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Final Design Report

Project Name: **Optimus Syria**

Sub Project: **GCD**

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Abstract

This report documents the work carried out over the last few months of the Optimus project, which forms the basis for the development of a grid code for wind turbines in Syria. The future Syrian grid is to be transformed from its current dependence on fossil fuels to a renewable future. It is therefore necessary to analyse the existing electricity feed-in guidelines, anchor them in the developed wind turbine and design them for future adjustments. The report outlines the current generation and grid infrastructure, the physical principles of grid control, the existing grid connection guidelines for generation units and a comparison with international standards. In addition, the various grid codes will be implemented in the wind turbine on a wind farm basis using DigSilent PowerFactory simulation software and tested for functionality. [1]

The aim of the work is to provide an overview of how grid codes are generally structured and how they need to be adapted to a fossil-based energy system, in this case Syria, in order to achieve sustainable energy production. Ultimately, the developed Optimus wind turbine (OSyr160-5.0) must incorporate these guidelines in its hardware and software in order to ensure future-proof operation of the plant throughout its entire service life [2].

List of abbreviations

- PCC: Point of Common Coupling
- *PETE:* PUBLIC ESTABLISHMENT FOR TRANSMISSION OF ELECTRICITY
- HVRT: High-Voltage Ride Through
- LVRT: Low-Voltage Ride Through
- ZVRT: Zero-Voltage Ride Through
- MENA: Middle East and North Africa
- PAEM: Pan Arab Electricity Market
- TSO: Transmission System Operator
- PV: Photovoltaic
- p.u.: per unit
- SCR: Short-Circuit Ratio
- FLH: Full Load Hours
- IEEE: Institute of Electrical and Electronics Engineers
- VDE: Verband der Elektrotechnik
- PS: Power System

List of symbols

Symbol	*Description*	*Unit*
P	*Active power*	*W*
P_m	*Momentary active power*	*W*
Q	*Reactive power*	*var*
S	*Apparent power*	*VA*
S_{sc}	*Short circuit power*	*VA*
S_{WF}	*Wind farm apparent power*	*VA*
V, U	*Voltage*	*V*
Z_{sc}	*Short-circuit impedance*	Ω
R_{sc}	*Short-circuit resistance*	Ω
X_{sc}	*Short-circuit reactance*	Ω
I	*Current*	*A*
I_d	*Active current component*	*A*
I_q	*Reactive current component*	*A*
f	*Frequency*	*Hz*
P_lt	*Long term flicker*	-
P_st	*Short term flicker*	-
C_p	*Coefficient of performance*	-
deltaU	*Voltage Dead Band*	*p.u.*
K_deltaU	*Reactive support gain*	-
ΔU	*Voltage difference*	*p.u.*

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1 Introduction

Although Syria has moderate reserves of oil and gas, which have so far been used primarily for its own energy supply, many of the production and refinery sites have been damaged by the recent war. Above all, the production structure, with its large power plants, is typically centralised. In a high-risk region, however, it is particularly important to decentralise energy supply in order to minimise vulnerabilities. Moreover, renewables are favourable compared to fossil fuels due to their forever availability nature.

Optimus Syria is a student project of a certain Master's in Sciences program in Wind energy engineering in Germany, where the students developed a turbine to design stage tailored for Syria.

Whenever a generator must be connected to the public electricity grid or power system (PS), certain care is needed so that the system works smoothly such as normal operation voltage range at the grid connection point, frequency, etc. The grid operator aims to keep the grid function with minimal downtimes and for this purpose, operator publishes documents that inform the generators of these requirements and keeps updating every few years, so that unsatisfactory performance is reduced. These documents or standards are published in various methods as per region. Often a country or a state appoints a single body which publishes the Grid Code documents. In Syria it is the public body PETDE (Public Establishment for Transmission and Distribution of Electricity), and in Germany it is VDE-FNN (Verband der Elektrotechnik Elektronik Informationstechnik e.V - Forum Netztechnik/Netzbetrieb).

The grid code operator requires a certificate of compliance that says that the power plant behaves as per the published standards. In Syria, these are primarily two documents that we are concerned about for the sake of integrating wind power with their grid:

1. PETDE, Transmission Grid Code, 2014 [3]
2. PETDE, Rules and conditions for connecting renewable energy projects, 2022 [4]

Similarly in Germany, the important relevant documents for our use case are:

1. VDE-AR-N 4110, Technical connection rules for medium voltage [5]
2. VDE-AR-N 4120, Technical connection rules for high voltage [6]

Certainly, it was advantageous to have German Grid Code documents in consideration as it is very well documented and has been so for a long time. While Syrian documents do have details, we shall see in the following parts some important details are missing. Fortunately, this gave us scope to suggest improvements to the Syrian electricity institute and the Damascus university. The list of all grid code standards was helpfully consolidated by DNV.

Currently, the supply of electricity in Syria is not sufficient to meet the demand. For households, it is only a few hours per day of supply [7]. In mid-2025, improvements were made by introducing a pattern of 2 hours on and 4 hours off in most provinces. Because of many years of conflict, many power plants and transmission lines are damaged, and the investment has not been sufficient for a reliable grid. Generation is constrained by fuel shortages: many thermal plants sit idle without adequate gas/oil supply, and key resources and infrastructure are not fully under unified control. According to a report from UN, as in late 2025, effective generation capability was around 1.6 GW compared to 9.5 GW during pre-war period in 2011 [8]. There are also fuel shortages, i.e. many thermal power plants sit idle.

There are about 25,582 km of transmission lines at 2025 end [9]. There are four levels of transmission and distribution voltages available: 0.4 kV as low voltage, 20 kV as medium voltage, 66 kV as high voltage, 230 kV as extra high voltage or high voltage. Syria's transmission and distribution owner/operator (PETDE) describes widespread substation destruction/disrepair and very high losses, citing transmission technical losses estimated at "more than 6%" and very high distribution losses (PETDE text cites almost half of 22% distribution losses)

The source of electricity in Syria is mostly based on fossil fuels with little renewable energy usage as shown in the table below. In 2025, Syria and Saudi developer ACWA Power signed a framework agreement to study roughly 2.5 GW of renewables (about 1 GW solar PV + 1.5 GW wind), with potential grid-scale storage also considered.

S No.	Power type	Power value (MW)	Count
1.	Oil	2781	5
2.	Gas	2346	4
3.	Hydro	1535	6
4.	Gasoline	750	1
5.	Solar	17	27
6.	Wind	11	2
	Total	**7780**	**64**

Table 1: Distribution of power capacity by fuel source in Syria

A Syria-focused sector brief using Ministry of Electricity data reported electricity output falling from about 49,000 GWh (2011) to about 12,900 GWh (2023) (roughly a 75% decrease). One estimate cited in 2025 stated production around 2,600 MW versus demand around 9,000 MW, implying a very large gap that must be covered by self-generation or remains unmet [10]. Because grid supply is limited, a large share of real electricity use is met through a patchwork of diesel generators and, where affordable, rooftop solar, rather than recorded grid consumption.

The World Bank approved a US$146 million grant (SEEP) focused specifically on rehabilitating high-voltage transmission lines and critical high-voltage substations, plus technical assistance and implementation support. SEEP explicitly targets two damaged 400 kV interconnector transmission lines to restore regional connectivity with Jordan and Türkiye and improve system stability (fewer blackouts via connection to stronger grids). The same program highlights that Syria's T&D system has very high losses and that many substations were destroyed or left in disrepair, making the "backbone grid" unreliable [11].

2 Site and turbine details

The OSyr160-5.0 turbine is 5 MW class machine, with the following specifications:

S No.	Variable	Value
1.	Rated power	5 MW
2.	Rotor diameter	160 m
3.	Hub height	100
4.	Class	IIA
5.	Rated wind speed	10.86 m/s
6.	Generator type	DFIG
7.	Converter type	Partial
8.	C_p optimum	0.474
9.	FLH at Qattinah	4498

Table 2 Optimus Syria research turbine overview

The site of installation of this turbine was chosen as Qattinah, with 34°40’22”N, 36°35’59”E as the exact coordinates as in Figure 1.

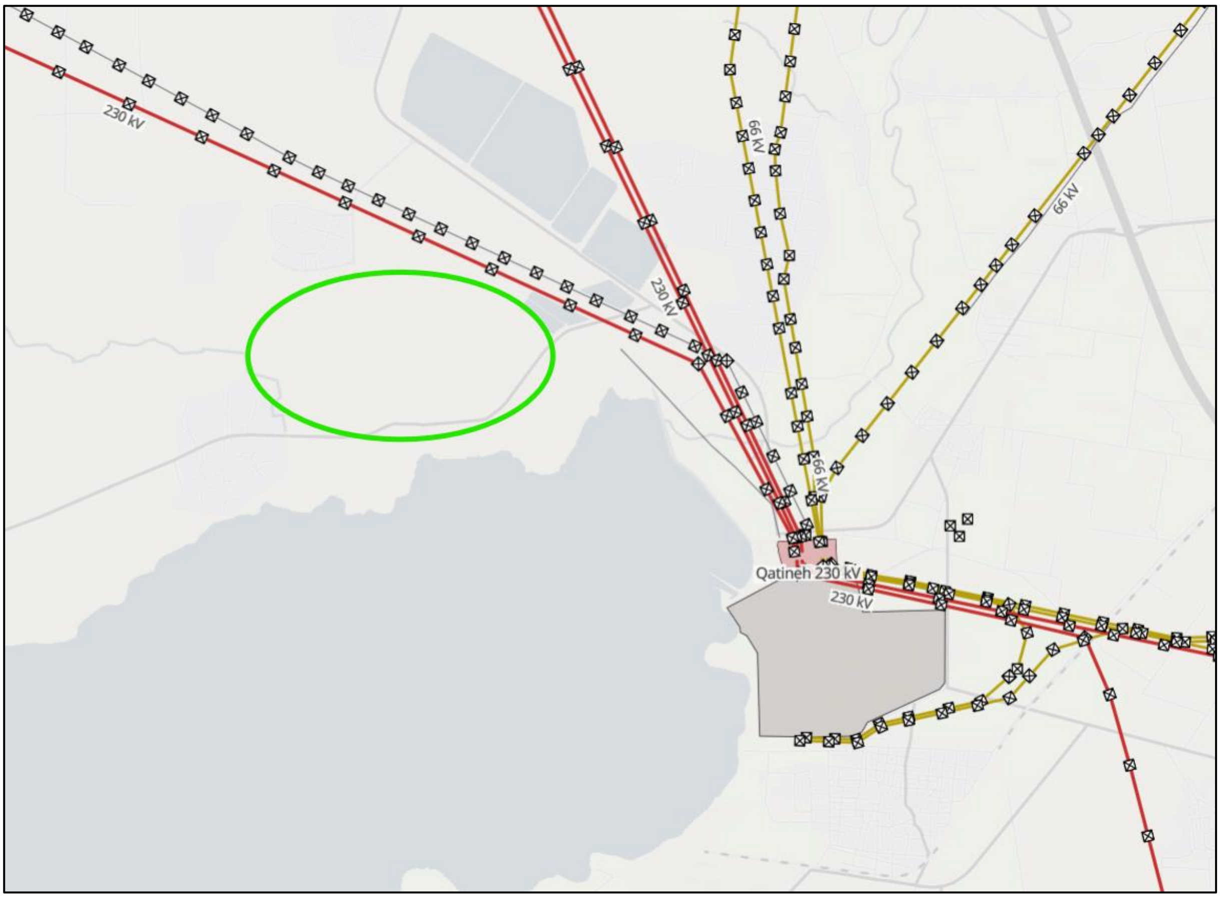

Figure 1; Wind farm location marked near Qattinah substation

The closest substation to the development site is Qattinah substation and hence it has been chosen as the grid connection point (GCP). It is a transmission type with 230 kV and 66 kV voltage lines available. The Syrian Grid Code says that to be connected to 230 kV, the power of wind farm must be more than 40 MW. Hence, 66 kV is chosen as the number of turbines are four which were planned by project development team. [4]

The details of power transfer and further details such as dynamics of voltage, current, short-circuits, frequency, ROCOF, etc. are unavailable for this substation. Therefore, some parameters had to be assumed as follows while some were preferably chosen to be worst case, which will be mentioned at its own place in further sections.

In Syria, the current situation of overall grid is good to be known. The availability of electricity is discontinuous with load shedding and average of four hours a day. Furthermore, the grid is mostly based on fossil fuels as in table below.

3 Electrical parameters

There are many variables in electrical PS to be considered as mentioned before such as voltage, current, short-circuit power ratio, ROCOF etc. This chapter is aimed at preparing a checklist of important ones.

Voltage and frequency steady-state ranges in different operation modes are given below [3]. Phase imbalances i.e. voltage deviations among phases shall be below 2%.

Operation state	**Frequency [Hz]**	**Voltage [kV]**
Normal	49.90 – 50.10	64.02 – 67.98
System stress	48.75 – 51.25	64.02 – 67.98
Emergency / extreme fault	47.5 - 51.5 Hz	64.02 – 67.98
Restorative / black start	-	-

Table 3: Grid operation states

Power factor should not be less than 0.98. However, special circumstances might be allowed based on review. Short circuit current must be at least 3 times the rated current. Voltage flicker is a representation of the visible light bulb flicker that occurs due to disturbance in voltage. It is measured in two variables: short-term(P_st) and long-term flicker(P_lt). While Syrian guideline follows IEEE 519-1992 with P_st < 1.0 and P_lt < 0.7, it is outdated. It is better to update to one of the recent regulations such as IEC 61400-21-9: 2019 [] with P_st < 0.35 and P_lt < 0.25.

Harmonics are voltage or current waveforms whose frequencies are integer multiples of the fundamental power frequency (50 Hz) caused by non-linear loads such as pulsating electronics in the power converter. Individual harmonics shall be less than 2% and Total Harmonic Deviation (THD) be less than 3% on 66 kV which, often, are calculated based on current waveforms [4].

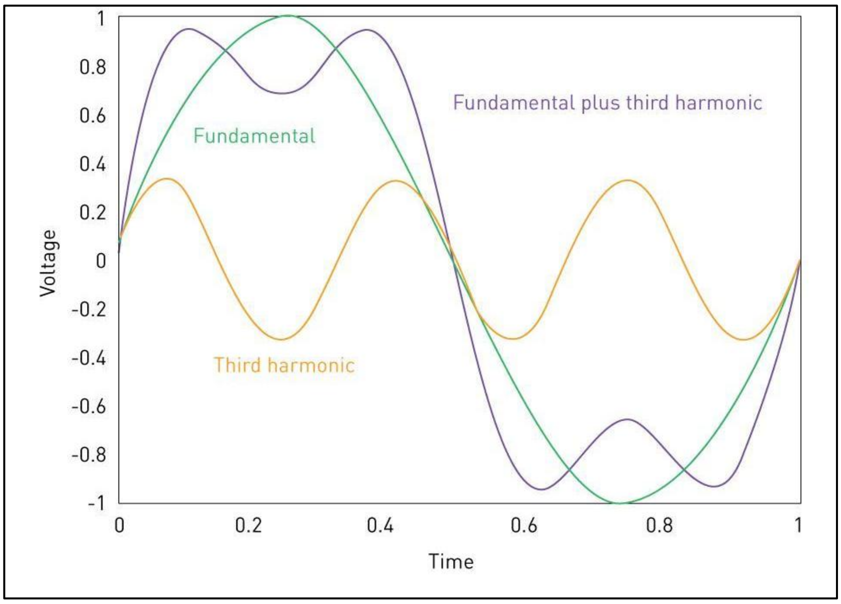

Figure 2: Harmonics

Active power – frequency and reactive power - voltage are important specifications to which any generator must adhere to the national or regional grid code. Unfortunately, the active power – frequency is unavailable in Syrian Grid Code documents and hence the German code VDE 4110 [5] is taken as reference as in Figure 3 below. Frequency acts as guide that informs the balance of power transfer between turbine and grid i.e. supply and demand respectively. When frequency increases, it means that there is more production of electricity from turbine than what is consumed by grid.

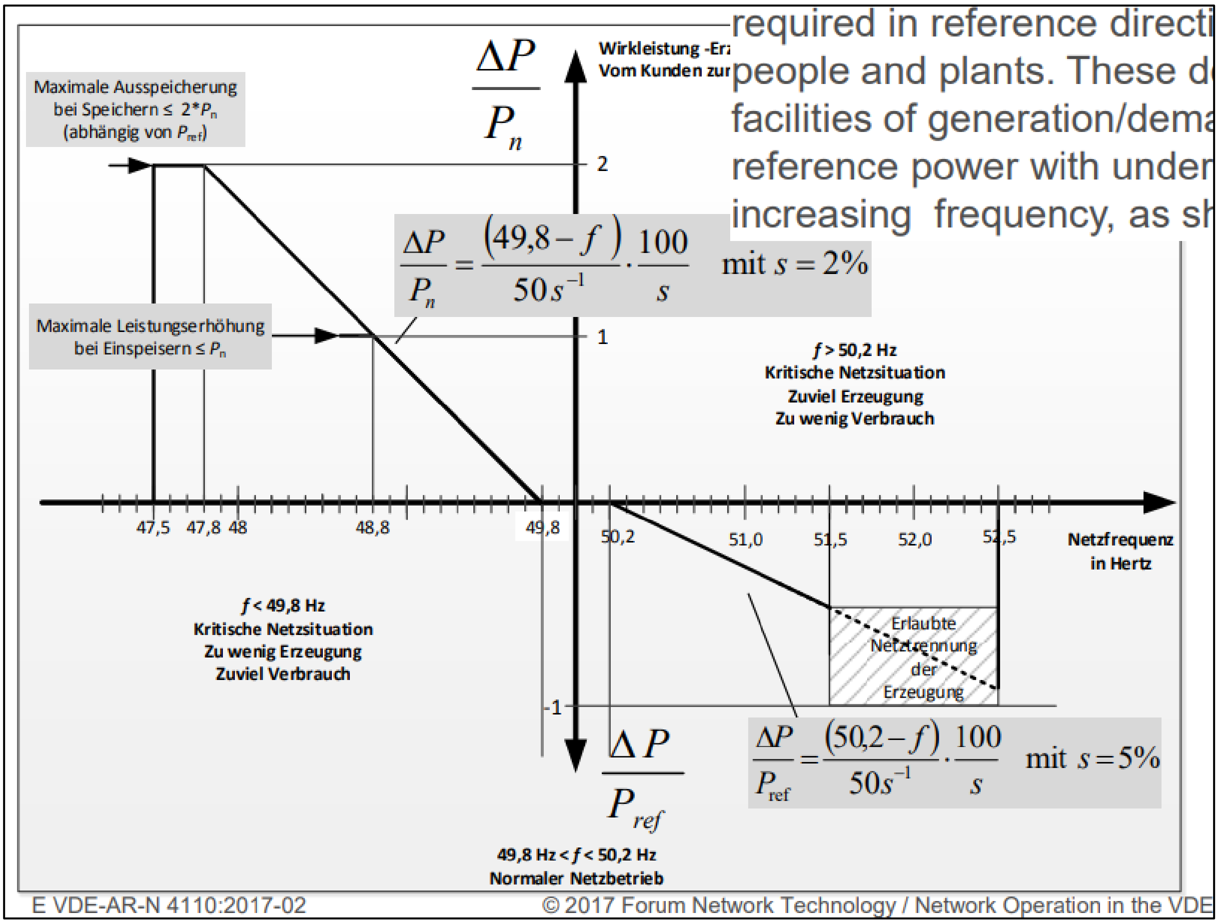

Figure 3: P-f droop characteristic

Reactive power and voltage relationship is another necessary condition to be met and is given below from Syrian grid guidelines. As voltage increases beyond certain limits, reactive power is absorbed from the grid by turbine to reduce the voltage down to normal and vice versa.

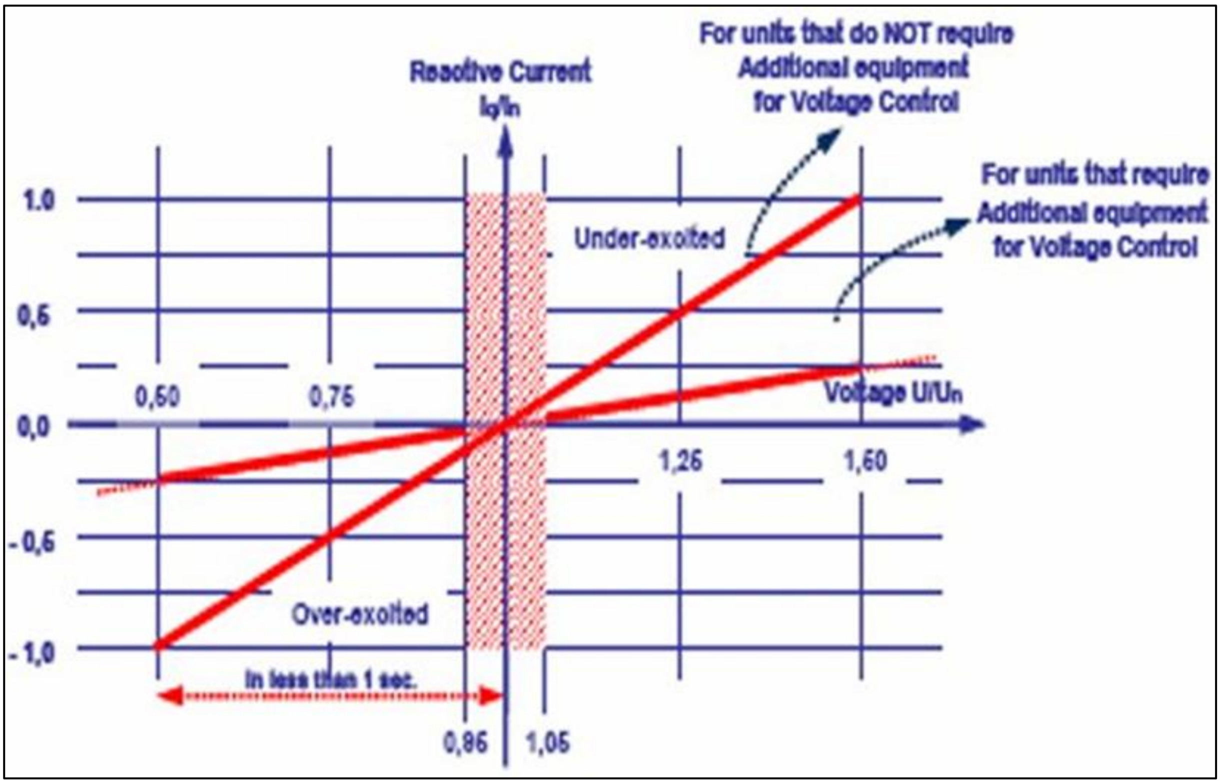

Figure 4: Q-U droop characteristic

FRT (Fault Ride Through) is another specification given as curve of voltage along time that tells us about the unusual condition of voltage at PCC for which the turbine must be connected and the duration. It could be divided into Low-Voltage Ride Through (LVRT) and High-Voltage Ride Through (HVRT). Only the LVRT requirement is given by Syrian transmission Grid Code as in Fig. 5 below.

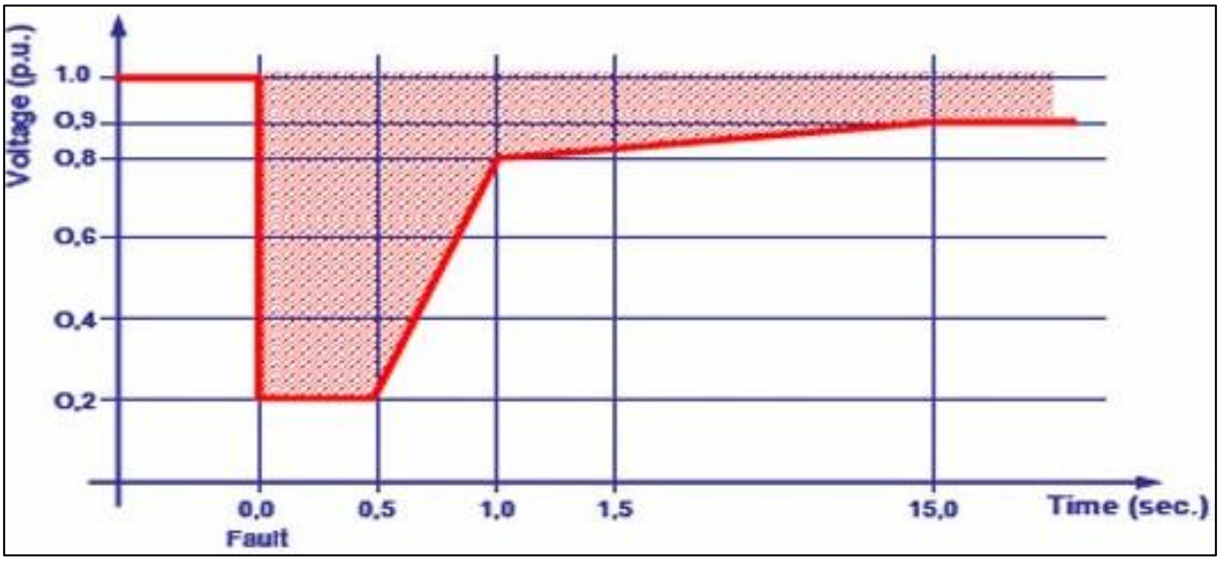

Figure 5: LVRT in Syria

Since only LVRT is available, HVRT is taken from German Grid Code VDE-AR-N-4110 given in Fig 7 [12, p. 37]. The figure also gives the LVRT in Germany which can be used for comparison with the Syrian one.

For the sake of checking the FRT behavior in PowerFactory, the impedance of the grid at the point of common coupling must be calculated during the short-circuit. This impedance is called as fault impedance.

Let $Z_{fault} = fault\ impedance$
And $S''_{k\,max} = short\ circuit\ power$
The remaining variables are hopefully understandably simple.

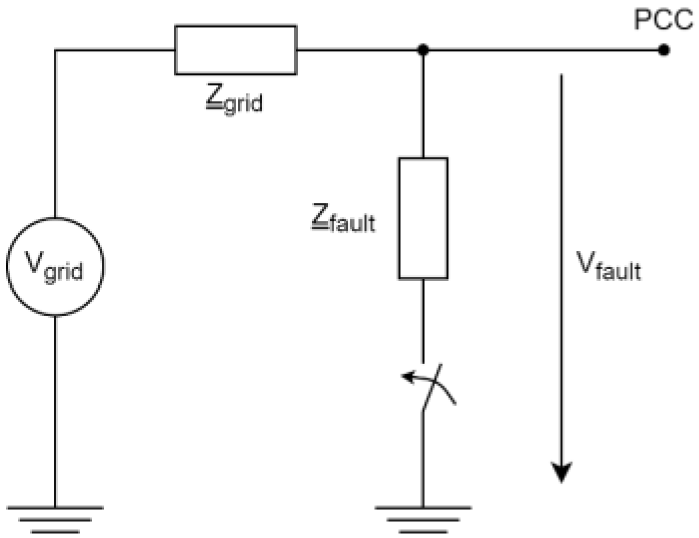

Figure 6: Fault diagram at PCC [13]

$$Z_{grid}(complex) = \frac{c.(V_{grid})^2}{S''_{k,max}} \quad (3.1)$$

$$Z_{fault} = \frac{V_{fault} \cdot Z_{grid}}{V_{grid} - V_{fault}} \quad (3.2)$$

$$X_{grid} = \frac{Z_{grid}}{\sqrt{1+\left(\frac{R}{X}\right)^2}} \quad (3.3)$$

$$R_{grid} = \sqrt{{Z_{grid}}^2 - {X_{grid}}^2} \quad (3.4)$$

S No.	V drop (%)	t (s)	V_fault (kV)	V_grid (kV)	Z_grid (magnitude)	R/X	S" k,max (MVA)	Z_fault X (ohm)	Z_fault R(ohm)
1	100	0.15	0	66	1.917	0.18	2500	0.00	0.00
2	80	0.5	13.2	66	1.917	0.18	2500	0.472	0.085
3	20	1	52.8	66	1.917	0.18	2500	7.545	1.358
4	10	15	59.4	66	1.917	0.18	2500	16.977	3.056

Table 4: Short-circuit or fault impedances

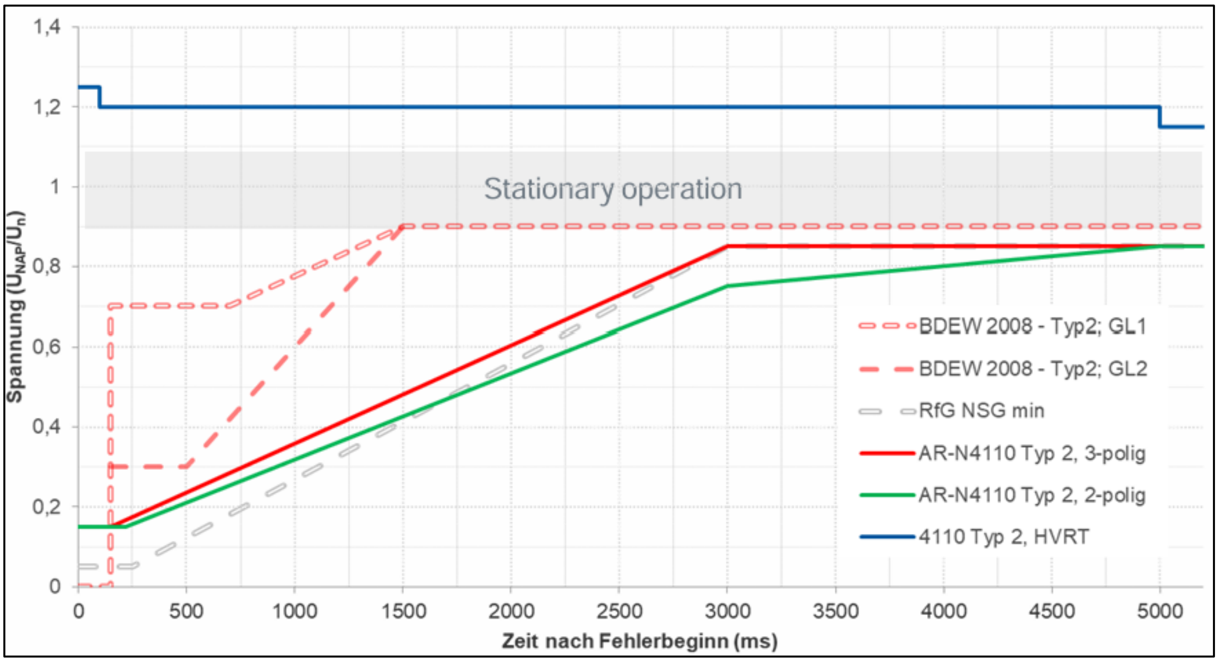

Figure 7: Past German Grid Codes

4 Development of Grid Code

4.1 Evolution of Grid Codes

Historically, PS were characterised by the presence of large-scale synchronous generators, which were typically centralised. These dispatchable assets constituted the fundamental components of the grid, providing essential rotational inertia and facilitating the delivery of bulk power to load centres via transmission networks. However, the global energy landscape is undergoing a paradigm shift towards a more diversified and decentralised generation mix. This transition is primarily driven by variable renewable energy sources, specifically photovoltaic (PV) and wind, which have reached technological maturity and cost-parity with conventional fuels.

The integration of variable renewable energy sources, which is occurring at a rapid rate, introduces significant operational complexities. In contradistinction to conventional thermal power stations, variable renewable energy sources are intermittent, location-dependent and inverter-based. As these technologies displace conventional synchronous machines, they fundamentally alter the system's dynamic response to disturbances. Additionally, concurrent trends of digitalisation, electrification, and decentralisation are reshaping the grid's trajectory, albeit at an increased systemic cost. System operators (SOs) are now charged with maintaining a delicate balance between flexibility, to manage supply and demand imbalances, and stability, to ensure recovery during contingencies.

In this evolving landscape, the multi-stakeholder nature of the grid comprising Independent Power Producers (IPPs), regulators, and planners requires enhanced monitoring and coordinated control. The capacity to execute operations in real-time effectively is no longer feasible through the utilisation of conventional methodologies alone. Instead, it relies on robust regulatory frameworks and technical principles, such as grid codes, to standardise the conduct and contributions of diverse assets across the system [14, pp. 8-9].

The advent of inverter-based resources (IBRs) precipitated the necessity for grid codes as a regulatory instrument to ensure system stability. The primary objective of these initiatives was to mandate that variable renewables contribute to grid security by emulating and eventually exceeding the stabilising characteristics of conventional power stations. While the initial regulatory framework concentrated on fundamental fault ride-through capabilities to avert mass disconnections, there has been a shift towards utilising the enhanced response speeds of power electronics for sophisticated frequency and voltage control. The purpose of these codes is to standardise "system-friendly" behavior, thereby reconciling the high-performance technical potential of modern inverters with the need for a stable, technology-neutral energy market [14, pp. 29-30].

Despite the existence of global fundamental guidelines such as the RfGs or the IEEE standards, it is important to note that grid codes may vary from one country to another. There are numerous factors that contribute to this phenomenon. The primary objective is frequently market-oriented, yet technical requirements are also frequently a salient factor. TSO's or member states are at liberty to select the parameters that most accurately align with their grid infrastructure, thereby ensuring operational security. In the European Union, for instance, the distribution of the grid extends across multiple countries.

This necessitates the fulfilment of precise requirements to ensure the seamless integration of generators within the grid. However, it should be noted that individual countries retain the prerogative to implement more stringent regulations if they deem it necessary.

It can thus be concluded that the national adaptation of the grid code will always be necessary in order to respond to the circumstances of the existing market and take all details into account. This is particularly true due to differences in the proportion of renewable, decentralised producers, which can vary greatly from country to country [14, pp. 79-80].

The harmonisation of grid codes is advantageous in a number of ways, primarily because it ensures that they remain essentially consistent across different regions. A primary benefit is the increased transparency and standardisation for manufacturers of power-generating units. It is imperative to note that each system, including OSyr160-5.0, must undergo a bespoke configuration process to align with the specific grid code requirements stipulated by the relevant national regulatory authorities. Significant deviations between these codes impose a substantial financial burden on OEMs due to the need for specialised hardware and software adaptations.

Concurrent with these manufacturing efficiencies, this technical alignment also facilitates broader systemic savings by optimising the regulatory landscape. The standardisation of grid codes has been demonstrated to facilitate significant economies of scale for network operators, through the streamlining of certification and conformity assessment processes across multiple jurisdictions. By pooling technical expertise and testing infrastructure, countries can eliminate redundant administrative overhead and minimise the high costs associated with individualised national compliance monitoring. Moreover, the establishment of a cohesive regulatory framework has the potential to mitigate financial impediments for manufacturers by facilitating the utilisation of a single certification across multiple markets. This, in turn, can result in a reduction in procurement costs and an acceleration in the implementation of system-compatible technologies [15, pp. 58-59].

While global harmonization offers clear economic benefits, the practical implementation of advanced grid codes depends heavily on a nation’s specific socio-economic and political stability, as seen in the MENA region. Syria is a member of the Pan Arab Electricity Market (PAEM), a regional organisation comprising Turkey, Iraq, Jordan, Egypt, Libya, Lebanon and Palestine. Syria is a country with a particularly strong physical connection to several other nations. To the north, it is bordered by Turkey; to the south, it is bordered by Jordan and Lebanon; and to the south-west, it is bordered by Iraq. In the broader context of the Middle East and North Africa (MENA) region, encompassing the states in the near and middle east, there are certain countries undergoing rapid transformation towards renewable energy sources. A notable example is Saudi Arabia, which is poised to augment its installed renewable capacity by 100-130 GW. The lion’s share of this increase is projected to come from PV [16]. It is imperative that these countries bring their grid code standards up to date and place greater reliance on system stability through complexity. Grid-forming codes are of significance in that they enable the system to maintain a high degree of resilience even at extremely high penetration levels. This ensures that the network can recover from disturbances without relying on a core of conventional thermal power plants. Conversely, Syria is deficient in the financial resources and political influence that are prerequisites for implementing such a radical transformation. It is imperative that the primary objective of the aforementioned entity is to rectify the damages incurred as a result of the war, whilst simultaneously ensuring the provision of uninterrupted power to the customer [14, pp. 56-57].

The development of grid codes in the near and distant future is contingent on the extent to which renewable energies are expanded in the respective country or region. The following subjects are of particular relevance in this context. Firstly, the term ‘black start capability’ is employed to denote the ability of a generator to initiate operation in the absence of an external power supply. Furthermore, it encompasses the capacity to recommence the functioning of all or a proportion of a grid following a comprehensive failure. The primary means of ensuring this at present is through the utilisation of large power plants that are equipped with synchronous generators. However, it is predicted that these will be displaced from the market in the future, and consequently, new renewable production units with grid-forming functionality will have to be installed. The establishment of a suitable framework for this technology is often proposed to be achieved by the introduction of an additional grid-forming market. Grid Codes will then encompass requirements such as serving as a sink to balance peaks and surges in system voltage, ensuring the generation of system voltage, or contributing to the fault level (short-circuit power) [14, 66, 68-70].

Furthermore, the question of controllability requirements, even for small variable renewable energy sources, the harmonisation of communication interface requirements and the integration of control systems are playing an increasingly important role. Another interesting aspect, particularly in the context of the current Optimus project, is the continuous roll-out of HVRT requirements in the medium and low voltage range, which are not yet enshrined in many grid codes. Overvoltage can occur in a number of situations, including large-scale generation or load shutdowns, earth fault elimination, and transient phases following the activation of large capacitor banks. Finally, LVRT behavior should be mentioned, but only on the low-voltage side, which does not affect conventional wind energy. However, the requirements in this instance are not as stringent as those for passing through zero voltages or the requirement for reactive or active power feed-in [14, p. 51].

However, other areas that will play an important role in the electricity system of the future, such as e-mobility, must also be taken into account, keyword vehicle to grid. The role-playing storage facilities, but also feeders, therefore also need a suitable framework in order to be able to participate in the system. The increase in the number of electric vehicles is substantial in certain countries. In view of the fact that the charging capacities in question are significantly higher than those associated with standard household connections, it is imperative that grid regulations are also established in this context. In accordance with prevailing conventions, these units are generally managed in a manner analogous to that of local storage facilities, should there be a desire to reintegrate active power into the grid [14, p. 55].

4.2 Design work

In order to apply the theory to the OSyr160-5.0 and the Syrian Grid Code, the existing PETE Grid Code from 2013 was first studied and evaluated. The following observations were made and a state of view is shown in table 5.

Grid Code Requirements	Covered	Grid aligned
Voltage and frequency operation range	yes	yes
Flicker/harmonics	yes	yes
Protection Criteria	yes	yes
Generating Unit Requirements	yes	yes
Reactive power Range & Voltage Control	yes	yes
Active power Range & Frequency Control	no	-
LVRT	yes	no
HVRT	no	-

Table 5: Content Syrian Grid Code

As previously discussed in section 4.1, not any grid code contains any specific regulations. The Syrian Grid Code has also some lacks or not grid aligned of requirements, which were revised in this team project. The following specifications will be discussed.

Active power Range & Frequency Control:

The requirement for frequency control capability via active power was not included in the PETE code and was copied from this VDE Guideline 4110. In the event of overfrequency, it is imperative to regulate the feed-in of active power. In the event of underfrequency in the system, the plant must be brought to nominal load, if possible, or the active power must be increased for a limited time in the nominal load range. This phenomenon can be attributed to inertia response or Fast Frequency Response (FFR) [14, p. 30].

The following equation is employed to calculate the precise active power regulation, which is required for the frequency operation to be conducted within the range of 50.2 and 51.5 Hz [1, p. 348]. More information´s are shown in Figure 3 in chapter 3.

$$\Delta P = 20 P_m \frac{50.2\,Hz - f_{grid}}{50\,Hz} \quad for\ 50.2\,Hz < f_{grid} < 51.5\,Hz \qquad (4.1)$$

HVRT:

The frame for the regulation of the generators in overvoltage events are also not mentioned in the PETE code. The generator and thus the Optimus turbine must remain connected to the mains for an overvoltage of 1.25 p.u. for 0.2 seconds and at 1.2 p.u. for 5 seconds. This lacuna was addressed by adopting the HVRT curve from VDE Guideline 4110 Type 2 of 2017, which is delineated in Section 3. This will become particularly important in the future when a greater number of wind farms are connected to the Syrian grid. In the context of large wind farms, a transition phase with high voltage is often observed following the rectification of a fault. This phenomenon can be attributed to events characterised by elevated levels of reactive power feed-in from renewable energy producers. A comparable incident transpired in Germany in 2012, wherein a sudden cessation of 1.7 gigawatts of wind power resulted in substantial overvoltage in a 420 kV transmission network. This example demonstrates the necessity of taking this requirement into account in future projections [14, pp. 51-52]. The exact rebuilt curve is shown in Figure 8 below.

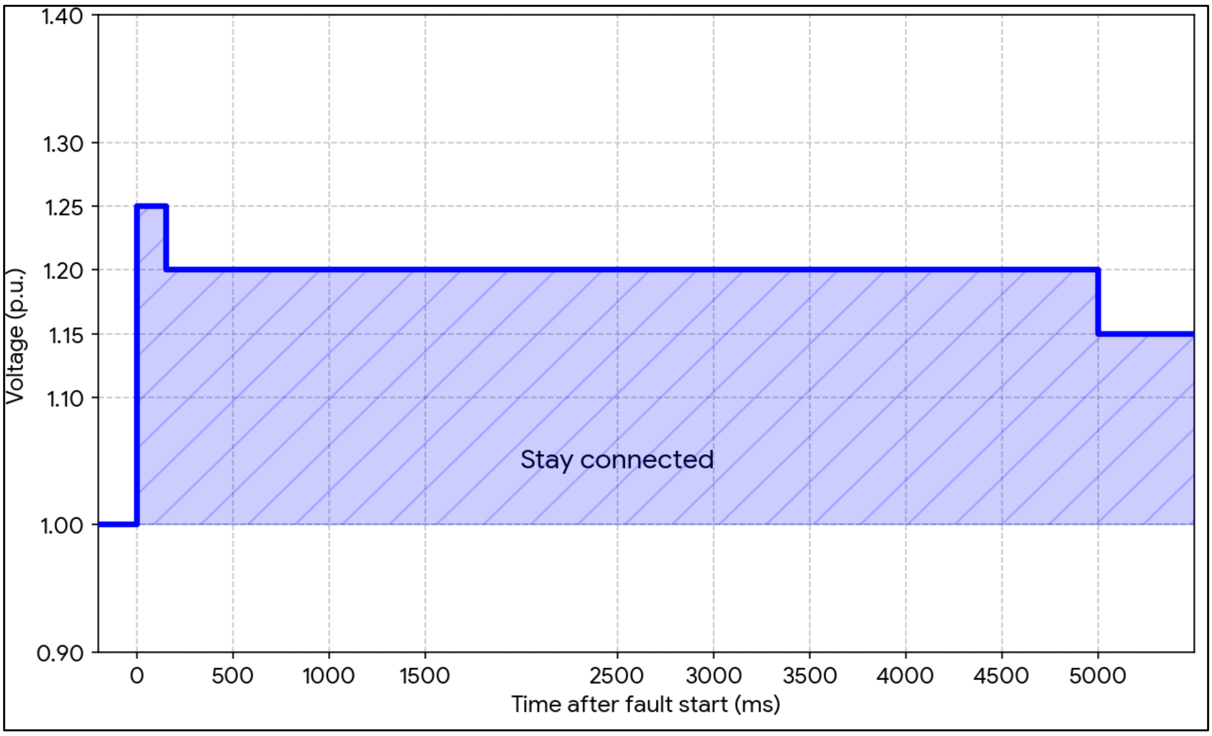

Figure 8: HVRT Optimus Syria

LVRT:

The requirement of the Low-Voltage Ride Through is given in the PETE with its behavior as already showed in Figure 5 in chapter 3. Historically, the LVRT requirement, which was exclusively designed for large power plants in Syria's energy system, has been shown to be effective. However, with the increase in renewable generation units, requirements in this area are also changing. An analysis of the development of LVRT behavior in the German Grid Code reveals the implementation of Zero-Voltage Ride Through (ZVRT) at the turn of the millennium, which was driven by the increased emergence of renewable energies. In 2017, the VDE Grid Code was amended to stipulate a maximum tolerable voltage dip of 85%. This 'step backwards' can be attributed to the substantial advancement of the grid over the past 15 years, during which numerous safety mechanisms have been implemented [14, p. 27].

It is evident that the Syrian government has not yet established such a security infrastructure, which is pertinent in the context of its power line infrastructure. It is imperative that wind and solar power plants maintain their connection to the grid and ensure the reliable delivery of active and apparent power, even in circumstances where voltage falls to 0% in the forthcoming decades [15, p. 87].

This requirement is supported by another real-life example from the past. In 2006, Spain had an installed wind power capacity of almost 12 GW. In accordance with the prevailing standards at the time, a voltage dip threshold of 85% was established for generators, with the consequence of disconnection from the grid for those exceeding this threshold. The TSOs identified the potential risk of large-scale outages that could be caused by this combination. Consequently, a response was implemented in 2007 in the form of an obligation for all new wind and PV installations to comply with the ZVRT. Installations failing to meet this requirement were subject to priority reduction or the suspension of their energy subsidies.

By 2009, the number of wind turbines retrofitted had surpassed 10 GW. This process was associated with high costs [15, p. 53].

The LVRT behavior was harmonised with Syrian regulations by implementing a 100% voltage dip for 150 milliseconds, based on the technical model of the BDEW 2008 [17, p. 23]. Despite the relatively limited scope of this parametric change, it has a substantial impact on fault tolerance and overall grid stability. With regard to its ZVRT property, the LVRT curve is analogous to the currently valid IEEE 1547 Grid Code, Version 2022, from the USA [18, p. 387]. The results are shown in Figure 9.

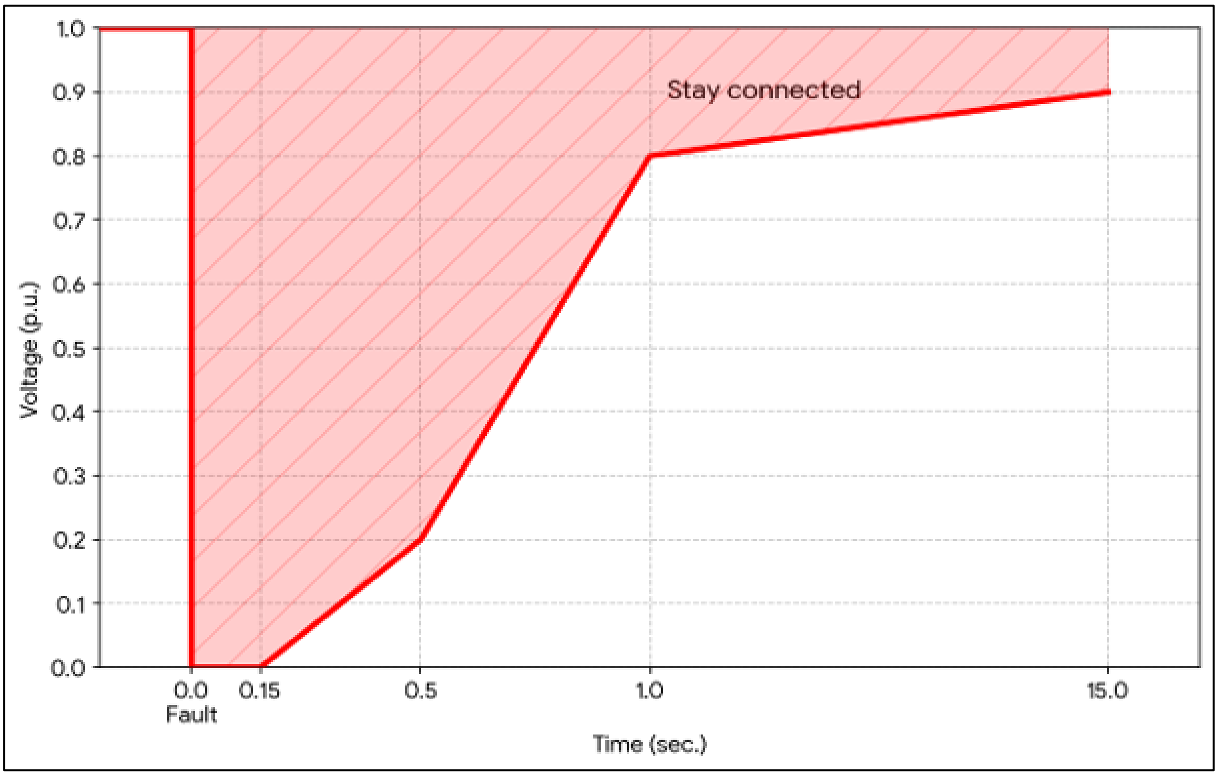

Figure 9: HVRT Optimus Syria

5 PowerFactory

PowerFactory is a leading network calculation software, owned by the German company DigSILENT, that is utilized for the purpose of calculating generation, transmission, distribution and industrial networks.

The software in question is capable of handling a wide range of functions, from standard operations to highly complex and demanding applications. These include wind power, decentralised generation, real-time simulation and performance monitoring for network testing and monitoring. PowerFactory is characterised by its ease of use, comprehensive Windows compatibility, and integration of reliable and flexible network modelling functions with state-of-the-art algorithms and a unique database concept. PowerFactory is a software that is ideal for highly automated and integrated solutions in business processes, due to its extensive data interface and scripting capabilities [19].

Figure 10: PowerFactory label – DigSilent

PowerFactory offers a substantial number of YouTube videos that are highly beneficial for those seeking to hone their proficiency in utilising the software. In conjunction with the predefined models, which plopping up automatically after opening the Software, it is more straightforward to comprehend how the working principles have noticeably reduced the effort at the initial stage. As illustrated in Figure 11, the application examples are presented in a manner that is both available and accessible.

Figure 11: Available Application Examples – PowerFactory

Windfarm layout

Subsequent to the initial results from the Project Development team regarding the windfarm size, the team initiated the creation of a replica in PowerFactory. The windfarm template provided a valuable point of departure for this study. In collaboration with the electrical drive train team, the defined parameter for the turbine and transformer was subject to constant refinement. As illustrated in Figure 5.3, the culmination of the park layout is constituted by four OSyr160-5.0, interconnected by a 0.96/20 kV step-up transformer and linked to a transfer station via cables. Subsequently, the grid connection cable is routed to the PCC situated at the Qattinah Substation. The system incorporates a condensator unit with the function of maintaining the voltage.

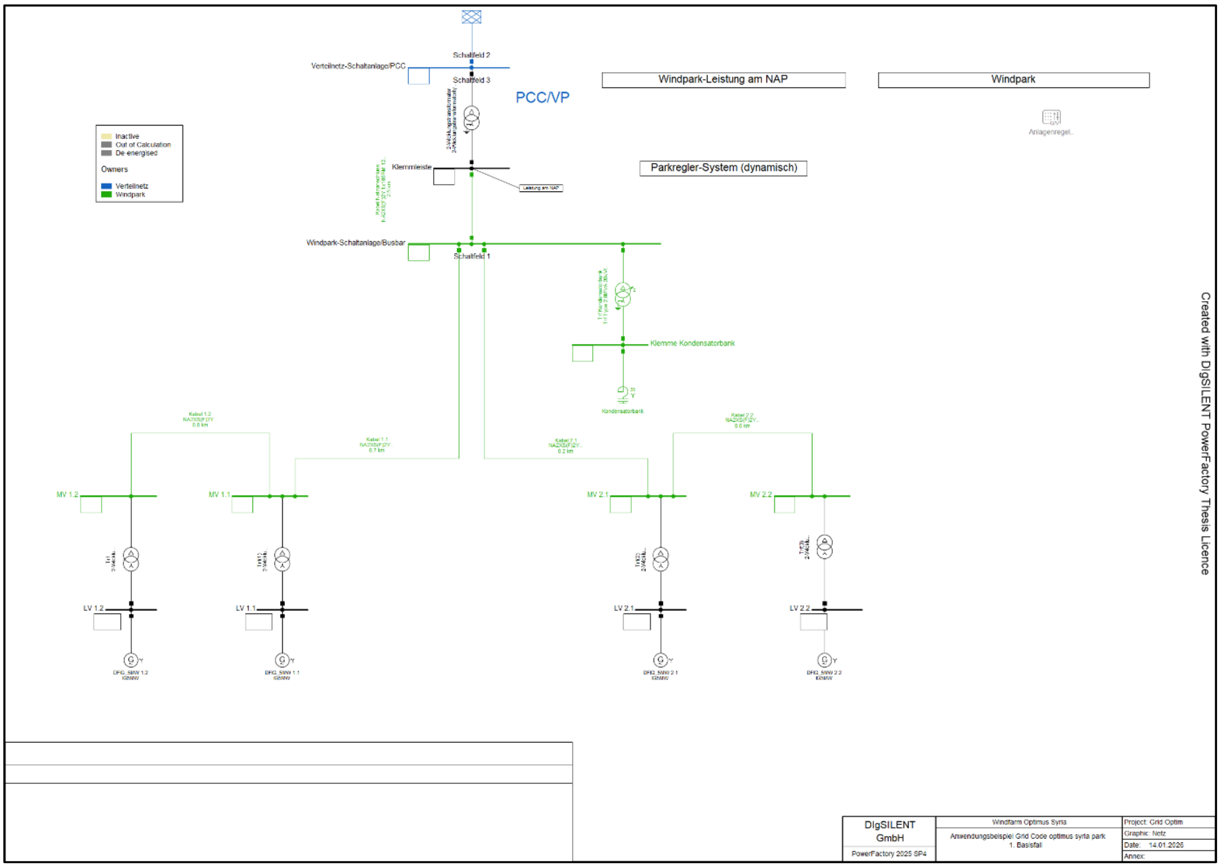

Figure 12: Optimus Syria windfarm – PowerFactory

In table 6 and 7 are the two given parameters from the electrical drive train team. Table 8 contents the big substation Transformer parameters, which were assumed.

OSyr160-5.0	
Machine type	DFIG
Apparent Power S [MVA]	5.733
Active Power P [MW]	5
Frequency f [Hz]	50
Rated voltage U [V]	960
Number of pole pairs p	3
Stator resistance R_s [p.u.]	0.0135
Mag. Reactance X_m [p.u.]	3.5
Stator reactance X_s [p.u.]	0.1
Rotor reactance X_{rA}[p.u.]	0.1
Rotor resistance RrA [p.u.]	0.04844

Table 6: Desgin Parameter OSyr160-5.0

OSyr160-5.0 Transformer	
LV-side [kV]	0.96
HV-side [kV]	20
Rated Power S [MVA]	5.31
Frequency f [Hz]	50
Short-Circuit Voltage uk [%]	6
Copper-losses [kW]	24.14
Short-Circuit Voltage uk0 [%]	3
No Load Current [%]	0.8
No Load Losses [kW]	3.5
Vector group	Dy11

Table 7: Desgin Parameter OSyr160-5.0 Transformer

Transformer Substation	
LV-side [kV]	20
HV-side [kV]	66
Rated Power S [MVA]	25
Frequency f [Hz]	50
Short-Circuit Voltage uk [%]	11
Short-Circuit Voltage uk0 [%]	3
Vector group	Dyn5

Table 8: Desgin Parameter Transformer Substation

5.1 Load flow analysis

Load flow analysis is steady state analysis to find out voltages, voltage angles, active and reactive power at one operation point with specified generation or demand. It can be used to find out the places of overloading by power and voltage limits before dynamic analysis.

As introduced above, load flow analysis is fundamental for PS analyses that answers the following questions such as acceptability of bus bar voltages, usage in percentage of various hardware resources such as transformers, transmission lines and generators, and weak spots in the grid. The same questions can be considered for future scenarios such as introduction of new wind farm, decommissioning of one, or temporary disconnection for repair or overhaul or extension or maintenance.

Load flow analyses were carried out to analyse the utilisation of individual components from the turbines to the grid feed-in point.

In order to initiate a load flow analysis, it is necessary to incorporate three fundamental components into the model: a generator unit, a power transport system, and a load. In this particular instance, the generators are evidently the OSyr160-5.0 turbine, the transportation lines are the ground cables of varying dimensions, and the load is the public grid. Within the PowerFactory “Data Manager”, there exists a designated folder that can be utilised for the purpose of predefining the various simulation cases. The relevant ones for this project are illustrated in Figure 13. This is a highly beneficial feature, as it eliminates the need to restart the process from the initial stage. This is particularly advantageous when dealing with parameters, time settings or component selection, which are typically initiated from the beginning. Activation of the simulation case is achieved by clicking on the relevant option, which subsequently opens the simulation window and displays the relevant plots.

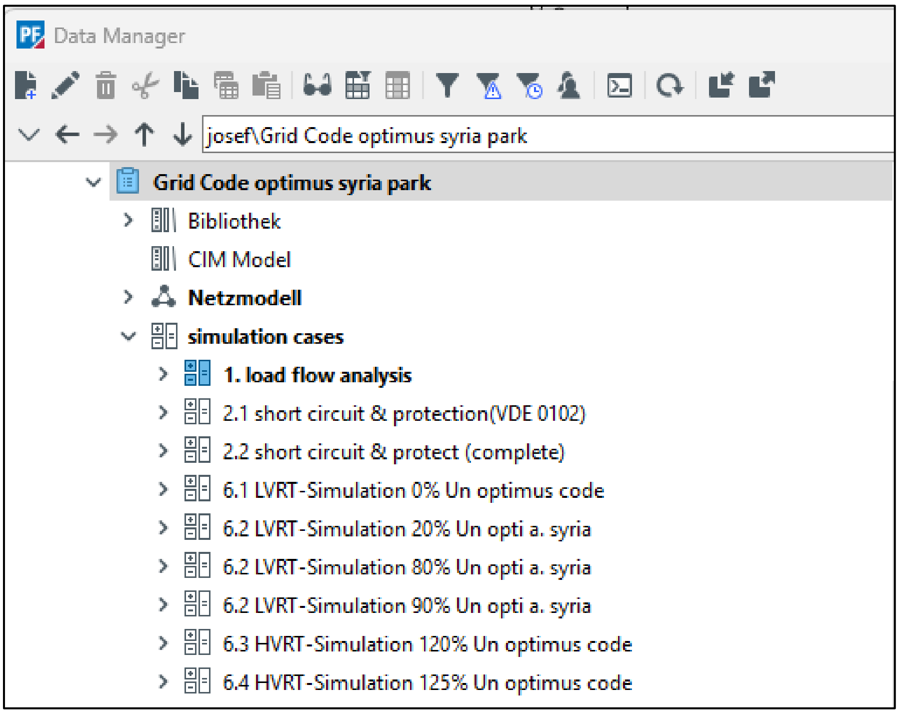

Figure 13: Simulation cases – PowerFactory

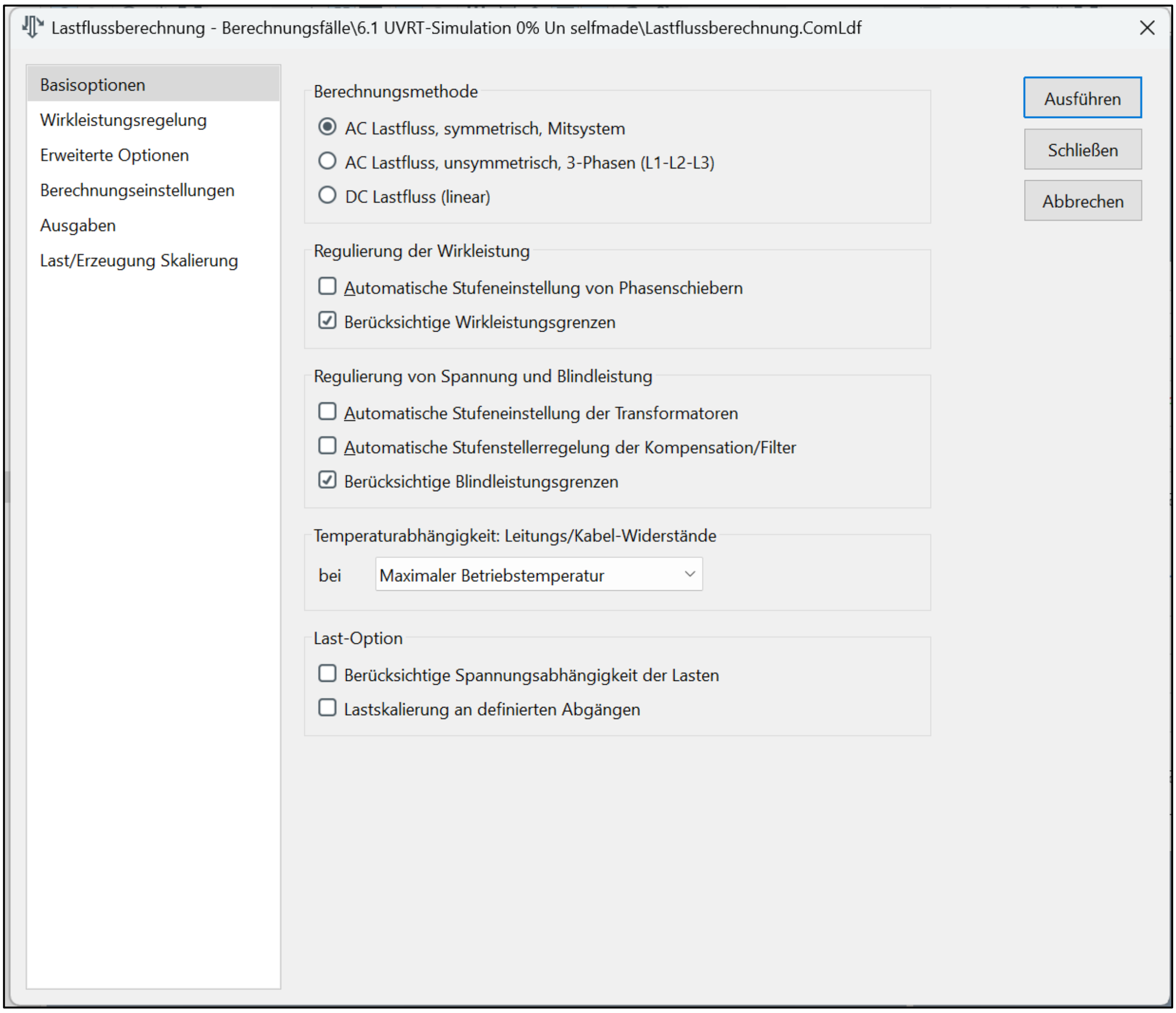

Figure 14: Load flow analysis settings – PowerFactory

For the load flow analysis, the Newton-Raphson method was employed, which is the established numerical standard for solving power flow equations. The calculation is performed through iterative numerical steps. The successful convergence of the algorithm is verified via the "output window".

The calculation parameters were configured as illustrated in Figure 14. Specifically, the 'AC load flow, balanced, positive sequence' method was selected. To ensure realistic grid conditions, both active and reactive power limits were taken into account. Additionally, the temperature dependency of the cable resistance was set to the 'maximum operating temperature' to simulate a worst-case scenario regarding thermal losses.

The simulation is initiated by executing the command, and the corresponding results for this study case are detailed in Chapter 6.1.

5.2 Short Circuit Simulation

Short-circuits are among the most frequent occurrences in PS, representing a critical state where a connection with low impedance is established between two or more points in an electric circuit. In such an event, current flows unintentionally through this bypass rather than through the intended conductors. These faults can severely damage or even destroy components of the electric circuit by causing extreme overheating and excessive thermal stress.

The reasons for the occurrence of short-circuits are diverse and often environmental or age-related. Common causes include the ageing of insulation and the breakdown of insulation due to overvoltage, such as during a lightning strike. Furthermore, mechanical interference, for instance a branch falling onto a conductor or damage caused during construction works, frequently leads to faults. Additional factors include the contamination of insulators on overhead lines and busbars, as well as human failure during maintenance or operation.

The consequences of short-circuits can be devastating for the reliability of the grid. Beyond the immediate high thermal and mechanical stress on individual PS components, which often leads to their total destruction, short-circuits cause an interruption of energy supply due to suppressed voltage levels. On a larger scale, such faults can compromise system stability, potentially triggering a chain reaction that leads to a widespread blackout [20, p. 10].

Therefore, short-circuit calculations are conducted to ensure the reliable and safe operation of PS. These studies are essential for the proper dimensioning of all electrical components, as they must be capable of withstanding the maximum thermal and mechanical stresses occurring during a fault. Furthermore, such calculations provide the necessary data for protection coordination, allowing for the precise setting of protective devices to minimize fault duration and limit the impact on the rest of the network.

The configuration parameters for the short-circuit analysis are displayed in Figure 15. For this simulation, the fault is initiated at the PCC. The calculation is performed in strict accordance with the VDE 0102 Part 0 and DIN EN 60909-0 standards for evaluating three-phase short-circuit currents. The analysis employs the standard methodology defined by these regulatory frameworks to ensure results are consistent with industry requirements.

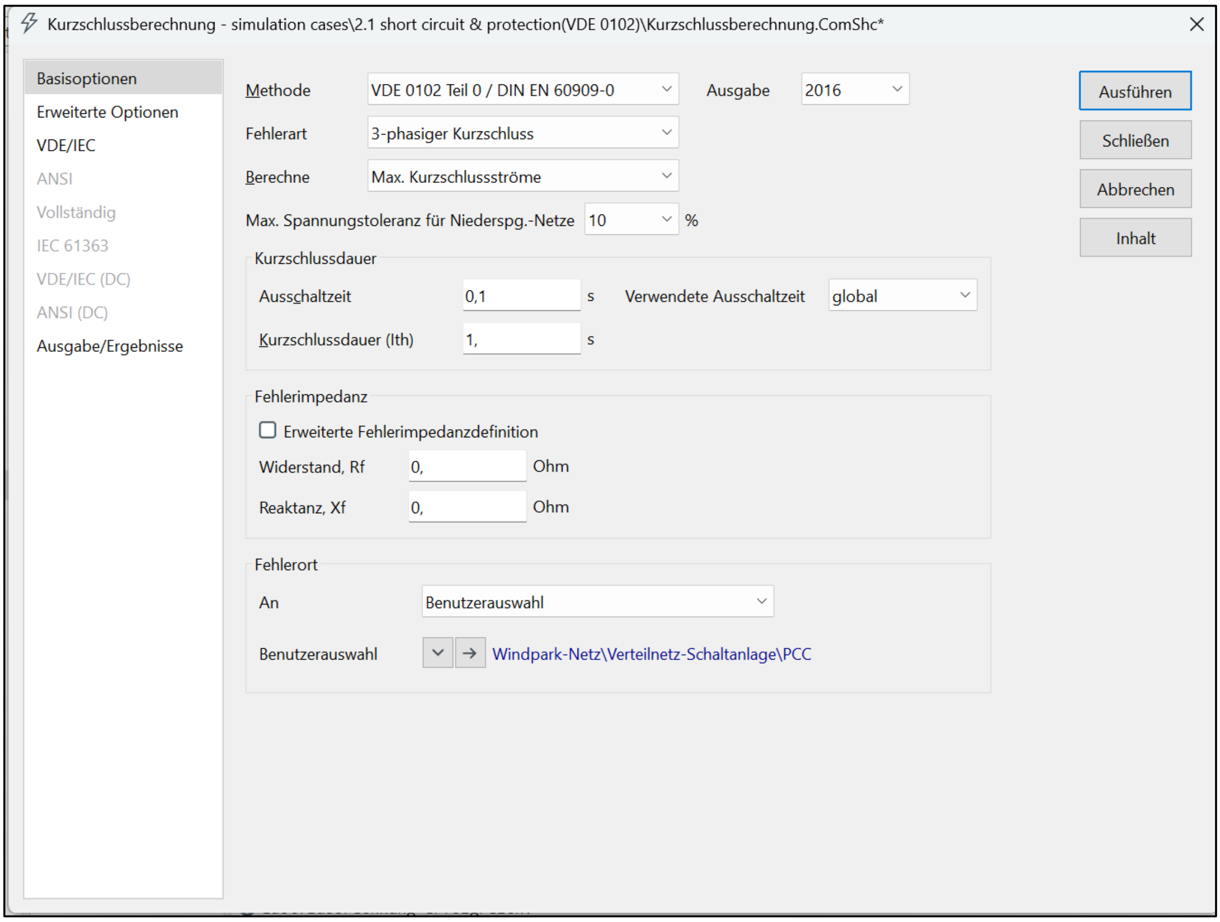

Figure 15: Short cirucit VDE 0102 settings – PowerFactory

Following the initial load flow analysis, the simulation is initiated via the execution command. The software confirms the successful completion of the calculation in the output window, with the detailed numerical results presented in Chapter 6.2.

5.3 RMS-Calculations

RMS (root mean square) modeling is primarily based on a balanced representation of the PS network, where calculations are performed on an equivalent positive sequence basis. This methodology implies that individual phase values are not modeled. Furthermore, RMS simulation techniques typically utilize a short time range, which is considered sufficient to capture general trends in system behavior but remains unable to resolve any transients occurring at a faster rate.

The use of an RMS-based approach is favored for its computational efficiency and simplified mathematical formulas. Historically, this approach was essential due to constraints in computing power, particularly for transmission-level simulations where processing time can be a significant factor. For several decades, RMS simulations have proven to be a reasonable approximation of overall system behavior. In most steady-state analyses, such as load flow or simplified stability studies, high-frequency components, which RMS techniques do not capture, are generally not considered critical [21].

Simulation steps

In this project, RMS simulations were employed to analyze the Fault Ride Through performance of OSyr160-5.0. Following the definition of simulation scenarios in Chapter 5.1, each case was executed individually to ensure a precise evaluation against the specified Low-Voltage Ride Through and High-Voltage Ride Through characteristics.

This individual approach was essential to validate the dynamic behavior of the Optimus turbine under varying fault conditions. The simulations specifically modeled short circuit events with predefined maximum durations to assess the system's robustness. A primary objective of this analysis is to determine whether the turbine complies with grid code requirements by remaining synchronized with the network and maintaining grid supporting behavior during transients.

Furthermore, the evaluation focuses on key performance indicators, including active and reactive power exchange, frequency stability at the Point of Common Coupling, and the resulting thermal loading on the grid connection cable.

To begin the simulation process, it is essential to define the specific monitored nodes and components within the Variable Selection dialog, as illustrated in Figure 16. This step ensures that all relevant measurement points within the wind farm are correctly captured for the subsequent analysis.

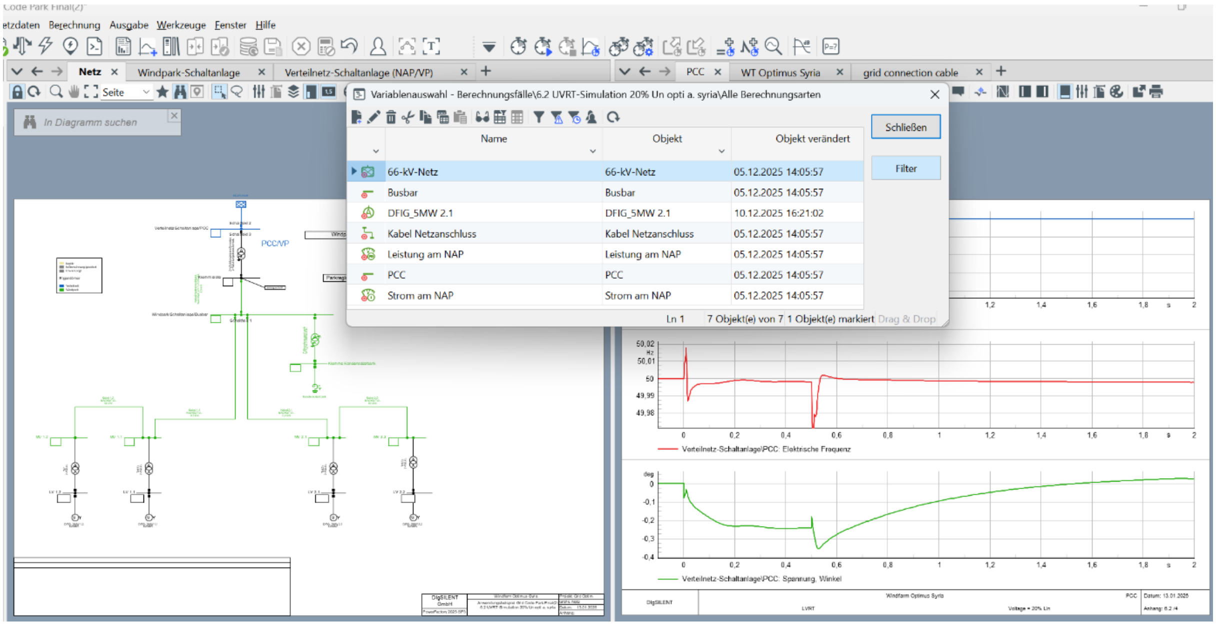

Figure 16: Variable selection – PowerFactory

Each system component and network node offers a comprehensive range of selectable parameters. Figure 17 illustrates the specific electrical variables configured for OSyr160-5.0, ensuring that all critical performance metrics are captured during the simulation process.

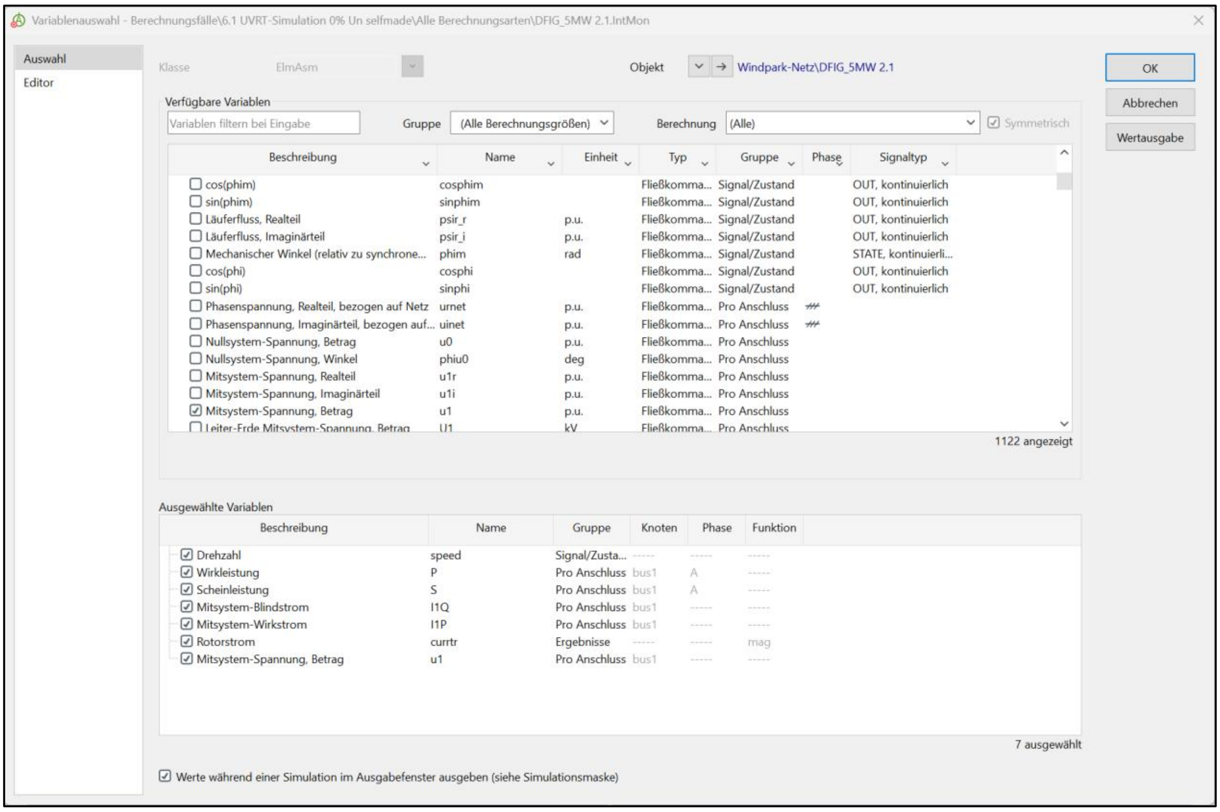

Figure 17: Variable selection OSyr160-5.0– PowerFactory

The second stage of the simulation process involves the definition of a fault event, specifically a three-phase short circuit. The primary objective is to induce a voltage dip at the PCC within a defined temporal window, as illustrated in Figure 18.

To isolate the fault at location 4 from the rest of the network, a switching event is configured to open circuit breaker LS4 after a duration of 500 milliseconds. This timing aligns precisely with the maximum duration specified for a 20 percent residual voltage level according to the LVRT characteristic. Under these specific conditions, the turbine is mandated to remain synchronized with the grid and maintain stable operation.

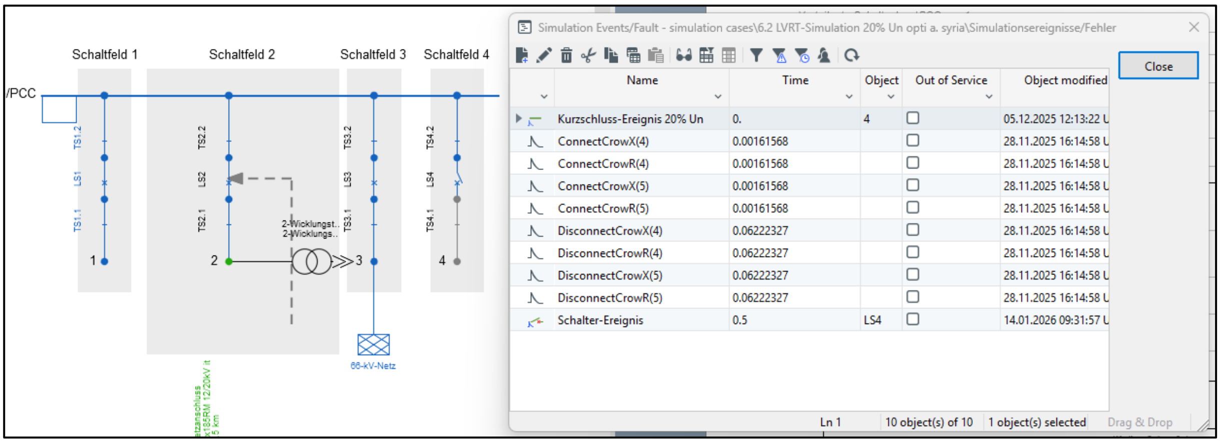

Figure 18: Fault location and switch event – PowerFactory

To achieve the targeted voltage drop at the PCC, it is essential to implement the precisely calculated fault impedance. Figure 19 illustrates the specific values for the resistance and reactance used in this scenario, which refer back to the parameters established in Chapter 3, Table 4.

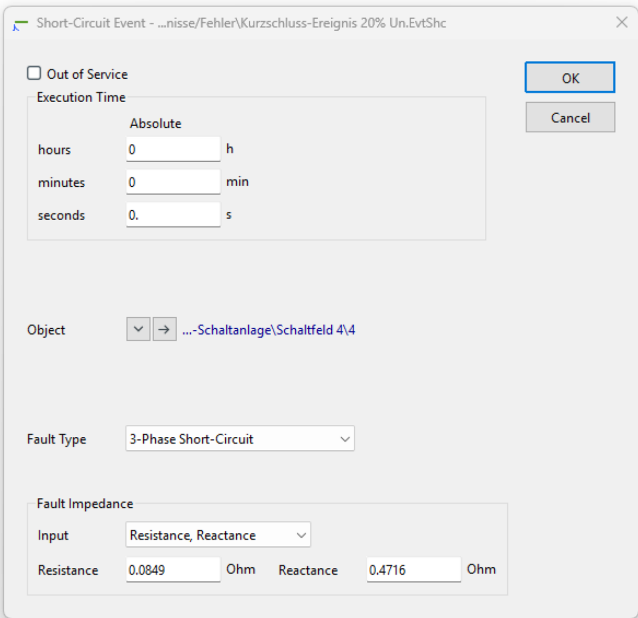

Figure 19: Short circuit event setting 20% – PowerFactory

Once the configuration phase is complete, the destination for the simulation output is specified within the execution control dialog. Following the initial simulation run, the data for the previously selected variables are recorded in the designated storage directory. Plot 20 illustrates the calculation setup, including the selection of the predefined fault event and the configuration of the results file path.

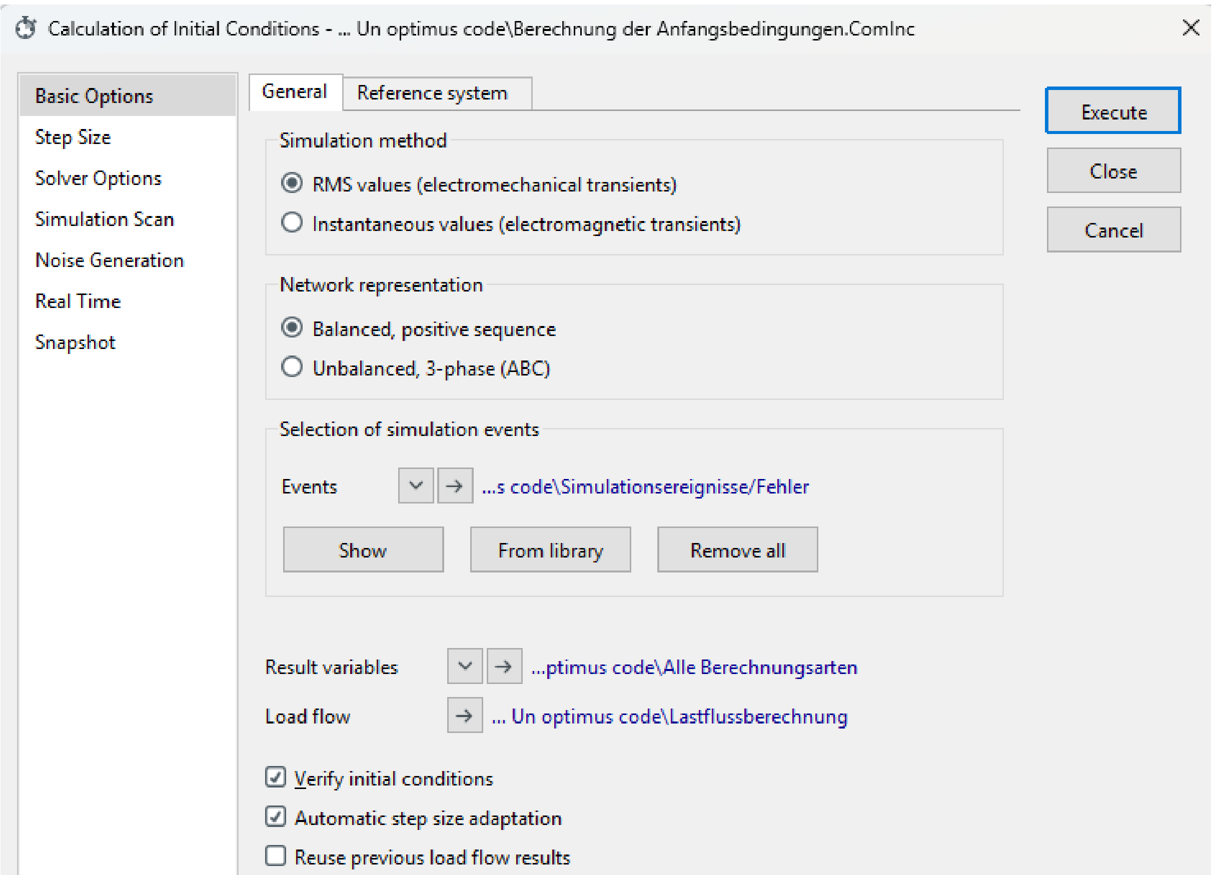

Figure 20: Calculation of Initial Conditions / RMS – PowerFactory

Graphical representation is essential for the effective interpretation of the simulation data. For RMS-based calculations, time-series plots are utilized to visualize the dynamic response and transient behavior of the system accurately. Within the simulation environment, the specific measurement nodes and their associated electrical variables are assigned to the respective graphs through the plot configuration interface. Once the simulation is re-executed, the results are automatically updated and rendered, providing a clear visual basis for the subsequent performance assessment.

To ensure that the simulation adheres to the specified LVRT and HVRT boundaries, a simulation monitoring function can be implemented (see Figure 22). This feature integrates the predefined LVRT and HVRT characteristic curves as active reference trajectories within the calculation environment.

By utilizing this monitoring tool, the simulation can be configured to terminate automatically if the turbine response exceeds these permissible limits. This provides a robust mechanism for verifying whether the system remains within the mandatory grid code envelopes throughout the transient event.

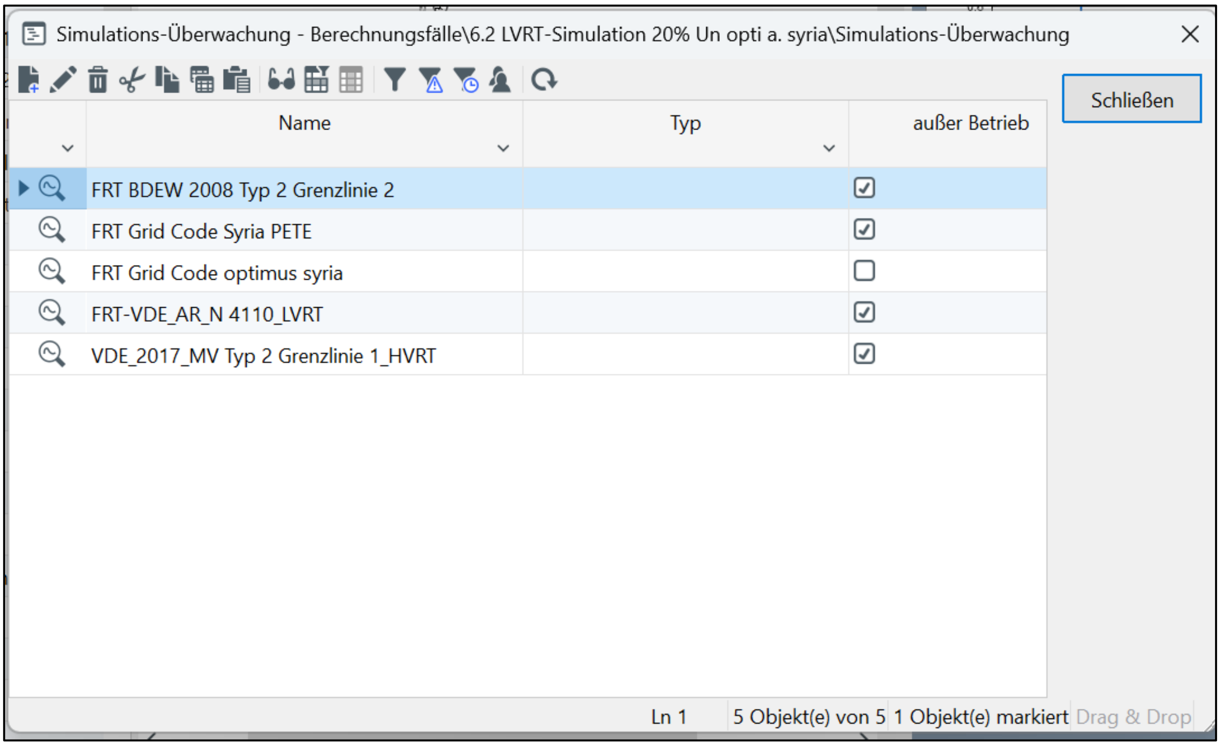

Figure 22: Simulation monitoring – PowerFactory

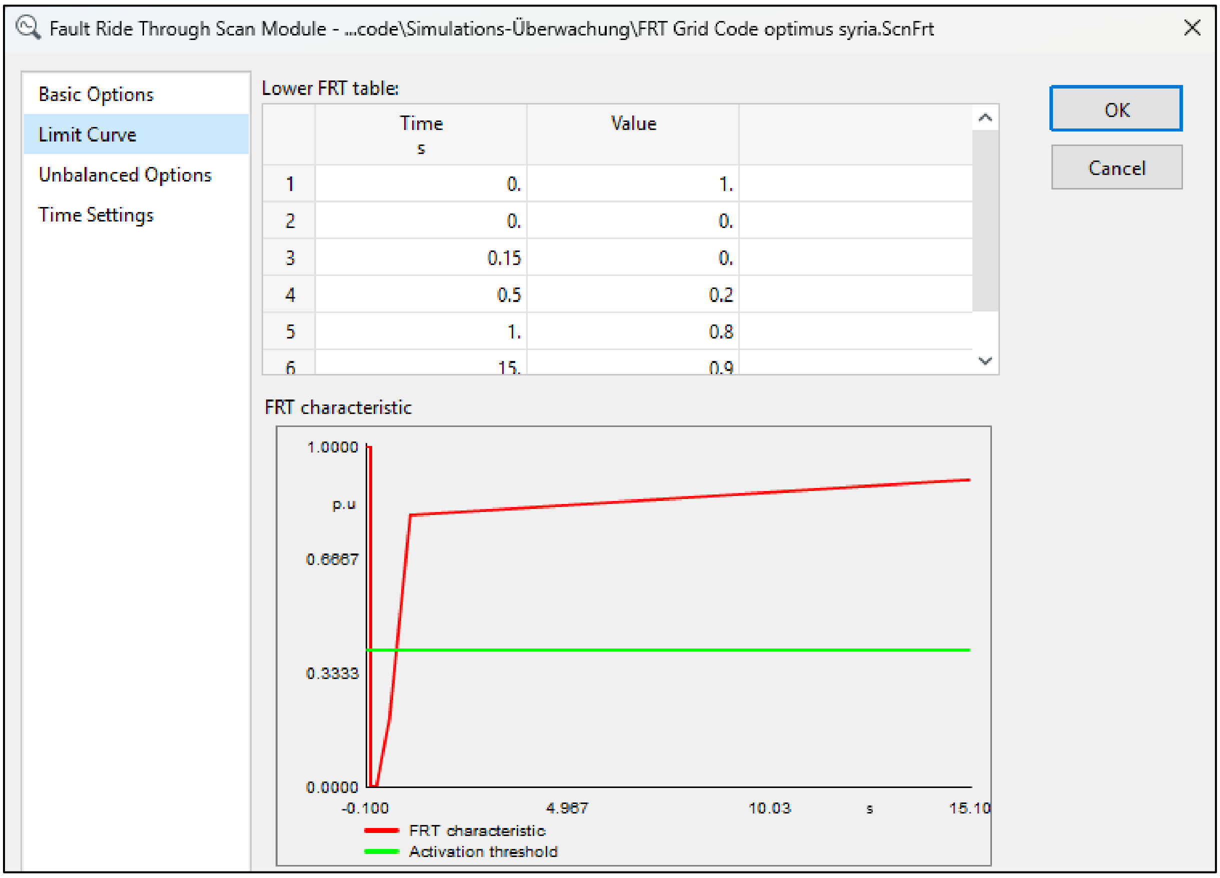

Figure 21: LVRT Optimus Syria_simulation inspection – PowerFactory

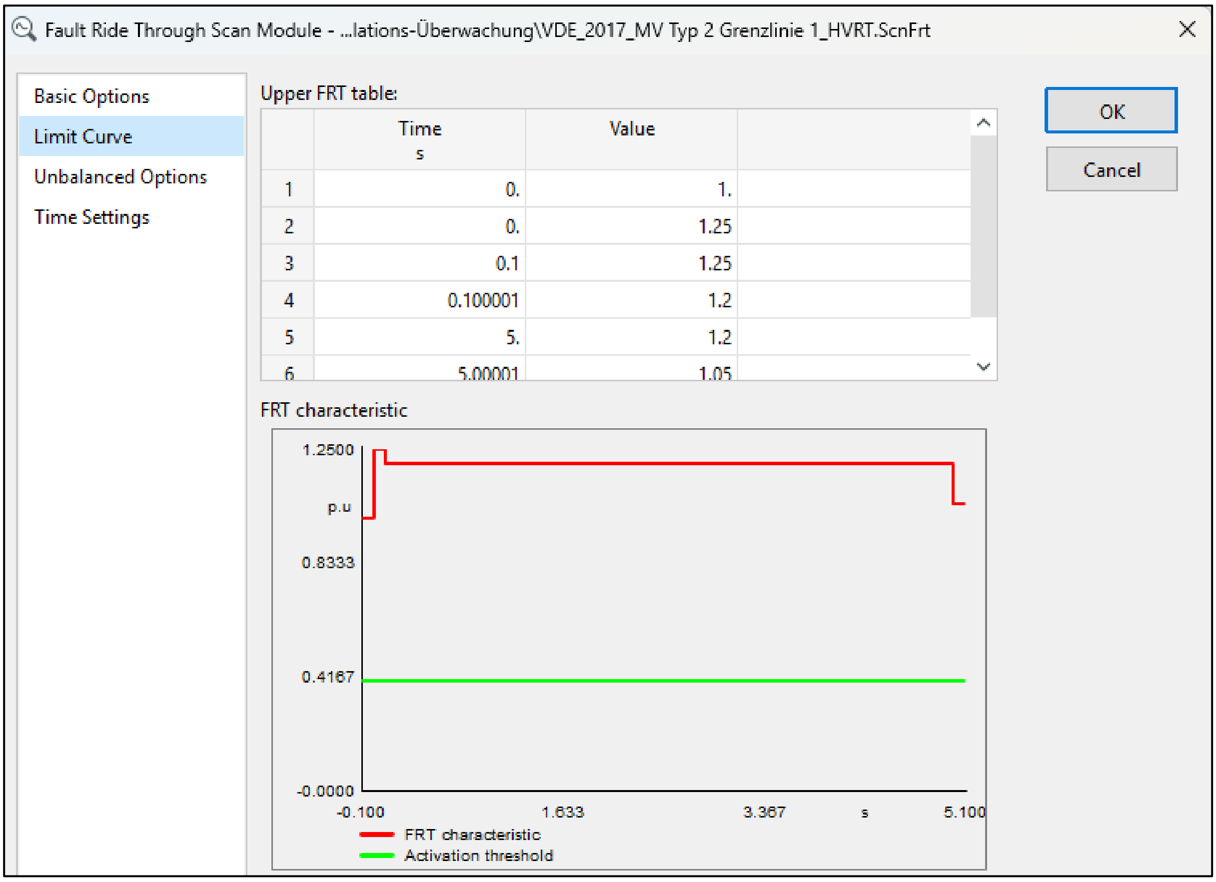

Figure 23: HVRT Optimus Syria_simulation inspection – PowerFactory

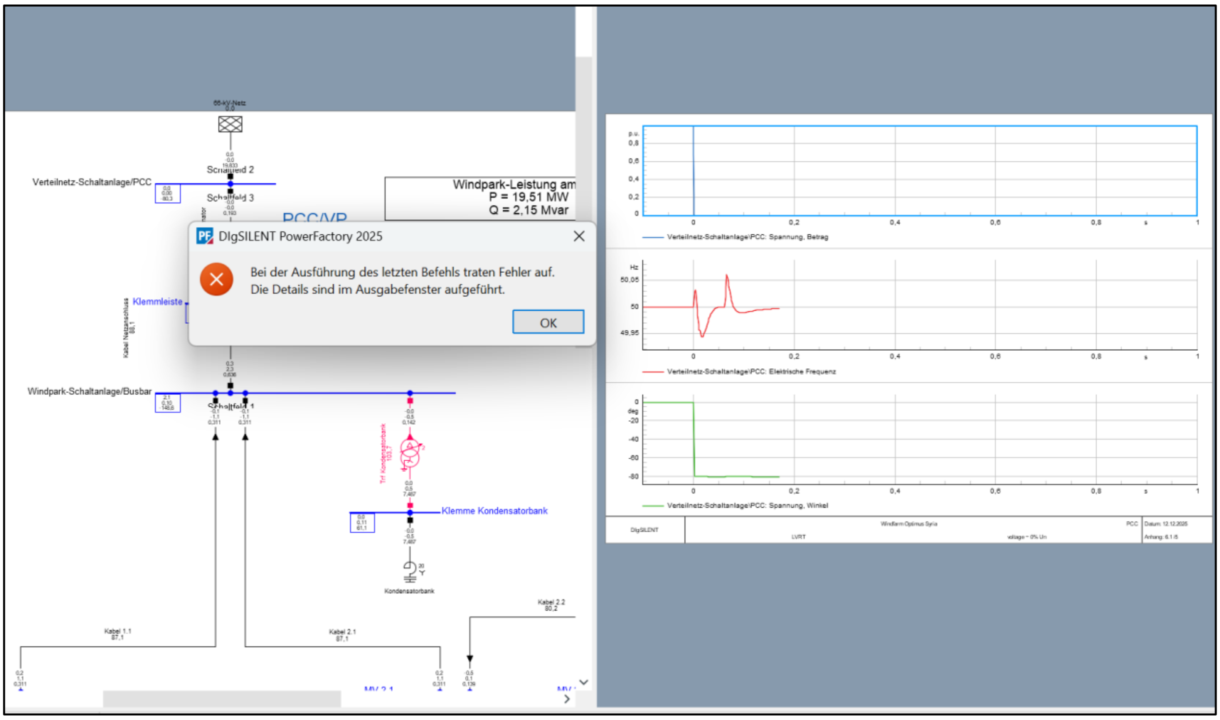

Figure 24: Simulation stop for not following the FRT curve – PowerFactory

6 Simulation Results

6.1 Load flow analysis

In collaboration with the project development team, the turbine positions were established based on an optimized Annual Energy Production (AEP) analysis. This layout served as the foundation for determining the distances between individual turbines and the connection to the Qattinah substation, which is situated adjacent to the existing oil and gas power plant. The internal collector system for the four OSyr160-5.0 turbines is configured into two separate strings, each consisting of two units. This dual-string topology was selected to ensure optimal component loading by achieving a balanced distribution of power through the electrical infrastructure. These two strings converge at the transfer station, where the cumulative power is then transmitted to the main substation for grid injection.

As illustrated in Figure 25, the wind farm delivers 19.51 MW of active power to the grid injection point at full capacity. This measurement is recorded at the point of common coupling upstream of the 20/66 kV transformer. During this operating state, 2.94 Mvar of reactive power is drawn from the grid. This is due to the capacitor bank being disconnected from the farm circuit to support the upstream grid infrastructure. Total electrical losses from the point of generation to the feed-in point are calculated at 430 kW. The maximum equipment utilization, reaching a peak of 93.5 percent, is indicated by the color coding in the diagram. While the OSyr160-5.0 transformers are sufficiently dimensioned, the cable network has been designed for high-cost efficiency. With an average utilization of approximately 80 percent, the cables still maintain an adequate operational margin. Furthermore, all voltage levels at the busbars remain within the specified target ranges, confirming the stability of the system design.

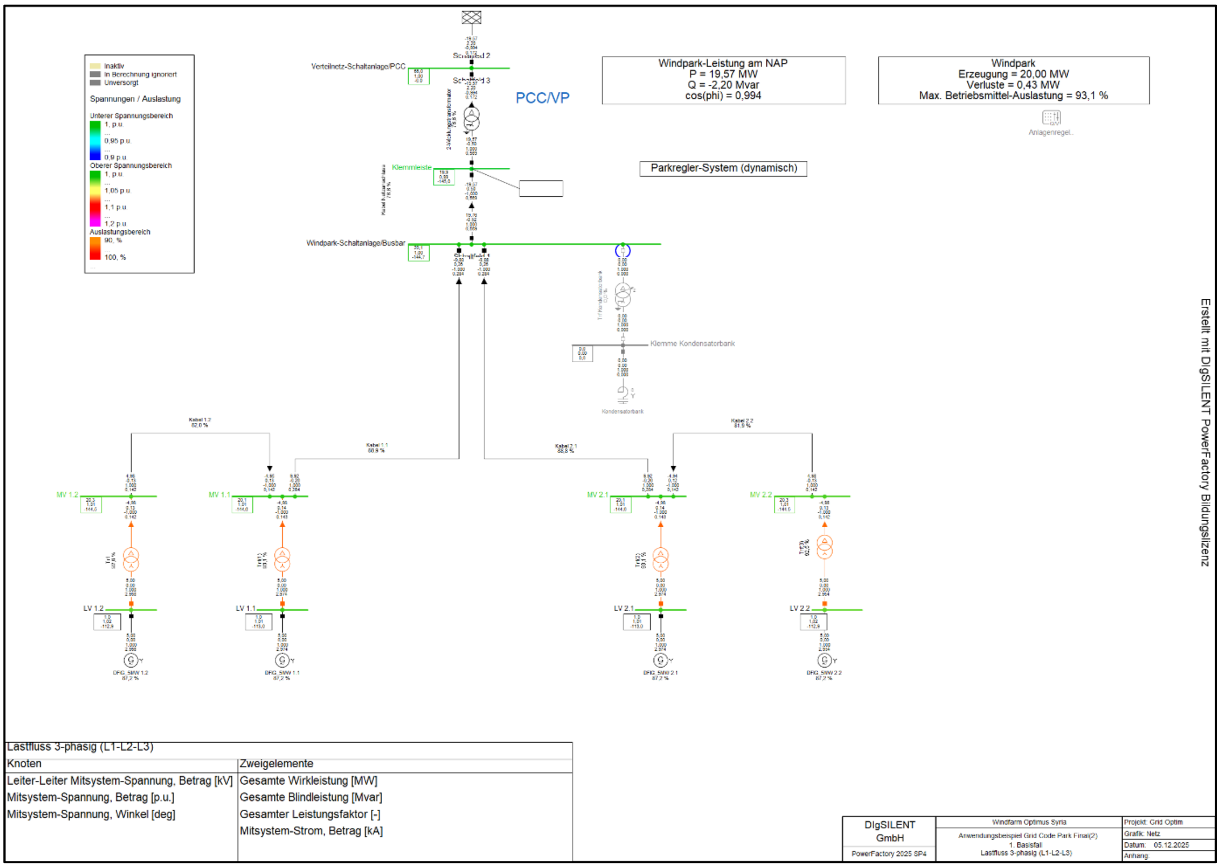

Figure 25: Optimus Syria windfarm load flow model– PowerFactory

According to the load limits of the cables following types were chosen, which are also visible in the park layout Figure 12 in chapter 5.

Cable WT 2.2-2.1 & WT 1.1-1.2	
Type	NA2XS(F)2Y 1x50RM 12/20kV it
Rated Voltage [kV]	20
Rated Current [kA]	0.173
System Type / Phases	AC / 3
Nominal frequency [Hz]	50
AC-Resistance R'(20°C) [Ohm/km]	0.644
Reactance X' [Ohm/km]	0.146

Table 9: Cable parameters – NA2XS(F)2Y 1x50RM 12/20kV it

Cable WT 2.1-transfer station & WT 1.2 -transfer station	
Type	NA2XS(F)2Y 1x150RM 12/20kV it
Rated Voltage [kV]	20
Rated Current [kA]	0.32
System Type / Phases	AC / 3
Nominal frequency [Hz]	50
AC-Resistance R'(20°C) [Ohm/km]	0.211
Reactance X' [Ohm/km]	0.122

Table 10: Cable parameter – NA2XS(F)2Y 1x150RM 12/20kV it

Cable grid connection	
Type	NA2XS(F)2Y 1x185RM 12/20kV it
Rated Voltage [kV]	20
Rated Current [kA]	0.361
System Type / Phases	AC / 3
Nominal frequency [Hz]	50
AC-Resistance R'(20°C) [Ohm/km]	0.169
Reactance X' [Ohm/km]	0.118

Table 11: Cable parameters – NA2XS(F)2Y 1x185RM 12/20kV it

6.2 Short Circuit Simulation

Short circuit power of grid connection point [20, p. 37]

$$S_{sc} = \sqrt{3} * V_{rated} * I_{sc} = 3 * |Z_{sc}| * I_{sc}^2 = \frac{V_{rated}^2}{|Z_{sc}|} \tag{6.2.1}$$

$$V_{grid} = V_{rated} = undisturbed\ V\ in\ grid \tag{6.2.2}$$

$$Z_{sc} = R_{sc} + j\,X_{sc} \tag{6.2.3}$$

Stiffness of the grid is described by the short-circuit power or the short-circuit ratio

$$Short - Circuit\ Ratio: SCR = \frac{S_{sc}}{S_{WF}} \tag{6.2.4}$$

Input Values

$$S_{WF} = 4 * 5.733\ MVA = 22.932\ MVA$$

Short circuit calculation – PowerFactory results

Busbar voltage level [kV]	20	66
Initial Short-circuit power S_{kss} [MVA]	213.5	2500
Initial Short-circuit current I_{kss} [kA]	6.163	21.869
Peak Short-circuit current I_p [kA]	14.877	49.209

Table 12: Short circuit results

Optimus Syria windfarm

$$S_{sc\ (66\ kV)} = \sqrt{3} * 66\ kV * 21.87\ kA = 2493.22\ MVA$$

$$SCR_{(66\ kV)} = \frac{2493.22\ MVA}{22.932\ MVA} = 108.7$$

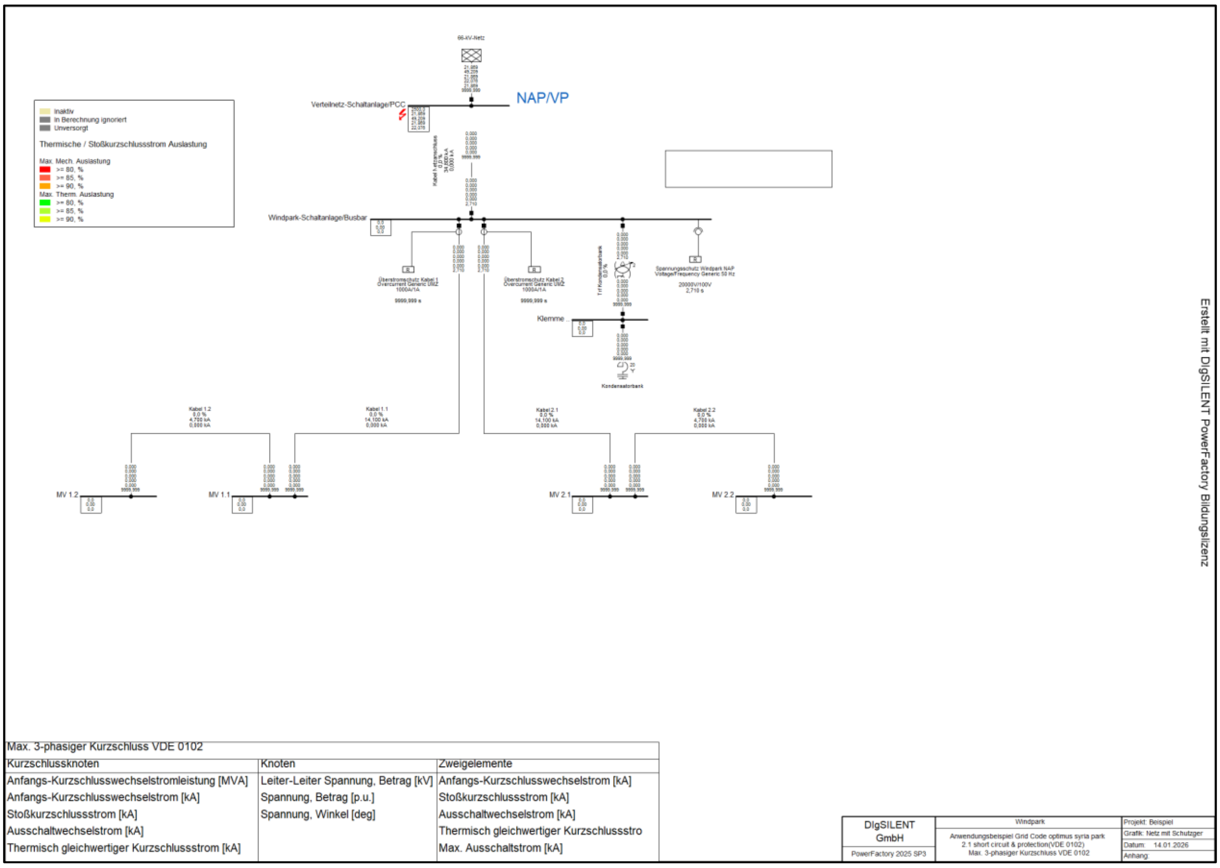

Figure 27: Short circuit VDE 0102 at PCC – Optimus windfarm – PowerFactory

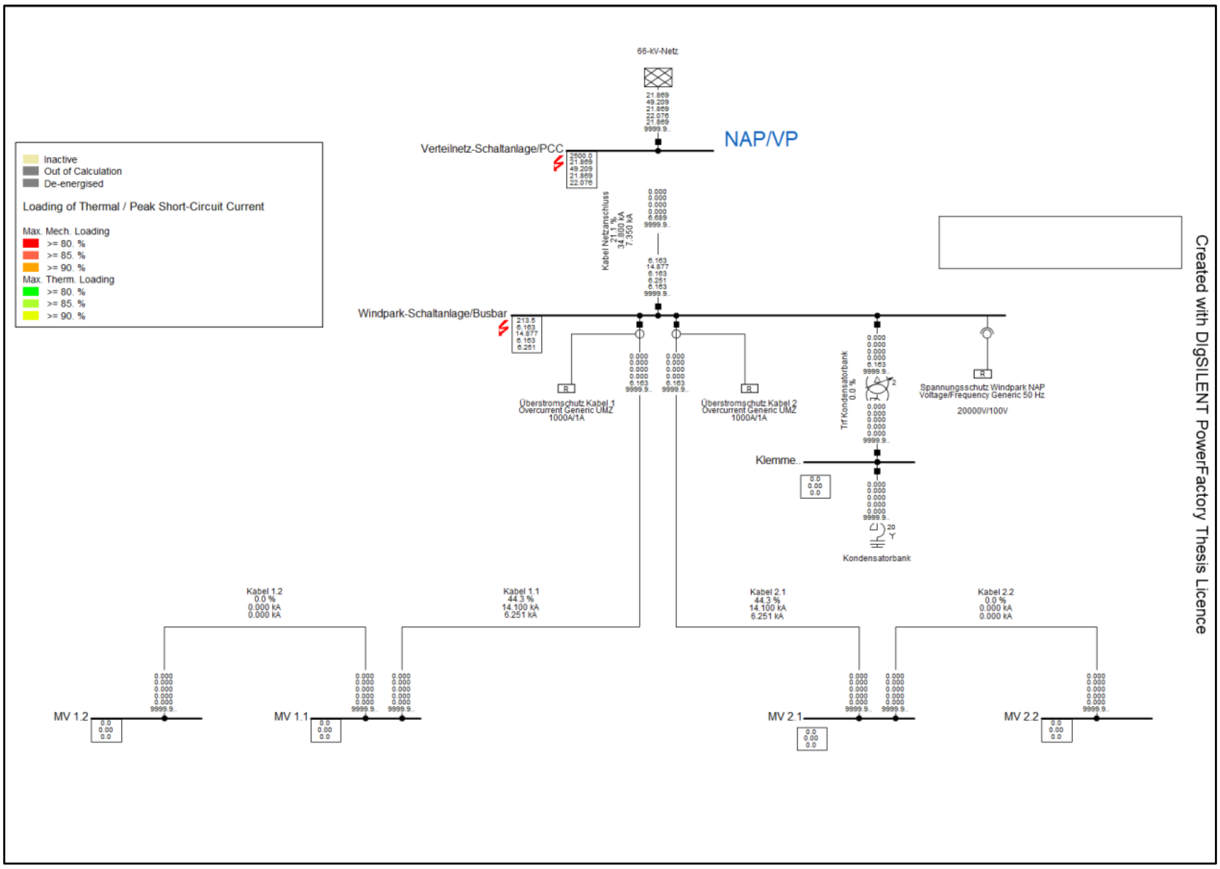

Figure 26: Short circuit VDE 0102 all busbars – Optimus windfarm – PowerFactory

6.3 RMS Simulation

6.3.1 LVRT

Figures 28 to 31 illustrate the peak loading on the wind farm components during the Low-Voltage Ride Through simulations. The data points are captured at the conclusion of each voltage dip, specifically at the 150 millisecond mark for the zero percent residual voltage scenario, as documented in the title block of Figure 28.

These results clearly show the significant voltage drops at the busbars and the simultaneous transient overload of the transformers. However, since these fault conditions are restricted to a very short duration ranging from a few milliseconds to several seconds, the thermal and mechanical stresses remain within the permissible design limits. Consequently, the functionality of the components is not compromised, and no further safety precautions or technical reinforcements are required.

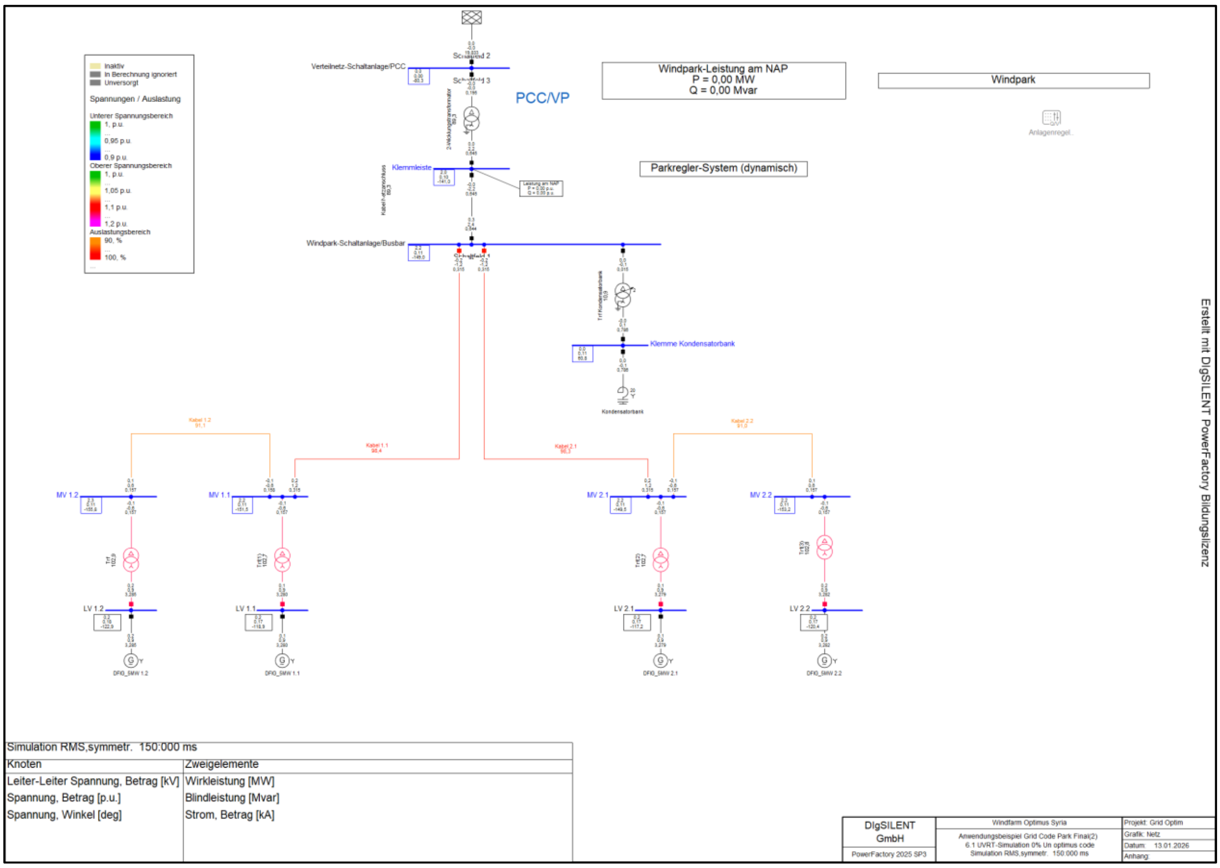

Figure 28: Load flow – LVRT 0% – PowerFactory

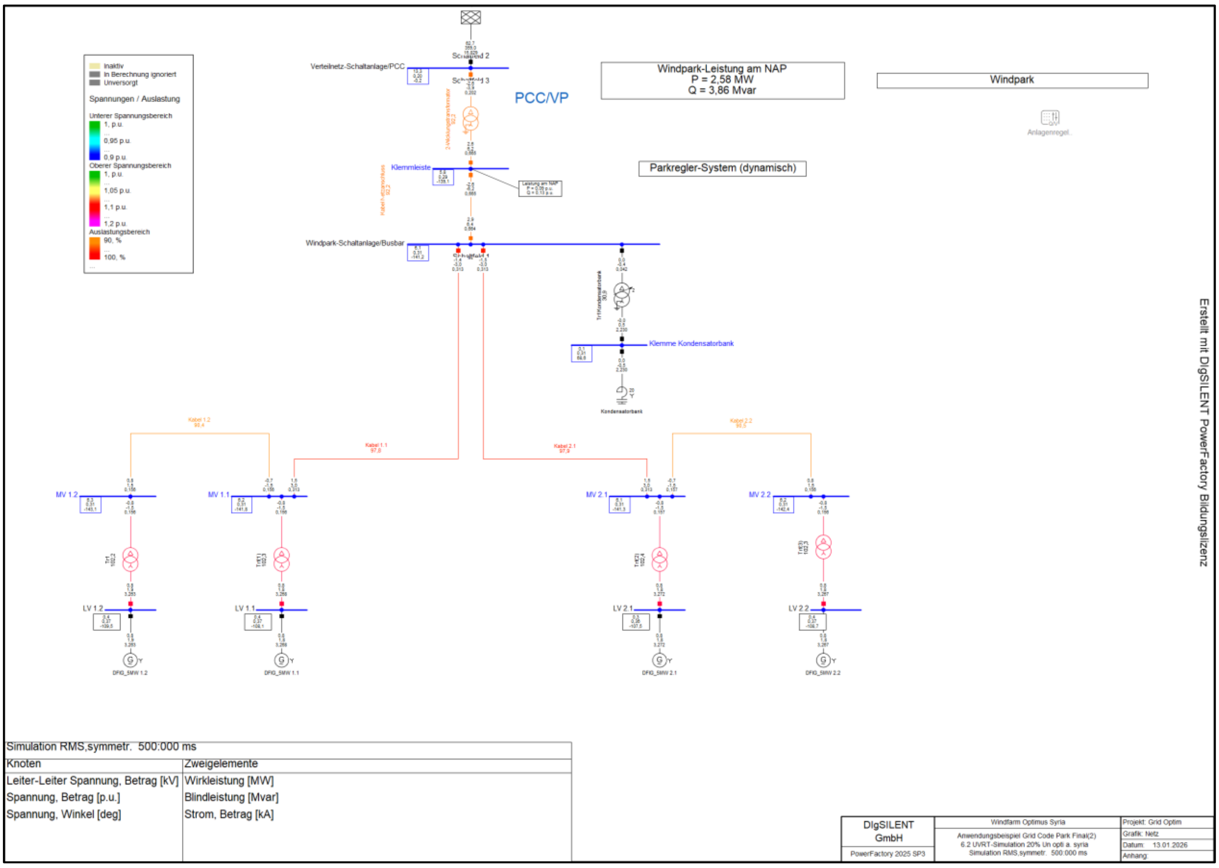

Figure 29: Load flow – LVRT 20% – PowerFactory

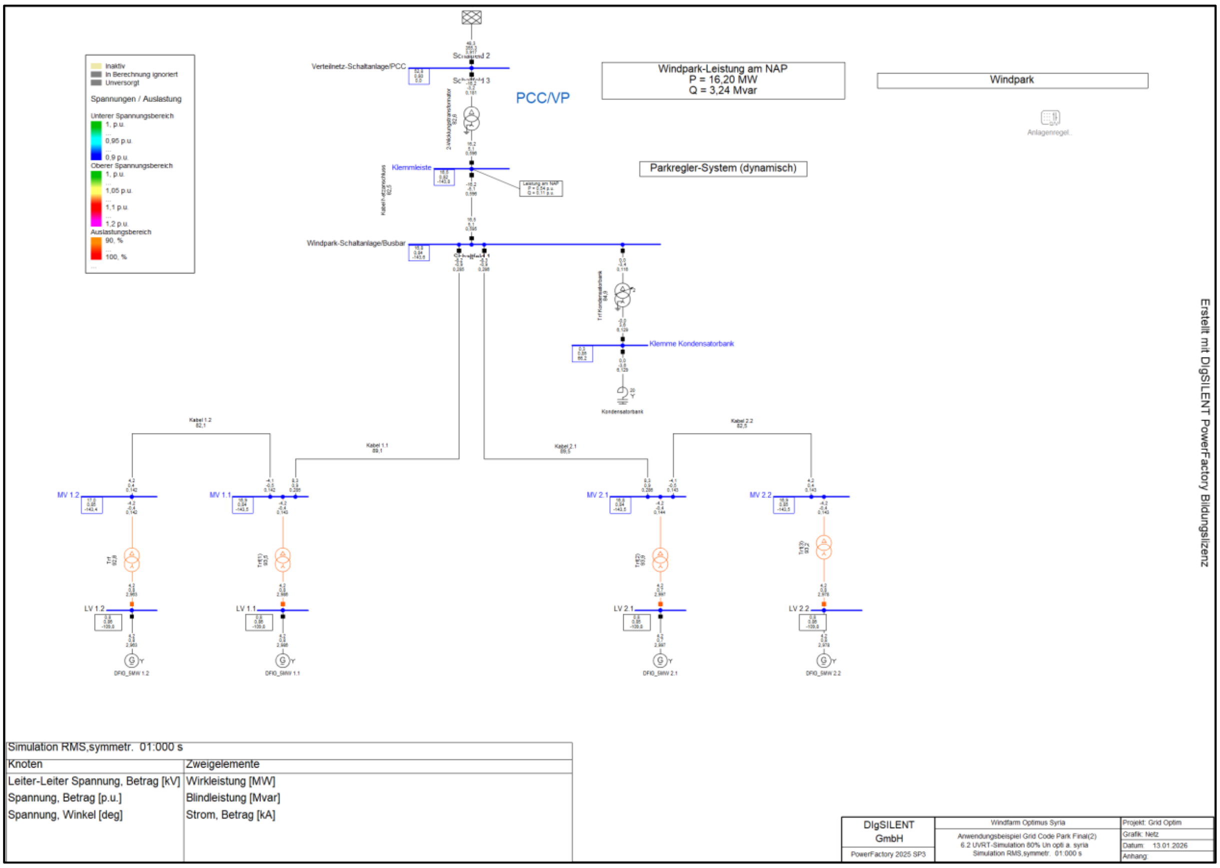

Figure 30: Load flow – LVRT 80% – PowerFactory

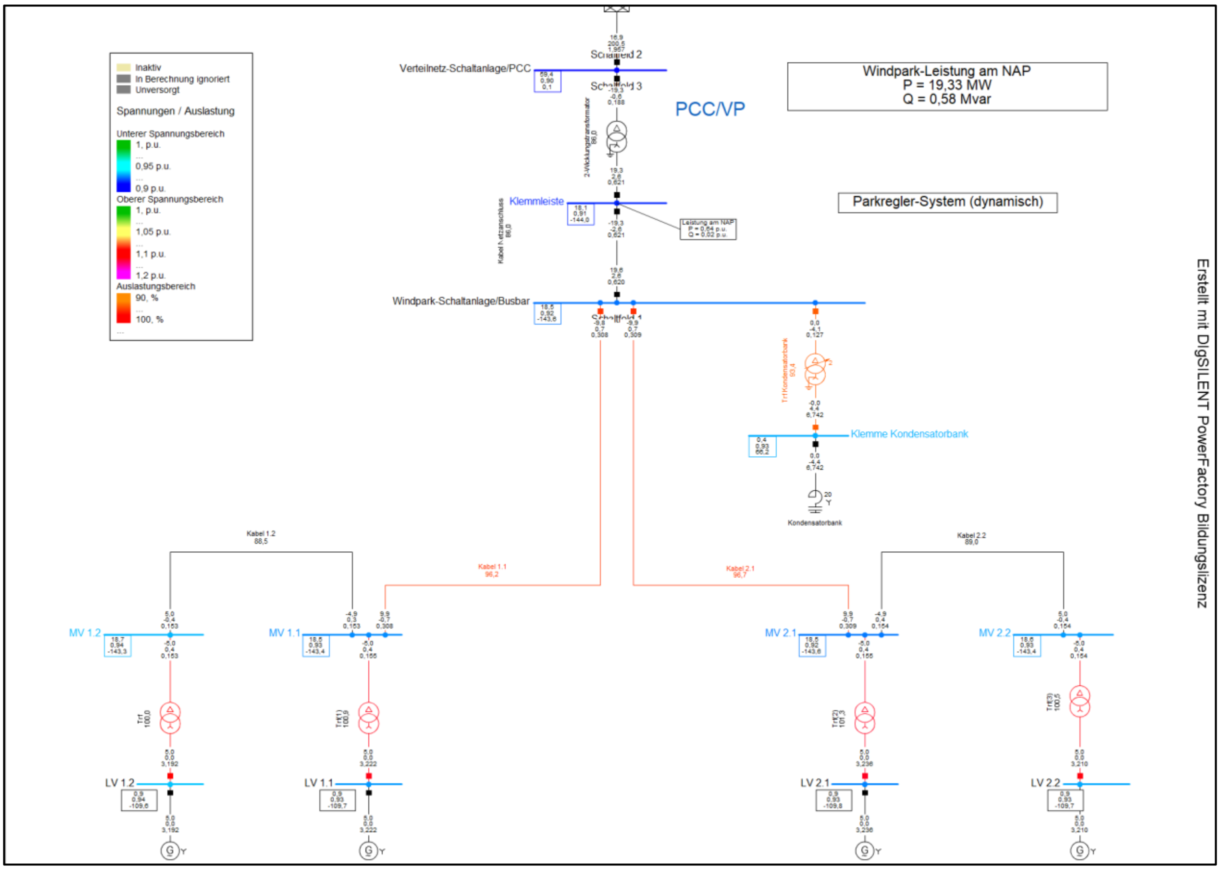

Figure 31: Load flow – LVRT 90% – PowerFactory

0% voltage

Figure 32 illustrates the dynamic response of the OSyr160-5.0 turbine during a 150 ms ZVRT event. Prior to fault inception, the turbine operates at its rated setpoint with an active current injection of approximately 3 kA. In response to the steep voltage dip, the system provides a transient reactive current injection, peaking at nearly 10 kA within the first few milliseconds to support the grid voltage. Following fault clearance, the turbine exhibits a stable recovery characteristic, returning to its pre-fault steady-state operating point by t = 1.0 s.

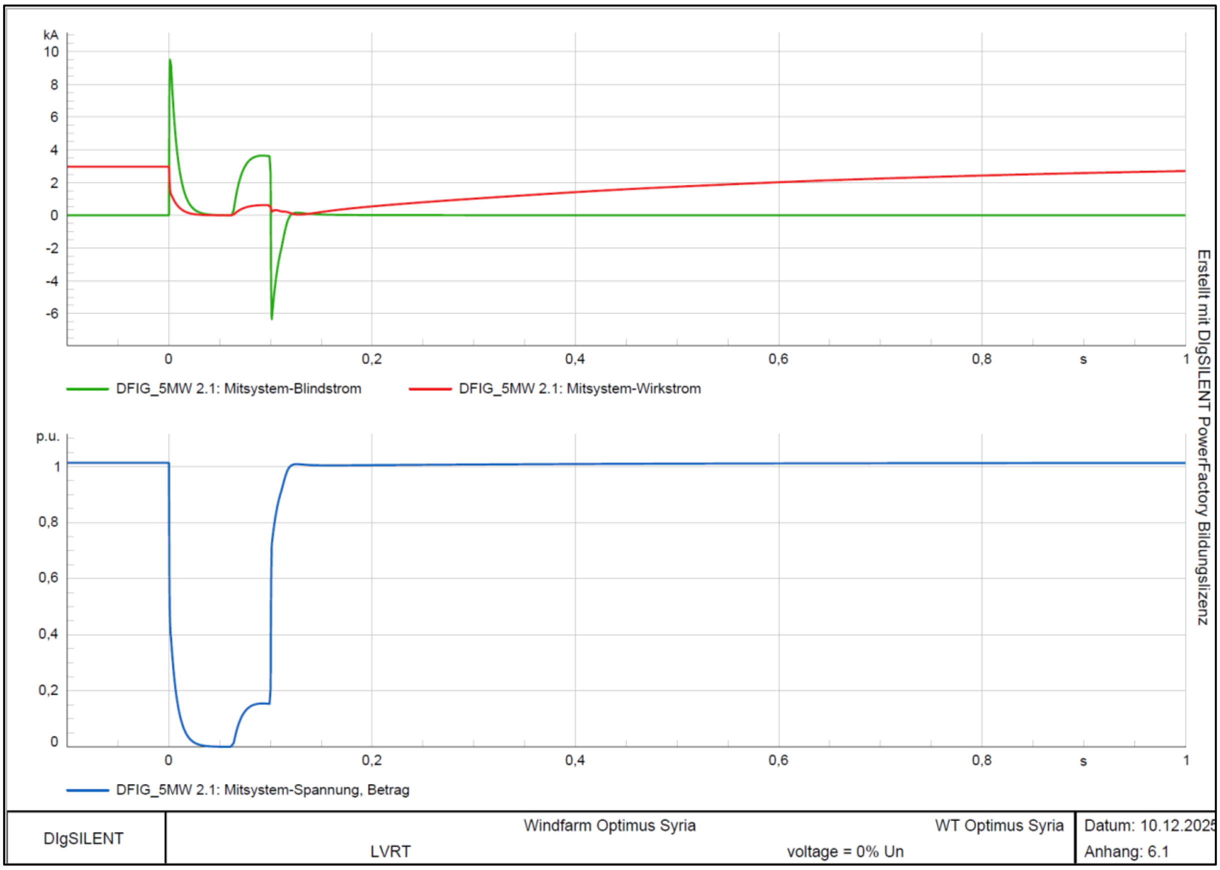

Figure 32: LVRT 0% – Optimus turbine – PowerFactory

Diagram 33 illustrates a solid three-phase fault, resulting in a voltage collapse to 0% at the PCC. During this event, the grid frequency exhibits a transient oscillation of approximately ±0.06 Hz around the nominal 50 Hz setpoint. Simultaneously with the voltage drop, the phase angle undergoes a significant shift, jumping to -80°.

The corresponding loading of the grid connection cable (see Diagram 34) shows a brief but substantial surge. This peak aligns with the transient active and reactive power profiles of the Optimus turbine. The graph further depicts the evolution of the active and reactive power, highlighting the system's dynamic response to the fault and its subsequent stabilization.

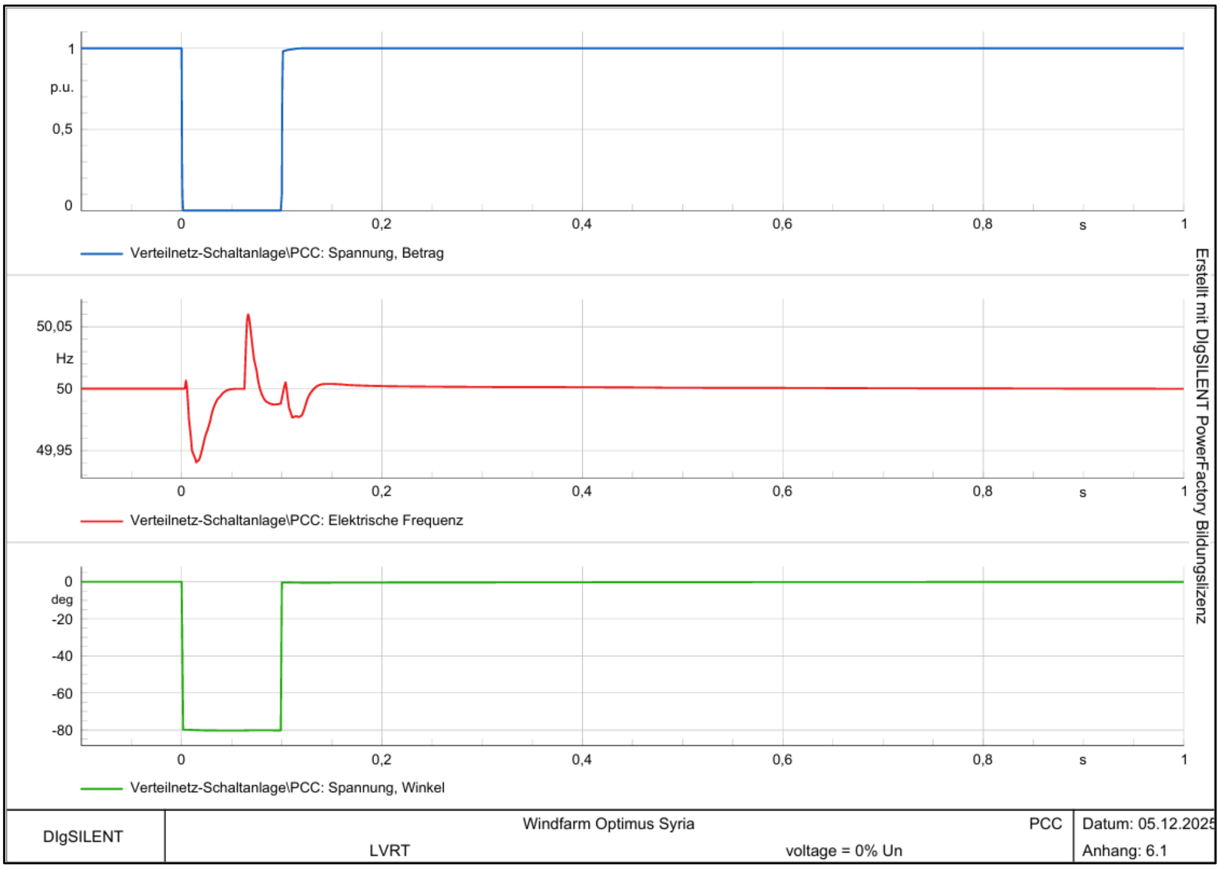

Figure 33: LVRT 0% – PCC – PowerFactory

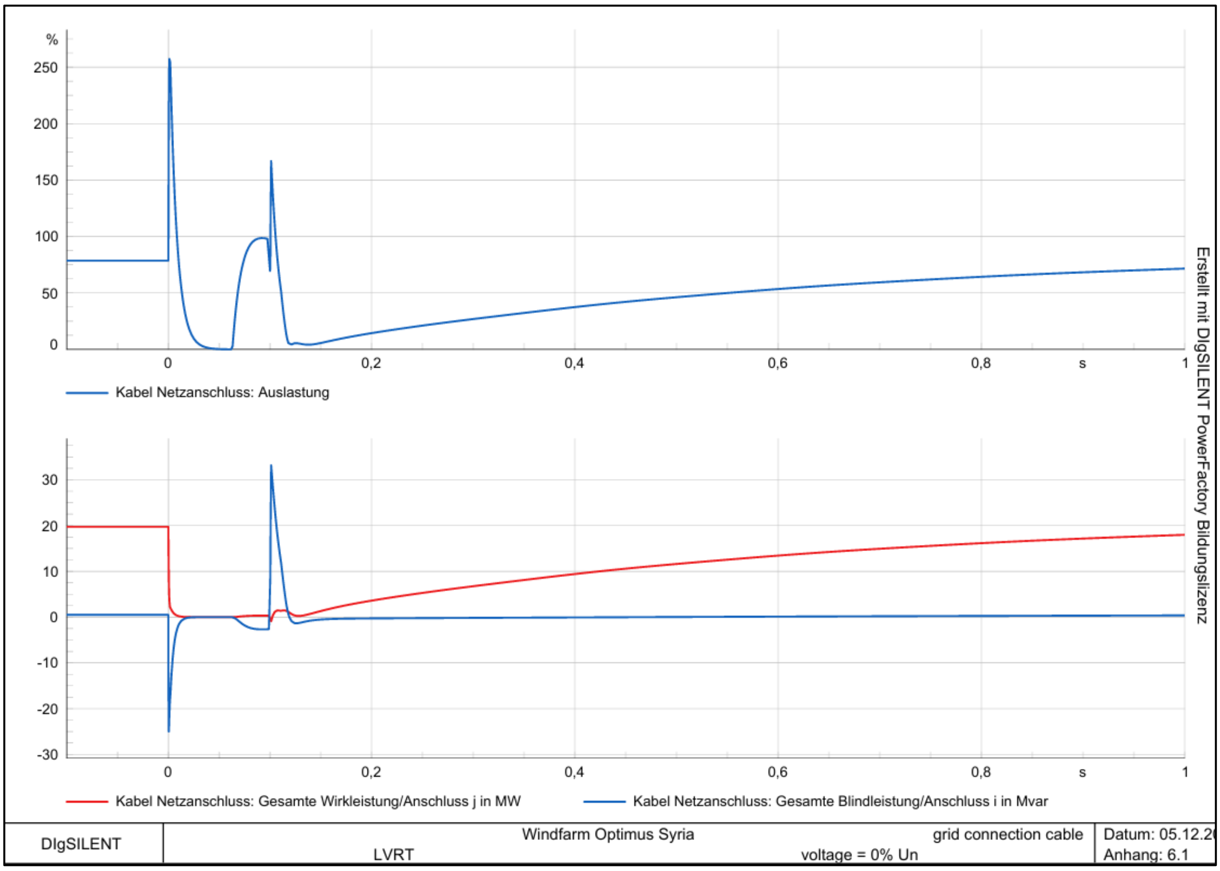

Figure 34: LVRT 0% – Grid connection cable – PowerFactory

20% voltage

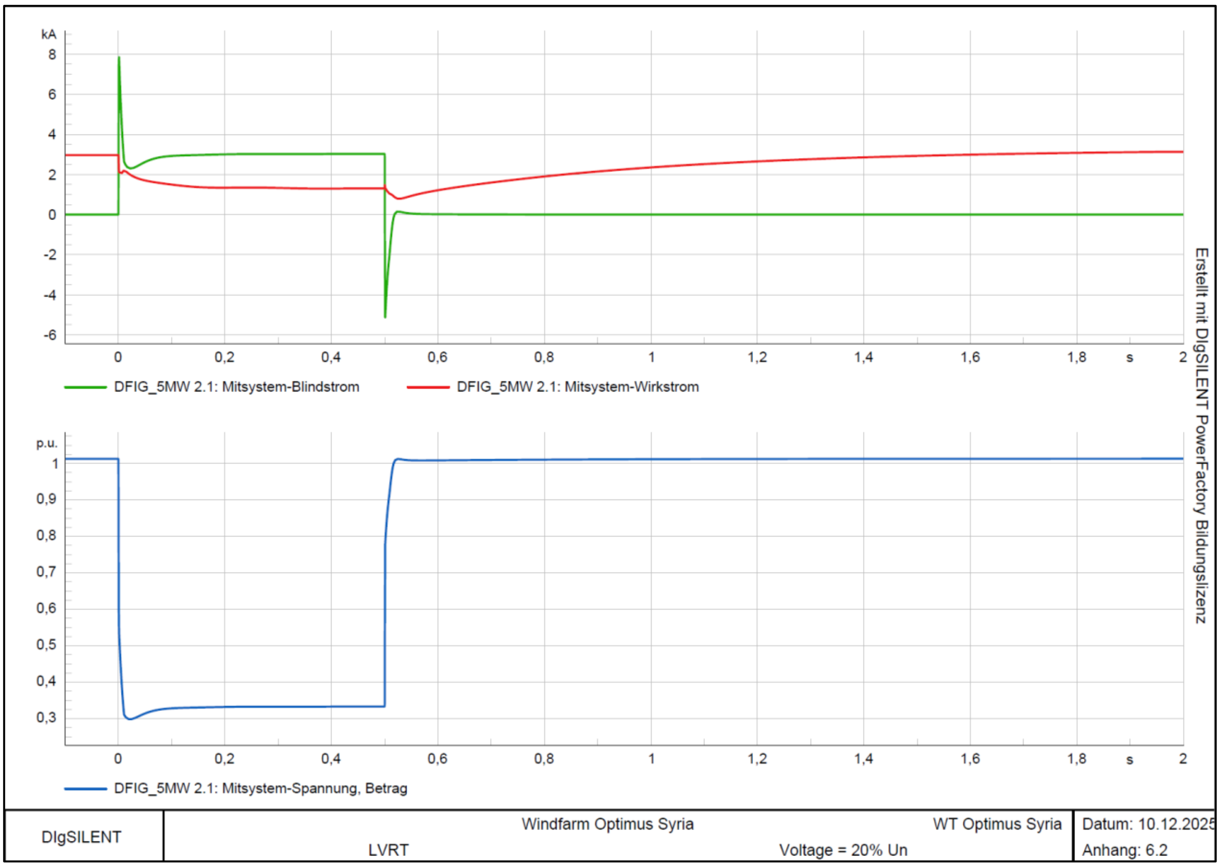

Figure 35: LVRT 20% – Optimus turbine – PowerFactory

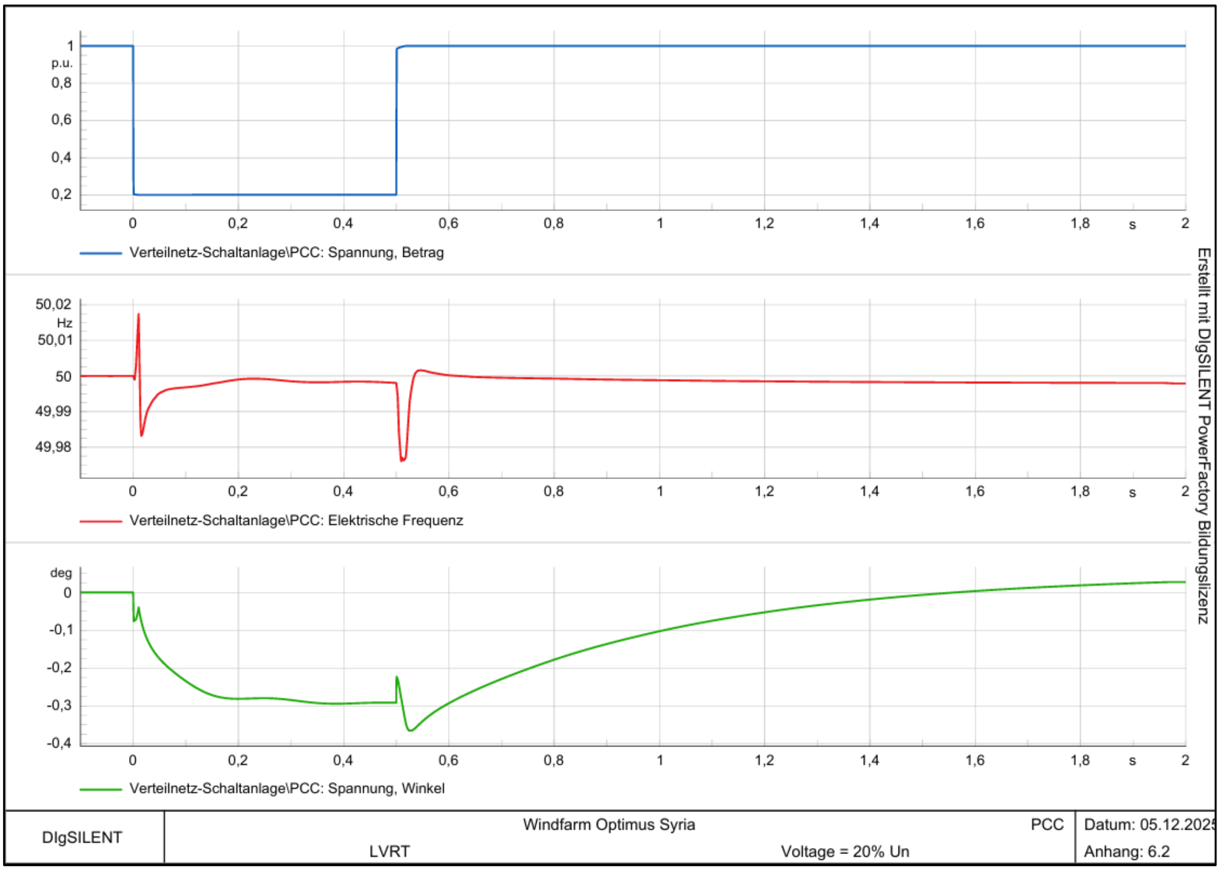

Figure 36: LVRT 20% – PCC – PowerFactory

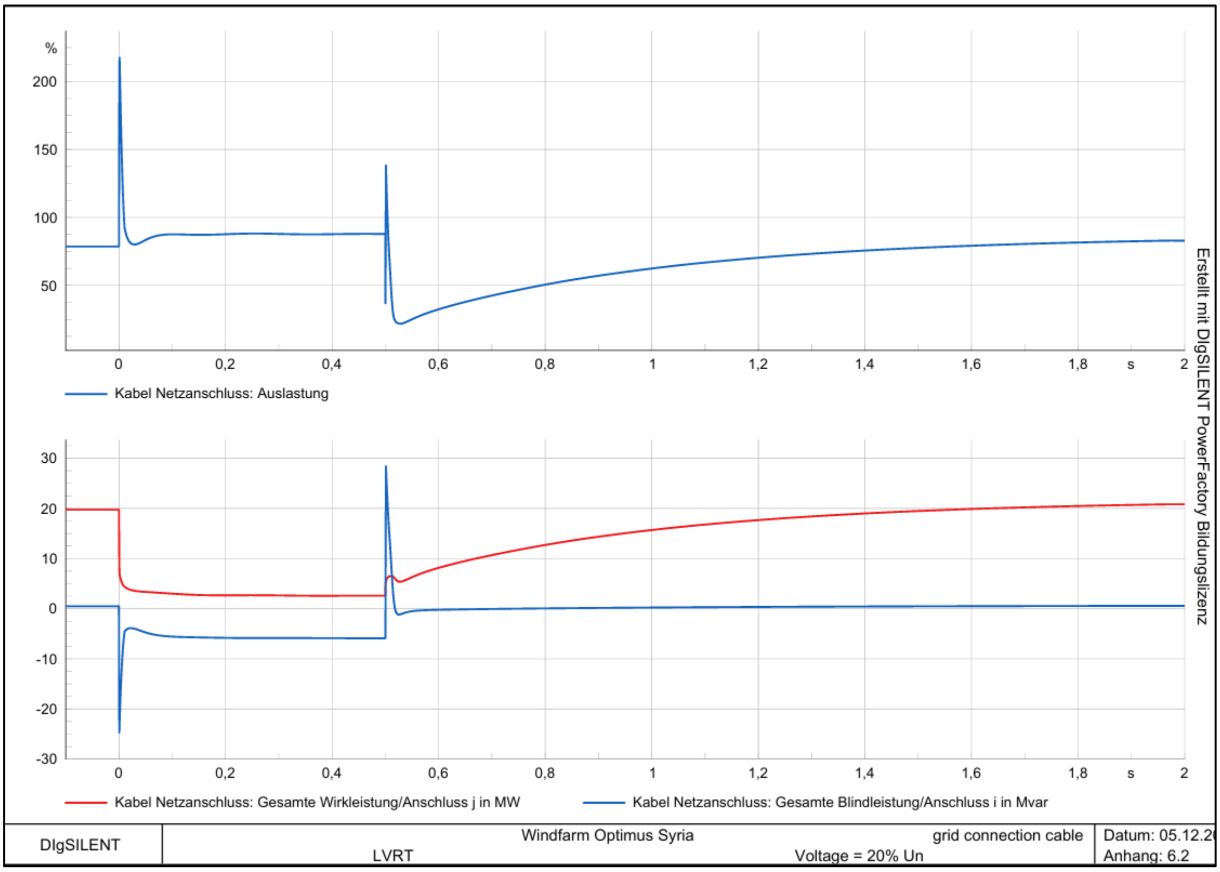

Figure 37: LVRT 20% – Optimus turbine – PowerFactory

80% voltage

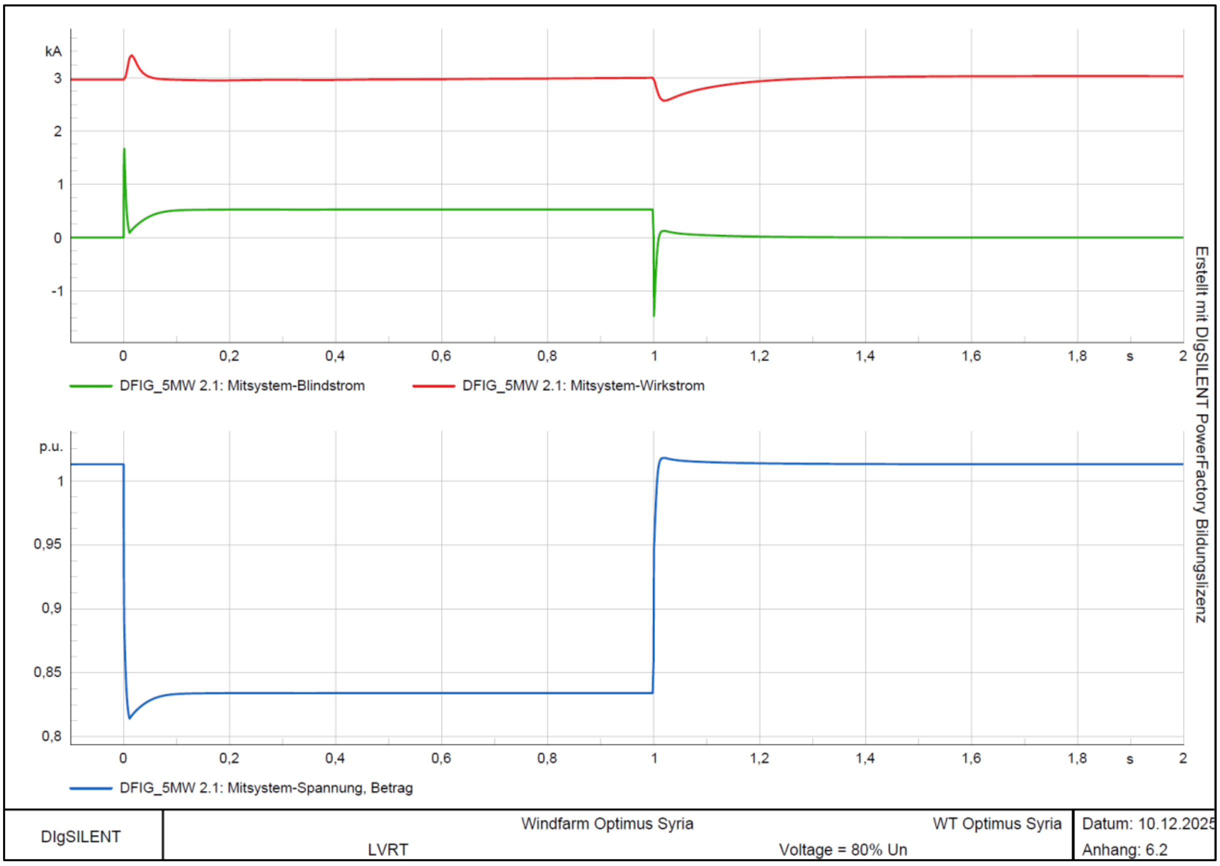

Figure 38: LVRT 80% – Optimus Syria – PowerFactory

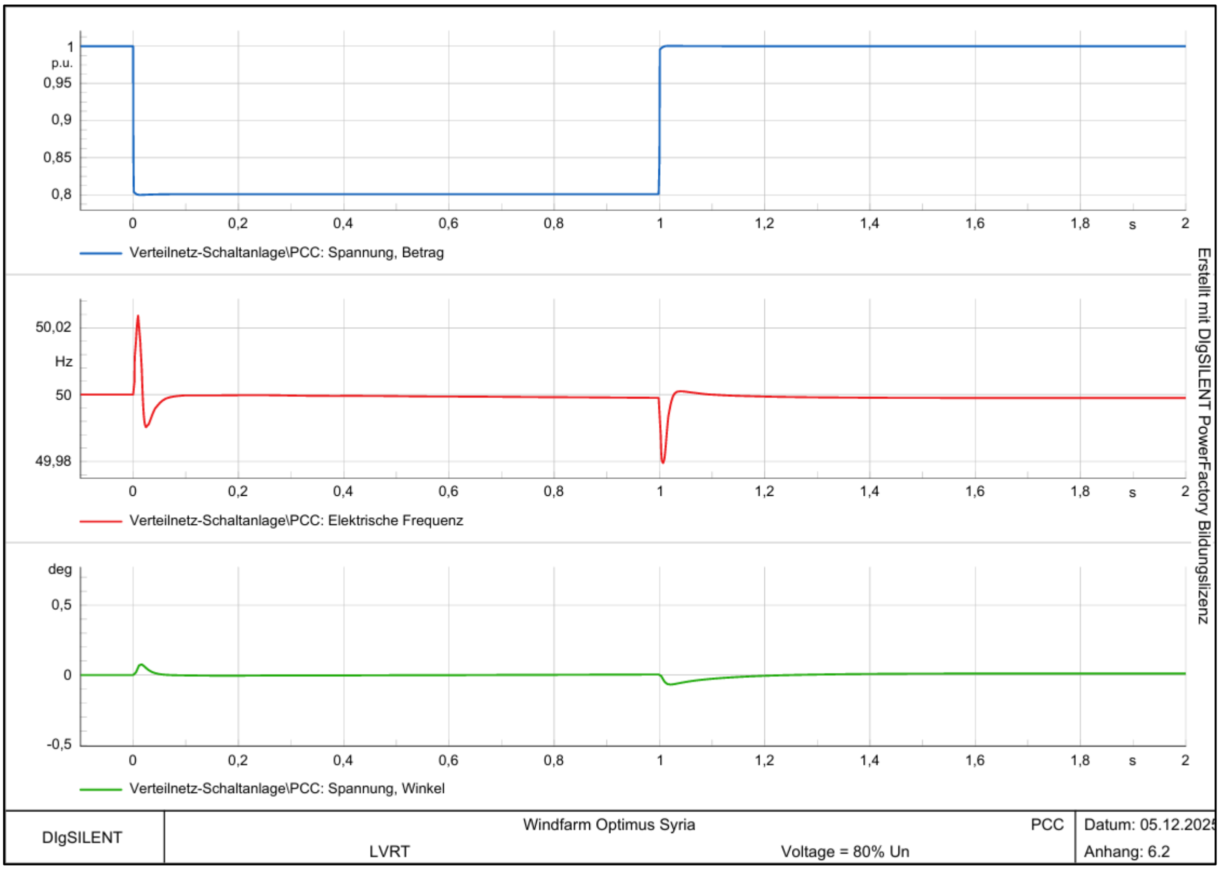

Figure 39: LVRT 80% – PCC – PowerFactory

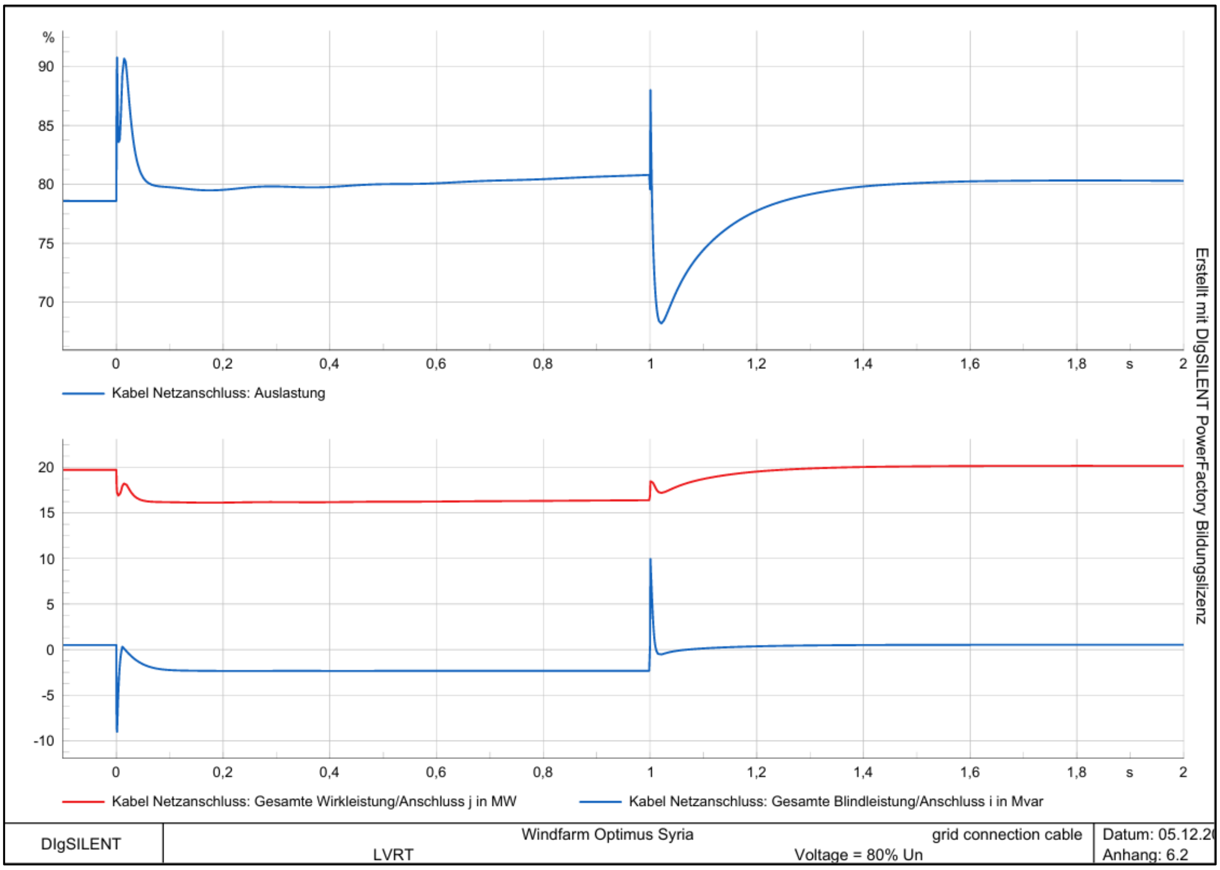

Figure 40: LVRT 80% – grid connection cable – PowerFactory

90% voltage

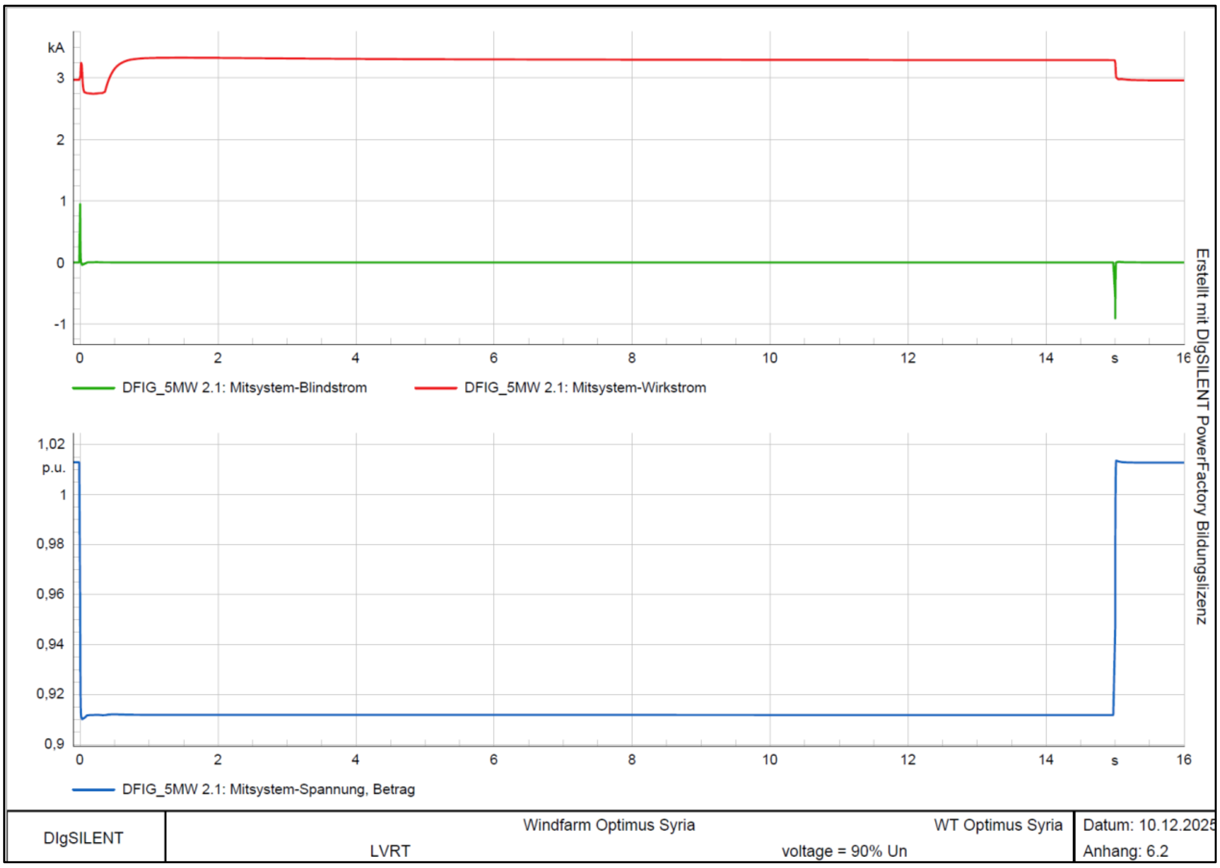

Figure 41: LVRT 90% – Optimus turbine – PowerFactory

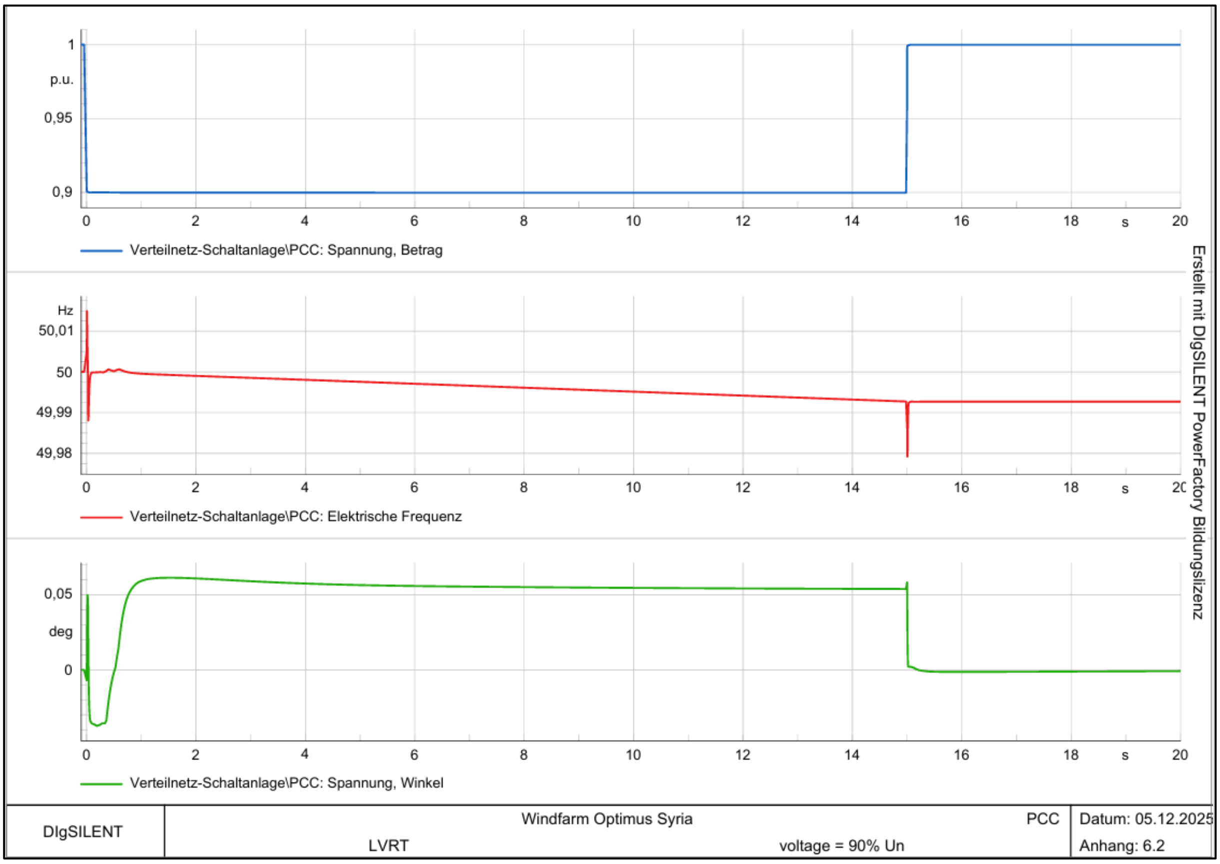

Figure 42: LVRT 90% – PCC – PowerFactory

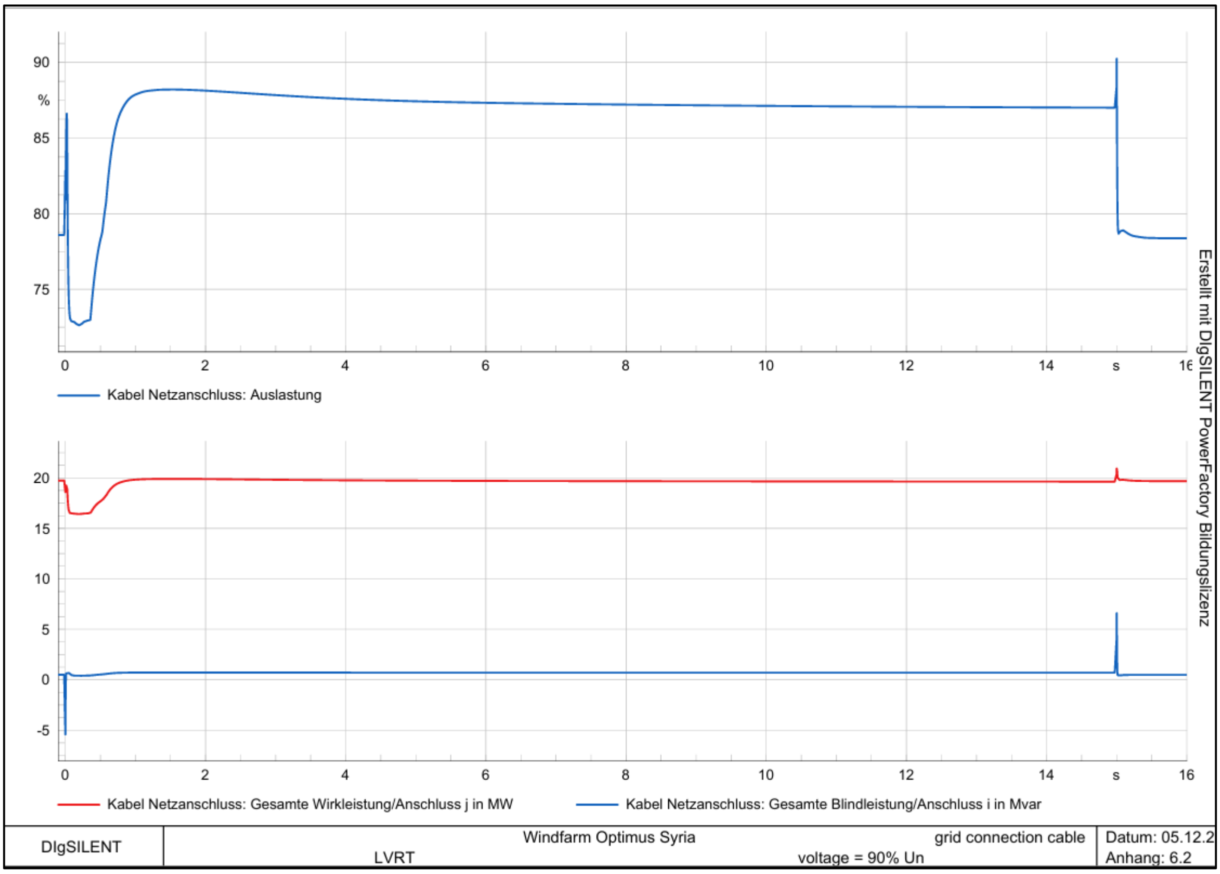

Figure 43: LVRT 90% – grid connection cable – PowerFactory

6.3.2 HVRT

As with the LVRT, the maximum component utilization was first examined in a load flow overview for the High-Voltage Ride Through, as displays in Figure 44 and 45. The overvoltages at the busbars are clearly visible. The respective utilization levels are moderate and do not exceed 100% in any

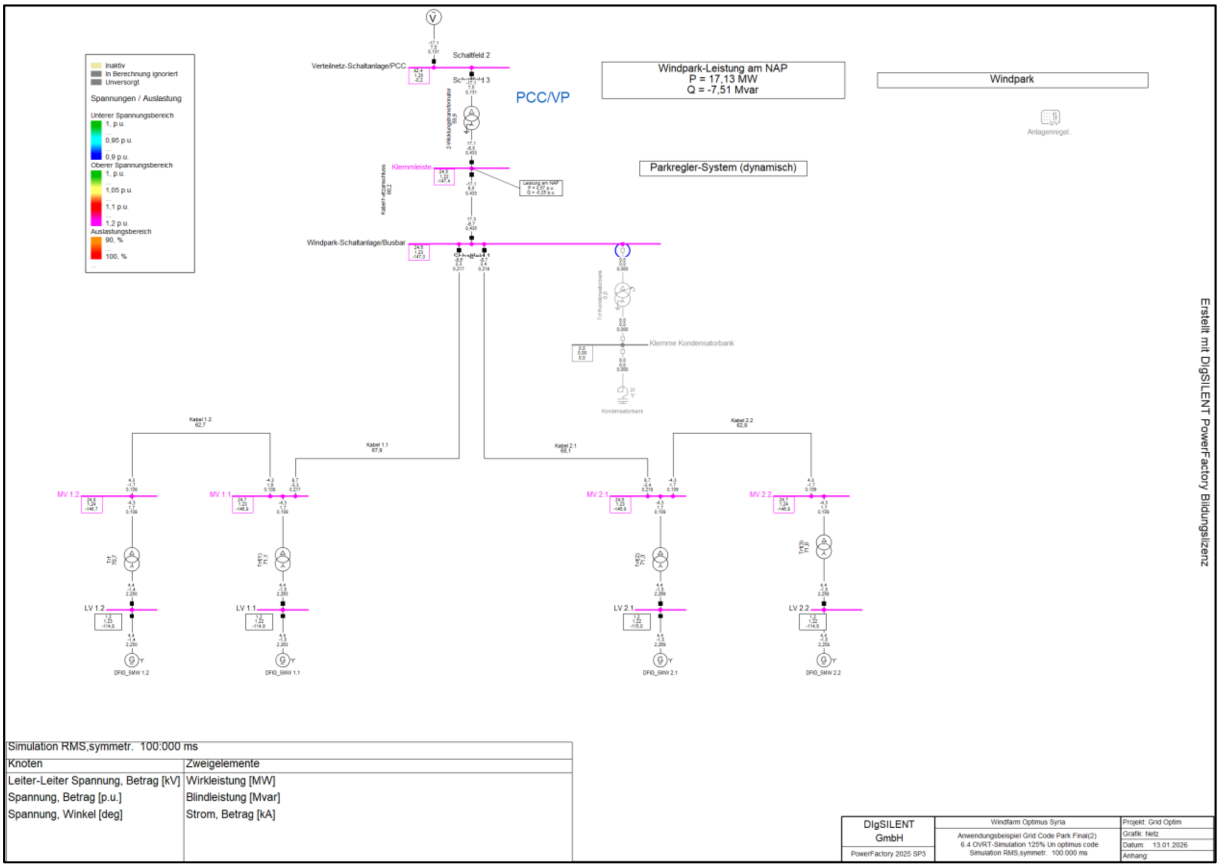

Figure 44: Load flow – HVRT 125% – PowerFactory

case.

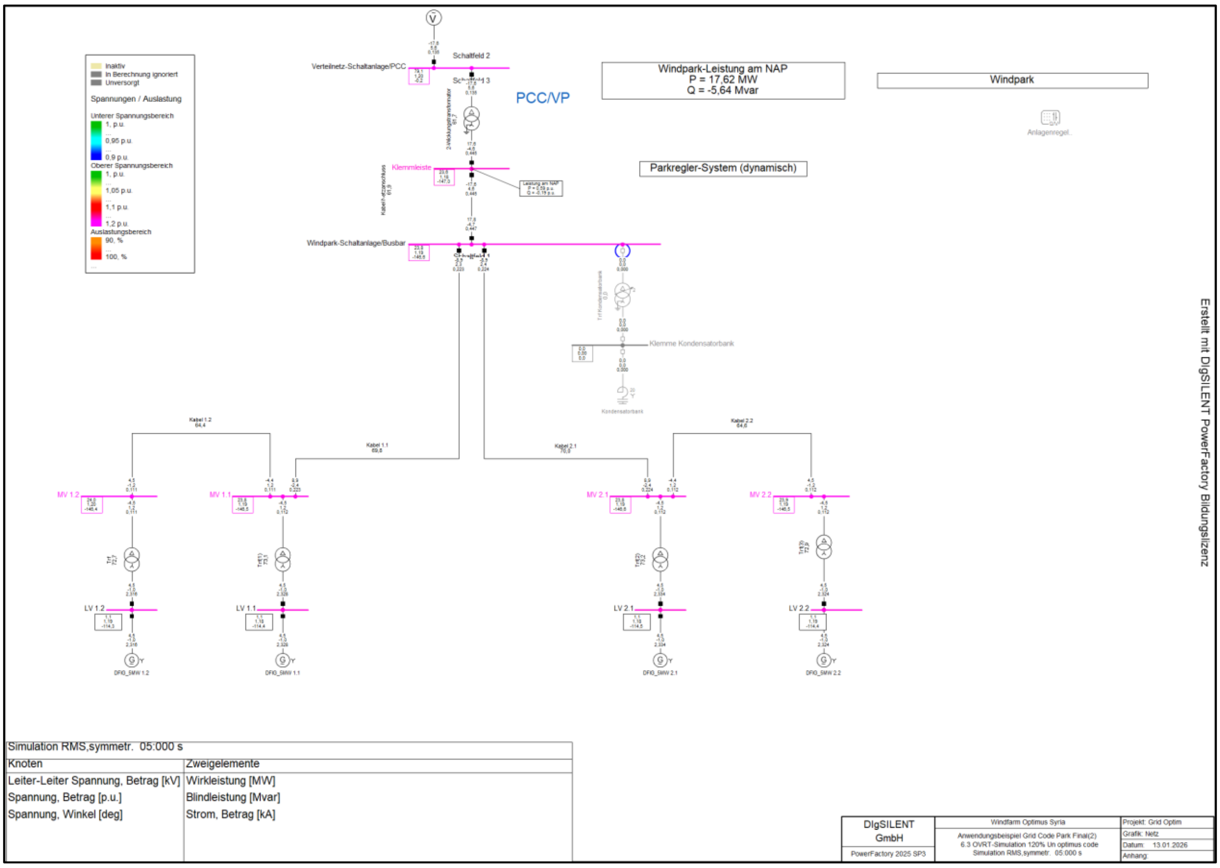

Figure 45: Load flow – HVRT 120% – PowerFactory

125% voltage

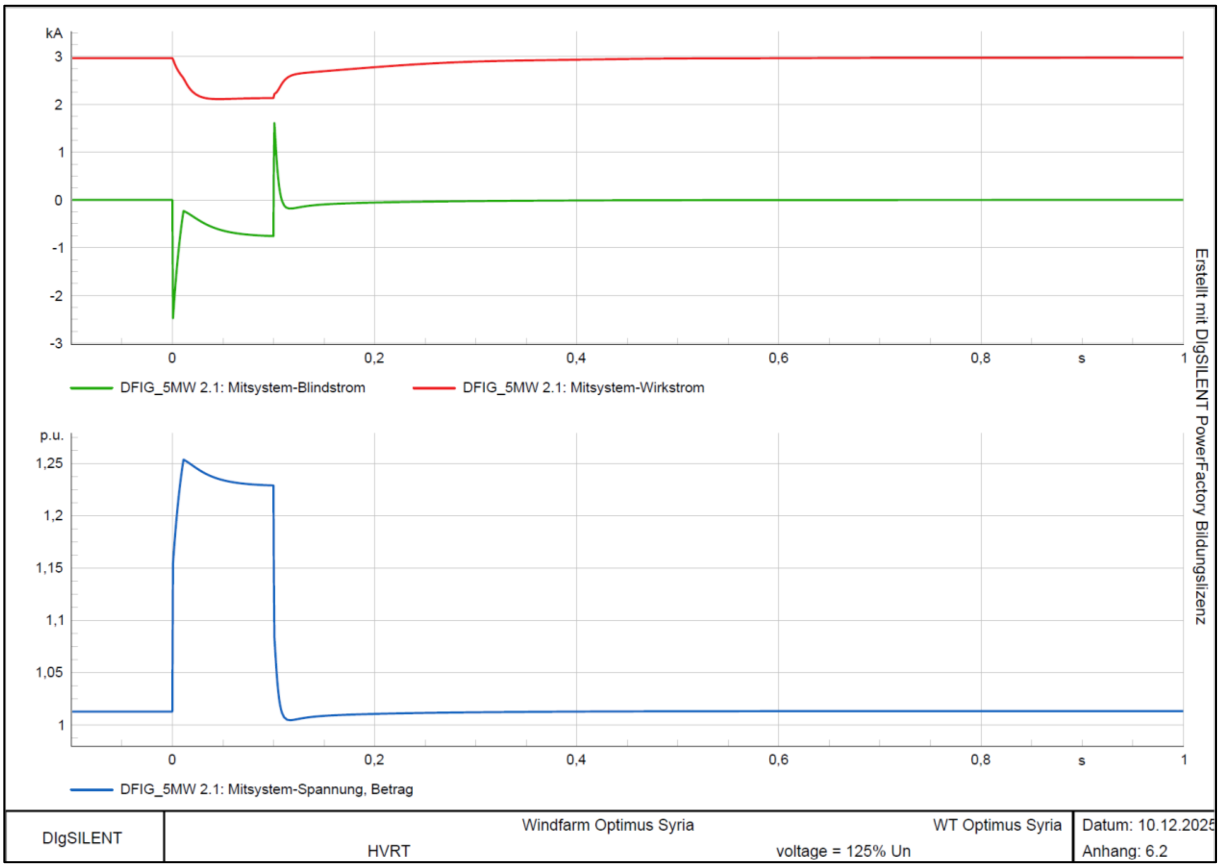

Figure 46: HVRT 125% – Optimus turbine – PowerFactory

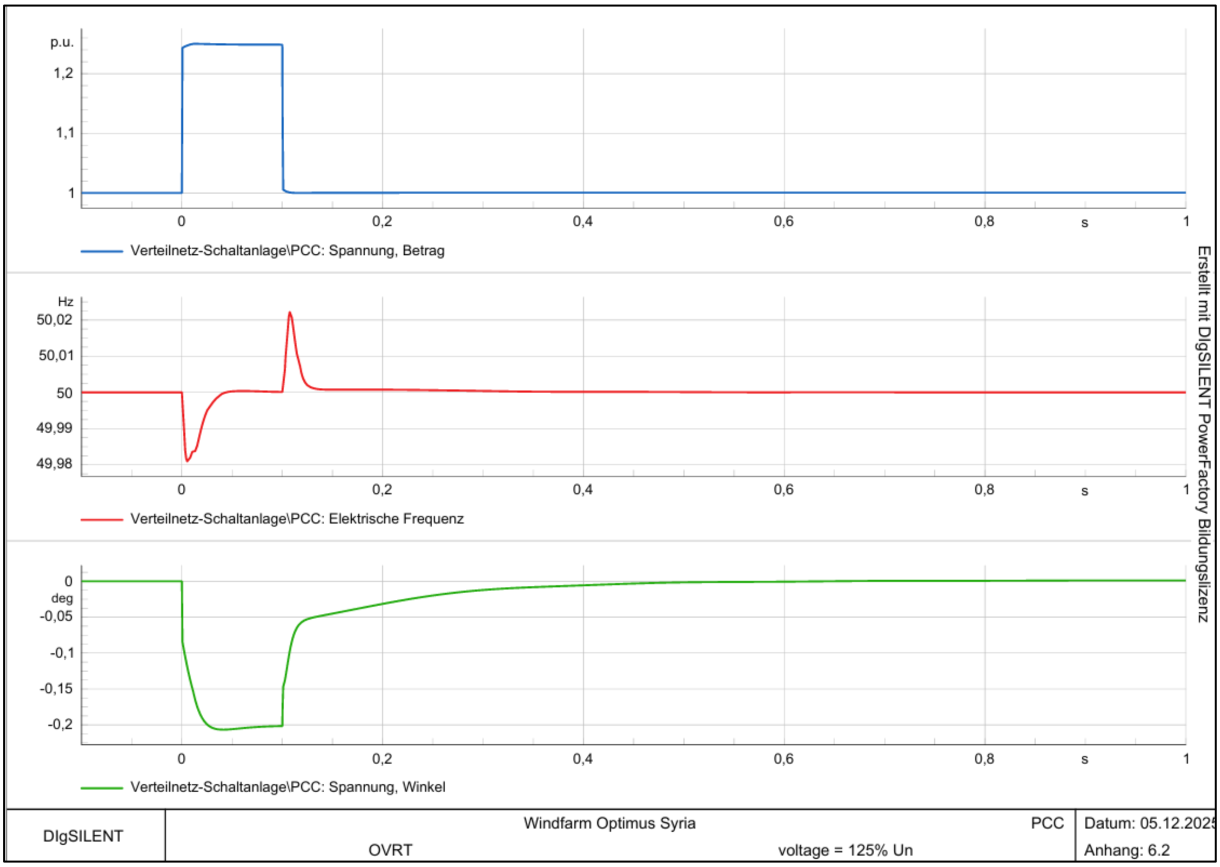

Figure 47: HVRT 125% – PCC – PowerFactory

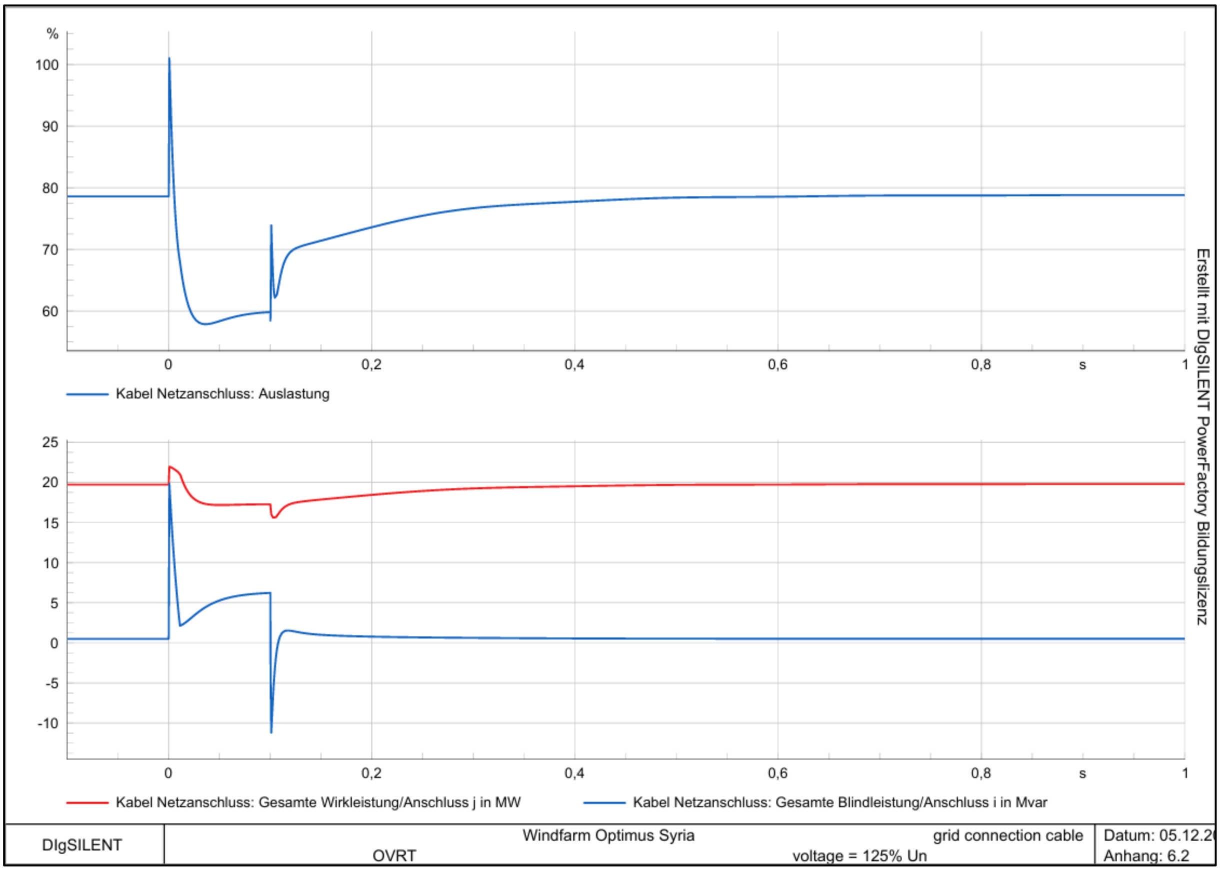

Figure 48: HVRT 125% – grid connection cable – PowerFactory

120% voltage

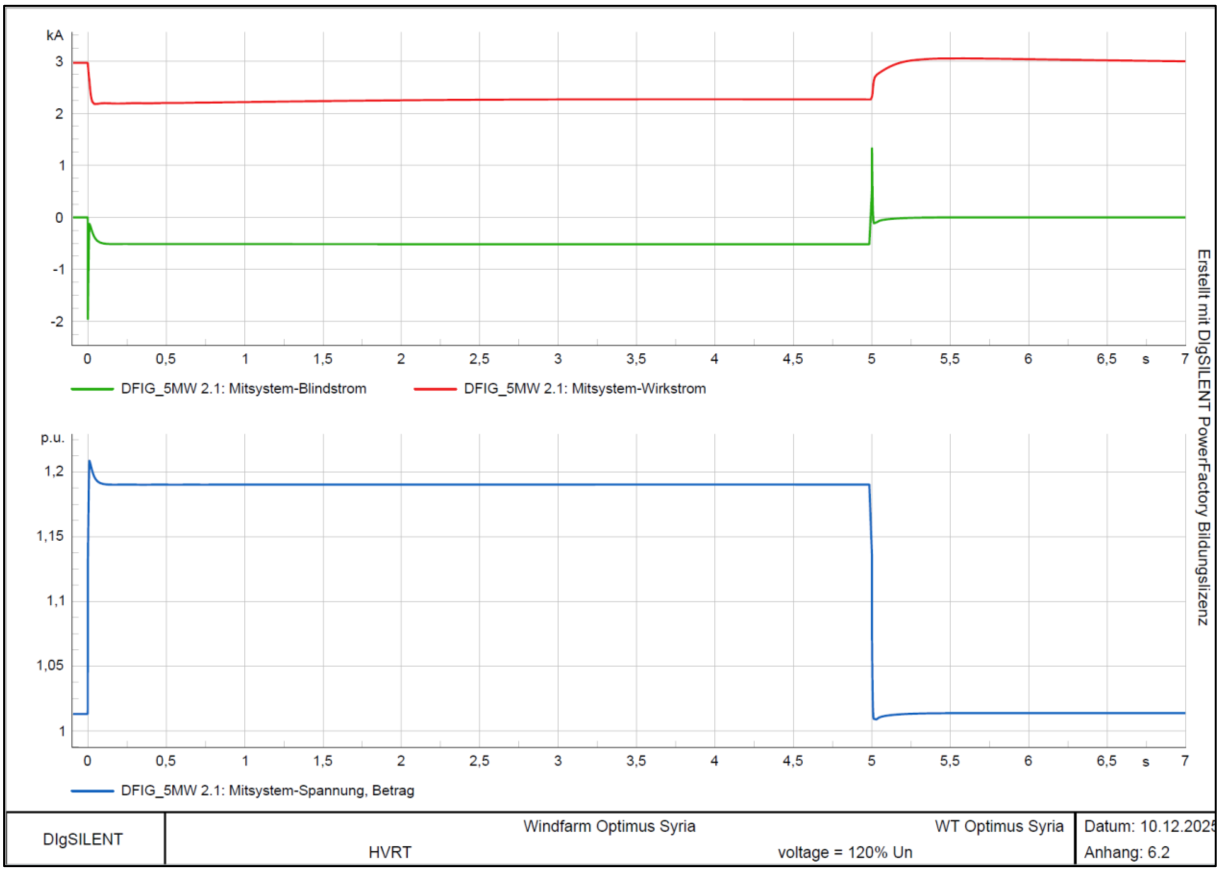

Figure 49: HVRT 120% – Optimus turbine – PowerFactory

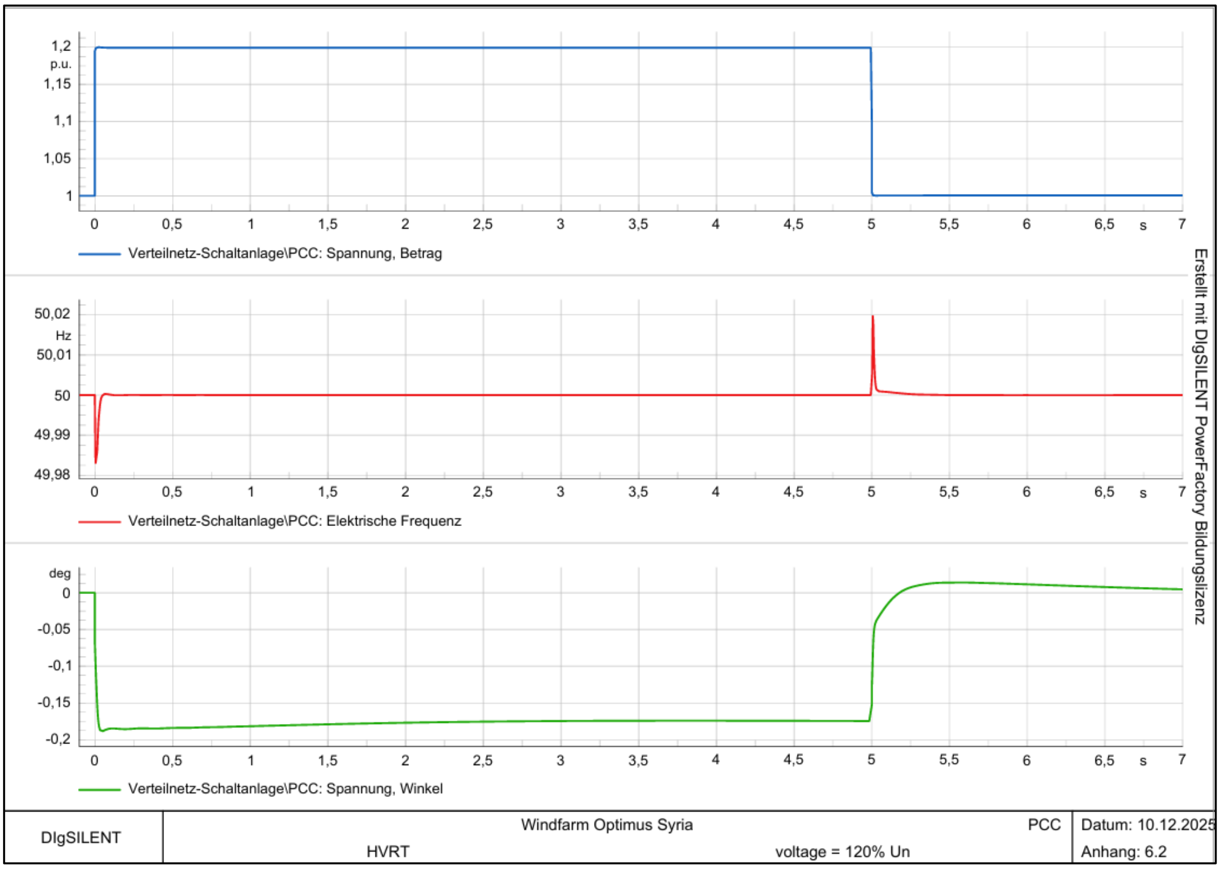

Figure 50: HVRT 120% – PCC – PowerFactory

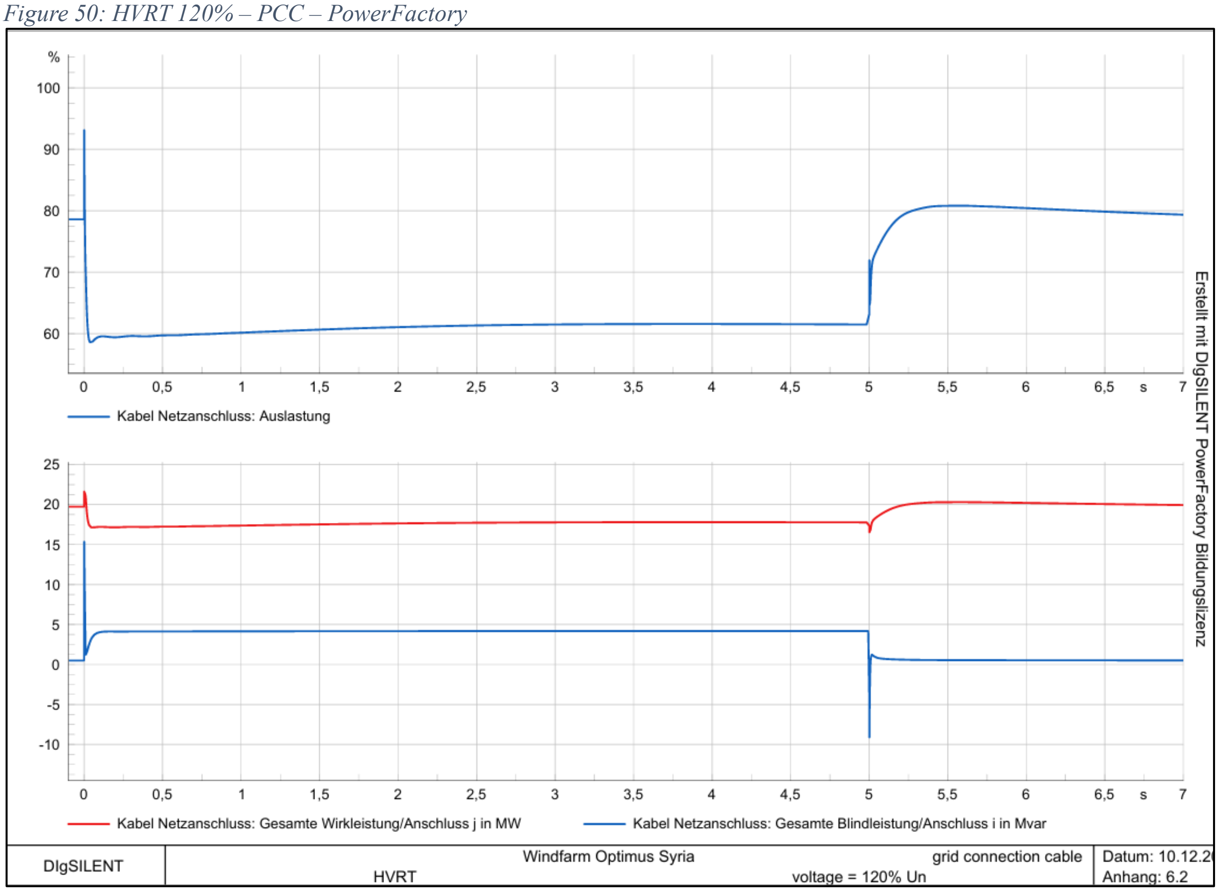

Figure 51: HVRT 120% – grid connection cable – PowerFactory

7 Conclusion and Outlook

7.1 Conclusion

Load Flow/short-circuit simulation

The results presented above validate the successful integration of the OSyr160-5.0 turbine into the wind farm concept. The strategic placement of the system in close proximity to the substation facilitates highly efficient power transmission. Based on current planning data, electrical power losses at full load are recorded at 0.43 MW, which corresponds to a total loss of 2%

Furthermore, the calculated Short-Circuit Ratio (SCR) of 108.7 indicates an exceptionally robust grid connection. However, it must be noted that the Optimus turbine is not the sole generator at this specific grid node. Consequently, the grid's hosting capacity must be evaluated in the context of the cumulative power feed-in from all connected units to ensure long-term stability.

FRT Simulation and Q-U Control Evaluation

To evaluate the OSyr160-5.0 turbine's compliance with the reactive current control specifications derived from the Q(U) droop characteristic (Figure 4), the following equations are applied to the simulation data [22, pp. 32-34]. For generating units without auxiliary voltage control equipment, the required k-factor is defined as 2. This parameter is implemented within the P-Q controller as $K_{\_\Delta U}$ (see Illustration 52). Furthermore, the voltage dead band (deltaU) is a critical factor in this context. Although the target specification for this value is 0.05, the current simulations utilize a value of 0.1. While this parameter can be adjusted in future iterations by updating the controller settings, the subsequent analysis and calculations are based on the current 0.1 setpoint.

$$I_n = \frac{S}{\sqrt{3} \times V_{gen}} = \frac{5{,}733\ kW}{\sqrt{3} \times 0.960\ kV} = 3.448\ kA \tag{7.1}$$

$$\text{LVRT: } \Delta U = (1.0 - U - \ deltaU) \tag{7.2}$$

$$\text{HVRT: } \Delta U = (1.0 - U + \ deltaU) \tag{7.3}$$

$$I_q(p.u.) = \Delta U * K_{deltaU} \tag{7.4}$$

$$I_q(kA) = I_q(p.u.) * I_n \tag{7.5}$$

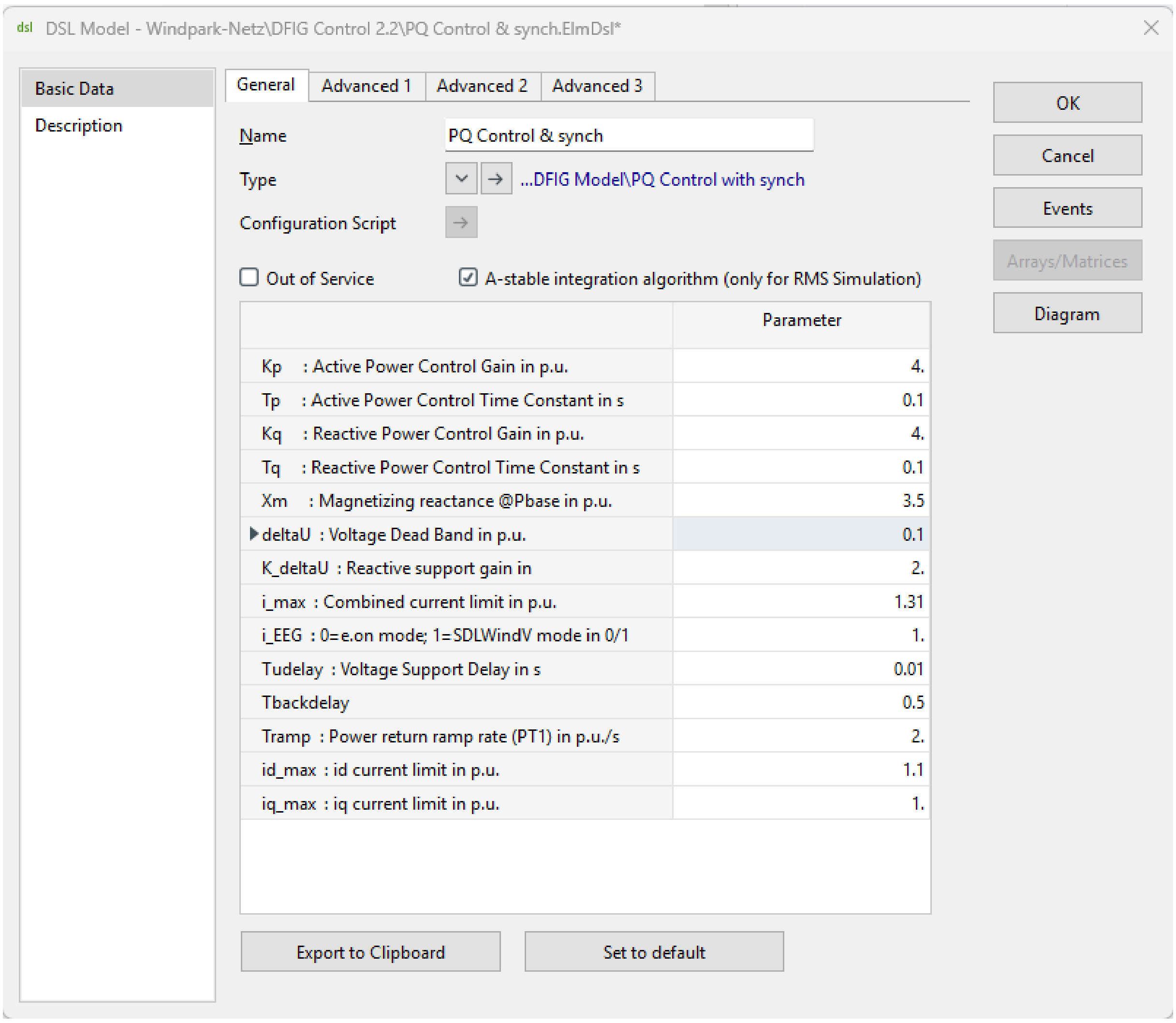

Figure 52: PQ Controller settings – PowerFactory

When a voltage dip occurs, such as the scenario with 20 percent residual voltage, the system must switch to an over excited mode to support the grid. This specifically means the injection of reactive current to stabilize the voltage. According to the grid code, this situation requires a 100 percent reactive current injection. In our case, this corresponds to the nominal apparent current of 3.448 kA. Graph 35 clearly demonstrates that this value is maintained consistently over the required period.

The calculated and required reactive current feed-in values for the various voltage cycles are summarized in Table 13 below.

Voltage in %	ΔU (p.u)	I_q (p.u.)	I_q (kA)
125	0.15	-0.3	**-1.034**
120	0.1	-0.2	**-0.690**
90	0	0	**0**
80	0.1	0.2	**0.690**
20	0.7	1	**3.448**
0	0.9	1	**3.448**

Table 13: FRT reactive current injection values

A subsequent evaluation of compliance with the P(f) droop characteristic specified in the grid code was not feasible due to minimal frequency deviations during the simulation. Since the control response is only triggered outside the dead band (below 49.8 Hz or above 50.2 Hz), the turbine remained in normal operation mode. These frequency thresholds were not reached due to the high stiffness of the connected public grid. Consequently, further simulations with more significant frequency excursions will be required to fully validate this control feature.

Furthermore, fault clearance is guaranteed in compliance with the previously established grid code specifications. The turbine demonstrates a grid-stabilizing response through the controlled injection of active and reactive power. In all simulated scenarios, the frequency at the PCC successfully recovers toward the nominal setpoint, or an acceptable approximation thereof, following the fault duration.

7.2 Outlook and Future Work

PQ Capability, UQ Characteristics and Harmonics/Power Quality Assessment

Derivation of PQ Capability Curves: Future work could focus on defining the specific operating limits, accounting for converter current ratings and thermal constraints under varying wind speeds. This ensures the OSyr160-5.0 turbine provides the necessary reactive power reserves required to maintain system stability and reliability as defined in the grid objectives.

Optimization of UQ Characteristics: Further research could aim to tailor the voltage-reactive power response of the Optimus turbine design to enhance static voltage stability within “weak grid” environments. This adaptation is crucial for meeting technical requirements for grid connection and ensuring effective voltage control.

Harmonics and Power Quality Assessment: Future research could include dedicated harmonic analysis using predefined simulation cases to evaluate the impact of the Optimus turbine electronics on the grid. This testing is vital to ensure that the harmonic emissions of our specific design remain within the strict limits defined by the grid code to prevent interference with other connected equipment and maintain overall power quality.

Hot-line system

Future studies should investigate the implementation of a dedicated bypass circuit at the Qattinah substation. This “hot-line” would allow the wind farm to decouple from the main transmission grid during systemic failures, directly supplying local medium- and low-voltage networks. This strategy aims to maximize turbine utilization by avoiding curtailment during transmission-level outages, thereby significantly improving the security of supply for the local population.

While the wind farm’s control systems are designed to actively support the grid through reactive power injection and frequency response, further infrastructure enhancements are mandatory to ensure stability during full islanded operation. Specifically, the integration of Battery Energy Storage Systems (BESS) or Static Synchronous Compensators (STATCOM) could be required to provide the necessary grid-forming capabilities and dynamic voltage support that the main transmission system usually provides. These systems act as a “synthetic slack,” compensating for the loss of the main grid’s reference signal and ensuring that local protection devices can reliably detect and clear faults to maintain system integrity.

Park scaling

As illustrated in the following figures, future work could investigate the potential for upscaling the wind farm project using the OSyr160-5.0 technology. A primary expansion site is located next to the village Um Aledam approximately 10 km northwest of the substation, which offers a favorable balance between distance and increased installed capacity. Furthermore, the integration of a technically optimized Energy Storage System (ESS) could significantly enhance the security of supply for the Homs district. Given the high SCR and the robust nature of the existing 230 kV infrastructure, the substation is well-positioned to accommodate this additional power injection without compromising grid stability.

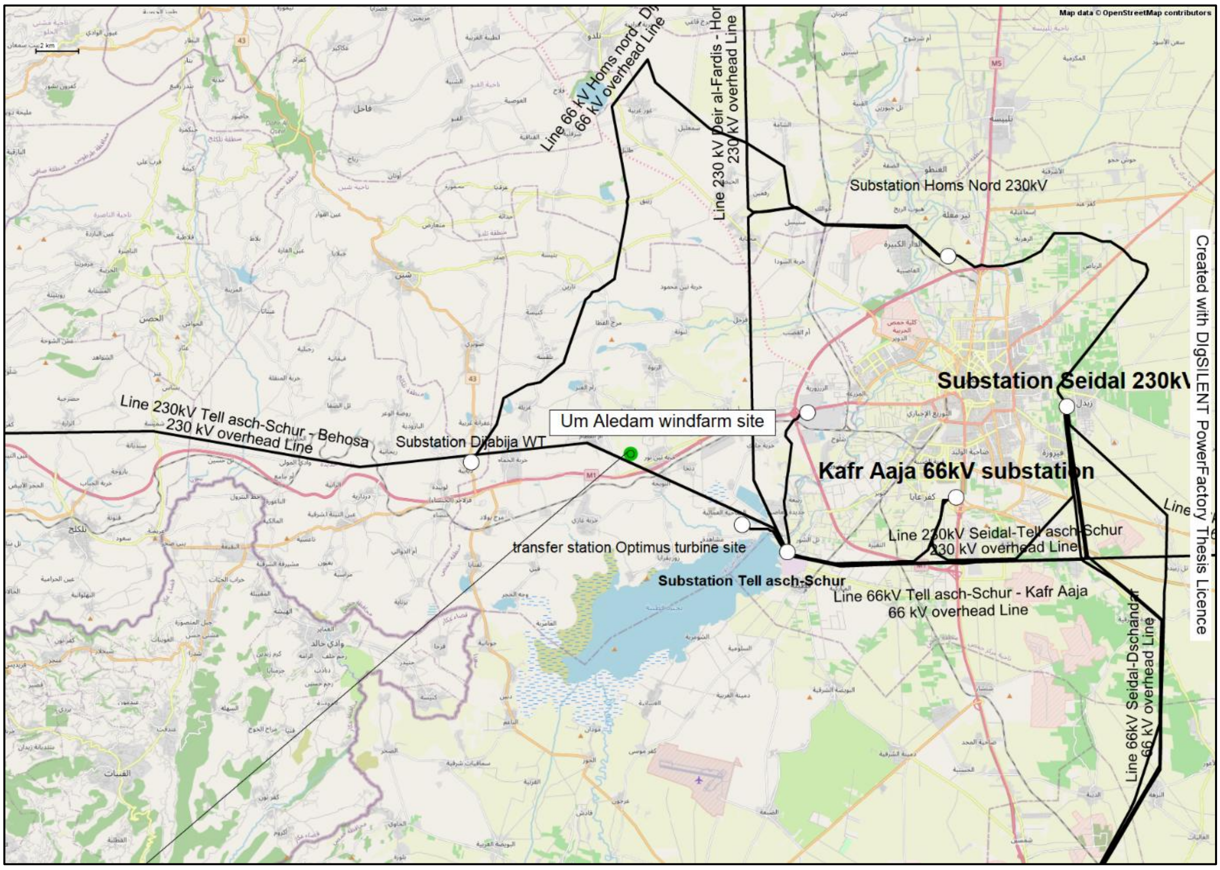

Figure 53: Um Aledam windfarm site - grid infrastructure around Homs – PowerFactory

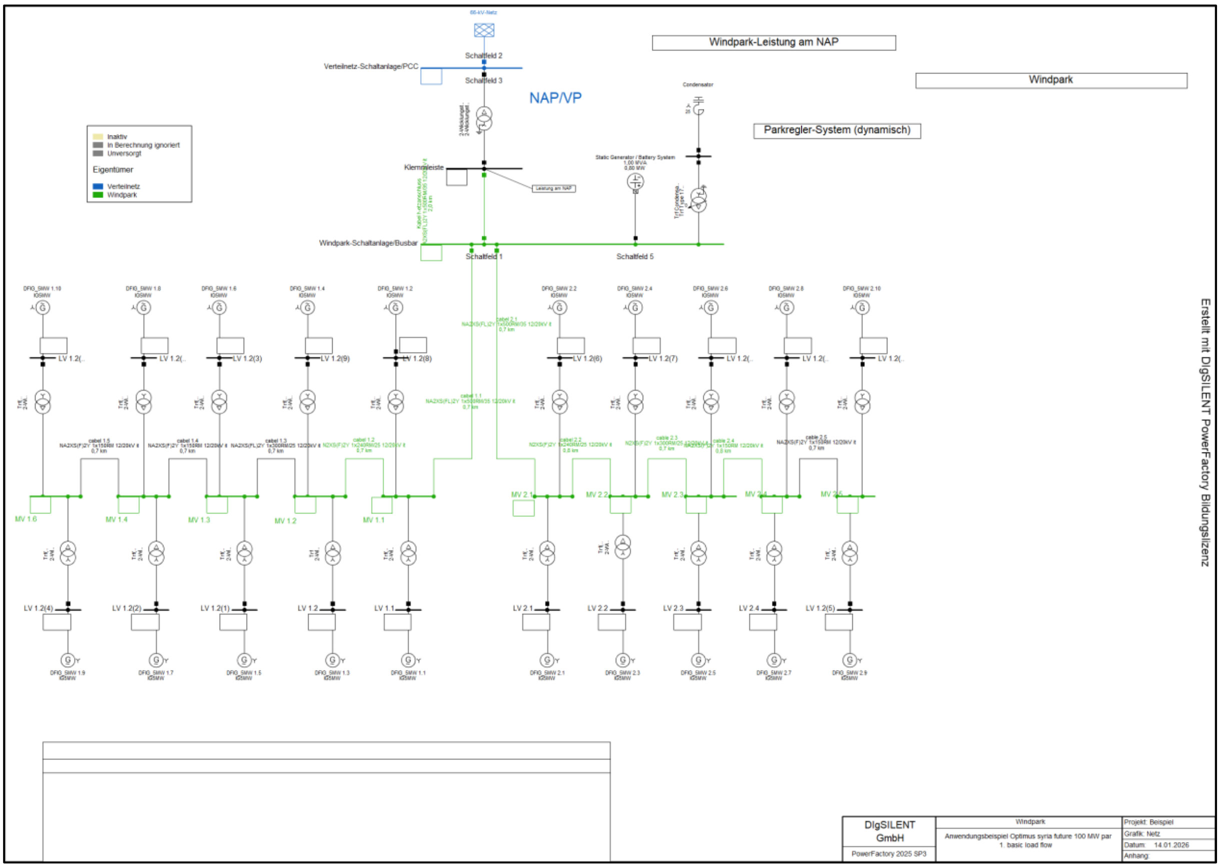

Figure 54: Possible future 100 MW windfarm Optimus turbine – PowerFactory

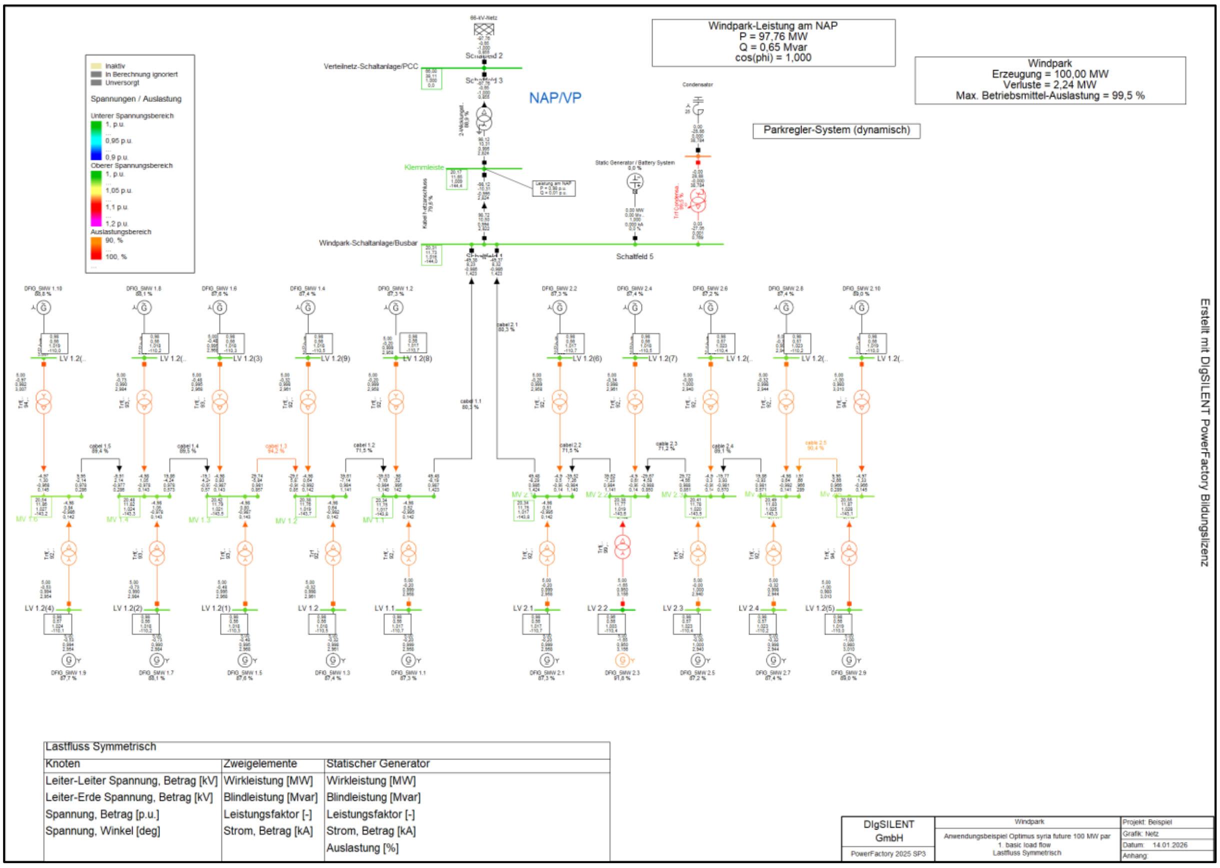

Figure 55: Load flow possible future 100MW windfarm Optimus turbine – PowerFactory

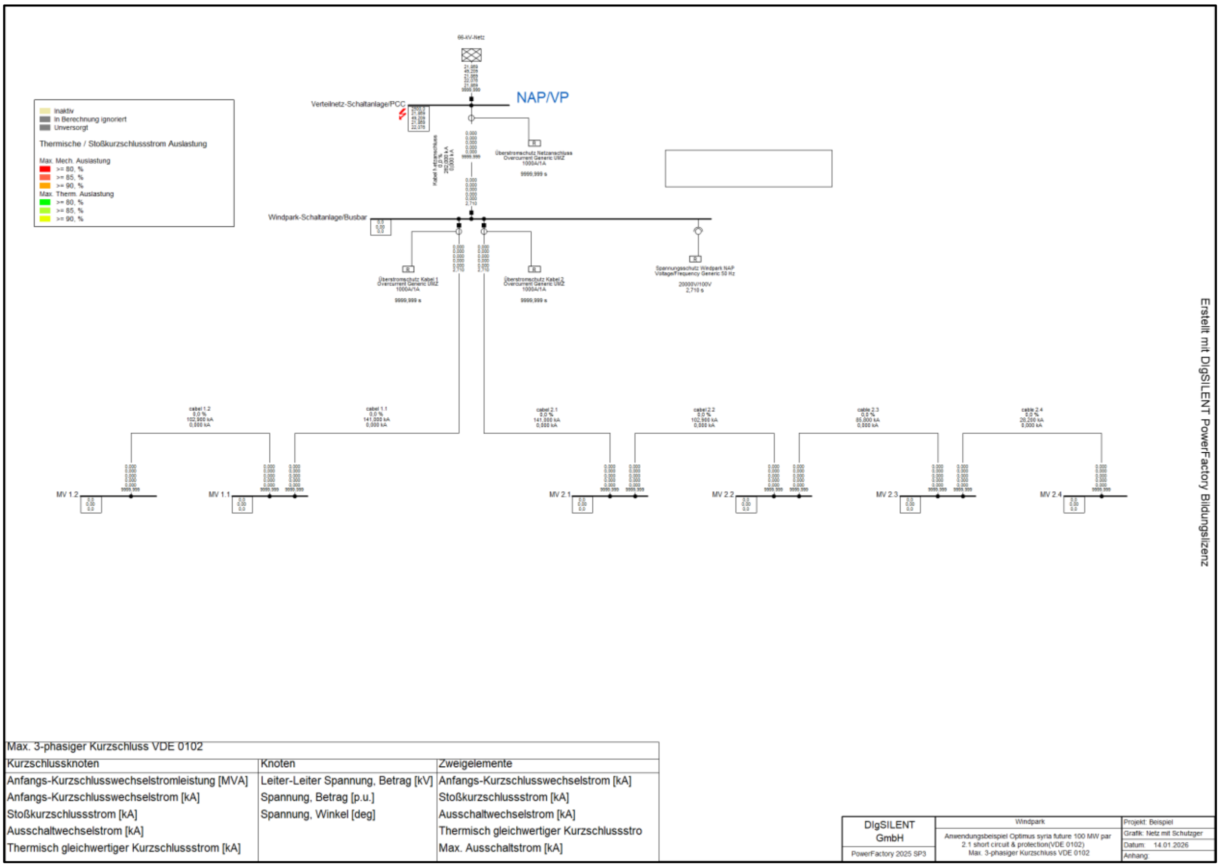

Figure 56: Short circuit VDE 0102 simulation – 100 MW windfarm – PowerFactory

8 Workload

Working as a two-person team has been a rewarding experience that provided much more than just technical insights. Our collaboration was a blend of different cultural backgrounds and perspectives, which significantly sharpened our communication skills and taught us to approach complex problems with a more flexible and open mindset. Whether meeting in person, coordinating online, or studying in the library, the process of organizing our workflow greatly enhanced our shared time management abilities.

Our journey was not without its hurdles. We faced significant challenges, such as limited access to specific grid data from Syria and technical setbacks like the PowerFactory licensing issue. However, these obstacles ultimately strengthened our resilience. We learned to find creative workarounds and bridge knowledge gaps through intensive research and mutual support.

In terms of our workflow, most of the core objectives were tackled jointly to ensure a high level of quality. For specific subtasks, we adopted a strategy where one team member would prepare the groundwork followed by a thorough peer discussion to finalize the results. This collaborative 'four eyes principle' ensured that we remained aligned throughout the project. A detailed breakdown of the individual tasks and responsibilities can be found in the table below.

Tasks	Responsible person
Analysis of the Syrian grid	Team
Study of several different Grid Codes	Vijay Bogala
Grid Code research Syria	Team
PowerFactory model Optimus windfarm	Team
PowerFactory Load and short circuit calculation	Team
PowerFactory RMS calculation	Josef Remberger
Introduction – Report	Vijay Bogala
Site and turbine details – Report	Vijay Bogala
Electrical parameters – Report	Vijay Bogala
Development of Grid Code – Report	Josef Remberger
PowerFactory – Report	Josef Remberger
Results – Report	Josef Remberger
Conclusion/Discussion – Report	Team

Table 14: Summarized tasks over the project time – responsibilities

We would like to say a big thank you to our supervisor, Prof. Dr.-Ing. R. Saiju, who helped and guided us well. I’d also like to thank Marc Notrott, who was always there to answer questions about PowerFactory. We would like to thank the colleges we worked with, especially the Electrical Drive Train team, for their good cooperation.

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