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Benefits from the Comprehensive Planning of the High and Medium Voltage Network

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Abstract *- Nowadays, the reconstruction of existing electricity networks plays an important role. The main objectives are to offer an adequate quality of power supply and to minimize the costs of aspired final-state networks, which are developed in the long- term network planning. Due to the complexity, the state-of-the-art network planning is, on the one side, separated in the long- term network planning and the expansion network planning, and is, on the other side, separated in each voltage level - e.g. the high voltage (HV) or medium voltage (MV). Regarding the voltage level, an additional benefit of the voltage comprehensive planning has not been estimated yet. Therefore, this research is done by comparing the long- term network planning results in terms of costs and the quality of power supply from both planning procedures, which are the separate planning and the comprehensive planning of HV and MV networks. Furthermore, the benefit of the voltage comprehensive planning is evaluated, and general statements regarding this planning type are made.*

Keywords **- Long-term network planning, Voltage comprehensive planning, Distribution networks, Technical restrictions.**

1. INTRODUCTION

Due to the energy market liberalization, the cost pressure to the network operators is getting higher. Moreover, the equipment of existing networks is outmoded and is approaching to the end of the life time. Therefore, it is necessary to reconstruct the existing networks. Nowadays, the development of the aspired final-state networks plays an important role to offer an adequate quality of power supply and also to minimize the total costs in the future. The state-of-the-art long-term and expansion network planning tools use the concept of separate planning of each voltage level by neglecting the networks of other voltage levels and their interactions. Thus, the technical restrictions such as the voltage quality, the short-circuit restriction, and the reliability of the power supply have been solved by the network of each voltage level. Nevertheless, there are nowadays faster computer technologies and new algorithms of network planning tools that lead to the possibility to consider and develop several voltage level networks together with an acceptable computer calculation time. Therefore, the idea to expand the system boundary to cover both of HV and MV networks to get more degrees of freedom in network planning is occurred. (In Germany the normal voltage level is 110kV for HV network and 20 kV for MV network.) Because of the possibility that components of one voltage level can be used to help the other voltage level solve the technical restrictions when the HV and MV networks are planned together, the total costs are expected to be lower. However, at present an additional benefit of voltage level comprehensive planning by reducing the costs for all considered networks has not been estimated yet. Therefore, this research is done for the main objective, which is discovering the range of benefit by the comprehensive planning of HV and MV networks, leading to the basic idea in developing a software tool for the voltage comprehensive planning of HV and MV networks, which is developed in a PhD thesis at the Institute of Power System and Power Economics at RWTH Aachen University.

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2. NETWORK PLANNING CONCEPT

In the network planning process, two main important factors which are costs and the quality of power supply have to be considered.

Economics point of view: The total costs consist of the investment costs, the operation costs, and costs of losses. (Fixed costs for staff, administration, taxes, etc. are not considered.) All considered costs are not possible to directly sum up because each component has different life time and is integrated in the network at different dates. Therefore, the annuity method [1] is necessary to compare costs of different networks by transferring the costs to be annual costs (costs per year).

In the economics point of view, the total costs are expected to be as low as possible. However, the balancing between costs and the quality of power supply is necessary for network planning. Therefore, the technical restrictions are also the crucial factors.

Technical restrictions that normally considered are explained below:

- The first restriction that has to be considered is the maximum capacity of the equipment to find out the type and the number of components in the networks. During the operation, the loading has to be lower than the maximum allowed loading.
- The voltage quality is another restriction that has to be considered. The voltage level has to be kept in an

acceptable range which is regularized in Germany in a DIN standard to ensure an adequate voltage quality of the customers. The voltage drop of the network can be obtained from the load flow calculation. Normally in Germany the MV/LV customer substations in the normal case are allowed to have a maximum voltage drop regarding the nominal voltage level of approximate 5 to 6 percents, and in the case of (n-1) of 10 to 12 percents. (n-1) or (n-2) is supposed to be single or double line outage contingency simulation consequently. Obviously, the voltage drop requirement is one part of the network planning to limit the extension of the network.

- Another factor is the short-circuit current that has to be lower than the maximum breaking capability of the short-circuit breakers.
- One of the most important factors is the reliability of the network. It can be separated into two parts which are deterministic reliability and probabilistic reliability [2]. Deterministic reliability is used to analyze the power quality influenced by the configuration and the operating principles of the network. The often used (n-1) criterion requires that the outage of one arbitrary network component must not lead to the overloading of component and intolerable disturbances of the supply. In some cases, (n-2) failures also have to be considered, e.g. in case of common-mode failure, to ensure an adequate probabilistic reliability.

Probabilistic reliability method has been developed over the last decades and is now gaining importance in practical application. The basic idea of this method is to predict the reliability of the supply at the relevant nodes of the network on the basis of the statistical data, gathered from the past, describing the operation behavior of the network components. All credible outages that can occur and affect the system will be considered. The results come out in terms of the supply interruption frequency [1/a], the supply interruption duration [hour], and the supply interruption probability [min/a].

3. THE VOLTAGE-LEVEL COMPREHENSIVE PLANNING

Normally, each voltage level network is separately planned due to the complexity of the planning procedure. In every network planning, the basic deterministic reliability which is (n-1) criterion has to be fulfilled. It means that the reserved components have to be taken into account.

There are two choices to solve the (n-1) criterion: the separate and comprehensive planning of HV and MV networks. In case of the separate planning, there are two system boundaries that each one covers only HV or MV network. For this case, to fulfill the (n-1) criterion in HV parts, at least two HV transmission lines have to be connected to the HV busbar and at least two HV/MV transformers are needed in each HV/MV substation (As shown in Fig. 1). The reason is if one transformer or HV line has an outage, another one has to be able to transfer all power to supply the load to customers.

In case of the comprehensive planning, there are more degrees of freedom because the system boundary is expanded to cover both of HV and MV networks. It is possible to use MV components to assist HV components solving the technical restrictions. Obviously from this example, the number of HV components, which are HV/MV transformers and HV transmission lines, are reduced. To fulfill the (n-1) criterion, MV transmission lines are used to supply power to end customers in the HV component failure case. By comparing the costs, HV components have much higher costs than MV-components, especially for the switchgear that costs about ten times higher. Therefore, the total costs by the comprehensive planning of HV and MV networks are expected to be lower than costs by the separate planning. To get the exact result whether the comprehensive planning of HV and MV networks can give the benefit, this research has been done.

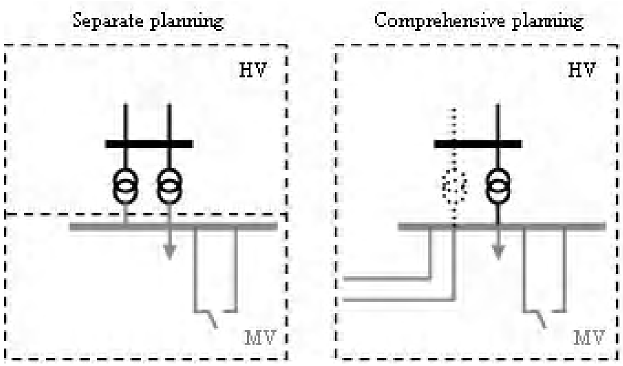

Fig. 1. Example of the separate and comprehensive planning of HV and MV networks of one substation.

Moreover, there are some restrictions for the voltage level comprehensive planning as follows:

- In this research only link structures are taken into account in MV networks, because, instead of ring structure, these lead to the capability to transfer the power between substations to solve (n-1) criterion.
- The LV level is not taken into account, because normally LV networks are used only for distributing power to the end customer in radial networks, but not for transferring power between substations.

4. METHODOLOGY

In this research, a lot of networks are planned by using two planning procedures, which are the separate planning and the comprehensive planning of HV and MV networks. The results from both procedures are compared in terms of costs and the quality of power supply. The conclusion of method is shown in Fig. 2.

Up to now, HV and MV networks have been separately planned. In this research, HV networks are manually planned, planned by own man, and MV networks are automatically planned, planned by helping of software tool. Because of separate planning, each network has to solve the technical restrictions by its own by neglecting effects from each other. The minimum costs from each one are found out. In the part of the comprehensive planning, HV and MV networks are manually planned and considered together. Some HV components are reduced by increasing some MV components to supply the power to the substations. During planning, the technical restrictions have to be solved. At the end, the costs and the quality of power supply from both planning procedures are compared to find out the range of benefit by the comprehensive planning of HV and MV networks.

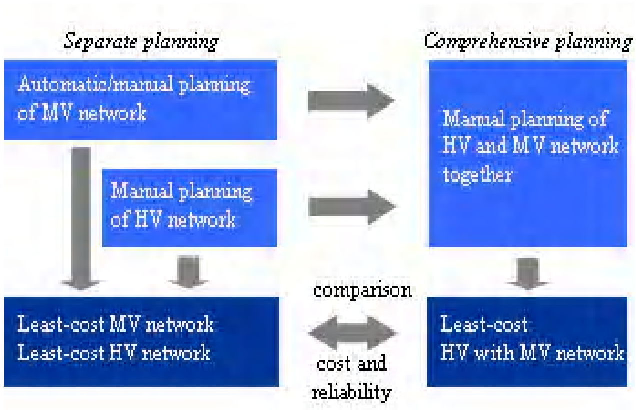

Fig. 2. Planning procedure.

Base case

By planning of HV with MV networks, there are more degrees of freedom and the larger system boundary to consider and design the network, so base networks with only small amount of substations are firstly planned in this part of the research for the clearer result.

There are 3 areas; A, B, and C. Area A and B are in the consideration and contain each own HV/MV transformers. Area C is modeled to describe the rest of the networks. The external power source is connected at the substation A. The designed network is shown in Fig. 3a.

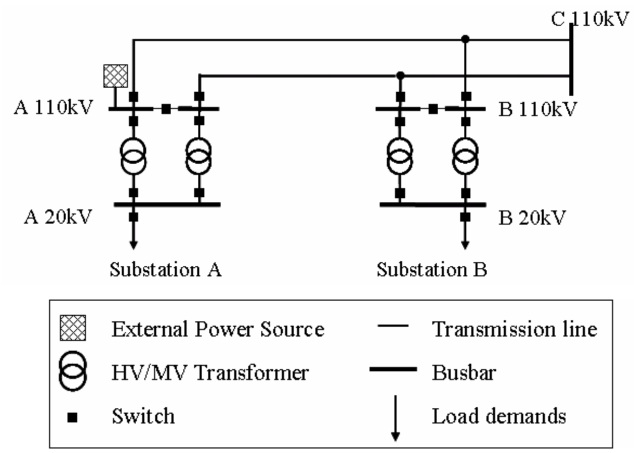

Fig. 3a. The designed network.

Three scenarios are designed:

Scenario 1 (Fig.3b): only HV networks (the separate planning of HV and MV networks)

Firstly, the separate planning is done by considering only HV part and the total costs are tried to reduce as much as possible. As shown in Fig.3b, to reduce the costs, the blind connection is used at the switchgear in the substation B because it can decrease the number of switches between HV transmission line and HV/MV transformer. (The blind connection is normally connected to the substation with a busbar switchgear or by two branch lines, which are connected via two 'T-sleeves' to other power lines.)

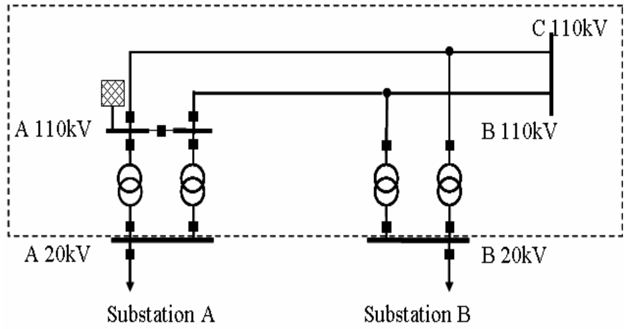

Fig. 3b. Scenario 1 (only the HV network).

Scenario 2 (Fig.3c): the HV with MV networks (the comprehensive planning of HV and MV networks)

The system boundary covers both of HV and MV network, therefore it is not necessary anymore to use only HV components to solve the (n-1) criterion connecting the substation to the HV network. From Fig.3c, it can be seen that in the substation B only one HV/MV transformer and one HV transmission line are enough by using the MV transmission line to help supply power from the substation A to B. Furthermore, in the substation A, one transformer could be removed depending on the load, so that each substation offers the reserve to the other one in a transformer failure case. Depending on the rest of the network, one of the HV power line could also be removed.

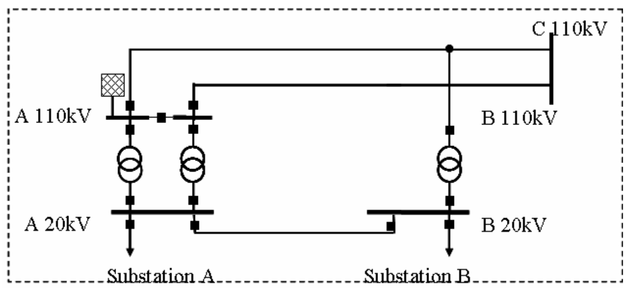

Fig. 3c. Scenario 2 (the HV with MV networks).

Scenario 3 (Fig.3d): only the MV network connection of the substation B (the comprehensive planning of HV and MV networks)

As aforementioned, there are more degrees of freedom, so it is also possible to use no HV component in the substation B. All power to be supplied to the end customers in the substation B flows totally via the MV transmission line from the substation A.

Load demands from the customers and distance between substations A and B are varied for all scenarios. Thus, the type and number of components have to be changed to fulfill the technical restrictions. After all technical restrictions have been solved to be within acceptable ranges, total costs and the probabilistic reliability from each case are calculated and compared with each other.

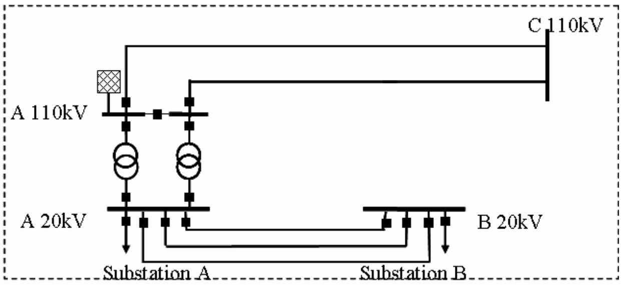

Fig. 3d. Scenario 3 (only the MV network).

5. THE RANGE OF BENEFITS BY THE COMPREHENSIVE PLANNING OF HV AND MV NETWORKS

From the last section, the research has done by increasing the value of load demands of the customers from 10MVA to 60MVA. It leads to higher costs of networks from all scenarios. However, the ratios of increasing costs for any steps of increasing load demands for each scenario are not the same. At low load demands up to one point, the costs of scenarios 1 are still higher than the costs of the other scenarios, but at higher load demands, the result is in the opposite way. The so-called critical point is the point that the costs of two scenarios are the same and depend on the distance between substations. In the short distance- the critical points are quite at high load demands, but in the longer distance- the critical points are at lower load demands.

By comparing results from the separate planning (scenario1) and the comprehensive planning (senario2 and 3) of HV and MV networks, the areas of benefits to reduce the costs are found out and shown in Figs.4a and 4b for the comparison of scenario 1 with 2 and 3 respectively.

The curve comes from every critical point that costs from two scenarios are the same. The area under the curve is the area that the costs of the comprehensive planning are lower than the costs of the separate planning. The area above the curve is the area that the costs of the separate planning are higher. Therefore, it can be concluded that any point under the curve is in the range of benefit by the comprehensive planning of HV and MV networks.

It can be noticed from both curves that the range of benefit from the scenario 3 is less than from the scenario 2 because the area under the curve is smaller. It is because, in the scenario 3, the power supplied to the end customers in the substation B flows only via MV transmission lines, therefore it will be a higher outage probability due to two MV transmission lines having outage at the same time. Thus, it is not possible to consider only the (n-1) criterion, but also the (n-2) one has to be fulfilled in this case. Obviously, the number of MV transmission lines has to be increased at least one line, so the total costs are higher, leading to a reduction of the benefit.

From both graphs (Figs: 4a and 4b), the line connecting between any critical point is not smooth along the load axis. It is because of the different network scenario for each case. When load demands are higher, more components are needed to fulfill the reliability requirement; however, there is no exact level of technical data for each network.

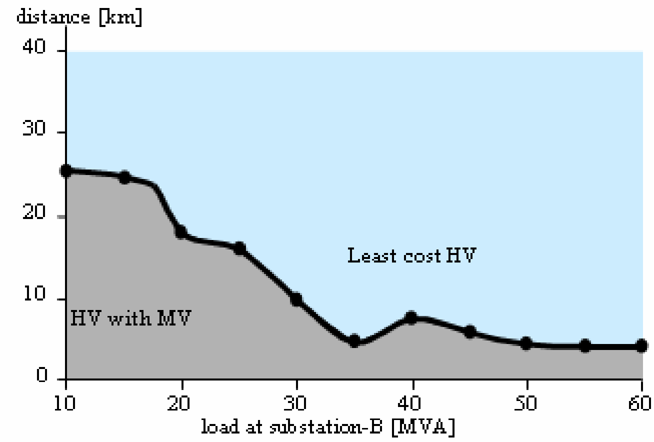

Fig. 4a. Graph of the cost-benefit by using the scenario 2 network compared to the scenario 1 network.

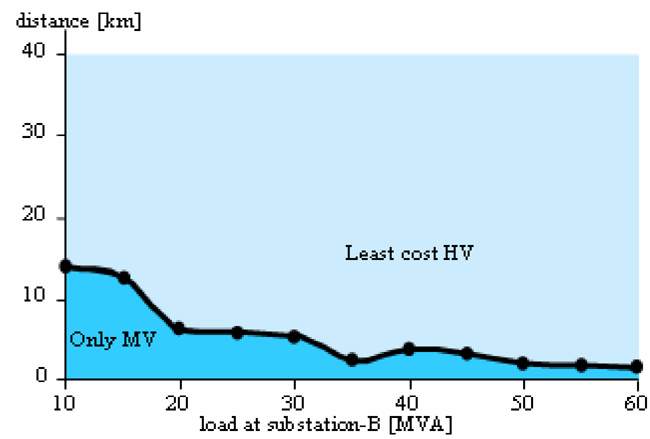

Fig. 4b. Graph of the cost-benefit by using the scenario 3 network compared to the scenario 1 network.

The development of the curves comparing the scenario 1 with 2 and 3 respectively is done for the 10kV and 20kV. Consequently, there is a higher benefit by using the 20kV for the MV level due to the higher capacity of the components. Thus, less quantity structure (number and type of MV components) in the MV level is needed.

Furthermore, the voltage restriction and the reliability are really important to consider while planning the network as aforementioned. Therefore, all restrictions have been proved prior to the result. Here in Fig.5, there is the probabilistic reliability (interruption frequency and interruption probability) at the critical points of the developed curves (Fig.4a) that the costs from the scenario 1 and 2 are equal. It shows that not only the costs at the critical point are equal, but the reliability is also nearly the same. The reliability of network in the scenario 3 is also found and shown in the same figure. It can be noticed that the reliability of the scenario 3 network is quite better than others because the (n-2) criterion is used in this case. Hence, the costs are higher and not the same as the other two scenarios.

The conclusion of the results is that planning HV and MV networks together can render the benefit by reducing the costs for some cases depending on load demands of customers (load) and the distance between substations (distance) by nearly equal probabilistic reliability. When loads are higher, the distance that is still able to use and gives the cost-benefit by planning HV and MV networks together is reduced, and vice versa.

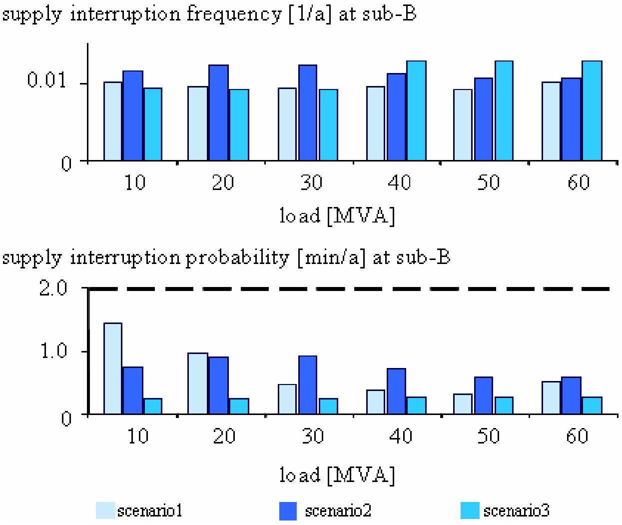

Fig. 5. Supply interruption frequency and the probability at the critical points.

6. IMPLEMENTATION

The idea and conclusion from the base case are proved by planning larger networks (both of homogeneous and inhomogeneous networks). Two planning procedures which are the separate planning and the comprehensive planning of HV and MV networks are done at 3 district area types; urban, suburban, and rural area. Each area type has different load density. (Urban area has high load density and rural area has low load density.) The load density depends on two factors which are load demands from the customer and the distance between substations.

In the first step, the HV and MV levels are planned separately. In this planning process, the HV level is manually planned and the MV level is automatically planned. In the second step, both voltage levels are comprehensively planned by using the network structures of the first step (separate planned) as input data. By the manual comprehensive planning, the total costs have been tried to reduce, being compared with those total costs of the separate planning. Least costs can be obtained by reducing the quantity structure of the HV components by the substitution of MV quantity structure. In this planning process, the technical restrictions, especially for the (n-1) criterion and the probabilistic reliability, still have to be in an acceptable range.

Here, only the results from the homogeneous network are shown. The probabilistic reliability is found in terms of the supply interruption frequency [1/a] and the supply interruption probability [min/a] as shown in Figs.6a and 6b respectively.

It can be noticed that for all district area types, the reliability quantities of both scenarios (the separate and comprehensive planning) are in an acceptable range (less than 2min/a). To fulfill the short circuit restriction of the short circuit breakers, the MV network cannot be operated as meshed network as in the HV level, thus the switches to open the part of networks are sometimes necessary. After switching in some cases, a higher interruption frequency occurs in the comprehensive planning because of solving the (n-1) criterion in the MV level. In this research, it is supposed that each substation is equipped with remote controlled short circuit breakers, which can be closed in a few minutes, so that the effect on the interruption probability can be nearly neglected.

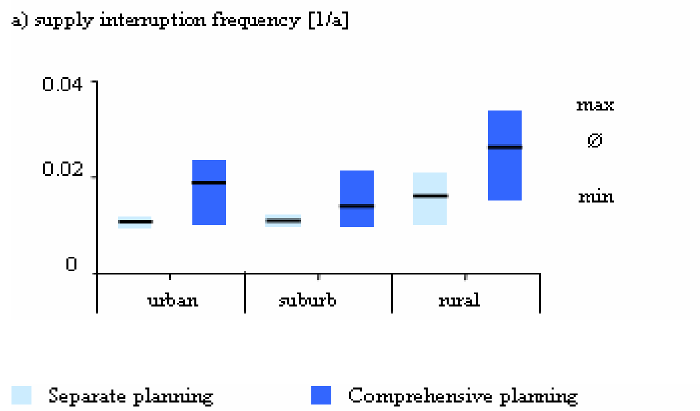

Fig. 6a. Supply interruption frequency [1/a].

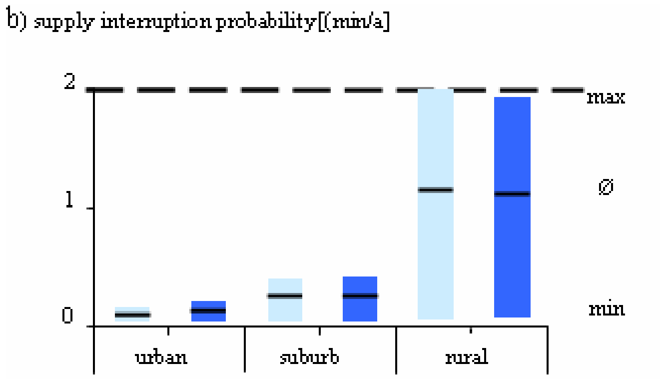

Fig. 6b. Supply interruption probability [min/a].

In Fig.7, the annuity costs of networks are shown. It can be noticed that in case of the comprehensive planning of HV and MV networks, the costs of HV quantity structure are lower while the costs of MV quantity structure are higher. However, the total costs depend on the area type. While planning HV network with MV network in the urban and suburban area, the total costs can be reduced by the comprehensive planning. In the rural area, overhead lines are normally used to connect among quite far away substations, and then leading to the higher probability of common mode failure. Thus, the (n-2) criterion has to be considered as mentioned before in the base case research. Therefore, the total costs of the networks in rural area are higher when HV and MV networks are planned together. Thus, in rural areas, the separated planning is preferred, because the substitution of the HV quantity structure by the MV structure as done in other area types leads to higher costs and worse reliability.

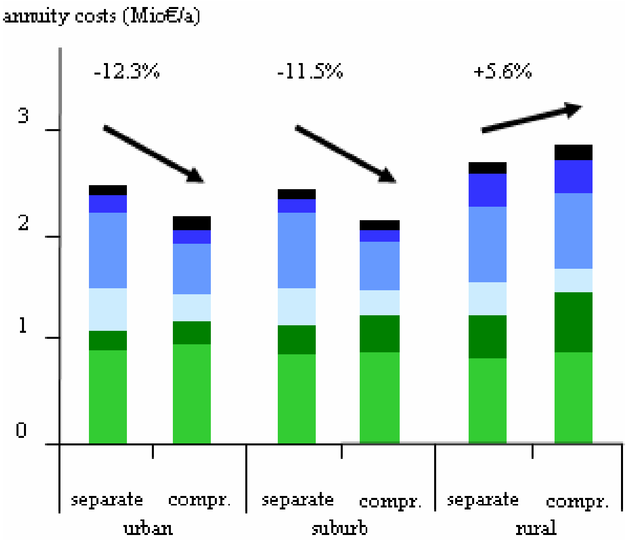

Fig. 7. Annuity costs for all district area types.

7. CONCLUSION

The main goal of this research is to identify the range of benefit by the comprehensive planning of HV and MV networks. The research is done by planning networks regarding to two different planning procedures, which are the separate planning and the comprehensive planning of HV and MV networks. Load demand of customers (load) and the distance between substations (distance) as well as the district area types are variable factors. All results are compared by the crucial concept of network planning, which is the balancing between costs and the quality of power supply.

From the basic analysis by planning the three substation network with factors of load and distance, the conclusion result is that there is a benefit of comprehensive planning of HV and MV networks in some cases, while considering the technical restrictions, comprising the voltage range, the short-circuit, the (n-1) criterion, and the probabilistic reliability. The range of benefit by the voltage comprehensive planning is only at some amount of load and distance. To get cost benefit at the high load area, it is possible only at the quite short distance. When the load is lower, the range of distance that can offer benefit is increased.

To find out the conclusion in dealing with the area district type, the homogeneous and the inhomogeneous networks are also designed in this research for different load densities. The solution conclusions from both homogeneous and inhomogeneous networks are the same. In the urban and suburban area, it can be possible to get an addition cost reduction by the voltage level comprehensive planning. On the other hand, in the rural area, the substitution of the HV network with the MV network might affect worse reliability and might need more components to solve the technical requirement. This leads to higher costs than using the separate planning. Thus, there is no benefit in planning the HV and MV level together in rural areas.

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APPENDIX

Cost Data

Table A.1. Cost data

	Type	Investment Costs [T€]	yearly Costs [T€/a]	cost of Operation [%]	annual Factor [%]	service Life [a]
Substation 110kV	110kV-Station					
	- circuit breaker	400.00	44.400	3.00	8.10	30
	- Isolator	10.00	1.110	3.00	8.10	30
cable+trench 110kV	Cu500	300.00	21.990	0.33	7.00	80
	Cu800	319.40	23.412	0.33	7.00	80
overhead+pole 110kV	pole for singleoverhead	100.00		1.00	7.00	80
	Single line AS240	35.00		1.50	7.50	40
	pole+overheadline	135.00	10.976	1.13	7.00	
Substation 20kV	20/10kV-Station					
	- busbar	(costs of busbar neglectable)				
	- circuit breaker	39.00	4.329	3.00	8.10	30
	- Isolator	1.00	0.111	3.00	8.10	30
cable+trench 20kV	Al150	60.00	4.200	0.00	7.00	80
	Al240	63.10	4.417	0.00	7.00	80
	Al300	67.30	4.711	0.00	7.00	80
	Al400	73.20	5.124	0.00	7.00	80
overhead+pole 20kV	AS120	20.00	1.626	1.13	7.00	80
110/medium voltage Transformer	25MVA	400.00	35.200	1.60	7.20	50
	31.5 MVA	500.00	44.000	1.60	7.20	50
	40 MVA	575.00	50.600	1.60	7.20	50
	63 MVA	800.00	70.400	1.60	7.20	50

[T€] in thousand Euros , [%] based on the Investment costs

Technical Data

Table A.2. Transmission line data

	Volt (kV)	Type	R' (Ω/km)	X' (Ω /km)	G' (nS/km)	C' (nF/km)	Imax (kA)
cable	110	Cu500	0.036	0.101	0	370	0.67
		Cu800	0.028	0.091	0	200	0.8
	20	Al150	0.206	0.12	0	261	0.32
		Al240	0.125	0.111	0	270	0.355
		Al300	0.1	0.108	0	330	0.403
		Al400	0.078	0.104	0	370	0.471
overhead line	110	AS240	0.121	0.39	0	9.36	0.645
	20	AS120	0.237	0.37	0	10	0.41

Table A.3. Transformer data

Volt (kV)	Snom (MVA)	Uk (%)	Pcu (kW)	Pfe (kW)	IN (%)	Uupper (kV)	Ulower (kV)	Ntap changer
110/20	25	11.2	110	21	0.17	105	22.5	9
	31.5	12.5	119.7	22	0.14	105	22.5	13
	40	16	180	20	0.09	105	22.5	13
	63	13.5	180	20	0.09	105	22.5	13