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

BSc. Graduation Thesis

Group 09.01

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TU Delft

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 [19]. 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].

1.1. Project objective

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 nodes of the power system of the wind modules. 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 assure 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. Hence, the solar modules do not generate any reactive power. Since the transmission grid operates in AC conditions, the DC power has firstly to be converted to AC in order to be fed back into the grid. For this conversion process, DC/AC inverters are used. These inverters will either generate or absorb reactive power **??**. This reactive power has to be taken into account in order to design an accurate as possible solar farm.

In addition, advanced control schemes are designed to find the optimal setpoints in the substation that satisfy TSO requirements. 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.

The project aims to use the case study, shown in Fig. 1.1, to design an accurate model of 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]

that shows the effects of 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 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.

For the scope of this project, a realistic model of the system behaviour shall be designed and tested. The models for the PV- and WTG farm of the case study are combined and tested under critical conditions, such as low wind speed, low solar irradiance, or both for high reactive power requests from the TSO. The problem formulates: "When is the system able to satisfy high load demands at the PCC under critical, i.e. too low or too high, generation of power from the renewable energy systems?"

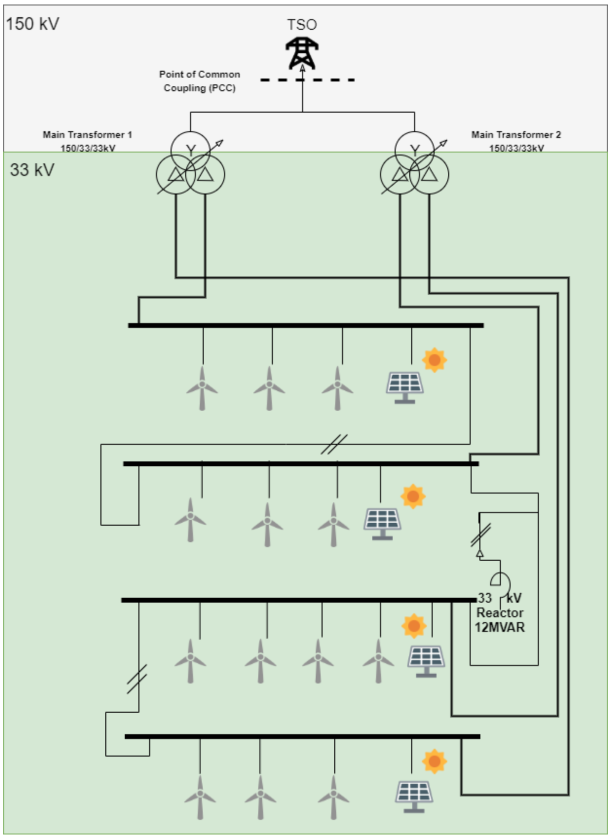

Figure 1.1: Simplified schematic of case system

1.2. Test models and state-of-art

In order to perform several power system analysis, information about the power system is needed, which consists of the system topology and nodal power injections. The nodal power injections consist of active- and reactive power, which are either measured or determined. In Fig. 1.2 the input and output data of an iterative power flow calculation is shown.

Furthermore, in the iterative power flow calculation block certain equations are applied. The generic equation, as shown in Eq. 1.1, will be used in order to generate the voltage magnitude p.u and angle of all nodes iteratively. However, there is one bus, frequently allocated to the bus at the PCC, for which the voltage magnitude p.u and angle are known. This bus is called the slack bus. In this bus the active and reactive power injections are determined with the known voltage magnitude p.u and angle in order to check whether certain requirements at the PCC are fulfilled. In the remaining nodes the voltage magnitude p.u and angles of the busses will be determined with the known values of the active and reactive power injections. These busses

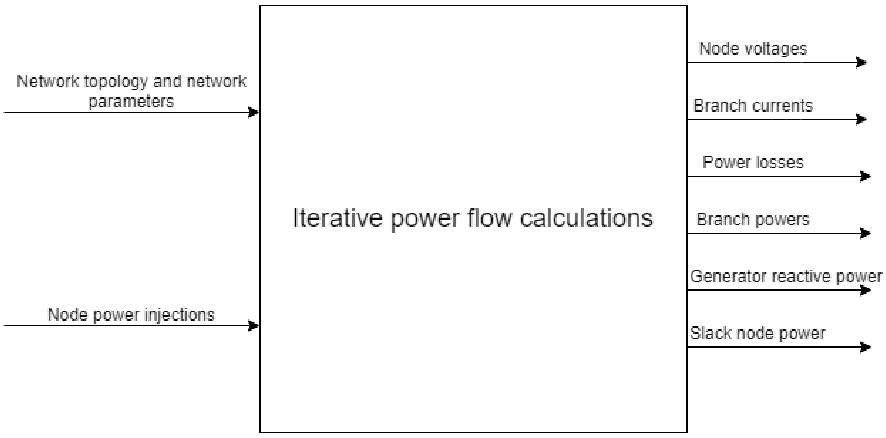

Figure 1.2: Block diagram with the input and output data in order to perform power flow calculations.

are called PQ-busses and are used since they give rise to a set of finite equations, which will result in a finite number of solutions for the magnitudes and angles. For the PQ-busses, there are in principle two equations generated, one for the active power and one for the reactive power, as shown in Eq. 1.2 and 1.3. Since the unknown variables in all PQ-busses are the voltage magnitudes p.u and angles, a state variable matrix **x** can be constructed, as shown in Eq. 1.4, from which all the PQ-busses can be solved iteratively by solving Eq. 1.5.

$$I_{[Nx1]} = Y_{bus_{[NxN]}} \cdot U_{[Nx1]} \tag{1.1}$$

$$P_i = f_p(U_1, U_2, ..., U_N, \delta_1, \delta_2, ..., \delta_N) \tag{1.2}$$

$$Q_i = f_q(U_1, U_2, ..., U_N, \delta_1, \delta_2, ..., \delta_N) \tag{1.3}$$

$$\mathbf{x} = [\delta\, U]^T \tag{1.4}$$

$$f(\mathbf{x}) = 0 \tag{1.5}$$

Different algorithms have been designed to solve **x** in Eq.1.5 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 [16]. 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. A more precise schematic is visible in App. A.1.

A fluctuation in wind/solar profile, causes a fluctuation in the 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]. This probabilistic behaviour is to test the system under the most common operating situations, i.e. common wind/solar profiles, since little variation from the rated wind speed is included to the model. Additionally, the probabilistic model offers the possibility to create both random load demands and generation capabilities in the system at random dispatches. Therefore occasionally violating physical constraints of the system. This offers a test model for alert operating conditions [2]. Hence, the probabilistic model offers a suitable test model under different operating conditions. Compared to use of historical data, which can vary throughout time periods (per season or year), this test model runs more situations.

[2] alert operating conditions in which physical constraints are violated or there is a high vulnerability to disturbances

To model daily wind profiles, research makes use of:

1. a Weibull distribution

2. historical data

3. a versatile distribution that combines Beta, Cauchy and Gaussian to model a daily wind profile [20]. [9]

However the majority makes use of Weibull PDF, since it was determined that the distribution resembles real life situations the most [18] [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 [22].

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[15].

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 [14] [7] [17]. For the probabilistic model of the RES, the reactive power output is unknown in case of insufficient data about the system itself.

Due to its maturity and proven performance as open source tool, Matpower was selected for the design of a model in steady state and AC conditions. MATPOWER is a MATLAB package aiming to solve steady-state power simulations [21]. 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 system configuration 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 the 3-winding transformers. These will be approximated with an equivalent 2-winding transformer model. 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 of both wind profile and WTG's components for the specific case study, using only one model will yield inaccurate results of the power flow. To model such WTGs under fluctuating wind profile conditions, the best model is achieved by combining both methods. The different operating conditions is tested with the probabilistic behaviour, while the PQ/RX model determines the exact output of wind modules after internal losses. Therefore, a correct estimate of the active, reactive power generation and voltage profile is formulated for each dispatch profile.
Next, the same can be done for the PV modules. The models for reactive power capability and probabilistic solar irradiance are combined. In reality, most of the time, both PV- and WTG farm will be active. All generating strings, Fig. 1.1, influence the system simultaneously in normal-and critical operating conditions. With the farm being fully active, voltage profiles can deviate a lot from the ideal 1 p.u., leading to violation of technical constraints.

1.3. Thesis outline

To formulate a correct answer for the project objective, 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.5), is analysed. Out of the results, a conclusion will be made in Chap. 6 and a discussion about the results can be formulated in Chap. 7. This discussion offers room for improvement and recommendations for future researchers modeling power flows for similar case studies.

2

Programme of Requirements

2.1. Functional 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. A.1. Additionally, tap positions for the equivalent model of 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).

2.2. Model requirements

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. A.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.

The satisfaction of mandatory requirements can be tested once the system converges on MatPower for a NR power flow, after the system parameters are updated or sent to the optimization scheme. In reality, system losses account for approximately 20 percent of the total power generated in a substation. This will be a reference value to determine if the data of the components was implemented correctly. , Trade-off requirements are:

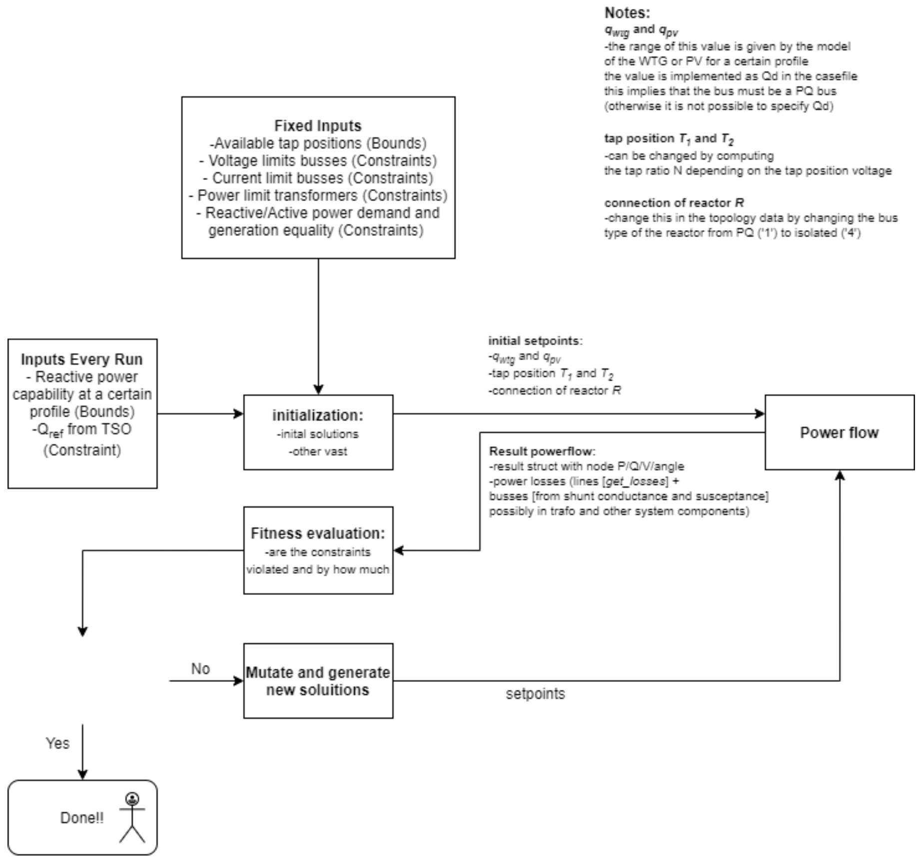

Figure 2.1: Interaction between optimization and modeling of the power flows

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 case study 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 equivalent model of the 3-winding transformers. This tap position is updated in the system topology according to the procedure in Fig. 2.1.

6. Include losses generated by the equivalent model of the 3-winding transformers' 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 [14]. However, for this research the PQ-capability curves of the WTG's were available [13] and no data is supplied about the impedances of the rotor and stator of the WTG's. This resulted in considering the implementation of the PQ and RX models as an additional requirement. In a later phase, the PQ and RX models could be designed using data from other researches in order to give an as accurate as possible estimation of the PQ-capability curves. Eventually, these estimations can be used in order to give a comparison between two different modeling methods.

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.

3. Provide a detailed explanation of the values of the parameters used in the Weibull-distribution.

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

1. The design of a visualization model for 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.

2. 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.

3. 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 for power control at the PCC is provided of the system configuration, 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

Model of the system configuration

For the design of the model, the data in [13] [11] was used. This offers the configuration with assigned bus numbers, cables',transformers' type and length shown in Fig. 3.1. Here, the rightmost generation string of bus bar 7,12,16,23 are the PV strings. In App. A.1, the system configuration is shown with maximum voltages for bus bars and maximum current for branches. On the left, the base voltage is indicated for each section of the substation.

Since [13] offered insufficient data of capability curves of the WTG and PV- farm, certain assumptions were made. Firstly, it was decided to make the slack node the PCC, i.e. bus bar 1. The voltage magnitudes and angles of each bus were compared to the PCC node, with a magnitude of 1 p.u. and 0 degrees. To implement the constraints for the voltage profile, it was decided to determine this from the main transformer data. The transformer data indicates the maximum input/output voltage and current. These values are shown in Tab. 3.1. Although the cable type can handle more, the main transformers set the limits for the system configuration.

The shunt reactor is assumed to be disconnected unless indicated differently by the optimization scheme. Ideally, it is connected only in case the generating strings cannot satisfy a reactive power demand from the TSO.
Branch 7 to 12 and 17 to 23 are disconnected. These branches are required for safety in case of faulty conditions, i.e. overcurrent or overvoltage at the bus bars. The current will in such case be higher than 2500 A, or higher voltage than 36 kV.

To determine impedance characteristics of each branch, the cable type and configuration was analysed.

3.1. Design of the WTG capability curve

3.2. Design of the PV-farm

For the design of the PV-farm, there was not any data supplied. This offered a degree of freedom in the design. Firstly, the type of solar modules has to be chosen. It was decided to implement the Sunpower X-Series solar modules, because these modules have a high efficiency of 22.2% and a sufficient amount of data about the modules is available online. With this data a realistic overview of the solar farm could be designed, in which the interconnection between the modules is indicated, the area used in order to etc...

Table 3.1: System constraints based on transformer data

	V_{max} (kv)	I_{max} (A)
primary side	33	735
secondary side	171.316	808.6

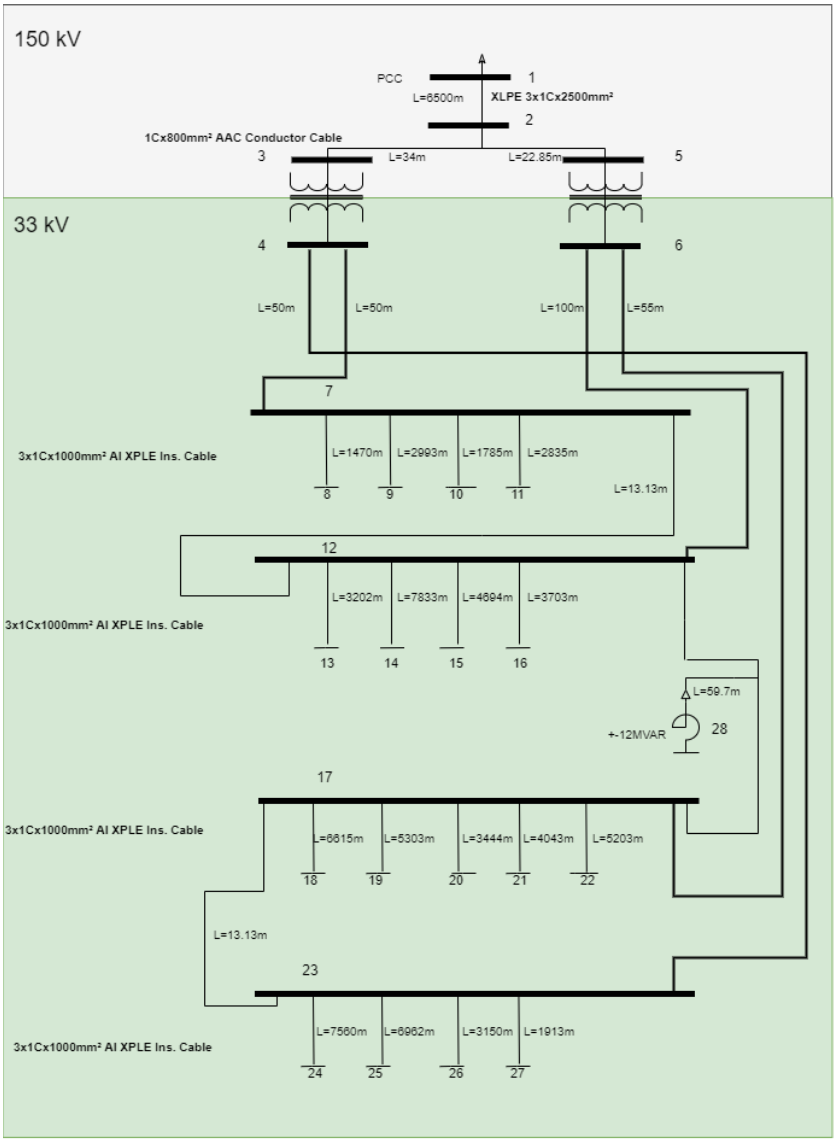

Figure 3.1: Overview of case system used in MatPower

4

Test models for operating conditions

To test the system behaviour, the model is tested under different operating conditions. A total of 16 dispatches are made; 4 hours divided in 15 minute dispatches. More dispatches will be confusing to analyse and less will be insufficient data. For the correctness of the tests, it is important to disconnect or neglect components that are not part of the test. Therefore, on the voltage profiles, the effects caused by changing the tap position, will be neglected. The tap position is assumed to be fixed and nominal, 1 p.u. This assumption is not valid anymore for 4.8.

For each test model the following procedure will be followed:

1. Normal operating conditions:
   (a) Determine maximum active and reactive power for each string.
   (b) Determine most suitable random distribution that can be applied as test model.
   (c) Generate random load demands centered around 0 MVAr. The variation will be 'x' % from the maximum reactive power that each string can generate.
   (d) **Run power flows** for each dispatch. From which:
      i. Determine the voltage profile for each bus.
      ii. Determine the active and reactive power losses for each branch.
      iii. Determine which busses violate physical constraints. Additionally, note which load demands correspond to this behaviour.
      iv. Determine which bus and branches have the highest losses in MVA. Additionally, note which load demands correspond to this behaviour.
      v. Repeat this test 5 times for similar dispatches. From this, the most common bus with limiting voltage profiles and branches with high power loss are noted. Then, a relative percentage is made compared to average behaviour of other busses/ branches.
2. With the load demands close to maximum values known and a better overview of the system behaviour, critical operating condition are determined.
   (a) The random distribution will be centered around the average maximum reactive power of each generating string.
   (b) A small variance is applied to the distribution.
   (c) The test is ran again in a same manner as for normal operating conditions.
   (d) The behaviour for critical operating conditions is determined.

4.1. Fixed wind speed and random load demands

4.2. Fixed solar irradiance and random load demands

4.3. Random wind speed and random load demands

4.4. Random wind speeds and high load demands

4.5. Random solar irradiance and high load demands

4.6. Fixed wind speed and random load demands

4.7. Fixed wind speed and random load demands

4.8. Random tap position and random load demands

4.8.1. Random tap position with fixed wind speed and random load demands

4.8.2. Random tap position with random wind speeds, solar irradiance and random load demands

5

Results

6
Conclusion

7
Discussion

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A

Appendix

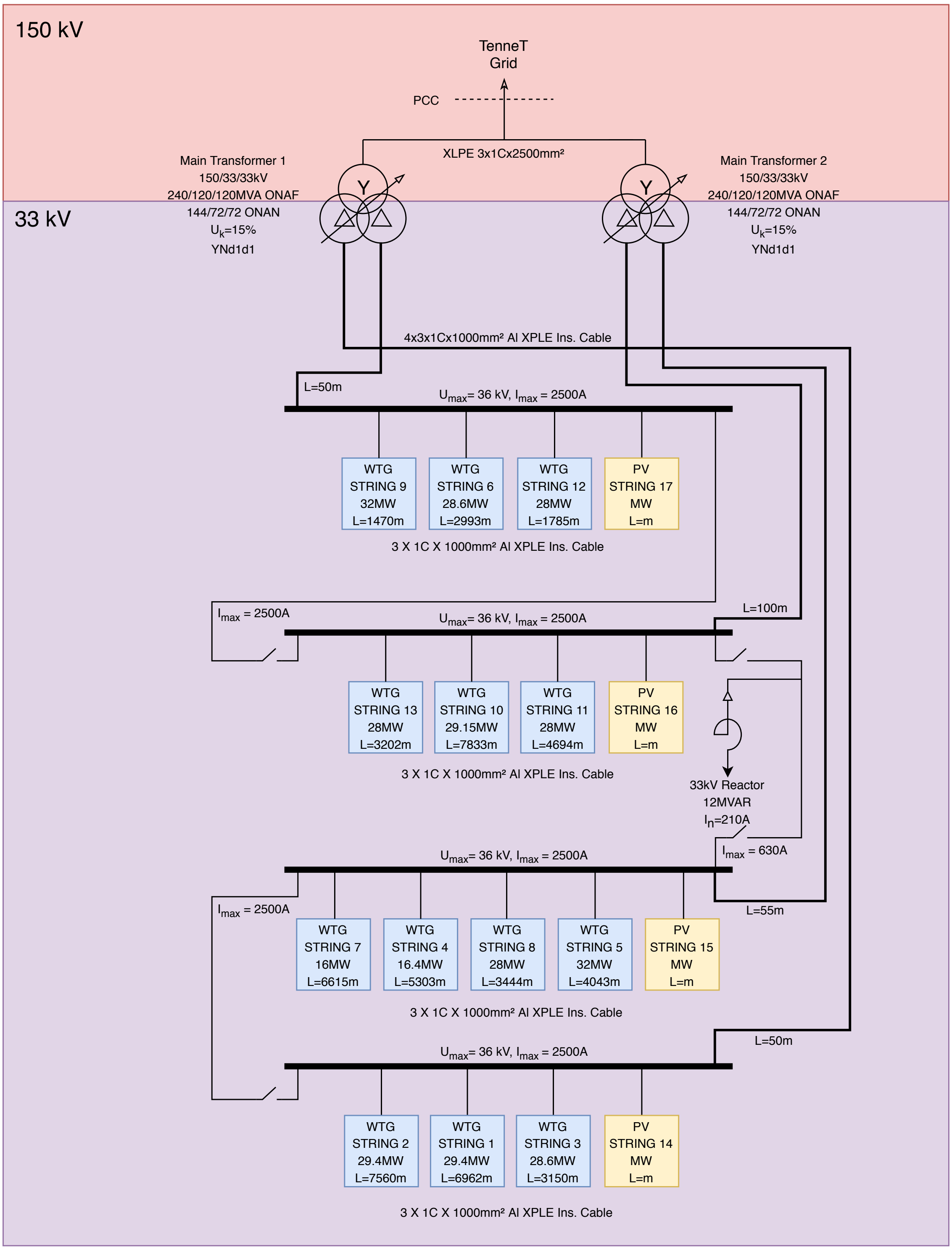

Figure A.1: Schematic of case system