	27-28	08-09	13-14	17-32	2	2	2	2	2	3	6	51	39	41	45	35	9	41	54	58	41	2	**1**	6	5	2	**1**	**1**
24-28	06-07	08-09	13-14	17-32	272	272	272	272	272	60	16	12	16	15	14	14	21	11	10	9	5	11	79	300	289	267	262	250
06-07	27-28	09-10	13-14	17-32	3	3	3	3	3	5	7	58	47	48	49	40	11	46	62	69	46	5	2	18	15	6	4	2
24-28	05-06	08-09	13-14	31-32	545	545	545	545	545	95	23	5	6	6	6	6	17	5	5	5	4	42	337	899	879	803	727	650
24-28	06-07	08-09	13-14	30-31	283	283	283	283	283	42	12	3	**1**	**1**	2	2	4	3	4	4	12	77	383	849	812	670	557	444
27-28	07-20	08-09	13-14	17-32	14	14	14	14	14	36	69	233	222	223	223	190	108	200	233	237	166	20	3	**1**	**1**	**1**	2	5

(hour →)

Table 9. Best configurations for *System C* in the different periods

period	open branches					losses in the relevant period [pu]
day (single-rate)	06-07	27-28	08-09	13-14	31-32	2.87021
	06-07	24-28	08-09	13-14	31-32	2.87796
	06-07	27-28	09-10	13-14	31-32	2.88656
	06-07	24-28	09-10	13-14	31-32	2.89431
	06-07	27-28	08-09	13-14	17-32	2.90124
daylight	06-07	24-28	08-09	13-14	31-32	2.46800
	06-07	24-28	09-10	13-14	31-32	2.48153
	06-07	27-28	08-09	13-14	31-32	2.48573
	06-07	24-28	10-11	13-14	31-32	2.49875
	06-07	27-28	09-10	13-14	31-32	2.49925
night	26-27	07-20	08-09	12-13	16-17	0.12360
	27-28	07-20	08-09	08-14	14-15	0.12361
	27-28	07-20	09-10	12-13	16-17	0.12390
	26-27	07-20	08-09	12-13	15-16	0.12426
	27-28	07-20	09-10	12-13	15-16	0.12427

Table 10. Ranking of the configurations for *System C* according with the performance index (2)

daily ranking with the index (1)	open branches					performance index (2)
2	06-07	27-28	08-09	13-14	31-32	3.29
7	06-07	27-28	08-09	13-14	17-32	2.49
1	24-28	06-07	08-09	13-14	31-32	1.65
73	27-28	07-20	08-09	13-14	17-32	1.37
9	06-07	27-28	09-10	13-14	17-32	1.31
4	06-07	27-28	09-10	13-14	31-32	1.10
71	06-07	27-28	08-09	13-14	16-17	0.91
3	24-28	06-07	09-10	13-14	31-32	0.818
13	24-28	06-07	08-09	13-14	30-31	0.816
14	06-07	27-28	10-11	13-14	17-32	0.67

5. CONCLUSIONS

A dedicated analysis with time-dependent loads has been carried out to indicate how to assess the technical convenience of changing the system configuration during a typical day. For each time period, the calculations can be performed by considering the solution techniques adopted in Part 1 of this paper [1]. In particular, with the proposed approach the operator is enabled to find a suitable set of radial configurations once, then making this set of configurations available for executions with time-dependent loads and generations, instead of running an optimal reconfiguration method starting from an initial solution at each time period.

The results indicate that in general keeping the same configuration throughout the day is not convenient. The number of configuration changes can be limited by ranking the configurations according to some performance indices and determining the groups of hours in which some configurations remain in top-ranked positions. These results are in line with the fact that configuration changes occurring many times during the day could be impractical on the point of view of the distribution system operation. Nevertheless, the current advances in distribution automation could make intra-day distribution system reconfiguration a viable task. A comprehensive analysis of this aspect requires taking into account the costs of performing switching actions in the distribution system [8]. If intra-day distribution system becomes viable, the analysis presented may assist the distribution system operators appropriately.

Work in progress deals with the use of the results obtained in the determination of the radial network configurations to calculate different objective functions that can be handled in a multi-objective optimization framework.

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