TACTICAL CONGESTION MANAGEMENT:
THE OPTIMAL MIX OF DECENTRALISED GENERATORS IN A DISTRICT.

Nadine CROES
TNO – The Netherlands
nadine.croes@tno.nl

Frank PHILLIPSON
TNO[1] – The Netherlands
frank.phillipson@tno.nl

Max SCHREUDER
TNO – The Netherlands
max.schreuder@tno.nl

ABSTRACT

A first step in congestion management is making sure that the average production and consumption per time unit over time match as well as possible, we call this tactical congestion management. The main question in this paper is: what is an optimal mix of DGs such that electricity loss is minimized.

INTRODUCTION

Distributed power generation is becoming more attractive as it relies on renewable energy sources, such as solar panels. Also it achieves higher efficiencies in power generation. Distributed generation can increase efficiency of the grid by reducing the distance between generators and consumers of electricity. In addition, distributed generation could enhance security of energy supply and contribute to a diverse energy portfolio. Since governments are promoting the use of Decentralised Generators (DGs) by e.g. implementing a feed-in premium, it is expected that there will be a significant increase in share of DGs in the energy supply.

DGs using renewable energy sources exhibit high fluctuations in production over time, so electricity generated by DGs will probably not match load demand and can cause over- or underproduction of electricity. For this you will need intelligent congestion management systems. A first step in congestion management is making sure that the average production and consumption per time unit over time match, we call this tactical congestion management. The main question here is whether a tactical optimal mix of DGs exists, that minimizes the mismatch of production and consumption, measured by the total energy loss in a particular district. This article is based on the work described in the TNO[1] thesis of Nadine Croes [1].

APPROACH

We designed a mathematical optimization model of the electricity grid where the infrastructure, supply and demand, and their mutual effects are modelled. Using this model we can find the optimal mix of DGs in a district, that minimizes energy loss while making sure that all demand is satisfied. In addition, we avoid overload in cables and transformers. The DGs that we consider in this first step are micro Combined Heat and Power (micro-CHP) systems and Photo Voltaic (PV) solar cells. Later other types of DGs, such as windmills, can be added. The model focusses on a district consisting of only houses. In this district all houses can generate (a part of) their own power using decentralized power generation. Any overproduction is supplied back to the grid. We include an optional storage system in the model to help capture overproduction and if possible reduce energy loss. In addition, we model extra demand from heat pumps (that rely on electricity) and electric vehicles.

RELATED WORK

There are two papers that are related to ours. [2] minimized energy loss for optimal sizing and placement of distributed generation using a genetic algorithm. This paper discusses a simulation approach for the optimal sizing and placement of a DG for a minimum annual energy loss with time varying load model. It is made sure that the voltage levels are within the acceptable range and that the line flows are within limits. That paper focuses on the quality aspects of electricity, so voltage levels and reactive power are also considered. This means that the model in [2] is too complex for our purpose.

[3] presents a multi period optimization model for a micro grid, aimed at maximizing its benefit, i.e. revenues-costs. The optimization model includes the use of DGs relying on wind and solar, an electrochemical storage and interruptible load. DGs are incorporated into the low voltage grid where both technical and economic aspects are considered. The obtained problem is a Mixed Integer Non-Linear Programming (MINLP) problem and is solved using a genetic algorithm. Even though this model minimizes cost, we obtain a model with similar structure due to the fact that it also tries to find an optimal mix of DGs. This similarity is especially present in the constraints of the storage system and DGs. In [3] the authors have gone one step further and allow the DGs and storage system to be controllable. This creates a system resembling the smart grid.

The search for the optimal penetration level[2] of DGs is graphically depicted in Figure 1, based on [4]. The idea is that because the distance between feeder and load is reduced, the transportation losses decrease. But as Figure 1 shows, this only applies to a certain DG penetration level. Once the optimal penetration level of DGs is reached the losses increase again. Higher DG penetration levels lead to situations where local production exceeds local consumption. This overproduction has to be converted into higher voltage levels and transported further away. Converting electricity from one voltage level to another creates loss and transporting electricity also creates loss, which thus means that overproduction will ultimately create more loss. So if too many houses start generating electricity, the increase in penetration levels of DGs becomes more of a disadvantage than an advantage.

---

[1] TNO (Netherlands Organization for Applied Scientific Research), P.O. Box 5050, 2600 GB DELFT, The Netherlands/

[2] Penetration level = ratio of capacity factor times total DG power installed and the peak power demanded on the feeder.

This graph gives a good illustration of what we are looking for.

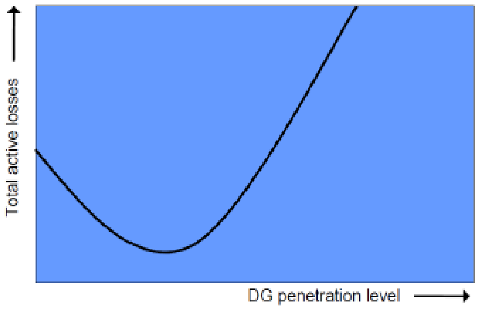

Figure 1: Relation losses and penetration level.

The study concludes that for low DG penetration levels energy loss decreases, but that for higher penetration levels energy loss starts to increase and can ultimately become higher than the losses in the base case. In addition, minimum losses are reached with high penetration levels if DG is sufficiently dispersed. Reactive power is also considered in the study and it turned out that controlling reactive power supplied by DGs have a big impact on distribution losses.

ASSUMPTIONS

Since we focus on one district connected to a Middle/Low Voltage (MV/LV) transformer, we do not model power plants, neither other districts' production and demand. We assume that power plants always supply the remaining demand of electricity.

There is limited data on the size of network losses freely available. The total network losses are estimated in [5] at 7 to 8% of the power consumed for the entire chain, i.e. from power plants to consumers. To find out whether incorporating DGs in the district decreases energy loss, we need to make some assumptions on the power losses in High-, Middle-, and Low-Voltage grids.

The loss of exporting electricity to outside the district, in case of overproduction in the district, is calculated by adding the losses in the LV-grid, losses in the MV/LV-transformer, losses in the MV-distribution grid, losses in the other MV/LV-transformer, and losses in the other LV-grid, which is estimated at around 6.9%. The average loss percentage for transporting within the district is estimated at around 1.1%. These percentages are averages and exclude the effect of temperature changes and different conductor materials[3].

For the calculation of energy loss from using the storage system we model a (not yet existing) storage system with a low self-discharge rate and a high efficiency in the center of the district. This futuristic storage system will be referred as StorageX, and we choose a self-discharge rate of 2% per month and an efficiency of 95%.

To make sure that the cables are not overloaded we include capacity constraints for each phase. This means that for each group of houses (connected to a phase) the amount of power transported is not allowed to be higher than some capacity. For the transformer we make sure that the amount imported to and exported from the district is not higher than the transformer's capacity.

Future electronic equipment such as electric vehicles are expected to be widely used in the near future. These electric devices will create the need for larger grid capacity and have quite a volatile electricity demand. This can cause problems on the electricity grid.

DATA

The DGs that we consider are micro-CHP systems and PV solar panels. The amount of electricity that each of these DGs will generate is unknown, but one can make some assumptions and use the characteristics of these DGs to make average profiles. Micro-CHP systems depend on heat consumption, PV solar panels on sunlight. The production of electricity by micro-CHP systems and PV solar panels is variable but still quite predictable. Monte Carlo simulations have been performed on the DGs' production profiles to create varying input profiles.

We obtained an average demand profile, which is the base demand, and it is given as a percentage of the total average year demand for every 15 minutes. This base demand profile is used to model the demand for all houses. To create different variants of demand for each house we performed Monte Carlo simulations on the base demand for each season.

The focus is on a group of houses in a district. But as there is no one district that represents all districts and one house that represents all houses, we need to make some assumptions on the district composition and the different types of houses. Our definition of a district is a group of houses connected to an MV/LV transformer. We assume that there are 250 houses in the district. Five types of houses are considered: detached, semi-detached, terraced, apartment and maisonette. The average demands and shares of houses are reported in Table 1 where the average demand is the average year demand typical for the house type and the share of houses is the overall share of each house type in the Netherlands.

	Demand	Share
Detached	5000	14.8
Semi-Detached	4000	12.4
Terraced	3500	42.6
Apartment	3000	25.5
Maisonette	3500	4.7

Table 1: Average Demand and Share for Each House Type

Using these data we can construct a district that represents the average composition of houses in the Netherlands.

THE OPTIMIZATION MODEL

The optimization model is a Mixed Integer Quadratic Programming (MIQP) problem, due to some binary variables and quadratic objective function due to the loss formula. MIQP problems are in general hard to solve. We

---

[3] For more details see [1]

used two methods to simplify the problem: we reduced the problem size and relaxed the binary variables so we now have a QP problem. This problem is well solved by AIMMS and the CONOPT solver. For more details about the mathematical model see [1].

FIRST EXERCISE

To get some feeling for the calculation of loss and energy flow of our model we tested it with four scenarios: the No DGs scenario, the quarter mix scenario (a quarter of the houses have both micro-CHPs and PV solar panels), the half mix scenario (half of the houses have both micro-CHPs and PV solar panels) and the maxed out scenario (all houses have both micro-CHPs and PV solar panels). In each scenario we calculate the production and the amount consumed for each house from the main grid. Then we calculated the total import, export and the amount transported within the district. From this we calculate losses for every time period.

In Figure 2 we plot the total energy loss for each scenario. This is the same graph as we saw earlier by [4] but now using the results from our simulation model. With the optimization model we want to find the lowest point in the graph by vitiating both percentages of the DGs.

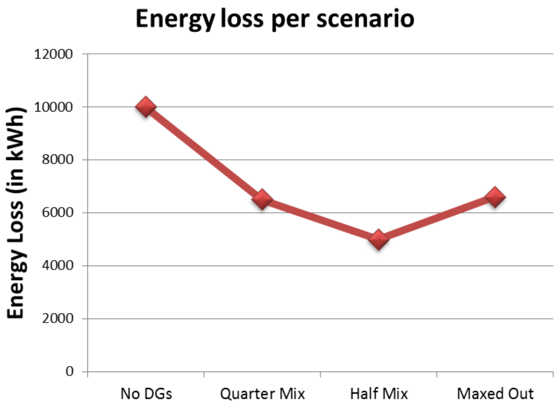

Figure 2: Loss in scenarios

RESULTS

In this section we discuss the main results obtained from the optimization model. The model was solved with and without the possibility to export, with and without a storage system, and for different amounts of electric vehicles and heat pumps, and gives us a huge amount of results.

From all these results, we need to extract recommendations on the mix of DGs that should be implemented in a district. To this end we distinguish four scenarios in time: 1) the current period , being the current grid without (many) DGs; 2) a transition period, where DGs generate electricity; 3) transition period 2, also in the future, where DGs generate and more usable storage systems exist, and; 4) a future period, with an efficient storage system and extra demand from electric vehicles and heat pumps. In all scenarios we assume export to other districts is not possible. Overproduction is assumed to be lost.

The characteristics of these scenarios with the optimal mix of DGs are reported in Table 2. Notice that over time more DGs are needed in the district until it leads to all houses having both types of DGs. This follows from the high demand of electricity when using electric vehicles and heat pumps and storage systems with increasing efficiencies.

	Current Period	Transition Period 1	Transition Period 2	Future Period
DGs	-	+	+	+
Storage	-	-	+	+
HPs & EVs	-	-	-	+
Micro-CHP	Low	23%	94%	100%
PV	Low	54%	100%	100%

Table 2: Characteristics of the Periods With Optimal Mix

The storage we assume here is the future high efficient storage system, storageX. With the current known storage systems the percentage of micro-CHP varies from 38% (in low efficient storage systems like flywheel) to 80% (in highly efficient storage systems like NaS). The percentage of PV will vary between 75% and 100%.

The introduction of (the optimal mix of) DGs and the storage possibility reduces the average loss per household. Following from our model energy losses are reduced from 13.4 kWh per household in the current situation to 7.8 kWh by introducing the optimal mix of DGs and to 5.7 kWh by the addition of an efficient storage system in combination with the optimal mix of DGs in that situation. This is depicted in Figure 3.

Because we use average data and an average composition of districts, one should not simply implement our optimal mix of DGs and expect that it is the best one in all situations. All districts have different compositions and different demand patterns.

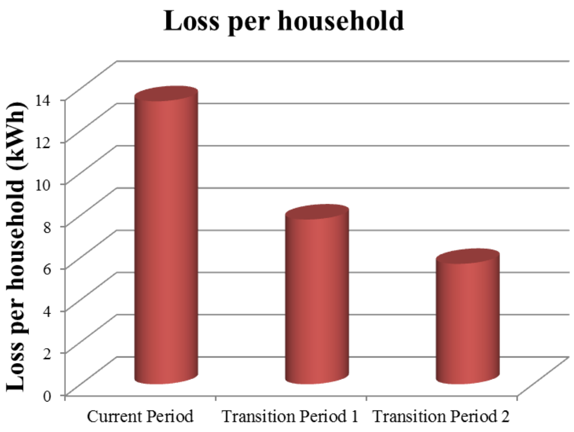

Figure 3: Saving due to efficient mix and storage system.

All optimal mixes in the scenarios without heat pumps and electric vehicles are feasible solutions: the cable capacity constraints are not violated. In the case of heat pumps and electric vehicles most solutions are not feasible. So in the district with current cable and transformer capacities it is not possible for houses to have electric vehicles. Also, only one house on each phase is allowed to have a heat pump. This is very unfortunate, but these future electric devices have too high demands and will overload transformers and cables. Hence, if one wants to include electric vehicles and heat pumps in a district, the cables and transformers must be reinforced to be able to handle such a large increase demand or more sophisticated real time matching algorithms should be used to shift supply and demand in time.

IMPLEMENTATION

This section has a less formal approach with the aim to provide ideas and suggestions on how an optimal mix of DGs can be implemented. Viable implementation of DGs in an optimal mix is heavily dependent on the situation at hand; new districts or existing districts. In the first case, one can use our solutions to predict the optimal mix of DGs in that district. Actual implementation requires balancing the interests of a multitude of stakeholders; DSOs, households, house owners, contractors, local government etc.. The interests of these stakeholders must be aligned and subsequently costs for installation could then be shared by stakeholders, based on their particular interests. For instances, for the DSO this could be less cost upgrades in infrastructure, for households this could be lower energy prices and for local government reduction of greenhouse emissions could be of great importance. Implementing our solutions in existing districts will be also be challenging. Again, key will be to balance stakeholders interests. For instance most households do not want to take the risk to invest in new technologies unless there is some financial assistance from the government, like subsidies. Besides being offered financial stimuli, consumers also need to change their mind set, e.g. a district would need the collaboration of all homeowners to be able to create the optimal share of DGs allowed in the district. Such a collaboration between many homeowners will be difficult. In the Netherlands, however there are cases where groups of people collaborate to invest in DGs, such as solar panels and wind turbines, even without the support from the government. However it must be noted that such initiatives, subsidised or not, tend to lead to sub-optimal solutions on a larger scale; the interest of the household will be satisfied by reducing its electricity bill, but DSO will need to strengthen the grid to cope with DGs feeding back into the grid, and possibly deal with increased line loss as well. Ultimately, at least in the Dutch situation, these costs will be fed back to consumers through the tariff structure.

CONCLUSION

The main question that we had to answer is: What is an optimal mix of DGs such that energy loss is minimized? Depending on the various assumptions, such as whether it is allowed to transport overproduction to other districts or use the storage system, and if there is additional demand from electric vehicles and heat pumps, we obtained different results. This means that we have obtained several solutions in the case study each under these different assumptions. However, the results indicate that implementing an optimal mix of DGs in the district can reduce energy loss substantially.

Using the optimal solutions with different input configurations we found that in all cases there is a big improvement compared to the grid without DGs. So our solutions can be used as a guideline for incorporating DGs in a district. These results also show that instead of arbitrarily deploying DGs in the district, it is essential to balance interests of all stakeholders, thereby creating sustainable solutions, so that large reductions in energy loss can be achieved.

REFERENCES

[1] N. Croes, 2011, *Impact of Distributed Generation on Energy Loss: Finding the optimal mix*, TNO, Delft, The Netherlands.
[2] D. Singh, D. Singh et K. Verma, 2008, “GA based Optimal Sizing & Placement of Distributed Generation for Loss Minimization”, *Journal of Knowledge-Based and Intelligent Engineering Systems*, vol.12, 147-156.
[3] E. Mashhour et S. Moghaddas-Tafreshi, 2009, “Integration of distributed energy resources into low voltage grid: A market-based multiperiod optimization model”, *Electric Power Systems Research*, vol.80-14, 473-480.
[4] A. Wals et M. Scheepers, 2003, *New approach in electricity network regulation. An issue on Effective Integration of Distributed Generation in Electricity Supply Systems*, Energy Research Centre of the Netherlands (ECN), Petten, The Netherlands.
[5] EnergieNed, 1996, *Electricity Distribtion Grids*, Kluwer Techniek Elektro/Elektronicas.