Power flow control in a substation of a wind- and solar farm

BSc. Graduation Thesis

Group 09.01

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Abstract

Renewable energy generation is nowadays increasing around the world, especially wind- and solar power generation. However, increasing wind and solar power integration into the grid has a significant effect on the power system. The variability and uncertainty of these energy sources proposes new challenges for companies involved in grid management. In order to face these challenges, advanced control schemes and optimization algorithms has to be implemented in order to ensure stability and efficiency of the power flow. But these algorithms can only be implemented if the power flow in the system is modeled accurately. This thesis explains how the power flow in a substation of a wind- and solar farm in Zeewolde, the Netherlands, is modeled in order to guarantee efficiency and stability.

Preface

The scope of this thesis is to provide an accurate model of the power flow in a substation with renewable energy sources, the Zeewolde wind-and solar park. The thesis is part of a project given by ABB. ABB aims to use this model as a complementary solution to satisfy TSO requirements at the point of common coupling with minimal losses in power and maximum stability. We would like to thank our supervisor dr. ir. José Rueda Torres for his exceptional guidance throughout the project. In cooperation with José, we were able to iteratively formulate requirements that would satisfy a realistic representation of the substation. Especially, dr. ir. José made an effort in providing the best quality of guidance under the COVID-19 circumstances. Furthermore, our gratitude is expressed for Dennis Groenenberg and Jan who constantly provided us with the information of the Zeewolde park needed for fulfillment of the scope of the project. Lastly, the complete project would not have been possible without the help of our colleagues, Alexandru Neagu, Dennis Groenenberg, Jin Han Bai and Laurens Beijnen. Because of you, the motivation stayed high while being in an enjoyable online atmosphere.

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Contents

1
Introduction

In the past decade, the renewable energy market has increased significantly [18]. Equivalently, the current methods for energy provision such as coal, are becoming less popular. Ongoing research has the aim to make the transition to renewable energy as safe (f.e., no overloading) and efficient (f.e., no transmission losses) as possible [2].

Ideally, once the substation is connected to the grid, the substation provides its full capacity at all times. However due to fluctuations in wind- and solar profiles, the Transmission System Operator (TSO) requirements cannot always be satisfied at the Point of Common Coupling (PCC) [10]. There is also loss in several of the components which form the subsystem such as power loss in the transmission lines, bus bars, transformers and even in the Wind Turbine Generators (WTGs) and PV panels. Since these losses will effect the power generated and the power delivered at the Point of Common Coupling, they have to be taken into account in order to implement an accurate model for the system. In the stator rotational energy of the blades of the wind turbines is converted into electrical energy. Since the conversion is made with magnets, AC current production occurs. This gives rise to different AC voltages on the bus nodes of the power system of the wind module. These voltages can be lagging or leading to the current in the power system, which gives rise to either absorbing or generating reactive power by the wind turbines. However, at the nominal value of 1 p.u, the voltages will not be lagging or leading, but in phase with the current, which will result in no reactive power. One of the requirements of the Transmission System Operator is to control the reactive power and make sure that, when needed, the reactive power at the Point of Common Coupling is brought to zero. The power in the PV module is generated in DC conditions. So the solar modules do not generate any reactive power. However, this DC power has to be fed into the grid. Since the grid operates in AC conditions, the DC power has firstly to be converted into AC power. This is done by connecting an inverters at the output of a section of the solar module. These inverters can also generate or absorb reactive power depending on whether the output voltage of the inverter is lagging or leading the output voltage of the solar modules. In figure 1.1, a simplified overview of the power system is given. Eventually, the main goal of the three subgroups is to satisfy the requirements of the TSO, concerning the reactive power generation or absorption, under all conditions. In addition, advanced control schemes are designed to find the optimal setpoints in the substation. The setpoints indicate the power flow through each generation string. The optimisation is based on the system's configuration and non-idealities, but also on the grid code requirements [1]. This mathematical scheme cannot determine the feasibility of the given setpoint in reality. It needs information of the substation's power flows. Through communication between the modeling and optimization entity, the scheme can make its search space smaller and find a global optimum. Therefore, an accurate model of the power flows has to be provided which takes into account the fluctuating wind/solar profiles and components' non-idealities. When the optimization algorithm sends setpoints to the model, the model returns the actual feasibility by providing the power flows

[1] "Grid codes specify the electrical performance that generation assets must comply with in order to obtain the required approval for its connection to a grid."[5]

in each of the branches in the system configuration. Dependent of the development status of a project, this model can indicate if the system configuration is to be improved/changed. Additionally, it provides the feasibility for future expansion of the substation without violating any physical constraints. Steadily, increasing the RES generation for the growing energy demand worldwide.

In order to solve the power flow of the substation, a set of equation of voltages and (power) flows corresponding to a specified pattern of load and generation has to be solved [20]. It is assumed the busses are PQ busses, which translates in knowing the variables P_f and Q_f for the bus. This form is depicted in Eq. 1.

$$f(x) = 0$$

$$\text{with x} = \begin{bmatrix} V_\theta \\ V_{magnitude} \end{bmatrix}$$
$$\text{and f} = \begin{bmatrix} f_P(V_\theta, V_{magnitude}, P_f \\ f_Q(\theta, V_{magnitude}, Q_f \end{bmatrix} \quad (1.1)$$

Different algorithms have been designed to solve Eq.1 in an iterative manner. Reason for more algorithms are its solving (or convergence) time and accuracy for specific networks. These modern algorithms still make use of the two conventional approximation methods, Gauss-Seidel method [8] and Newton Raphson method [15]. Gauss-Seidel is a simpler technique requiring less computation per iteration. The computation time is sensitive to the system parameters. Therefore, the majority bases the algorithm on Newton-Raphson, since the system converges in less iterations, which gives smaller computation time, more accuracy and makes it less sensitive to other system parameters. This makes it suitable for a complex system, as shown in Fig. 1.1.

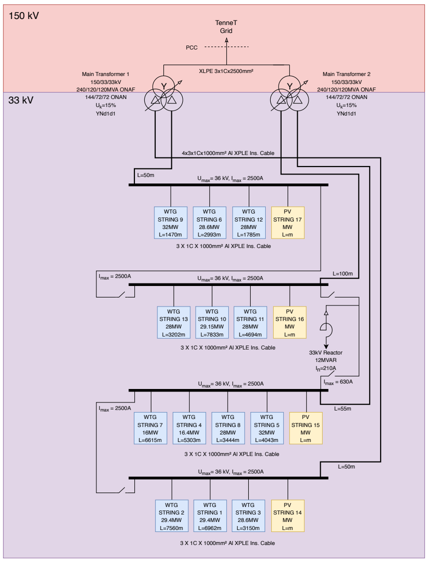

Figure 1.1: Simplified schematic of case system

A fluctuation in wind/solar profile, causes a fluctuation in power generated. Current methodology takes this fluctuation in wind/solar profiles by designing algorithms that describe a probabilistic behaviour of wind speed and solar irradiance [3] [4] [1] . Research makes use of a Weibull distribution [9], historical data or a versatile distribution that combines Beta, Cauchy and Gaussian to model a daily wind profile [19]. However the majority makes use of Weibull PDF, since it was determined that the distribution resembles real life situations the most [17] [12] [9].For solar irradiance, each research makes use of an own model. These models can be divided into:

1. Design based on historical data and chosen PDF [21].
2. Beta distribution [6] [9].
3. Weibull distribution [6].
4. Design based on spatio-temporal stochastic model with each spatio(or season such as sunny, cloudy,etc.) having own stochastic parameters[14].

Out of these models, the probability for output power is determined. This offers a solution in case of insufficient or inaccurate wind-and profile data. Other research, suggest a π- model of the individual WTGs and PV panels to determine the output active- and reactive power. It makes use of properties of the system. This provides an accurate solution if all data is known, i.e. datasheet of the WTG as well as the profile data [13] [7] [16]. For the probabilistic model of the RES, the reactive power output is unknown in case of insufficient data about the system itself.

Due to the short amount of time, it was decided to design a model in steady state and AC conditions using MATPOWER. MATPOWER is a MATLAB package aiming to solve steady-state power simulations [20]. For this model the basic Newton-Raphson method is used. More sophisticated methods would be possible if the system was a radial network, where each load has its own generator. The case study in Fig. 1.1 analyses a network system, which has multiple generating sources for a single load. Also, the sophisticated methods, are focused on reducing computation time, which is not part of the scope for this project.

The challenge for this project is to have an accurate model of the power flow for a substation that combines both wind-and solar generation under normal and extreme weather conditions. The state of art does not seem to analyse such a case study. Research does address the effects of such a substation on the transmission grid, but not on the substation. In addition, there shall be looked at the loss effects of 2/3-winding transformers. The sub group responsible for optimisation shall find the optimal tap position and send it to the modeling subgroup. This interaction is visible in Fig. 2.1. Due to insufficient data for the modeling of WTGs

in the case study under fluctuating profile conditions, both probabilistic and PQ/RX models are combined, yielding correct estimate of the active and reactive power generation for each dispatch. Next, the models for reactive power capability and probabilistic solar irradiance are combined for the PV module. Lastly, the models are combined and tested under critical conditions, such as low wind speed or high reactive power requests from the TSO. The problem formulates: "When can the substation satisfy high load demands under critical, i.e. too low or too high, generation of power?"

To formulate a correct answer, the thesis will delve into the necessary requirements to determine what it means to have an accurate power flow model. Once requirements are determined in Chap. 2, a procedure (Chap. 3) with subsequent results (Chap.4), is analysed. Out of the results, a conclusion will be made in Chap. 5 and a discussion about the results can be formulated in Chap. 6. This discussion offers room for improvement and recommendations for future researchers modeling power flows for similar case studies.

2 Requirements

As mentioned in Chap. 1, to formulate a correct research, the problem shall be divided in smaller subproblems. The model should be able to:

- Indicate when constraint limits of voltage and/or current are violated in each branch or bus of the substation.
- Indicate losses in each branch and bus for given setpoints.
- Update the components in the system topology each time a new setpoint is given.
- Consider influences in power generation due to fluctuating wind- and solar profiles.

To determine how the model will indicate if requirements are satisfied, one needs a correct definition of setpoints received from the optimization scheme. The interaction of the subgroups is specified in Fig. 2.1. For the case study, the setpoints will be given in the form a dispatch vector, which indicates the required reactive power from the RES strings, 13 WTG strings and 4 PV strings, shown in Fig. 1.1. Additionally, tap positions for the 3-winding transformers are required and the connection status for the reactor. Usually the reactor is disconnected, but if the wind-and solar module cannot satisfy the requested reactive power at the PCC, the reactor will be connected and provide reactive power (+- 12 MVAr).

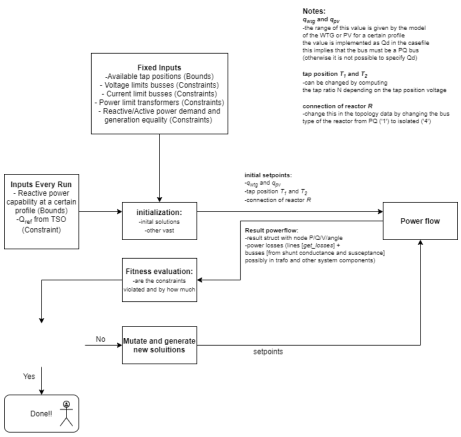

Figure 2.1: Interaction between optimization and modeling of the power flows

The sub problems are formulated in Mandatory requirements, Trade-off requirements and optional requirements. Mandatory requirements are:

1. Formulate a case structure (or system topology) which connects each node of Fig. 1.1. This includes the PCC, wind-and solar strings, transformers and cable data.

2. Before receiving setpoints from the optimization scheme, the available active and reactive power, with tap position from each transformer is sent to the optimization scheme. With this information and system, the optimization scheme can determine the first vector of setpoints.

3. The system topology has to be updated two times after each given setpoint. The first update is to change the active and reactive power generation according to the wind and solar dispatch. The second update is to change the the reactive power of the generation strings.

4. Active and reactive power losses in each transmission line have to be calculated after given setpoints.

Trade-off requirements are:

1. Generate loading demands with a normal distribution to test for which PCC requests constraints are violated at each bus and branch of the Single Line Diagram [11]. Unchanged rated power is assumed for each string.

2. Design a daily dispatch for wind profile based on a Weibull PDF.

3. Design a daily dispatch for solar profile based on a Beta PDF. Here, a sunny day with maximal sun hours of the Zeewolde area, is assumed.

4. Design a daily dispatch for solar profile based on a Beta PDF, for different spatio-temporal situations. Here, solar profile can be sunny and partly cloudy. More profiles can be added at a later stage.

5. Include losses generated by changing the tap position of the 2/3-winding transformer's. This tap position is updated in the system topology according to the procedure in Fig. 2.1.

6. Include losses generated by the 2/3-winding transformer's the inner-and outer winding in the transmission lines.

It should be noted that for each wind/solar dispatch design, it is assumed that the uncorresponding RES system module is inactive. For example, when the PV power generation is modeled with the designed solar irradiance daily dispatch, the WTGs are considered to be inactive. The same counts for the wind daily dispatch design and the inactive PV module. Once each design is tested individually, the dispatches can be combined in a normal random distribution function for wind-and solar PV power active simultaneously.

Furthermore, there are also optional requirements, which are not needed to design, implement and test our model, but can be implemented in the future in order to add new insights to our research. The optional requirements are:

1. Design the PQ and RX models used in state of the art research in order to model the PQ-capability curves of the wind turbines [13]. However, since the PQ-capability curves of the WTG's were already given to us by ABB and no data is supplied about the impedances of the rotor and stator of the WTG's, designing the PQ and RX models is considered an additional requirement. The PQ and RX models could be designed later in the process using data from other researches in order to give an as accurate as possible estimation of the PQ-capability curves. This estimation can then be used in our research in order to compare the capability curves of the models with the capability curves given to us by ABB.

2. Provide an accurate overview of the solar farm implemented. This overview consists of the interconnection of the solar modules, the type of DC/AC converters used and considering the cable losses inside the solar farm.

Additional requirements are needed for a prototype of the project. These requirements are:

- Make a visualization model of the Single Line Diagram of the case study, with the power flow and losses indicated for each of the strings. Note: For the prototype, it is not of importance from which component, i.e. cable or transformer, the loss is generated.

- Include graphs for the voltage and/or power deviation from 1 p.u. at the PCC node. This is the most important node, since it is the connection to the TSO. This deviation is for every iteration of given setpoints.

- Include graphs for the voltage and/or power deviation from 1 p.u. at an exemplary WTG string and PV string. This deviation is for every iteration of given setpoints.

Concluding, once mandatory requirements are satisfied, a sufficiently accurate model is provided of the case study, because it includes transmission losses and most importantly, the behaviour of the RES modules for rated power output. In addition, trade-off requirements will supplement the model by testing the system configuration under different situations determined by the probabilistic behaviour. Furthermore, optional requirements firstly add a new level of accuracy to the model, since additional losses in the farms are accounted for. Secondly, they could give new insights to research, since results of state of the art models are compared with the results of the models used in this research. Additionally, losses of previously ideally assumed components are included, providing actual power flow in the system topology.

3
Procedure

4

Results

5
Conclusion

6

Discussion

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A

Appendix