

**RIGA TECHNICAL UNIVERSITY**  
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**PLANNING OF DISTRIBUTED  
GENERATION IN MEDIUM VOLTAGE  
ELECTRIC POWER SYSTEMS**

**Summary of the Doctoral Thesis**

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# **DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES**

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 9 November, 2017 at the Faculty of Electrical Engineering of Riga Technical University, 12/1 Azenes Street, Room 306.

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## **DECLARATION OF ACADEMIC INTEGRITY**

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Engineering Sciences is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Oleg Kochukov ..... (Signature)

Date: .....

The Doctoral Thesis is written in English. The total number of pages is 155 including appendixes. The Thesis contains 23 tables and 73 figures. The bibliography contains 75 titles.

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# 1. GENERAL DESCRIPTION OF THE WORK

## Topicality of the Subject

In the past, power systems were dominated by conventional, load-following generation that injected large amounts of power into an extra high voltage transmission network, built in the middle of the last century. Transmission carries out bulk energy transport from these large generators to load centres from where electricity is delivered to end consumers at a number of voltage levels via passive distribution networks. The present and future power systems based on high penetration of renewable and low carbon distributed generation (DG) are quite different.

Today, a large number of generators are connected and much more planned to be connected at every level of the distribution network, and integration of these new resources into all aspects of the power system will be the key to ensuring the evolution of an economically efficient and effective system based on sustainable generation sources.

However, the existing system has been optimised to meet the requirements of conventional generation and many of these arrangements do not provide a level playing field for the introduction of DG or realisation of its full value, potentially acting as a barrier to the development of effective decentralised system. It is clear that facilitating the integration of DG into the existing system will require a re-development of the regulatory, technical and commercial arrangements that underpin the current system.

Since transfer from the passive load system to autonomy or even energy surplus systems is a great change for distribution systems, a new method for design and planning is of high importance. The design and planning of the distribution system historically was based only on load assessment and forecasts; this approach now has to be superseded by a complex approach considering both load and generation elements of the network.

As DG mostly use renewable or low carbon energy resources to produce electricity, DG integration will make a large contribution to meeting the targets set for introduction of renewable and low carbon generation. This is appreciated in most European countries and relevant support mechanisms are created.

Despite the opinion that DG is an expensive source of energy, there are potential economic benefits in addition to ecological ones. The increase in value of electricity up to the point of consumption is driven primarily by the added cost of network transportation and distribution services required to deliver power from centralised generators to the customers elsewhere in

the network. DG is located closer to the consumer and has fewer requirements for the transport services afforded by the transmission and distribution networks.

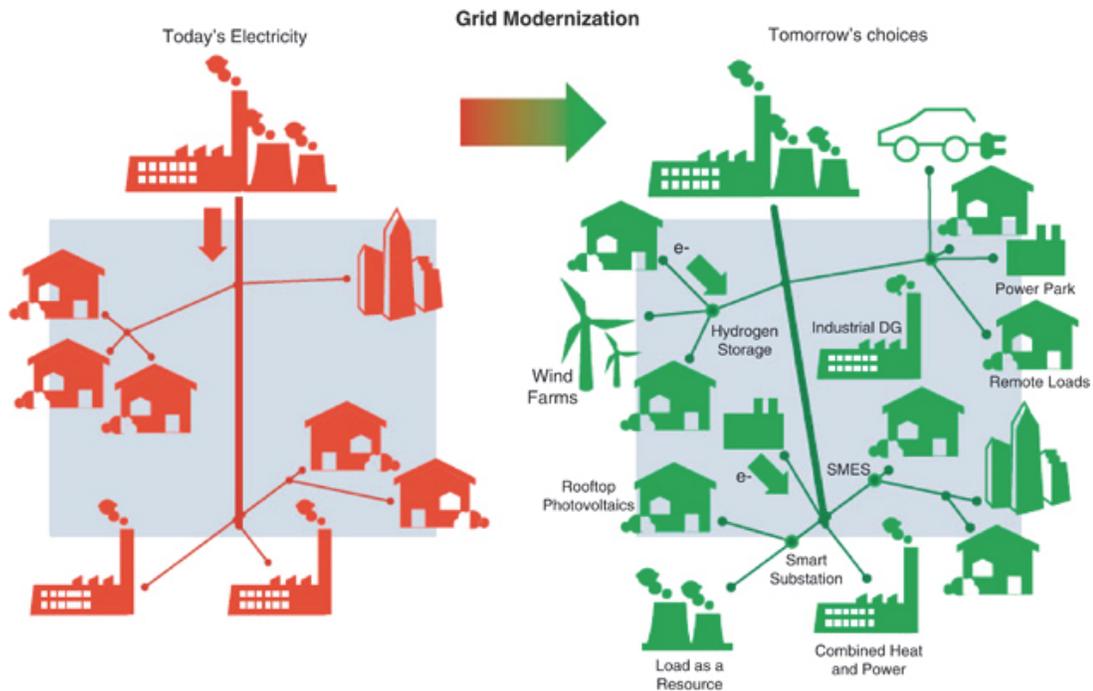


Fig. 1.1. Past and future distribution systems [1].

These benefits generated by the favourable location of DG and ecological benefits are recognised by most European governments and resulted in support mechanisms – special tariffs for renewable generation, which gave a huge boost to DG development. However, the question if the distribution network is ready for these changes was never clearly answered, assuming that there is enough capacity for years ahead.

The current situation has proved that it is not the case – the amount of “free” capacity in the network is rapidly decreasing and government targets are at risk, since it is not economically viable for the developers to reinforce the network at their own cost. This thesis is extremely topical today as it aims to investigate this problem and offers solutions.

**Eric Gunther, CTO Enerex: “The deployment of DER on power grids around the nation is happening much faster than most experts expected just a few years ago, and the tools needed adjust for the changes in many cases do not yet exist” [2].**

## **Hypothesis and Objectives of the Thesis**

The main hypothesis of this work is that the presence of distributed generation in the distribution network is growing and will continue to grow. However, there is a number of problems, which are described in the previous chapter, including the absence of an appropriate planning tool. Author believes that the most efficient way to overcome these problems is to create a methodology for distributed generation and distribution network planning. This is the main goal of the thesis.

In science and practice, depending on the field of study, there are different ways of proving a hypothesis. There are three main ways: deductive reasoning of the hypothesis assumptions, logical proof of the hypothesis, direct detection of hypothesis assumptions. The latter is used in this thesis.

The proposed methodology includes:

- innovative models of the most used DG types;
- a complex load model;
- a unique inverter short circuit model;
- electric vehicle grid integration model;
- operation principle of the overall model.

Important goal of the research is to find the factors that will influence operation of future DG and distribution network, to understand this influence and develop approaches of integration of these factors in methodology.

## **Methods and Tools of the Research**

The methods and tools of the research include (but are not limited to):

- survey of real developers of new distributed generation;
- selection of SCADA data based on set criteria;
- inverse transform sampling technique for wind speed probability data calculation;
- logarithmic and linear trendline techniques for wind turbine power curve matching;
- integral equation solver in Mathcad software for building solar irradiance curve in solar farm model;
- processing and graphical representation of the results with MS-Excel and Mathcad software;
- AutoCad drafting software for schematic drawings.

### **Scientific Novelty of the Thesis**

1. Development rate, development tendencies, operation principles and earning mechanisms of DG in Europe have been studied and the scale of the problem has been identified in line with the need for a new assessment tool.
2. A large unique survey has been undertaken between real developers of new and existing DG in the United Kingdom to understand the background of real DG behaviour.
3. Innovative models of most popular DG and load have been developed, specifically adjusted for planning purposes.
4. All practical, mathematical and theoretical aspects of the research resulted in a complete and detailed network-orientated DG planning methodology.

### **Practical Importance of the Thesis**

The developed methodology can be used for DG planning tasks in European medium voltage distribution power systems. Taking into account multiple advantages and uniqueness of the methodology, it will be of interest to government authorities, regulators, utilities, DNOs, TSOs and consultancy companies. The methodology allows checking of DG and renewable energy targets against the capability of existing medium voltage distribution networks. This will give the possibility to justify and change the targets if necessary, as well as highlight particular network problems and reinforcement associated costs.

### **Scope of the Thesis**

Scope of the thesis is structured so as to prove the defined hypothesis in a logical and clear manner. The author analyses the development vector of European distribution systems and highlights the challenges. The thesis describes the factors that are driving DG presence in the network, how these factors influence the behaviour of DG as well as their effect on the distribution system. The existing approaches to DG planning are analysed in detail to understand the advantages and to find flaws.

It was desired to provide a detailed description of the proposed methodology, including mathematical models, practical considerations and overall algorithm specifically aimed for accurate, detailed and valuable results. The thesis describes the effect of DG on transmission system, but does not fully cover this subject. A test case is presented to finalize the research and to prove the efficiency of the methodology.

### **Approbation of the Doctoral Thesis**

The results of the study have been reported and discussed at the following conferences.

1. O. Kochukov, A. Mutule. Model for Evaluation of Large-Scale Power System Interconnection Costs and Benefits. International conference of young scientists on energy issues 2011 (CYSENI 2011). 26–27 May, 2011. Kaunas, Lithuania, INSPEC database.
2. O. Kochukov, A. Mutule, Z. Krishans. Model for Technical-Economic Analysis of ENTSO-E and IPS/UPS Power System Optimal Interconnection Concepts. RTU 52nd International Scientific Conference. 13–14 October, 2011. Riga, Latvia.
3. O. Kochukov, A. Mutule. Influence of energy market implementation in Europe on long-term development of the power system. Electric power engineering 2012 (EPE 2012). 23–25 May, 2012, Brno, Czech Republic, Web of Science database.
4. O. Kochukov, A. Mutule. Modeling of large electrical power system development under energy market conditions. International conference of young scientists on energy issues 2012 (CYSENI 2012). 24–25 May, 2012. Kaunas, Lithuania, INSPEC database.
5. O. Kochukov, A. Mutule, Z. Krishans. Application of Risk Assessment Method for Power System Interconnection Cost and Benefit Evaluation. The International Conference on Probabilistic Methods Applied to Power Systems 2012 (PMAPS 2012). 10–14 June, 2012. Istanbul, Turkey, IEEE Explorer database.
6. O. Kochukov, A. Mutule. Tasks of transmission planning in competitive energy market. International conference of young scientists on energy issues 2013 (CYSENI 2013). 29–30 May, 2013. Kaunas, Lithuania, INSPEC database.
7. O. Kochukov, A. Mutule. Approach to modeling of wind power plants in long-term planning tasks. RTU 54th International Scientific Conference. 10–11 October, 2013. Riga, Latvia.
8. O. Kochukov, A. Mutule. Load modelling in electrical power system long-term planning tasks. Elektroenergetika 2015. 16–18 September, 2015. Stará Lesná, Slovakia. Web of Science database.

Publications in internationally quotable scientific collections of articles.

1. K. Görner, C. Rehtanz, N.Kolosok, E. Korkina, A. Glazunova, N.I. Voropai, A. Mutule, K. Brinkis, O. Kochukov. Coordinated monitoring of large scale interconnected power systems. IEEE PES General meeting 2013. 21–25 July, 2013. Vancouver, Canada, IEEE database.

2. A. Mutule, K. Briņķis, O. Kochukov. Testing of prototype for large-scale power system state estimation algorithms. Latvian journal of physics and technical sciences, 2013, No. 4. Scopus database.
3. O. Kochukov, A. Mutule. Unified model of multiple wind turbines. Latvian journal of physics and technical sciences, 2014, No. 4. Scopus database.
4. O. Kochukov, A. Mutule. Network oriented distributed generation planning. Latvian journal of physics and technical sciences, 2017, No. 2. Scopus database.

## **2. ANALYSIS OF EUROPEAN DISTRIBUTION NETWORK DEVELOPMENT TENDENCIES**

### **2.1. Regulations**

The EU's Renewable energy directive sets a binding target of 20 % final energy consumption from renewable sources by 2020. To achieve this, EU countries have committed to reaching their own national renewables targets ranging from 10 % in Malta to 49 % in Sweden. They are also each required to have at least 10 % of their transport fuels come from renewable sources by 2020 [2].

Furthermore, in order to decarbonise power sector, The Climate Change Act 2008 established a legally binding target to reduce the UK's greenhouse gas emissions by at least 80 % below 1990 year levels (to 100 g/kWh) by 2050 [3].

### **2.2. Development Tendencies of Distributed Generation**

Due to the initiatives mentioned in the previous chapter (but not limited to), there was a huge boost of Distributed Generation (DG) in Europe. The countries with the most installed DG, including renewable energy sources, are Germany, Spain, Denmark and the United Kingdom. Statistics shows that there already is 145 GW of wind farm capacity and 86 GW solar farm capacity alone installed in the EU in 2015 [4].

UK is one of the fast growing countries in terms of DG. Fig. 2.1 shows medium voltage connected DG plants of more than 1 MW in part of the United Kingdom. It proves that DG is an essential part of generation mix today.

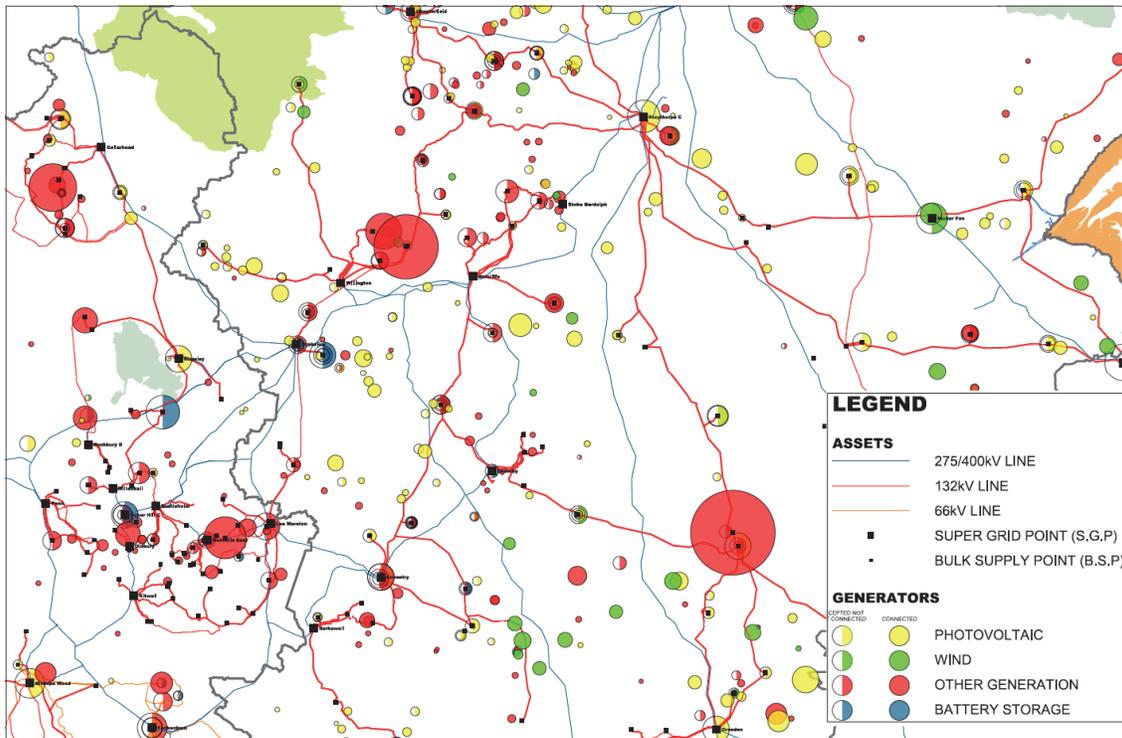


Fig. 2.1. Distributed Generation >1 MW in part of the United Kingdom (area of approx. 9000 km<sup>2</sup>) [5].

### 2.3. Active Network Management (ANM)

In electricity distribution networks, Active Network Management (ANM) describes control systems that manage generation and load for specific purposes. This is usually done to keep system parameters (voltage, power, phase balance, reactive power and frequency) within predetermined limits.

Previously, generation plant connection to a distribution network was only possible if at no network conditions there are overloads, unacceptable voltage rise or other network issues. With the development of electronics, programmable logic controllers (PLCs) and SCADA systems it became possible to control generation plants instantaneously in real time. Constrained (controllable) connections become extremely popular and will be even more popular in future. This is explained by a number of benefits, the main being lower cost of connection. In certain situations, a generation plant becomes unacceptable on the network only under certain very rare conditions, e.g. during very low demand hours. By installing an ANM system, DNO is able to restrict the output capacity of DG even if it is required for a few hours per year.

## **2.4. Real Statistics**

Statistics presented in this thesis covers a distribution network with geographical area of over 55 500 km<sup>2</sup> and 7.7 million customers (in the United Kingdom) [6]. It is extremely important to analyze the statistics, as it not only gives indication of what has already happened, but also allows predicting future tendencies.

The presented statistics shows the number of DG on the network in 2016. It shows “accepted” connections – schemes that have been offered by the DNO and accepted by developers. These sites will most likely be constructed and energized in the next 1–3 years. It also shows “offered” connections – schemes that have been offered by DNO, but not yet accepted by developers. These sites might be constructed and energized in nearest 1–3 years, if accepted.

The statistics shows huge amount of solar farms connected to the network and the tendency is the same for accepted and offered schemes. There is no connected battery storage, however, almost 1 GW is accepted or offered.

## **2.5. Distributed Generation Earning Mechanisms**

To understand why DG is present on the network and what is DG behaviour, it is important to review the main DG earning mechanisms [7], [8]:

- government support;
- energy sales to a supplier;
- frequency services for TSO;
- private contracts;
- reactive power services;
- capacity market (with or without government support).

There are many government support schemes for DG, especially for renewable energy sources, e.g. Renewables Obligation (RO), Renewable Heat Incentive (RHI) and Feed in Tariff (FIT). The most popular support scheme among the developers is FIT and the new Contract for Difference (CFD) scheme.

Though DG can theoretically participate in capacity market, normally it is not profitable. Therefore, there was a special government incentive to support DG participation in capacity market – Contracts for Difference. A Contract for Difference (CFD) is a new scheme for low carbon energy sources. It is a private law contract between a low carbon electricity generator and the Low Carbon Contracts Company (LCCC), a government-owned company. A generator party to a CFD is paid the difference between the “strike price” – a price for electricity reflecting the cost of investing in a particular low carbon technology – and the “reference price” – a measure of the average market price for electricity in the market. It gives greater certainty and stability of revenues to electricity generators by reducing their exposure to volatile wholesale prices, whilst protecting consumers from paying for higher support costs when electricity prices are high [9].

A feed-in tariff (FIT) is a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each technology. Rather than pay an equal amount for energy, however generated, technologies such as wind power, for instance, are awarded a lower per-kWh price, while technologies such as solar PV and tidal power are offered a higher price, reflecting costs that are higher at the moment [10]. Suitable distributed generation technologies are solar, wind, biomass, hydro, gas.

## **2.6. Survey of DG Developers**

In order to understand the behaviour of DG on the network, it is essential to know what income schemes are most popular for existing and for future DG. A big survey was carried out as a part of the thesis research work. The information was obtained by the author in communication with DG developers. This is a unique survey, which gives a view from a different angle to DG future, investigating if government support is enough to make DG projects economically viable and what particular support mechanisms are most interesting to real developers. The outline of the survey is shown in Table 2.1.

Table 2.1

## Outline of the Survey

|   |   |
|---|---|
| 3. Goal of the survey                           | Obtain information on most popular earning schemes of existing and planned DG |
| 4. Object of the survey                         | Developers and owners of DG   |
| 5. Number of existing generation sites surveyed | 22  |
| 6. Number of planned generation site surveyed   | 29  |
| 7. Capacity of generation site                  | 5 MW to 40 MW   |
| 8. Methodical basis                             | The developers were contacted by email and phone                              |

The survey has shown that most of the existing DG benefit from FIT, which means they can generate at any time and their income is not dependent on time or length of generation. Therefore, it is assumed that DG can generate at full capacity at any time. The exception is solar farms, which have natural limitations of solar irradiance.

A new technology that developers are looking to take advantage of is Battery Storage. Most of the developers are planning to participate in enhanced frequency response services, and one developer was planning to add Battery Storage system to the existing solar farm to be able to utilize an excess of energy for charging batteries and then generate when the solar farm output decreased.

This survey gives us a clear indication of the most popular DG earning mechanisms and potential behaviour of DG in future. The number of tariff supportive schemes proposed by government shows that most DG still are not economically efficient enough to compete with traditional energy sources.

### 2.7. Impact of Distributed Generation on Transmission Network

Even though analysis of the effect of DG on transmission network is not the goal of this thesis, it cannot be ignored due to its significance. This chapter gives a brief summary of this effect and describes several possible future scenarios.

Fig. 2.2 shows the comparison of a real typical demand daily profile at 250 MVA 275/132 kV substation [11] and simulated profile with significant presence of DG.

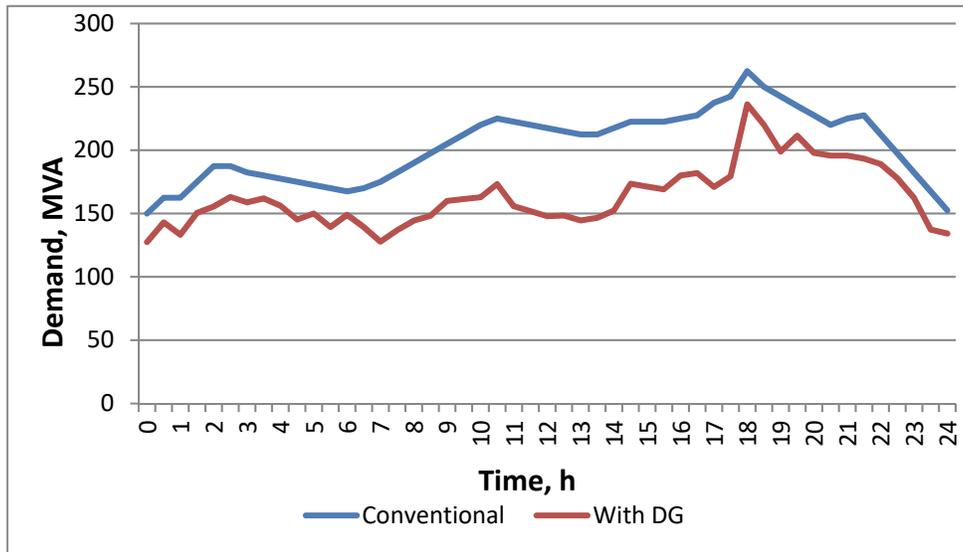


Fig. 2.2. Daily demand profiles at TSO and DNO connection point during peak demand – with and without significant DG.

In this case, the effect of “load masking” is observed. Gas, wind, biomass and similar DG are picking up relatively constant amount of the load throughout the day, but significant amount of solar farms cause noticeable demand dip of around 1 pm, when they generate the most. In the extreme case, at minimal load conditions this could even cause a reverse power flow from distribution to transmission network. The effect of “load masking” and reverse power flow will influence big power station operating regimes and power system interconnection power flow profiles. In [12], [13], [14] and [15] the author describes his research investigating what parameters are affected by interconnections and how to study changes caused by it.

### 3. ANALYSIS OF HISTORICAL AND EXISTING APPROACHES TO DISTRIBUTION SYSTEM PLANNING

#### 3.1. Existing Software of Power System Analysis

The model presented in this thesis is proposed for the use in existing or new power system analysis software, offering some new features, e.g. new models and complex approach to DG planning. There is plenty of power system analysis software available on the market, incorporating standard and unique features, but none of them is capable of complete DG

planning due to the complexity of the task. There are some models available, which partly assist the planning process, like the one described in [16] and [17], but there is a general lack of complex approach.

Using the existing tools, an engineer would be able to build a power system model and study a single steady state or transient up to several seconds. However, these tools lack or have very limited capabilities for planning, which would involve an option to automatically study multiple steady states and build time dependent models (a power station output during the year, not only for a single steady state). Therefore, the existing modelling tools are only partly used by engineers for planning purposes. The next chapter explains the existing approach to DG planning in modern medium voltage distribution systems.

### 3.2. Existing Approaches to DG Planning

**Economic approach.** The economic approach aims to study an economic effect of DG penetration. At the moment DG is not profitable enough without subsidies, therefore this approach is more suitable for developers, as there is no direct monetary profit for government from DG. This approach allows studying costs and benefits of installing a particular DG in a particular location. Selection of location of DG is not the aim of this approach, therefore distribution network parameters, like voltage and thermal loading are not considered. Generally, they cannot be used for long-term planning with many uncertainties. This approach is described in detail in [18].

**Scientific approach.** Most of the proposed scientific approaches are based on the selection of site location and DG size by optimization of single or multi-objective function under certain operating constraints. Usually, the objectives are minimization of line losses, maximization of DG capacity, social welfare and profit maximization, multi-objective. The main problem of this approach is that it does not take into account practical aspects of DG business and difference between the DNO and developer roles. This approach would be suitable if a DNO developed its own DG, but because it is not usually the case, this approach has low value for practical use.

**Practical approach.** The existing approach applied to DG planning by existing DNOs is not based on any optimization or long-term planning method. The description below is not based on information sources, but on author's experience.

Developers seek for best locations of DG, usually based on the availability of cheap land and/or landowners' willingness to develop DG on their land. Developers then apply to DNO

for a connection offer that would define how expensive it is to connect the proposed DG to the network. Connection costs are based on location, size of the plant, type of the plant, connection voltage, required network reinforcement works etc.

To define the required network reinforcement to connect the proposed DG, usually the following studies are carried out: load flow, voltage rise, voltage step change, fault level. If there is a constraint in the network that does not allow connecting DG without reinforcement, the developer has to pay for the reinforcement works or cancel the project.

In fact, there is no planning as such, since there is not enough incentive for DNOs to reinforce their network and there is no government support for such reinforcement (unlike reinforcement for load, which is usually subsidised by government). This approach does not allow forecasting of network behaviour in future and is very limited in terms of predicting available capacity and other essential network parameters in future.

## **4. PROPOSED APPROACH TO DISTRIBUTED GENERATION PLANNING**

### **4.1. Introduction and Philosophy of the Approach**

DG planning is a specific task, which requires special models of power stations and load. The downsides of existing commonly used models/tools are described in the previous chapter. For the purpose of DG planning, it is important to create an output curve which would accurately describe future behaviour of a power station and at the same time would not be too detailed in order to decrease computation time and simplify the design by reducing the number of input parameters.

The models presented in this chapter are unique and not based on any information sources, which would provide a complete solution. The models are based on the results of author's research and practical experience and are specifically developed for power system/DG planning purposes.

Input parameters to the models were selected in such a way that an engineer performing the calculation would be able to easily find the required parameters and let the model do the rest, e.g. the solar farm model only requires annual solar irradiance of the region which is studied. This approach significantly simplifies the user-machine interface (UMI) and total time of a study. The proposed models are complex – output changes during the day, at different days of the week, at different seasons and different years. This complication is implemented to reduce error and produce as accurate final results as reasonably possible.

This thesis is not just describing methods of modelling, it is thoroughly analysing practical questions, such as: what data usually is available to a planner; how this data can be efficiently used for calculations and what components are essential to include in the annual load profile of the models.

The models presented in this section include DG and load – steady state and short circuit, where necessary.

## 4.2. Proposed Models for DG Planning

### Solar Farm Model

Solar farm output has a predictable output pattern depending on solar irradiance. Because of the changing weather conditions, output curve can have peaks and dips and it is quite hard to describe the resulting curve mathematically. However, changing weather conditions can be averaged with a reasonable high accuracy of final results. In this case the output curve can be described with a parabola. Fig. 0.1 shows an example of real solar farm output curve in comparison to the modelled.

The power output curve is linearly dependent on solar irradiance curve, which has the same shape, so it is proposed to build the irradiance daily curve first. To build the curve it is proposed to identify 3 points: peak irradiance, first intersection with zero (sunrise), second intersection with zero (sunset).

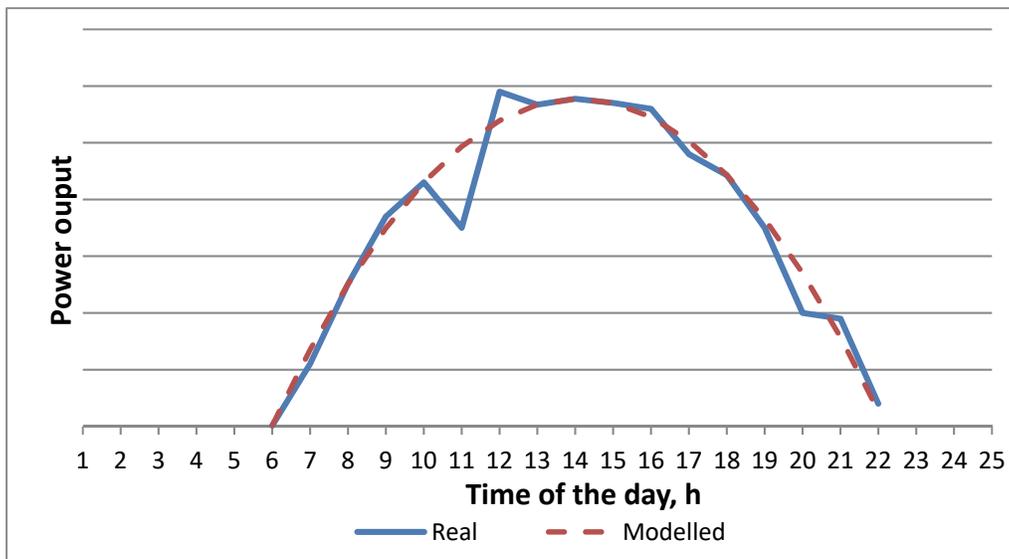


Fig. 0.1. Example of real and modelled solar farm power output.

The peak value depends on irradiance at a particular point. In most cases the data is available in the format of kWh/m<sup>2</sup> per year.

Obviously, solar irradiance is not distributed evenly throughout the year. The distribution is unique for each region, but known and easily available. For modelling purposes it is assumed that averaged distribution for Europe is the following: winter 8.1 %, spring 33.1 %, summer 42.4 %, autumn 16.3 %.

To translate averaged solar irradiance for a particular day (kWh/m<sup>2</sup> per day) to W/m<sup>2</sup> daily curve, it is necessary to solve the equation

$$\int_{x_2}^{x_3} f(x)dx = E_S, \quad (0.1)$$

where  $x_2$  is the time of sunrise,  $x_3$  is the time of sunset,  $f(x)$  is daily solar irradiance and  $E_S$  is averaged solar irradiance for a particular day of season S, kWh/m<sup>2</sup> per day.

As it was described before, daily power output and daily solar irradiance are assumed to be parabolas and can be described with a standard equation

$$f(x) = ax^2 + bx + c. \quad (0.2)$$

In order to build the parabola which includes 3 specified points, the following equations are used to calculate function parameters

$$a = \frac{y_3 - \frac{x_3(y_2 - y_1) + x_2y_1 - x_1y_2}{x_2 - x_1}}{x_3(x_3 - x_1 - x_2) + x_1x_2}; \quad (0.3)$$

$$b = \frac{y_2 - y_1}{x_2 - x_1} - a(x_1 + x_2); \quad (0.4)$$

$$c = \frac{x_2y_1 - x_1y_2}{x_2 - x_1} + ax_1x_2, \quad (0.5)$$

where  $a, b, c$  are function parameters,  $(x_1; y_1)$  are peak irradiance,  $(x_2; y_2)$  is the first intersection with zero (sunrise), e.g. (6; 0) means 6am,  $(x_3; y_3)$  is the second intersection with zero (sunset), e.g. (21; 0) means 21 p.m.

Now,  $y_1$  which stands for peak irradiance can be calculated, solving the integral equation (0.1) for  $y_1$ , using  $x_2, y_2, x_3, y_3$  specified before.

At this stage all the required coordinates of the parabola daily irradiance curve are known and the curve can be built. A separate curve for each season should be calculated – 4 in total.

To translate solar irradiance into output power, it is required to define the dependence. Usually manufacturers specify the output of a panel as current – voltage curve for different irradiance levels [19].

Several factors have to be applied to the final equation. An efficiency factor should be applied in order to model the panel ability to capture the given amount of solar irradiance. Also, it is important to consider that usually solar farms have more installed capacity than they are rated to, especially in countries with low solar irradiance to compensate for not ideal conditions. Another important component is the daily weather factor, which allows compensating for different level of cloudiness for different days.

### Wind Farm Model

Energy production patterns of some power plants, like gas power plants, are controllable and easy to predict, while wind turbines cannot be controlled and accurately predicted. Furthermore, modelling a parallel operation of multiple – from tens to hundreds – wind turbines is even a more complicated task, which involves numerous factors, e.g. wind speed distribution throughout the whole farm, the geographical landscape, different times of non-availability, etc. This chapter reviews the proposed model of a single wind turbine and the model of a wind farm, offering sets of ready-to-use data.

Wind behaviour can be described in different ways, one of which is wind speed probability density – a data set describing how likely is the occurrence of different wind speeds in a particular location. A real wind speed probability density is hard to describe mathematically due to peaks and dips. However, the Weibull function would give a very good approximation [20].

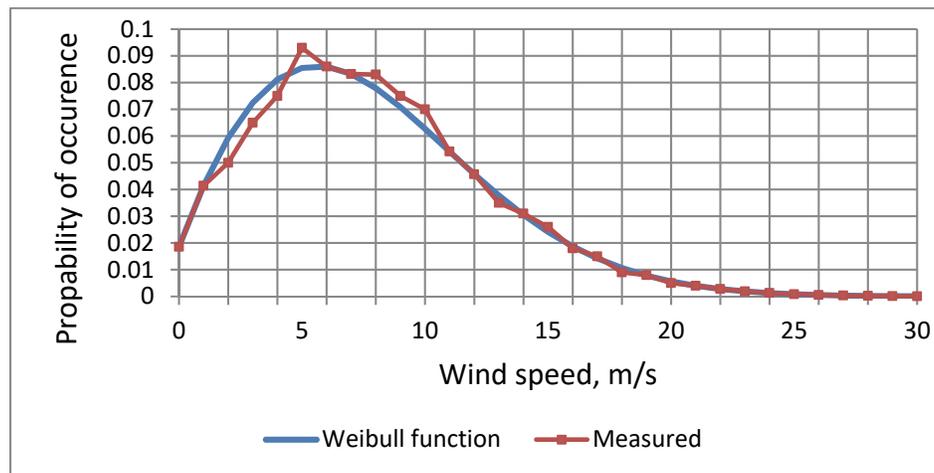


Fig. 0.2. Measured wind speed probability density and the best-fit Weibull function for mean wind speed of 8.4 m/s.

As an example, Fig. 0.2 shows the wind speed probability density measured at a WF location on North Harris Island (UK), with the mean speed of 8.4 m/s. The Weibull function is described with equation

$$f(x, \alpha, \beta, k) = \frac{\alpha}{\beta^\alpha} (x + k)^{\alpha-1} e^{-\left(\frac{x+k}{\beta}\right)^\alpha}, \quad (0.6)$$

$$\begin{cases} \alpha = 1.85; \\ \beta = 9.48; \\ k = 0.6. \end{cases}$$

In the same way, Weibull function can be fitted to different mean wind speed values. Some examples are covered within this thesis.

Another key parameter for a WF model is the power curve. Usually, these curves are constructed within the limits of a single model, although separated models could be created if required. Power curves are easy to obtain from the wind turbine manufacturer, so the input data are available to a planner. Power curves provided by the WT manufacturer are usually created on the basis of measured values or derived from the wind potential using complex equations. The curve shape between the cut-in and the rated wind speeds can be accurately described by a polynomial function.

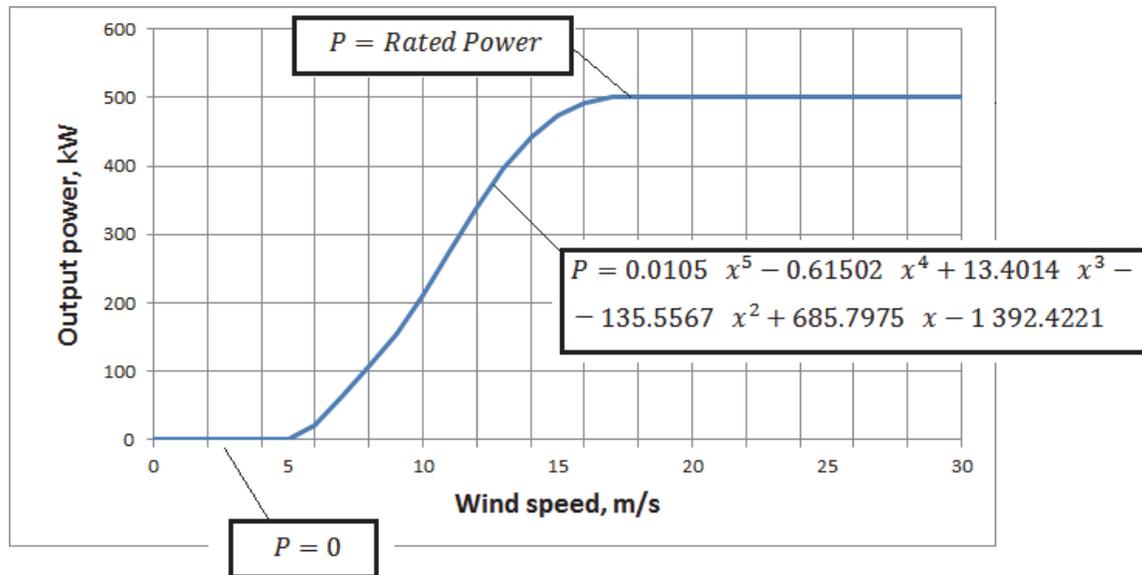


Fig. 0.3. Mathematical description of the power output curve of 500 kW wind turbine generator.

The equations shown in Fig. 0.3 give 98 % accuracy for a standard 500 kW wind turbine. In the same way equations can be obtained for wind turbines of any size. However, it will be shown below that 500 kW turbine equations are sufficient for the model. Important factors that need to be considered are seasonal correction (from 0.77 p.u. to 1.27 p.u.) and availability (proposed 0.9).

Even if there are identical wind turbines around the wind farm, it would be incorrect to multiply a single turbine's production curve by the number of turbines, as the wind speed at a particular time can vary significantly throughout the farm [21].

The analysis of historical data has shown that the maximal difference of power production can be up to 65 % between minimum and maximum or  $\pm 30$  % from the average. Analytically it was defined that maximal deviations from the average power value can be calculated as follows:

$$D = -0.0028N^2 + 0.5905N - 0.5886, \quad (0.7)$$

where  $D$  is maximal deviation from the average power and  $N$  is the number of turbines.

It is proposed to apply a random deviation from zero to  $D$  to 1/5 of turbines for flat terrain and offshore wind farms and to 1/4 of turbines for hilly terrain wind farms. It is proposed to calculate 864 operational states (values on the production curve) per year or three full days per month. Duration of one equivalent operation state will be  $8760 \text{ h} / 864 = 10.13 \text{ h}$ . Experimentally it has been defined that  $3 \times 24 = 72$  values per month give a simple but detailed enough curve that meets the requirements of planning tasks.

The model allows the WPP modelling for up to 200 turbines at one site. It gives a realistic energy production and meets the requirements of long-term planning tasks, described in Chapter 0.

### **Battery Storage Plant Model**

Battery storage is a new technology and SCADA data is not yet available for investigation. From the developers application it is clear that it is intended to charge batteries at night and discharge (generate) during high load hours, normally between 12.00 and 20.00. According to grid connection applications, most of future battery storage systems are meant to be built for enhanced frequency response services; operating time is expected to be from 10 seconds to 30 minutes.

The model of a Battery Storage Plant is assuming “worst case scenario” of 30 minutes of operation randomly between 12.00 and 20.00 and 30 minutes of charging time during the night at random hours. Since this operation is favourable from the grid point of view, battery storage plants almost certainly will not cause any issues in the network. However, simple analysis might indicate problems, so it is proposed to always use full analysis, including daily load and generation profiles to study this type of DG (see Chapter 5).

### **Short-Term Operating Reserve Power Plant Model**

Majority of STOR power plants are providing frequency response services with typical daily operating time of 1 minute to 2 hours. This purely depends on signals from National Grid and in order to build an accurate model, the transmission system would need to be modelled, which is outside of the scope of this thesis.

The analysis has shown that STOR plants operate 1–2 times a week during 1 hour in average with power output of 25 % to 100 % of rated power. The proposed model of STOR plant is the “worst case scenario” of 2 hours of operation randomly between 12.00 and 20.00. Even though in average STOR operates at 30 % to 40 % power, as a worst case scenario it is assumed that power output is always 100 %.

### **Other Power Plant Models**

Taking into account the results presented in Chapter 2.5, it can be concluded that most of the existing and future DG will be aiming to generate as many kWh as possible at any time. The exception is DG providing TSO services and power plants with natural limitations, like wind and solar power plants.

Limitations for other power plants are absent or unknown, e.g. gas power plants. These power plants rely on output control mechanisms, which can be very different from site to site and can be dictated by economical, technical, legal or other factors. For this reason, it is proposed to model power plants, that are outside the scope of this chapter, at constant maximum capacity.

### **The Load Model**

The Load Model described in this thesis is a complex multi-layer model based on the analysis of real load curves and involves:

- residential, commercial and industrial load models;
- electrical vehicle load model;

- electrical vehicle energy storage model;
- rooftop solar generation model (represented as reduction in load);
- load growth correction factor;
- seasonal correction factor;
- time zone correction factor.

To better understand the load behaviour in modern distribution systems, SCADA data for real load curves were analysed (in the United Kingdom, 2015–2016). The analysis included:

- four 33/11 kV substations;
- different substation types: urban, rural, mixed;
- different capacities: 9.5 MVA, 12 MVA and 25 MVA;
- data for 4 seasons for each substation;
- data for 2 weeks for each season for each substation.

As there are plenty of electrical load types, it is reasonable to describe and create models of main load types separately. Figure 4.4 and Fig. 4.5. show residential, commercial and industrial area averaged daily load profiles used in the model. These profiles are the results of analysis of the data set described above and the data available in [22], [23]. The goal was to create profiles that show a “true” load without “masking” the effect of DG.

These profiles would normally fit most locations and meet the accuracy requirement of distribution system planning tasks. However, they can also be modified in accordance to a specific requirement.

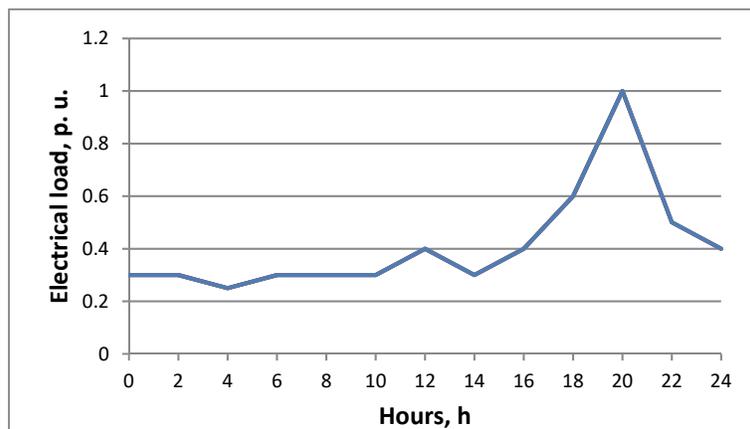


Fig. 0.4. Residential area averaged working day load profile.

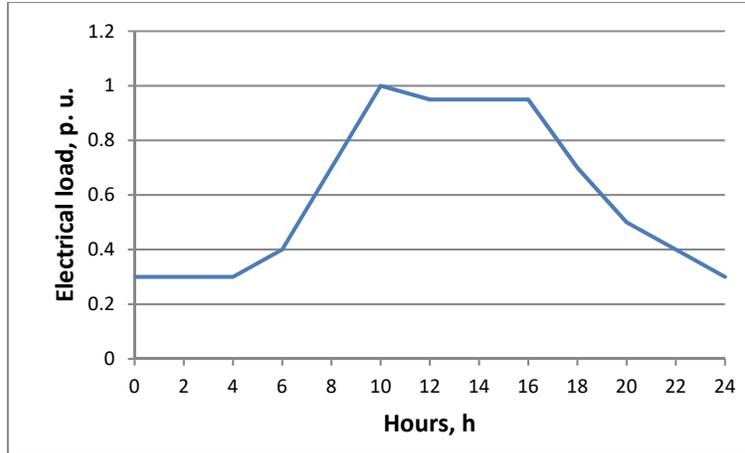


Fig. 0.5. Commercial area averaged working day load profile.

EV charging stations belong partly to residential and partly to commercial load. However, it is proposed to have a separate EV model, as it can potentially be a considerable part of future load. For the purpose of creating a simple EV model, the most popular commercial EV in Europe was analysed. It is Nissan Leaf with a 24 kWh battery and two options of charging system types: 3.3 kW or 6.6 kW [24]. Different charging scenarios are observed, e.g. night charging, charging while-at-work.

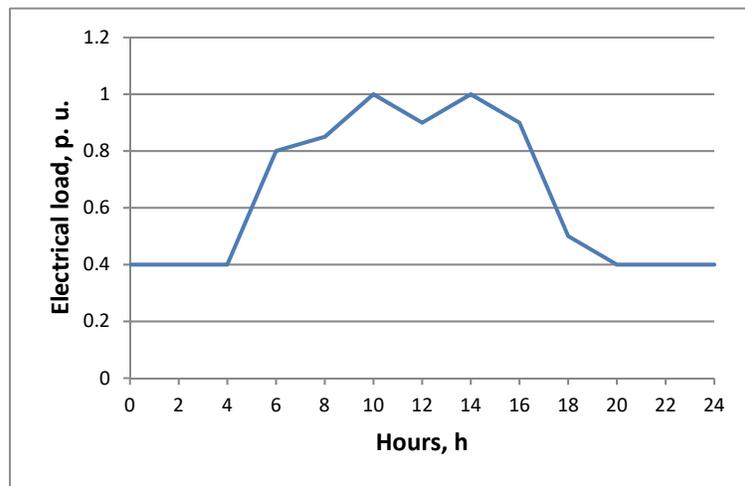


Fig. 0.6. Industrial area averaged working day load profile.

Night charging is the most popular way of charging an EV today due to a small number of charging stations available [25]. The thesis also shows the scenario of EV operation as vehicle-to-grid.

There are two proposed approaches to rooftop solar generation modelling. The first one is to use detailed equations described in the section “Solar Farm Model”. The second approach is simplified and based on the assumption that every second private house will have solar panels with average output power of 1 kW. The share of people living in private houses is assumed to be 40 % for the UK. Simple calculation gives the result of 20 % of domestic load during the day reduced by 1kW.

The task of the planning is to observe up to several years of future operation and achieve accurate results based on forecasts, assumptions, approximations and equivalentations. Annual load profile has to be simple but detailed enough, taking into account the following:

- the profile should include real load maximums and minimums;
- power values have to be linked to real time; this is required for some calculations, e.g. reduced combined load annual maximum;
- the profile should result in realistic annual energy consumption.

For each point (“node” or usually substation) of a distribution system it is proposed to create 24 averaged daily profiles – two for each month of a year, one for a working day and one for weekend days. The working day profile should be used as a basis and weekend day profile will have reduced commercial and residential load (it is proposed to use factor 0.5). There are 24 hours in a day and each hour reflects a total load from all daily profiles.

Mathematical expression for a node hourly load is

$$\sum_{i=1}^M P_{i+j} k_1 \left( 1 + \frac{k_2 n}{100} \right), \quad (0.8)$$

where

- $P_i$  particular hour load value of a profile;
- $M$  number of profiles (different load types) at a current node;
- $j$  time zone correction multiplier (0, 1, 2,  $j$ );
- $k_1$  seasonal multiplier;
- $k_2$  load growth multiplier (%; different for each profile);
- $n$  number of the year in the reviewed period (0, 1, 2,  $n$ ).

In such a way all 24 hours are calculated. Total number of calculated load operational states in the model is  $2 \times 24 \times 12 = 576$ . The total number of calculated operational states is 8760, where the remaining load values are duplications.

If exact load curves are available, they can be used in the model. However, a parameter that is more widely available is maximal (installed) load at a node, which can be assumed to be equal to transformer rated capacity. In this case only the transformer rating is required to build the model. The algorithm of transaction from maximal load to a realistic profile is presented in the thesis.

### Short Circuit Model of Power Inverter

Grid-tied power inverters in distribution networks became popular with the development of solar farms, wind farms, battery storage plants and other energy sources that do not produce 50 Hz AC output [28]. The model of an inverter for steady state network analysis is relatively simple and has only one input parameter – maximum power (see Chapter 4.2.1). However, fault current contribution analysis requires a more complicated model to reflect the correct behaviour of an inverter during fault in the system. Short circuit current contribution behaviour of standard rotating machines is well studied and there are many models offered in power system analysis tools. However, power inverter behaviour during a fault is very different. Fault current of inverters is sometimes assumed equal to its rated current or even neglected, which does not reflect real behaviour of inverters and lead to errors.

Inverter behaviour during a fault is dependent on control scheme, but usually there are two main parameters that inverter contributes to during a fault: peak short circuit current and steady state short circuit current.

The approach offered in this thesis is based on using a synchronous generator model to represent the power inverter. Synchronous generator short circuit current is expressed by equation

$$i(t) = \sqrt{2}E \left[ \left( \frac{1}{X_d''} - \frac{1}{X_d'} \right) e^{\frac{-t}{T_d''}} + \left( \frac{1}{X_d'} - \frac{1}{X_d} \right) e^{\frac{-t}{T_d'}} + \frac{1}{X_d} \right] \cos(\omega t) + \frac{E\sqrt{2}}{X_d''} e^{\frac{-t}{T_d''}}, \quad (0.9)$$

where

$E$  – phase to phase voltage (RMS), V;

$X_d''$  – sub-transient reactance,  $\Omega$ ;

$X_d'$  – transient reactance,  $\Omega$ ;

$X_d$  – synchronous reactance,  $\Omega$ ;

$T_d''$  – sub-transient time constant, s;

$T_d'$  – transient time constant, s;

$T_a$  – aperiodic time constant, s.

The goal of this approach is to adjust the parameters of equation (0.9) so that the resultant waveform would represent an inverter short circuit current. Since the equation (0.9) describes the sinewave form current, for simplicity it is assumed that the inverter short circuit current is sinewave, including the first peak. The target waveform is shown in Fig. 0.7.

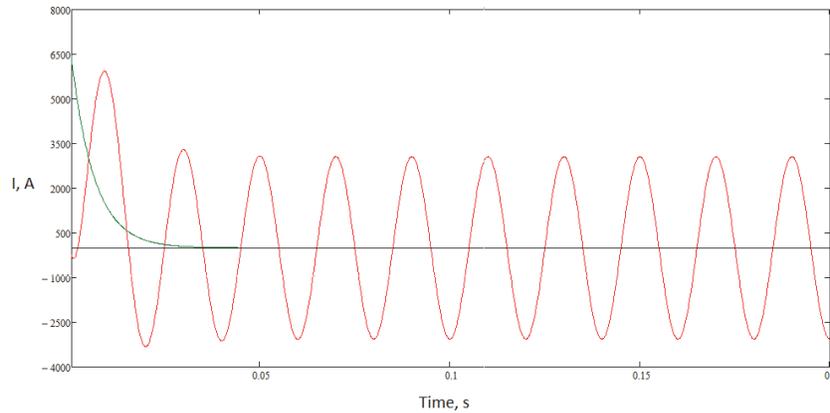


Fig. 0.7. Simplified target waveform of inverter short circuit current.

Some engineering assumptions and mathematical techniques are used to obtain the equations for all parameters. They are fully described in the thesis.

The model of inverter short circuit current was tested using real parameters that may be specified by a manufacturer. The resultant waveform exactly matches the shape of the target waveform shown in Fig. 0.7. It contains a pronounced first peak, very fast decay and steady state short circuit current. The modelled 10 ms peak and 70 ms RMS values had average error of 0.19 % and 0.33 %, respectively.

## 5. THE MODEL CALCULATIONS

### 5.1. Targets of the Model Calculations

Models are usually created for a specific task. In case of power system models, the target of the calculations usually is a set of system parameters, such as voltages, power flows etc. Since the methodology created in this thesis is meant to support the distributed generation planning, there is a set of specific calculation targets. There are two main target options for model calculations.

1. Target costs for DG development. What **DG capacity** can be installed having a defined budget (the Costs Target). It is most important for decision making at a government level to understand the outcome of particular investments.
2. Target for future DG capacity. How much **money** is required to install the defined capacity of DG (the Capacity Target).

### 5.2. Simulation Types

To study the effect of DG implementation in the distribution network, two approaches are proposed – Specific Operational State Simulation (SOSS) and Realistic Full Simulation (RFS). It is proposed that both approaches are used in parallel and the results are compared for a more balanced decision.

Specific operational state simulation approach is similar to the existing “practical” approach described above. The calculation is performed only for certain selected operational states to assess if a certain DG is acceptable on the network. It is proposed to study the following operational states in order to consider most common scenarios, including the worst case scenario: 1) power flow study (maximal load + maximal generation, minimal load + maximal generation; 2) fault level study (maximal load + maximal generation). The specific features of this approach are low risk, low realism and low coverage of scenarios.

To overcome some downsides of specific operational state simulation, it is proposed to use realistic full simulation (RFS) in parallel. This is the most natural way of modelling the future uncertainty. In this approach, generation and load parameters are modelled as realistic forecasted values for a defined period of time in future. It is a more complicated approach, since it requires precise models and calculation of multiple operational states. The models described in Chapter 0 were specifically developed for this purpose.

**Active Network Management.** As it was shown in Chapters 2 and Chapter 0, constrained (controllable) connections become extremely popular and will be even more popular in future. This is explained by a number of benefits, the main being the lower cost of connection. As alternative to network reinforcement, it is possible to install Active Network Management (ANM) equipment at the generation plant and restrict its operation under certain conditions. Based on feasibility studies in [29], a generation connection is considered to be viable, if forecasted annual availability is >70 % and the forecasted constraint time is <30 %. It is proposed to consider ANM as a second option in the following order: Conventional → ANM → Network Reinforcement. The availability is calculated by means of realistic full simulation by checking all operational states for network issues as follows:

$$A = 1 - \frac{h}{8760} \cdot 100, \quad (0.1)$$

where  $A$  is availability, %;

$h$  is the number of operational states with identified network issues.

**The main algorithm.** The main algorithm of the model for DG planning is presented in Fig. 0.1. The main idea of the algorithm is to add DG one by one to the existing network until the target is reached.

For each new DG the model will calculate the size, preferable location, connection type, required network reinforcement, and will check the behaviour of each new DG in the existing network. This involves multiple sub-algorithms, which are described further.

The basis of sub-algorithm of DG size selection is real DG development process. Usually, when there is a DG beneficial tariff in place, the developers search for a site and apply for a connection to a local DNO. The size and type of the proposed DG depends on a number of factors: type of generation, size of available site, developer's budget and a tariff the developer is going to apply for.

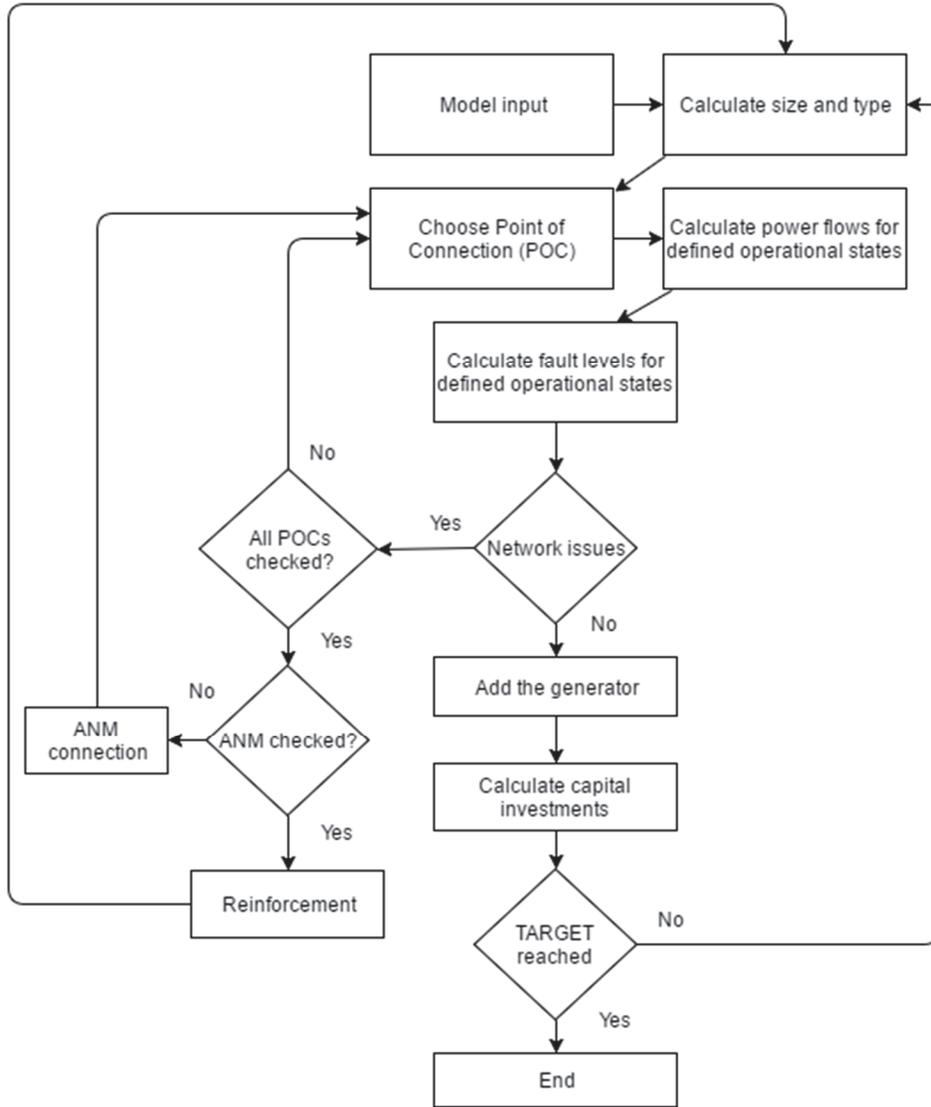


Fig. 0.1. The model calculation algorithm.

The statistics of the existing DG (see Chapter 2) was summarized to find the dependency between the size of DG and the number of DG plants not depending on technology type (see Fig. 0.2). This distribution can be approximately described by the equation

$$f(x, \alpha = 2, \beta = 35, k = 10) = \frac{\alpha}{\beta^\alpha} (x + k)^{\alpha-1} e^{-\left(\frac{x+k}{\beta}\right)^\alpha}. \quad (0.2)$$

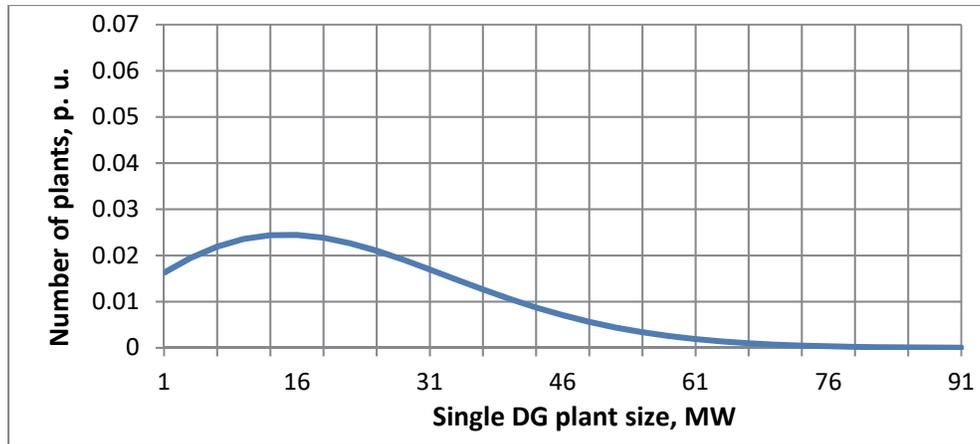


Fig. 0.2. Statistical distribution of DG plant sizes.

General awareness of developers of the amount of free capacity in different areas of the network is quite poor. For this reason, it is assumed that DG applications come for random locations. DG can be added to a randomly selected node in the model (random network location) with some limitations that are described in the thesis.

It is required to analyse the system under  $N - 1$  conditions due to the following rule: at any unexpected  $N - 1$  condition there should not be a situation when a network element is overstressed, since the control centre is not always able to react quickly enough to avoid damage to the network. This is achieved by disconnecting every transformer one by one and line at the connection voltage and above and re-checking the load flow. Fault level is only checked at normal operating conditions, as it is when it is the highest.

Reinforcement is the least favourable measure that can be taken in order to connect a planned DG to the network, since usually it requires considerable investments. The planner should input costs of reinforcing 1 km of overhead line (OHL), 1 km of cable, transformers for two voltage levels – one below the studied network level and one above. For example, if the object of study is a 33 kV network, it is required to input costs for 33/11 kV and 132/33 kV transformers. It is proposed to input two possible transformer size options for each voltage level to make the reinforcement in steps, e.g. replace the 45 MVA transformer with a 60 MVA, then with a 90 MVA transformer. Apparently, there should be a limit that is reasonable to be spent on reinforcement of a particular DG – it is proposed that 10 000 EUR/MW is a reasonable amount that can be spent on network reinforcement. If the reinforcement is insufficient and there are still network issues which cannot be solved, the current DG should be terminated.

DG significantly affect power flows in the system and have their own protection, which needs to be graded with DNO's protection. In some cases, it is possible to simply adjust the settings to achieve discrimination. However, the protection used in modern distribution systems is not always modern digital protection. Due to its complicity and the number of input parameters required for protection studies, it is not covered in this thesis. It is proposed that additional costs are added on top of total reinforcement costs to allow for protection studies and modifications (EUR 10 000 for schemes connected at voltage below 100 kV and EUR 100 000 for schemes connected at voltage above 100 kV).

### 5.3. Test Case Study

This chapter presents the test case for the developed methodology. The objective of the test case is to present a high level overview, rather than a full detailed calculation. In order to show a complete study, it would require developing of a software based on the described algorithms. Therefore, the calculation presented in this chapter is just an imitation of a part of the algorithm. The test case study is based on the network shown in Fig. 0.3.

The realistic example of distribution network consisting of full 132 kV and 33 kV networks and equivalent 11 kV and 275 kV networks was studied. The network element parameters are based partly on latest and partly on old practices. As initial condition, it is assumed that there are two DG power stations present in the network already. For the purpose of this example the calculation target is selected as 60 MW ("Capacity Target").

The calculations for the given test case are based on the models and algorithms presented previously. However, due to complexity, some simplifications and assumptions are applied and some calculations are omitted.

The calculations involved:

- specific operation state simulation;
- realistic full simulation;
- power factor correction;
- underground circuit reinforcement;
- ANM calculations, using the load and solar farm models;
- fault level calculations;
- economical calculation.

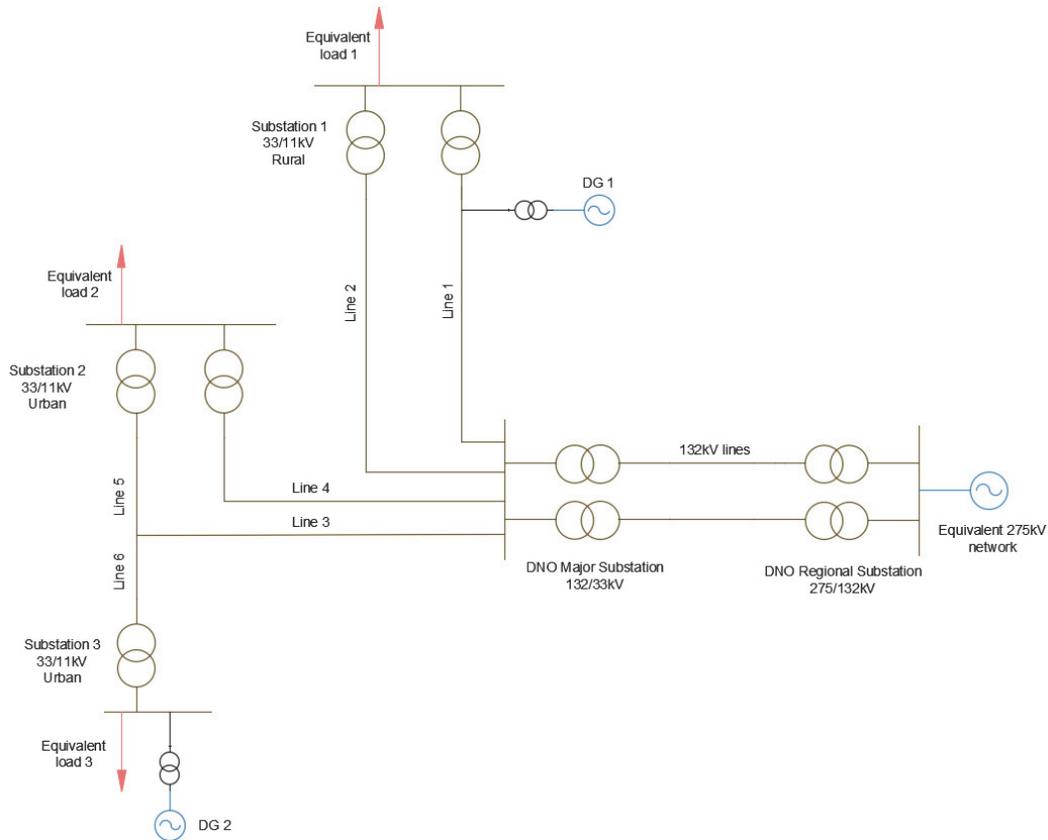


Fig. 0.3. Test case network.

As a result, three DG power stations were connected to the network with total capacity of 62 MW. Network related costs in this case are EUR 521 000.

## 6. CONCLUSION

### 6.1. Overall Conclusion

1. Existing distribution systems have been optimised to meet the requirements of conventional generation and many of these arrangements do not provide a level playing field for the introduction of DG or realisation of its full value.
2. As most DG use renewable or low carbon energy resources to produce electricity, DG integration will make a large contribution to meeting the targets set for introduction of renewable and low carbon generation. Despite the opinion that DG is an expensive source of energy, there are potential economic benefits in addition to ecological.
3. It became obvious that in order to accommodate the desired number of DG, network reinforcements are required. Due to the high cost of these reinforcements, many investors do not get involved in the DG projects, which puts government targets at risk.

4. There is a rapid growth in DG capacity on the network, including well-known technologies and new technologies, like battery storage and electric vehicles.
5. Smart Grid technologies have become common and most of new connected generation and large load are monitored and if necessary controlled (DSM, ANM). ANM opens the possibility to connect DG even if there are network issues and save reinforcement costs if applicable.
6. There is a variety of earning schemes for DG; the most used ones are fixed high tariffs, e.g. FIT. It means that most of DG generate at any time when they are available, which is a very important conclusion for creation of power station models.
7. The existing power system modelling tools and planning methods do not offer efficient DG planning capabilities. It was identified that most of the existing power system modelling tools are weak for any planning in general. Most of the existing planning methods lack practical considerations of the modern DG sector.
8. The analysis has proven that DG models should be detailed enough to give accurate final results. However, for the specific task set in this thesis, there is no necessity to consider certain aspects, e.g. individual solar cells and inverter rectifiers for solar farm model.
9. Inverter based DG fault current contribution cannot be ignored due to its significance and growing numbers of inverter-based DG in the network. To consider it, a special model is required, which was a part of this thesis.
10. In order to obtain accurate realistic results, apart from specific operational state calculations, it is required to use a realistic full simulation, which would include hourly models of generation and load, specifically developed for planning tasks.
11. It is extremely important to consider an ANM system when simulating the new DG connections. In certain cases, it might save millions of euro with minimal impact on future operation of the DG.
12. Simulation results give answers to the following important questions: 1) what DG capacity can be accommodated in the network with limited network development budget; 2) what investments are required in order to accommodate the defined DG capacity; 3) what particular reinforcements are required in order to accommodate the defined DG capacity; 4) network issue type and location; 5) possibility of application of smart technologies (ANM).

## 6.2. Future Work

It is possible to carry out all calculations manually or using available computer calculation tools. However, even power flow alone is extremely hard to calculate manually for large systems; considering the number of equations and algorithms involved, it would be practically impossible to implement the approach. Since this is a unique approach and there is no existing software tool that could do the required calculations, a new software tool is required in order to use the approach in efficient manner. Due to complexity and different specifics of new software development, it is not a topic of this thesis. A reasonable extension of this research work is the development of a software with the functionality required for the approach. The software can be easily produced by programmers using the proposed methodology, and it should have the following functionality (not limited to): build-in models presented in Chapter 0; possibility to input the specified data; power flow calculation; possibility to implement the algorithm described in Chapter 0; data base system for storing network parameters.

Another development direction is implementation of calculation for benefits gained from DG contribution to the security of supply. Effectively, this would reduce total capital investments required for the distribution system development. On the one hand, DG require investments in network infrastructure, on the other hand, it potentially reduces the investments related to the security of supply by generating electrically closer to the load. Even though this option is possible, it is not always utilized, since there are special requirements for a distributed generator contributing to the security of supply, e.g. protection, stability earthing etc. Majority of modern DG operate in parallel only with healthy network and automatically disconnect from unstable or islanded network.

Author is more than happy to support or take part in future work with interested parties.

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