# INFLUENCE OF DISTRIBUTED GENERATION ON ELECTRICAL ENERGY LOSSES IN DISTRIBUTION NETWORK

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## SUMMARY

Management and planning of electric power distribution systems have changed dramatically in recent years due to regulatory, structural, ownership and technological changes. While the new system organization has brought numerous advantages both to customers and Distribution System Operators (DSO), a number of challenges remain yet to be solved. One such a challenge is a connection of Distributed Generation (DG) in remote areas with low energy consumption. This paper is inspired by some practical problems related to DG connection approval in Bosnia and Herzegovina. The main objective of this paper is a calculation of the electrical energy loss variations caused by DG. Calculations are performed on a realistic middle voltage (10 kV) network in Bosnia and Herzegovina, with realistic system load data obtained from the AMI. The novelty of this approach compared to the exiting energy loss quantification methods is the use of Distribution Loss Factor (DLF) concept and its allocation to each DG connection node. It is expected that this paper will make a contribution towards investigation of the extent to which renewable sources contribute to the overall cost of the network. The obtained results are useful to both the DSO, for distribution network and DG planning purposes, and to the Regulators for energy policy and tariff design purposes.

**Key words:** distribution loss factor, distribution system, energy losses, generation, planning

## INTRODUCTION

Traditionally, power networks around the world have been built and managed by government owned, vertically integrated company. More recently, power systems have been significantly transformed. These changes are driven by the process of market liberalization and by the process of the energy transition.These who processes combined together present a new energy paradigm. The new system organization has brought a number of advantages both to customers and system operators [1]. However, a number of challenges remain yet to be solved, such as the connection of distributed generation sources in remote areas which have suitable natural and environmental predispositions, but the poor power system facility and low population density (and low energy consumption). This paper is inspired by some practical problems related to DG planning and connection approval encountered by the DSO in remote areas of Bosnia and Herzegovina. Some of these issues are briefly described in following paragraphs and highlight the need to further investigate the economic aspects of distributed generation integration in order to determine the extent to which renewable sources contribute to the overall cost of electrical energy. In particular, this paper shows how to calculate the electrical energy losses variations caused by the integration of distribution network. Calculations are performed on a realistic middle voltage (10 kV) network in Bosnia and Herzegovina, with realistic system load data obtained from Automatic Metering Infrastructure (AMI). Calculations are performed for different conversion technologies and include, hydro, solar and wind power stations. The novelty of this approach compared to the exiting energy loss quantification methods is the use of Distribution Loss Factor concept and its allocation to each DG connection node. Results presented in this paper are part of an ongoing research on influence of the renewable sources integration to the distribution network. It is expected that this paper contribute towards a creation of flexible and easy to follow business intelligence/analytics tool used to perform DLF approximation at desired node in network, for desired DG size and technology. The obtained results are useful to both to the DSO, for distribution network and DG planning purposes, and to the regulators for tariff and market design purposes.

## PROBLEM DEFINITION

In practice, it is observed that new DG connections are frequently requested on locations which are remote with respect to the areas with high load concentrations. Further, the application for connection of new DG in some cases comes unexpected and is not accounted for in DSO investment plans. This is problematic for a number of reasons. First of all, connection of new distributed generators have different impact on energy losses in the systems, some generators have potential to decrease total energy losses, while others increase them. This attribute depends on system configuration and condition, location of DG within the system, load demand and conversion technology. Most DSO conduct system studies as a part of connection approval process, based on load flow analysis which determine the impact of new connections on network technical parameters such as voltage, frequency, harmonics, flickers etc. However, there is limited evidence that standard preapproval studies investigate the effect that new DG has on price of electric energy. Current practice in Bosnia and Herzegovina does not treat the energy losses as eliminatory criteria in the connection approval process. It is therefore necessary to plan for new extensions and determine locations (and times) are which suitable for construction of DG. Further, it is observed that DG investments often rely on special/subsidized tariffs in order to be profitable. In Bosnia and Herzegovina tariffs are funded through renewable resources tax which is collected from electricity customers, currently set at 0,001 BAM for each kWh used. Once the so called status of privileged producer is obtained, the generators are allowed to sell more expensive energy and it is no longer possible to differentiate between DG with beneficial and non-beneficial effect on system energy losses and system operation in general. This means that some DGs (and practice shows that there are quite few of them) are rewarded for increasing the total energy losses of the systems. Finally, in the case of connection applications for DG in remote areas, it is necessary to incur significant investments in order to provide the infrastructure required for safe and secure connection. In many cases it is impossible to recover this type of costs and is typical example of misallocation of source through unnecessary and non-beneficial sunk cost which takes us further away from social optimum. For the reasons discussed above, it is necessary to adopt a planning tool which will be used to rank the locations in power system according to their potential to provide long term benefits both to customers and DSO. This is important and relevant for two reasons. Firstly, it can reduce energy losses, operation costs and prolong lifetime of power system components. Secondly, it can be used to form tariffs relevant for DG remuneration based on real cost of electricity in particular area. This means that misallocation of resource can be avoided, which leads to more successful establishment of social optimum.

## LITERATURE REVIEW

Concepts of power and energy losses in power system have been well referenced and discussed [2]. Utilities, in particular, are very interested to reduce losses because they have a direct influence on revenue. Apart from economic importance, energy losses have considerable social, environmental and technological implications. Influence of DG on energy losses in distribution network is increasingly drawing attention of Utilities and Regulators because of its impact on overall system costs. There are several attempts to quantify the energy losses. One of them is shown in [3] where the novelty was the use of relevant factors such as DG penetration and dispersion levels. For higher penetration levels there is a marginal increase in losses [2] but this is generally true this for penetration levels above 50% [1]. Power losses are largely dependent on the location of DG [1]. Reference [4] presents a comparative study for several loss allocation methods taking into account different levels of penetration of distributed energy. Three types of loss allocation procedures are compared in [5], namely pro rata procedure, marginal procedure and proportional sharing procedure.

## ENERGY LOSS CALCULATIONS

Market liberalization is introducing new pricing mechanisms and it is becoming increasingly important to transparently allocate energy losses to each market participant [4]. The classical market clearing procedure does not explicitely account for network losses and non linear electrical laws do not allow the determining power flow for a given generator and producer [5]. DLF is important parameter used for a number of purposes. It is used to estimate the average losses for energy conveyed in transmission and distribution network connection point [8]. In Spain, for example, it is used to allocate losses to each customer, taking into account its consumption characteristics. Further, it is used for regulatory porposes to determine the amount of losses recognised in annual retribution scheme of DSO. This approach has stirred some contraversy since it leads to the situationin which DSO with good losses performance will be recognised less expenses than DSO with poor losses performance [6] . Further, the consideration of site specific DLF is an important aspect of electricity market design in terms of how much reeward should be allocated to a particular DG for its output [7]. In Australia, for example, DFL calculated by Network Service provider and published each financial year by the Australian Energy Market Operator. Finally, DLF consideration appears to be very promissing methodology for distribution system planning purposes, specially the distributed resources planning and placement. In this paper it is proposed to use the DLF to allocate a portion of the energy losses to individual DG units. The calculation is tested on a realistic MV network shown in Figure 1. Realistic load and generation data obtained for the substation as shown in Figure 2 and Figure 3. DG connection point is used to demonstrate the application of the concept. The same approach can be extended to evaluate load customers as well and to allocate a portion of location specific losses to individual customers. The methodology adopted in this paper is presented in [7] and uses an incremental values which ensures that the DLF will better reflect the site specific impact of DG in terms of distribution system energy losses. In particular DLF is defined as:

$$\mathrm{DLF} = 1 + \frac{\text{Annual  energy losses without generator} - \text{Annual energy losses with generator}}{\text{Annual generation volume}} \tag{1}$$

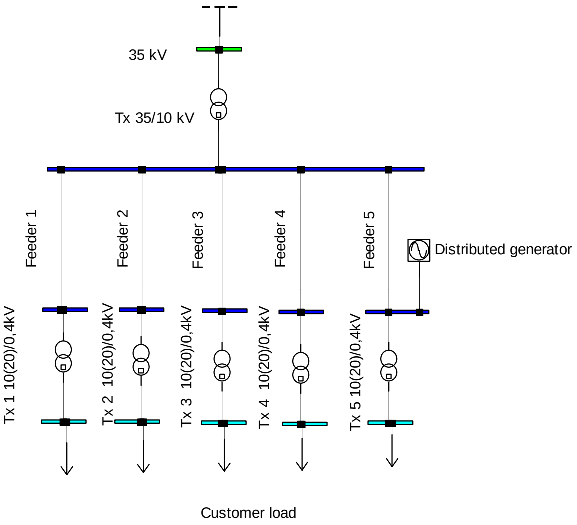

FIGURE 1 SINGLE LINE DIAGRAM OF A SIMPLE POWER DISTRIBUTION SYSTEM

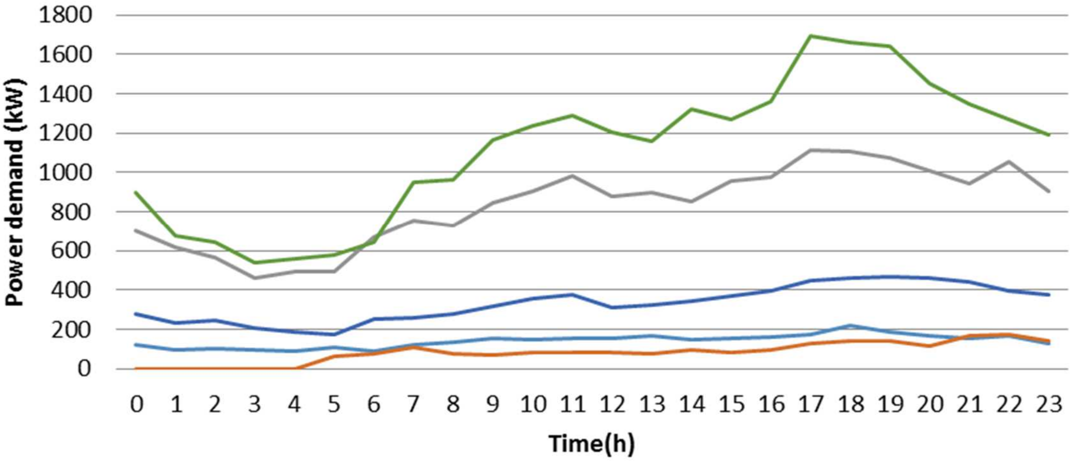

FIGURE 2 POWER DEMAND ON 10kV FEEDERS ON A DAY OF MAXIMUM YEARLY DEMAND

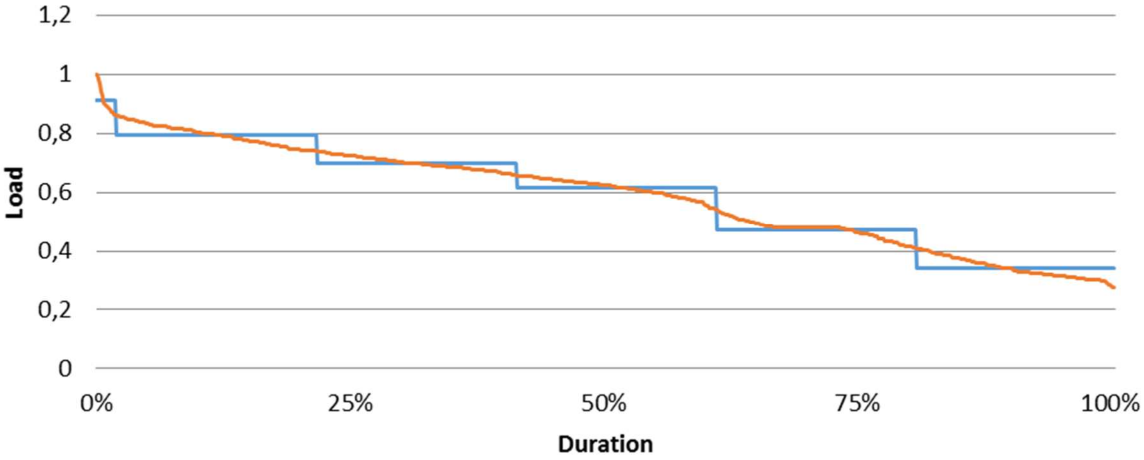

FIGURE 3 REAL AND NORMALISED YEARLY DURATION CURVE AT THE SUBSTATION

| Interval | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Load [kW] | 2859,00 | 2494,58 | 2193,70 | 1926,51 | 1487,85 | 1069,945 |
| Load [%] | 91,02% | 79,42% | 69,84% | 61,33% | 47,37% | 34,06% |

| | | | | | | |
|---|---|---|---|---|---|---|
| Duration [%] | 2,02% | 19,62% | 19,62% | 19,62% | 19,62% | 19,49% |

TABLE 1 LOAD DURATION FOR EACH INTERVAL-LOAD DURATION AND WEIGHTING

Using the results provided in Table 1, total yearly consumption of the area under consideration is:

$$\mathrm{Etot} = \mathrm{Th} \times \sum_{n1=1}^{6} \mathrm{En1} * \mathrm{Dn1} = 8760 * (2859.00 * 0{,}0202 \ + \ 2494.58 * 0{,}1962 \ + \ 2193.70 * 0{,}1962 \ + \ 1926.51 * 0{,}1962 \ \ 1487.85 * 0{,}1962 \ + \ 1069.94 * 0{,}1949) = \ 14.592.092.37 \ \mathrm{kWh} \quad (2)$$

Figure 4 shows real and normalised generation duration curve for the PV solar system. From data presented in table 2 total annual energy generation from 1MW PV solar power station can be calculated as follows:

$$Egen = Th \times \sum_{n1=1}^{4} En1 * Dn1 = 8760 \times \ (1.90 + 11.01 + 2.61) = 1.361.065{,}60 \ kWh \quad (3)$$

Table 2 shows generation and load weighing factors and it can be concluded that a total of thirty six different load flow simulation must be carried out in order to determine the losses on the system under consideration. Load flow results represent the absolute power losses for each combination of load and generation factors, as shown in Table 3. Using the load flow analysis results form table 1, total energy loss with no generation is calculated as:

$$Eloss(no \ gen) = Th \times \sum_{n1=1}^{6} Pn1 * Ln1 = 8760 * \ \times 70.90 = 621.086{,}10 kWh \quad (4)$$

Comparing the values of energy loss to the values of total energy consumption, it can easily be concluded that energy loss amounts to 4% of total energy supplied to the area. The Table 4 shows the weighting factors for each combination of generation output load demand load which in reality prespresent the percent of time a given combination of generation and load might occur. These weighting factors are multiplied by the absolute power loss values to obtain a normalised loss factor for generator. Now, the normalise loss factor is multiplied by the number of hours to obtain the total energy losses with generatin:

$$Eloss(gen) = Th \times \sum_{m}^{6} \sum_{n1}^{4} n1 * Dn1 = 8760 \times 68.96 = 604.098{,}34 kWh \quad (5)$$

Finally, using the values obtained so far and the value of DLF can be calculated as follows:

$$DLF = 1 + \left( \frac{621.086{,}10 - 604.098{,}34}{1.361.065{,}60} \right) = 1 + 0.0124 = 1{,}0124 \quad (6)$$

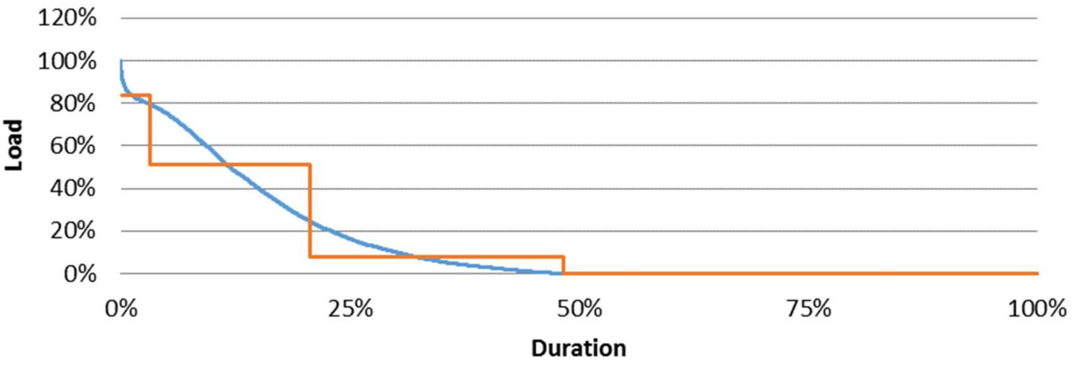

FIGURE 4 REAL AND NORMALISED GENERATION DURATION CURVE FOR PV

| Interval | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Generation(%) | 0 | 8.02 | 51.42 | 83.68 |
| Duration(%) | 51.66 | 23.78 | 21.43 | 3.12 |

TABLE 2 GENERATION DURATION FOR EACH INTERVAL-PV GEN. DURATION AND WEIGHTING

| | | Generation | | | | |
|---|---|---|---|---|---|---|
| | | Power(%) | 0 | 8.02 | 51.42 | 83.68 |
| | | Duration(%) | 51.66 | 23.78 | 21.43 | 3.12 |
| System load | 91% | 2.02% | 107 | 107 | 115 | 135 |
| | 79% | 19.62% | 90.6 | 90 | 99,49 | 119 |
| | 69% | 19.62% | 79.82 | 78,21 | 88,28 | 108 |
| | 61% | 19.62% | 70.47 | 70,6 | 80,59 | 101 |
| | 47% | 19.62% | 60.12 | 60 | 70,1 | 90,9 |
| | 34% | 19.49% | 49.67 | 49,68 | 62,48 | 84,44 |

TABLE 3 ABSOLUTE ACTIVE POWER LOSSES FOR THE PV SYSTEM BASED ON LOAD FLOW

| | | Generation | | | | |
|---|---|---|---|---|---|---|
| | | Power(%) | 0 | 8.02 | 51.42 | 83.68 |
| | | Duration(%) | 51.66 | 23.78 | 21.43 | 3.12 |
| System load | 91% | 2.02% | 0.010435 | 0.0048 | 0.00433 | 0.00063 |
| | 79% | 19.62% | 0.101357 | 0.04666 | 0.04205 | 0.00612 |
| | 69% | 19.62% | 0.101357 | 0.04666 | 0.04205 | 0.00612 |
| | 61% | 19.62% | 0.101357 | 0.04666 | 0.04205 | 0.00612 |
| | 47% | 19.62% | 0.101357 | 0.04666 | 0.04205 | 0.00612 |
| | 34% | 19.49% | 0.100685 | 0.04635 | 0.04177 | 0.00608 |

TABLE 4 ESTIMATED WEIGHTING FACTOR PV SOLAR SYSTEM

| | | Generation | | | | |
|---|---|---|---|---|---|---|
| | | Power(%) | 0 | 8.02 | 51.42 | 83.68 |
| | | Duration(%) | 51.66 | 23.78 | 21.43 | 3.12 |
| System load | 91% | 2.02% | 1.1166 | 0.5140 | 0.4978 | 0.0851 |
| | 79% | 19.62% | 9.1829 | 0.4199 | 4.1831 | 0.0000 |
| | 69% | 19.62% | 8.0903 | 3.6490 | 3.7118 | 0.6611 |
| | 61% | 19.62% | 7.1426 | 3.2939 | 3.3885 | 0.6183 |
| | 47% | 19.62% | 6.0936 | 2.7994 | 2.9474 | 0.5564 |
| | 34% | 19.49% | 5.0010 | 1.8854 | 2.6096 | 0.5132 |

TABLE 5 NORMALISED DEMAND LOSS FOR PV SOLAR SYSTEM

Previous procedure is repeated for the system with small hydropower station installed. Figure 5 shows normalized generation duration curve for small hydropower station. Using the data presented in Table 6-8 we have:

$$\text{Eloss(gen)} = 725.703{,}00\ \text{kWh} \tag{7}$$

$$\text{Eloss(gen)} = 3.546.908{,}00\ \text{kWh} \tag{8}$$

$$\text{DLF} = 1 - \frac{620.908{,}00 - 725{,}703}{3.546.908} = 1 - 0{,}295 = 0{,}9704 \tag{9}$$

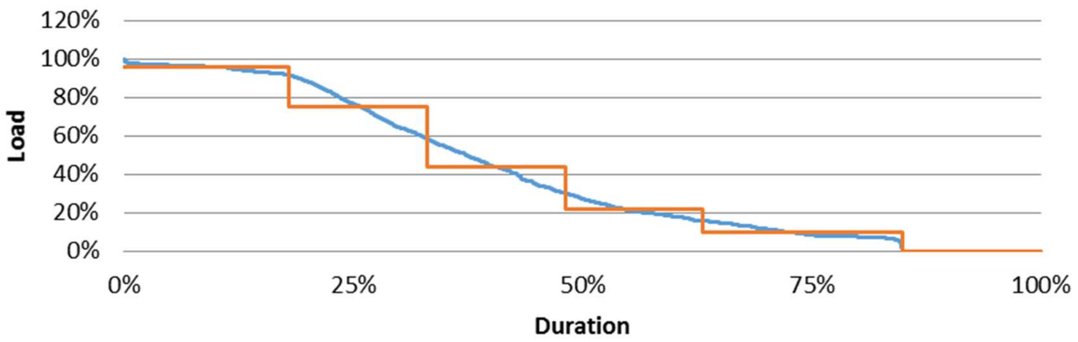

FIGURE 5 REAL AND NORMALISED GEN. DURATION CURVE FOR SMALL HYDROPOWER STATION

| | | Generation | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Power | 0.00% | 9.85% | 21.67% | 43.75% | 75.03% | 95.42% |
| | | Duration | 15.03% | 21.83% | 15.03% | 15.03% | 15.04% | 18.04% |
| System load | 91% | 2.02% | 107 | 107 | 107 | 112 | 128 | 144 |
| | 79% | 19.62% | 90.6 | 89.96 | 90.83 | 96.36 | 113 | 129 |
| | 69% | 19.62% | 79.82 | 78.21 | 79.3 | 85.06 | 102 | 118 |
| | 61% | 19.62% | 70.47 | 70.16 | 71.32 | 77.3 | 94.46 | 111 |
| | 47% | 19.62% | 60.12 | 60 | 61 | 67.8 | 83.97 | 101 |
| | 34% | 19.49% | 49.67 | 49.78 | 51.37 | 58.68 | 77.45 | 95.09 |

TABLE 6 ABSOLUTE ACTIVE POWER LOSSES FOR THE HYDRO SYSTEM BASED ON LOAD FLOW

| | | Generation | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Power | 0.00% | 9.85% | 21.67% | 43.75% | 75.03% | 95.42% |
| | | Duration | 15.03% | 21.83% | 15.03% | 15.03% | 15.04% | 18.04% |
| System load | 91% | 2.02% | 0.0030 | 0.0044 | 0.0030 | 0.0030 | 0.0030 | 0.0036 |
| | 79% | 19.62% | 0.0295 | 0.0428 | 0.0295 | 0.0295 | 0.0295 | 0.0354 |
| | 69% | 19.62% | 0.0295 | 0.0428 | 0.0295 | 0.0295 | 0.0295 | 0.0354 |
| | 61% | 19.62% | 0.0295 | 0.0428 | 0.0295 | 0.0295 | 0.0295 | 0.0354 |
| | 47% | 19.62% | 0.0295 | 0.0428 | 0.0295 | 0.0295 | 0.0295 | 0.0354 |
| | 34% | 19.49% | 0.0293 | 0.0425 | 0.0293 | 0.0293 | 0.0293 | 0.0352 |

TABLE 7 ESTIMATED WEIGHTING FACTOR FOR HYDRO SYSTEM

| | | Generation | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Power | 0.00% | 9.85% | 21.67% | 43.75% | 75.03% | 95.42% |
| | | Duration | 15.03% | 21.83% | 15.03% | 15.03% | 15.04% | 18.04% |
| System load | 91% | 2.02% | 0.3249 | 0.4718 | 0.3249 | 0.3400 | 0.3889 | 0.5247 |
| | 79% | 19.62% | 2.6717 | 3.8530 | 2.6785 | 2.8415 | 3.3345 | 4.5659 |
| | 69% | 19.62% | 2.3538 | 3.3498 | 2.3385 | 2.5083 | 3.0099 | 4.1765 |
| | 61% | 19.62% | 2.0781 | 3.0050 | 2.1031 | 2.2795 | 2.7874 | 3.9288 |
| | 47% | 19.62% | 1.7729 | 2.5698 | 1.7988 | 1.9993 | 2.4778 | 3.5748 |
| | 34% | 19.49% | 1.4550 | 2.1180 | 1.5048 | 1.7189 | 2.2703 | 3.3434 |

TABLE 8 NORMALISED DEMAND LOSS FOR HYDRO SYSTEM

Similarly the, procedure is reapeated for the case with wind power generator. Table 9 shows the weighting factors for each combination of generation output load demand load which in reality repesents the percent of time a given combination of generation and load might occur. Similarly to the previous examples, weighting factors are multiplied by the absolute power loss values from to obtain a normalised loss factor for generator which is then multiplied by the number of hours to obtain the total energy losses with generatios:

$$\text{Eloss(gen)} = 721.501{,}17\ \text{kWh} \tag{10}$$

$$\text{Egen} = 4.307.292{,}00\ \text{kWh} \tag{11}$$

$$\text{DLF} = 1 - \frac{620.908{,}00 - 721.501{,}17}{4.307.292{,}00} = 1 - 0{,}0233 = 0{,}9766 \tag{12}$$

| | | Generation | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 0 | 5 | 25 | 50 | 75 | 96.5 |
| | | Duration | 7% | 26% | 25% | 15% | 9 | 18% |
| System load | 91% | 2.02% | 107 | 105 | 108 | 117 | 128 | 145 |
| | 79% | 19.62% | 90.6 | 90.14 | 91.34 | 98.86 | 113 | 130 |
| | 69% | 19.62% | 79.82 | 78.3 | 79.83 | 87.63 | 102 | 119 |
| | 61% | 19.62% | 70.47 | 70.13 | 71.88 | 79.94 | 94.44 | 112 |
| | 47% | 19.62% | 60.12 | 60 | 61.3 | 69.1 | 83.9 | 111 |
| | 34% | 19.49% | 49.67 | 49.61 | 51.12 | 61.73 | 77.43 | 96.14 |

TABLE 9 ABSOLUTE ACTIVE POWER LOSSES FOR THE WIND SYSTEM BASED ON LOAD FLOW

|  |  | Generation |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  | 0 | 5 | 25 | 50 | 75 | 96.5 |
|  |  | Duration | 7% | 26% | 25% | 15% | 9% | 18% |
| System load | 91% | 2.02% | 0.0014 | 0.0053 | 0.0051 | 0.0030 | 0.0018 | 0.0036 |
|  | 79% | 19.62% | 0.0137 | 0.0510 | 0.0491 | 0.0294 | 0.0177 | 0.0353 |
|  | 69% | 19.62% | 0.0137 | 0.0510 | 0.0491 | 0.0294 | 0.0177 | 0.0353 |
|  | 61% | 19.62% | 0.0137 | 0.0510 | 0.0491 | 0.0294 | 0.0177 | 0.0353 |
|  | 47% | 19.62% | 0.0137 | 0.0510 | 0.0491 | 0.0294 | 0.0177 | 0.0353 |
|  | 34% | 19.49% | 0.0136 | 0.0507 | 0.0487 | 0.0292 | 0.0175 | 0.0351 |

TABLE 10 ESTIMATED WEIGHTING FACTOR FOR THE WIND SYSTEM

|  |  | Generation |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|
|  |  |  | 0 | 5 | 25 | 50 | 75 | 96.5 |
|  |  | Duration | 7% | 26% | 25% | 15% | 9 | 18% |
| System load | 91% | 2.02% | 0.1513 | 0.5515 | 0.5454 | 0.3545 | 0.2327 | 0.5272 |
|  | 79% | 19.62% | 1.2443 | 4.5982 | 4.4802 | 2.9094 | 1.9954 | 4.5911 |
|  | 69% | 19.62% | 1.0962 | 3.9942 | 3.9157 | 2.5790 | 1.8011 | 4.2026 |
|  | 61% | 19.62% | 0.9678 | 3.5775 | 3.5257 | 2.3526 | 1.6676 | 3.9554 |
|  | 47% | 19.62% | 0.8257 | 3.0607 | 3.0068 | 2.0336 | 1.4815 | 3.9201 |
|  | 34% | 19.49% | 0.6776 | 2.5139 | 2.4908 | 1.8047 | 1.3582 | 3.3728 |

TABLE 11 NORMALISED DEMAND LOSS FOR THE WIND SYSTEM

## CONCLUSION

This paper discussed important issues of interest to DSO, regulators, customers and investors. It was discussed that market liberalization and energy transition represent a new energy paradigm. One of the consequences of the new energy paradigm is that the process of distributed generation planning is conducted separately from the distribution network planning and development process. In order to create an optimum planning framework, it is necessary to adopt a holistic planning approach which is capable to determine the level of interaction between different system components. In this paper, it was demonstrated that optimal placement of DG can have beneficial effect on distribution network management. However, it cannot be achieved ad hoc, without appropriate planning methodology. In order to have positive effect on network energy losses, DG location and size need to be appropriately planned. In this process, few factors should be considered as crucial for determining the effect of DG on energy losses. The first one is that power demand of the feeder should be approximately equal to DG power output. Locations where DG production is larger than load demand are less likely to be beneficial in terms of loss reduction. The second criteria is that the daily DG power generation curve should coincide with power demand curve. This fact is dependent on technology and should be considered in the planning process. Finally, the influence of energy losses should be assessed and included in DG tariffs. This paper considers only energy losses while in reality, number of other challenges are encountered such as cost of investment, power quality, reliability indicators, infrastructure condition etc. which all have influence on system planning and DG placement. Future research needs to focus on identification of these factors and their investigation in terms of creation of new planning criteria. This approach would form a basis for creation of a comprehensive and easy to follow logical framework which would be used in the process of power distribution system planning and development. Calculations performed in this paper have demonstrated that estimation of DLF can prove to be cumbersome, work intensive and prone to error. Considering the fact that typical DSO owns large number of substation, it is obvious that system analysis and insight based on proposed DFL calculation methodology proves to be impractical. In particular, if DLF is to be used for network planning and DG siting purposes, it is necessary to develop a tool capable of automatically performing these calculations, for different system conditions and site locations. This is one of the suggestions for future work in this area.

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