FLEXStation

Flexible & Active – Power Electronic Substation

TEUE116234

Final Project Report

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Consortium information

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Partner 1	Technische Universiteit Eindhoven	Kennisinstelling
Partner 2	Enexis BV	Netbeheerder
Partner 3	Alliander NV	Netbeheerder
Partner 4 Coordinator / Penvoerder 1-12-2019 t/m 31-12-2021	KEMA BV	Groot bedrijf
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Executive summary

The future energy supply is going to change significantly at household- and neighborhood-level due to the increase in renewable energy generation, the further electrification of households, and the charging of electric vehicles. These changes will result in severe fluctuations in demand and supply and requires more flexibility in the distribution grids.

The goal of the project Flexible & Active-Power Electronic Substation is the development of a prototype of a Solid State transformer (SST) for a Power Electronics Substation (PES) as an alternative for a controllable distribution transformer.

The future distribution grid is modeled by Enexis and Alliander with scenarios of TU/e and DNVGL/KEMA. Based on the modelling, the functionality of the PES on both MV and LV side is determined. An economic evaluation is performed for the chosen SST solution compared to grid reinforcement or other conventional flexibility solutions. Norms and standards applicable to the SST are used to come up with a basic design. Components and software are designed, optimized and validated with simulations in the smart grid lab of TU/e. The prototype, based on components and modules produced by Prodrive technologies, is build and tested at TU/e. The prototype consists of 3 modules of each 0.8kV and 10kVA for 1 phase of a 10/0.4kV SST. KEMA developed a complete 3 phase system model suitable for real time simulation based on the prototype.

Currently the SST is too expensive compared to conventional solutions. One of the reasons for this is that existing acceptance test requirements for distribution transformers are difficult (and expensive) to meet and possibly solvable in a different way. An important step is made with this project for the Dutch knowledge institutes, industry and DSOs towards future flexibility of the distribution. This project served as a stimulus for many bachelor, master and PhD students to choose for the combination of high voltage technology and power electronics.

1. Introduction, goal and project organisation

Introduction

The future energy supply is going to change significantly at household- and neighborhood-level due to the increase in renewable energy generation, the further electrification of households, and the charging of electric vehicles. These changes will result in severe fluctuations in demand and supply and requires more flexibility in the distribution grids. Distribution grids are designed and constructed for a lifespan of a least 40 years but currently reach double the lifespan. This project would enable the distribution grid to acquire the needed flexibility, intelligence, robustness and modularity to cope with the upcoming energy transition changes in the next decades.

Goal

The project Flexible & Active-Power Electronic Substation concerns a four-year Dutch subsidised project from the TKI Urban Energy program. The goal of this project is the development of a Power Electronics Substation (PES) that can convert medium to low voltage as an alternative for regular distribution transformers and in particular a controllable distribution transformer. The use of power electronics opens the door to an integrated voltage control for rapid changing grid conditions. In particular, a strongly growing decentralised production in the Medium Voltage (MV) and Low Voltage (LV) grids is addressed, but also a growth in demand due to heat pumps and electrification of mobility. The PES could be a means to maintain grid stability despite the expected dynamics on the grid. Moreover, a PES can be designed with DC capabilities for the MV and LV level to connect potentially more efficient new technologies to the grid. These technologies include for example LED public lighting, PV solar generation, EV charging equipment and electric energy storage systems.

Project organization

This project includes the development, realisation and testing of the key element of a PES, the Solid-State Transformer (SST) prototype. The project consortium consists of TU/e, Enexis, DNV GL, Alliander, KEMA and Prodrive Technologies. The work was divided in work packages that were distributed amongst the consortium partners. First, the future distribution grid is modeled by Enexis and Alliander with grid-scenarios provided by the TU/e and DNV GL. Based on the modeling, the primary functions of the SST are determined. The economic evaluation of the SST, compared to the normal practice of increasing the grid's capacity, is performed by Enexis. The basic design of the SST prototype, the selection of components, and the writing of the software & firmware are done by a PhD at the TU/e. Detailed circuit design and manufacturing of electronic circuit boards for the prototype were done at Prodrive Technologies.

2. Project results

2.1 Analysis of future scenarios, functional requirements, and business case

2.1.1 Analysis of future scenarios

The main Impact of the energy transition from a LV-network perspective is the residential electricity supply and use. Ensuring adequate network capacity and power quality are the main requirements the Distribution System Operator (DSO) should focus on, to facilitate this transition.

Photovoltaics (PV), Electric Vehicles (EV) and Heat Pumps (HP) have been identified as new technologies that influence the LV-network the most. Thus, individual scenarios for adoption of these technologies have been created. Since the transition towards a sustainable energy supply can be facilitated in different ways, resulting in different adoption rates of the different technologies, two scenarios have been created for each of the above-mentioned technologies, a low adoption scenario and a high adoption scenario. These scenarios as shown in Figure 1 have been used in the analysis of possible bottlenecks for the electricity distribution. It should be noted that de deliverable comes from the early stage of the project, December 2017, which means that some estimates might change from the current point of view (Appendix A, Scenario Analysis).

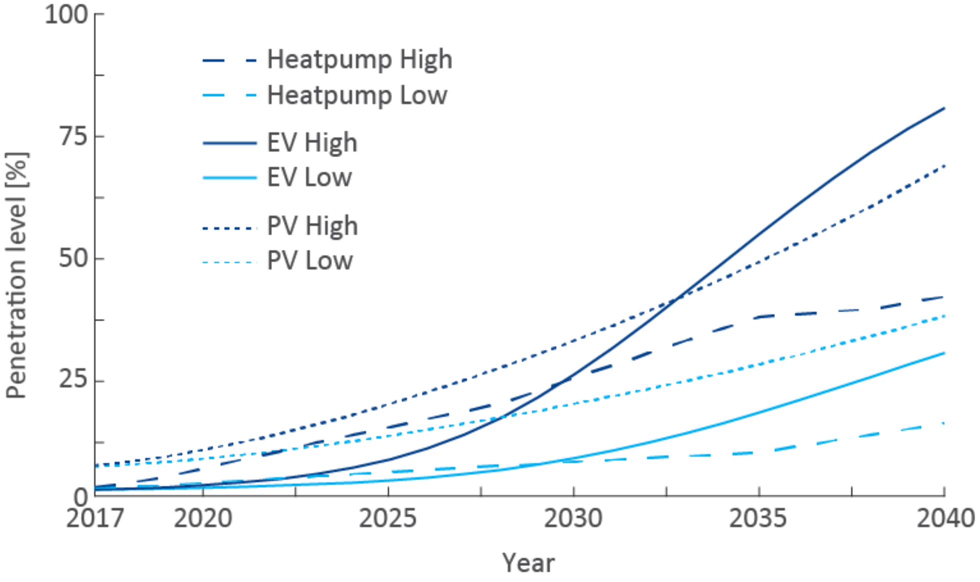


Figure 1 Load and Distributed Generation adoption growth scenarios used in the analysis, results from December 2017

From the prediction per technology, four total development scenarios were created, combining the technologies at the estimated high and low adoption levels. The scenarios labelled as Decentralized, Centralized, Fossil Fuels and Renovation are defined in Table 1. The results of the scenario analysis are shown in Figure 2 and Figure 3.

Table 1 Development scenarios resulting from various combinations of the individual low or high technology scenarios.

	Photovoltaics	Electric Vehicles	Heat Pumps
Scenario A: Decentralised	High	High	High
Scenario B: Centralised	Low	High	High
Scenario C: Fossil Fuel	Low	Low	Low
Scenario D: Renovation	High	Low	High

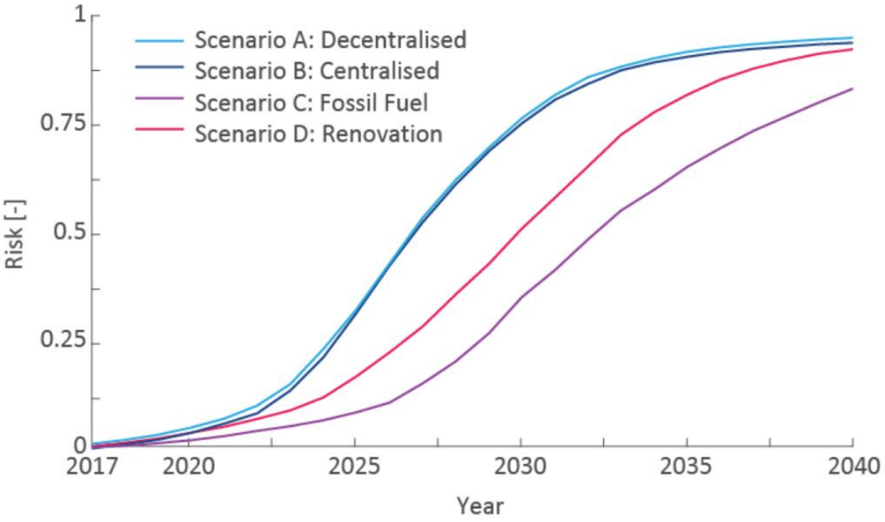


Figure 2 The risk of overloading/voltage violations in the LV network for the four scenarios between now and 2040.

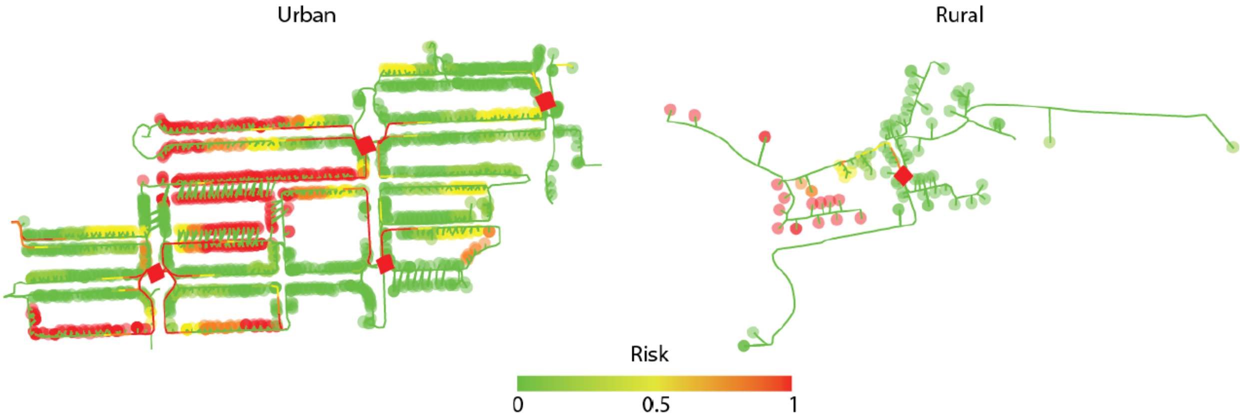


Figure 3 The risk in the network in 2040 for the decentralised scenario for a rural and urban LV network

According to the results of this study, the risk of overloading and voltage variations in the network (different for urban and rural areas) will already start to rise from the first year onwards. The risk in the first few years (5-9 years depending on the scenario) will be relatively small (<10%) and steadily increasing. Hereafter the risk can quickly increase, in a 5-year period the risk will increase by 35% points in the lowest scenario and up to 50% points in the highest scenario. It can thus be observed that there is limited time available to determine an adequate approach to mitigate these risks.

Overloading
The transformer is the part of the distribution network that is most susceptible to risks introduced by the transition towards a sustainable energy supply. In 2025 already close to 10 % of the transformers may need to be replaced, depending on which scenario becomes reality. In 2040 the number of transformers that experience overloading problems increases to between 50 and nearly all substations.

Voltage violations
Next to the risk of overloading, the voltage in the LV network should also be kept within the limits. In 2025 it is expected that already 5% of the customers experience voltages outside the limits, in 2040 this number rises to close to between 20 and 40% of the customers dependent on the scenario. The voltage violations are caused by both the increase in load (from both EV and heat pumps) as well as from the increase in generation in the form of PV. Because of this, the voltage risk shows a difference between the centralised and decentralised scenarios, while for the more load driven overloading problems the risks are equal. For scenarios with less extreme heat pump adaptation, the voltage violations from PV usually play the most important role in the determination of the risk. This is a very important conclusion, as the SST is conceived by default as a network element with existing voltage control, which makes it a possible solution for many locations with voltage violations, while it is one of the alternatives for replacing the many predicted overloaded transformers.

2.1.2 Functional requirements for the SST

The requirements for a SST were formulated by Enexis and Alliander, looking at their current operational needs, applicable standards, and future developments in the distribution. The requirements cover the medium and low voltage sides of the substations, regarding the bi-directional power flow, power factor, power quality (with emphasis on voltage control and frequency control on the low-voltage side), short-circuit requirements, reliability, maintainability, and environmental and housing requirements.

The detailed requirements of the SST are given in Appendix B, Functionality requirements of the SST.

2.1.3 Economical analysis of the SST

The study of the SST business-case, Appendix C (Economical Analysis of a SST), compared the SST with a Conventional Transformer with a (on-load) Tap changer (CTT). In addition to the traditional transformer functionality, both these transformer types include voltage control. The Conventional Transformer with an on-load Tap changer is a type of transformer that is currently used for locations where large voltage fluctuations are expected. It is only applied in a limited number of cases, compared to transformers with off-load Tap changers since it has higher costs.

In addition to voltage control the SST has more advantages that could be useful in the near future. For example, providing a DC voltage at the local neighborhood level may enable easy integration of storage or fast charge points into the grid. Another example is that an SST can reduce harmonics in the grid, as these are expected to increase in the future. In case of a CTT these extra functionalities can also be realised, but this would require additional investments, like an inverter for storage/fast charging or a harmonics filter.

This comparison considers the regular cost of a transformer, like investment, maintenance, transformer losses, etc. It also includes the cost of the extra functionalities that a CTT lacks in comparison with an SST. This of course depends on the future need for these extra functionalities. As this is still uncertain now, different scenarios are explored. Adding all these different costs results in the total system cost for an SST on the one hand and of a CTT on the other hand. The main conclusions of this research are:

- A Solid State Transformer (SST) cannot yet compete with a Conventional Transformer with an on-load Tap Changer (CTT) in the distribution grid. Besides the high investment cost, an SST also has high cost related to reliability (repair cost) and energy losses. The advantages of an SST, like harmonics reduction, voltage dip reduction and enabling of DC applications, cannot yet compensate for this. Additionally, for specific application there are further benefits, such as reduced weight and flexibility in shape.
- As the investment cost of an SST is likely to decrease drastically, it is expected that within 10 years total system cost of an SST will be comparable to that of a CTT, provided that there will be a future need for the extra functionalities an SST can provide. These functionalities include for instance 'voltage quality improvement', 'enabling storage near substations' and 'enabling fast charging near substations'.
- When looking at total system cost more closely, it appears that the extra investment of the network operator in an SST mainly leads to financial benefits to other parties, like private companies that invest in storage or fast charging stations. In the end this will of course benefit society as a whole. For a healthy business case however, the network operator may have to be compensated for the extra cost, when the SST would be implemented on a large scale.

The details of this study are given in paper 365 of the CIRED 2021 Conference.

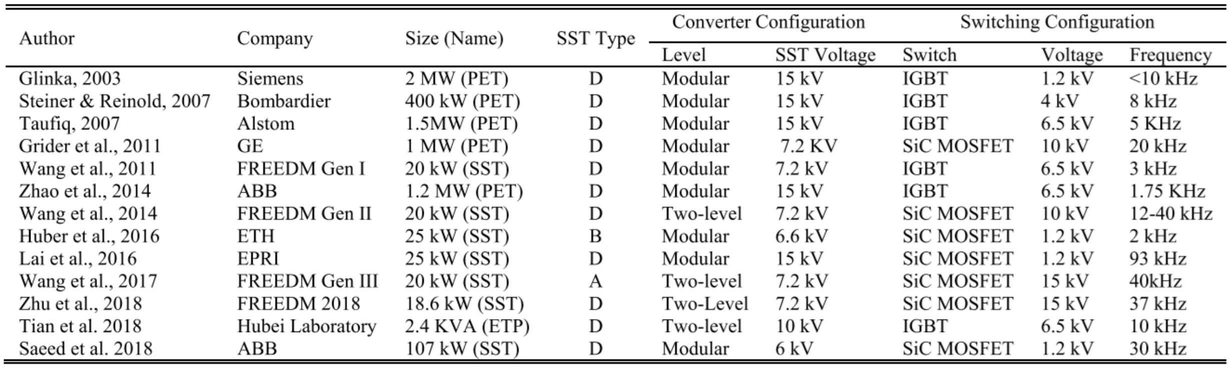
2.3 Design and testing of the power electronics

The design and testing of the prototype were done in several phases: conceptual design and computer simulations, detailed designed followed by the building of the prototype. Conceptual design was performed as a preliminary study into the availability (and cost) of available power electronics components, as well as the topology concepts. A topology was selected and built as a simulation. During these simulations a control strategy was devised. This was then followed by a detailed design of circuit boards, mechanics, and cabling. After the detailed design, the power electronics hardware was manufactured and tested.

2.3.1 Conceptual design of the SST and IEC60076-3

The conceptual design was kicked off with an investigation into the state-of-the-art and existing SST prototypes. In 2018 the state-of-the-art study led to six exiting prototypes being identified. In 2020 a paper summarizing the state-of-the-art of SSTs identified several more and made an excellent list. It is listed below.

TABLE 7. **Specifications and configurations of MV SST design under different companies.**



Author	Company	Size (Name)	SST Type	Converter Configuration		Switching Configuration		
				Level	SST Voltage	Switch	Voltage	Frequency
Glinka, 2003	Siemens	2 MW (PET)	D	Modular	15 kV	IGBT	1.2 kV	<10 kHz
Steiner & Reinold, 2007	Bombardier	400 kW (PET)	D	Modular	15 kV	IGBT	4 kV	8 kHz
Taufiq, 2007	Alstom	1.5MW (PET)	D	Modular	15 kV	IGBT	6.5 kV	5 KHz
Grider et al., 2011	GE	1 MW (PET)	D	Modular	7.2 KV	SiC MOSFET	10 kV	20 kHz
Wang et al., 2011	FREEDM Gen I	20 kW (SST)	D	Modular	7.2 kV	IGBT	6.5 kV	3 kHz
Zhao et al., 2014	ABB	1.2 MW (PET)	D	Modular	15 kV	IGBT	6.5 kV	1.75 KHz
Wang et al., 2014	FREEDM Gen II	20 kW (SST)	D	Two-level	7.2 kV	SiC MOSFET	10 kV	12-40 kHz
Huber et al., 2016	ETH	25 kW (SST)	B	Modular	6.6 kV	SiC MOSFET	1.2 kV	2 kHz
Lai et al., 2016	EPRI	25 kW (SST)	D	Modular	15 kV	SiC MOSFET	1.2 kV	93 kHz
Wang et al., 2017	FREEDM Gen III	20 kW (SST)	A	Two-level	7.2 kV	SiC MOSFET	15 kV	40kHz
Zhu et al., 2018	FREEDM 2018	18.6 kW (SST)	D	Two-Level	7.2 kV	SiC MOSFET	15 kV	37 kHz
Tian et al. 2018	Hubei Laboratory	2.4 KVA (ETP)	D	Two-level	10 kV	IGBT	6.5 kV	10 kHz
Saeed et al. 2018	ABB	107 kW (SST)	D	Modular	6 kV	SiC MOSFET	1.2 kV	30 kHz

Table State of the art of solid-state transformers: Advanced topologies, implementation issues, recent progress and improvements (M. Hannan, P. Ker, M. lipu, et al.)

As can be seen, in the past two decades, 13 prototypes have been built. It should be noted that none of these have been connected to the electricity grid and most of these are only partially realized in laboratories. A notable exception is the 2014 prototype by Zhao et al. in cooperation with ABB. This 1,2MW prototype incorporates many features of a practical SST design (for example easy to swap power electronics modules). What all these prototypes have in common though, is that none of these are designed to meet IEC60076-3. A crucial standard to which all grid transformers are tested and submitted to extreme grid conditions.

The IEC60076-3 states that MV transformers, and by extension SSTs, need to handle twice the input voltage for at least a 60 second duration. A grid condition that can for example occur during switching events. Additionally, the IEC60076-3 standard demands an isolation barrier between the MV & LV grids of 40kV$_{peak}$ @50Hz for 60 seconds. A test that does not pose any significant issues for conventional power transformers but poses great design challenges for an SST.

To determine the power electronics topology, several were quantitatively evaluated, and a single topology was selected for further evaluation, highlighted in Figure 4 below.

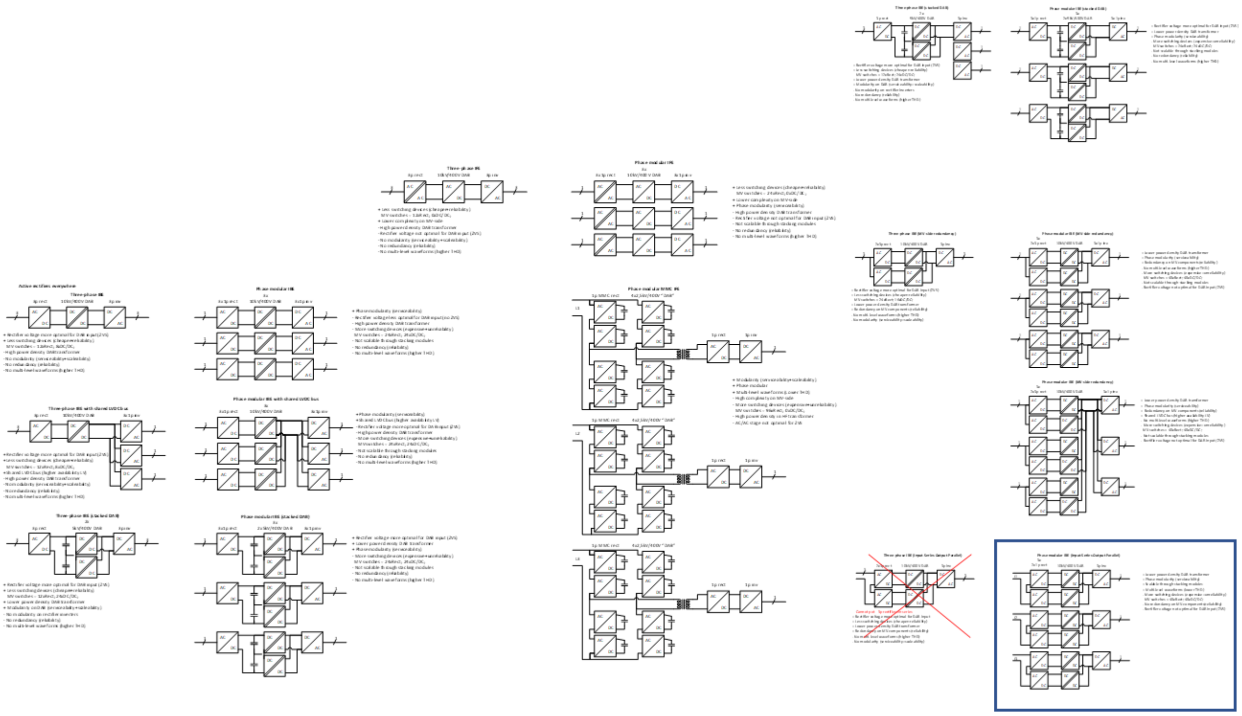
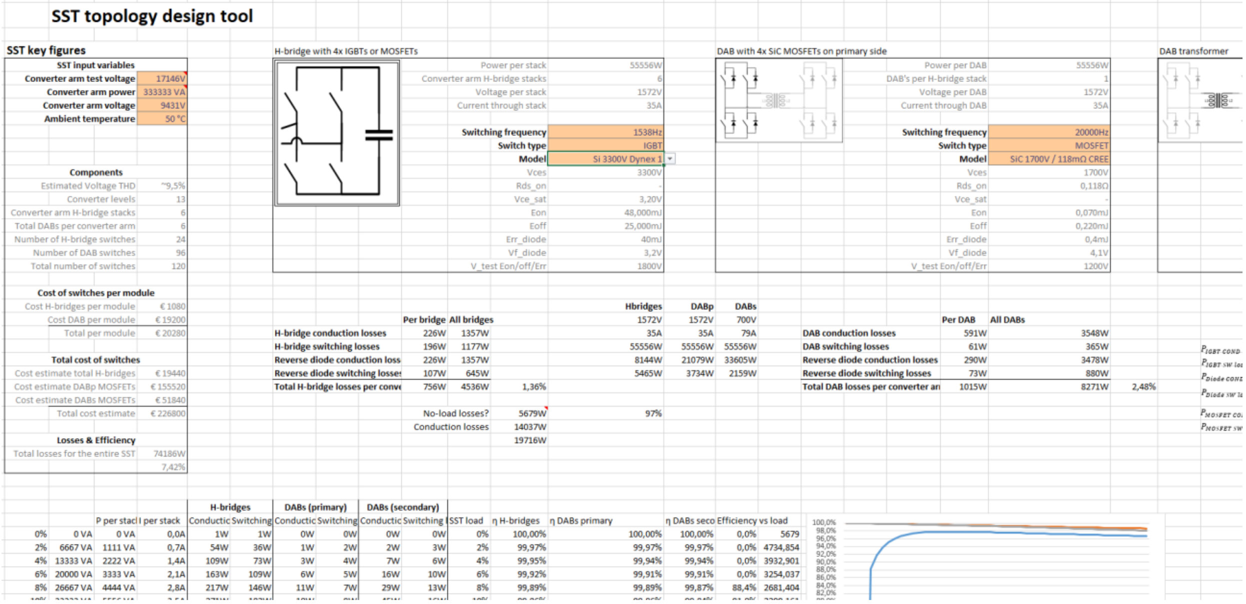


Figure 4 Schematic view of the topology selection

The selected topology is a Cascaded H-Bridge (CHB) that connects modules in series at the medium voltage input. This is done to divide-and-conquer the extremely high voltages (for power electronics standards). The outputs of the modules are all connected in parallel to an LV DC-bus.

After selecting this topology, an excel tool was built to quickly evaluate available power electronics switches (IGBTs & MOSFETs) and their impact on this particular topology. The higher the voltage rating of the switches, the less modules would be needed to cope with the voltage. The faster the switches complete a switching cycle, the less the energy losses. The image below shows a screenshot of the excel tool.



SST topology design tool

SST key figures

SST input variables	
Converter arm test voltage	17146V
Converter arm power	333333 VA
Converter arm voltage	9431V
Ambient temperature	50 °C
Components	
Estimated Voltage THD	~9,5%
Converter levels	13
Converter arm H-bridge stacks	6
Total DABs per converter arm	6
Number of H-bridge switches	24
Number of DAB switches	96
Total number of switches	120
Cost of switches per module	
Cost H-bridges per module	€ 1080
Cost DAB per module	€ 19200
Total per module	€ 20280
Total cost of switches	
Cost estimate total H-bridges	€ 19440
Cost estimate DABp MOSFETs	€ 155520
Cost estimate DABs MOSFETs	€ 51840
Total cost estimate	€ 226800
Losses & Efficiency	
Total losses for the entire SST	74186W
	7,42%

H-bridge with 4x IGBTs or MOSFETs

Power per stack	55556W
Converter arm H-bridge stacks	6
Voltage per stack	1572V
Current through stack	35A
Switching frequency	1538Hz
Switch type	IGBT
Model	Si 3300V Dynex 1
Vces	3300V
Rds_on	-
Vce_sat	3,20V
Eon	48,000mJ
Eoff	25,000mJ
Err_diode	40mJ
Vf_diode	3,2V
V_test Eon/off/Err	1800V

DAB with 4x SiC MOSFETs on primary side

Power per DAB	55556W
DAB's per H-bridge stack	1
Voltage per DAB	1572V
Current through DAB	35A
Switching frequency	20000Hz
Switch type	MOSFET
Model	SiC 1700V / 118mΩ CREE
Vces	1700V
Rds_on	0,118Ω
Vce_sat	-
Eon	0,070mJ
Eoff	0,220mJ
Err_diode	0,4mJ
Vf_diode	4,1V
V_test Eon/off/Err	1200V

DAB transformer

	Per bridge	**All bridges**	
H-bridge conduction losses	226W	1357W	
H-bridge switching losses	196W	1177W	
Reverse diode conduction loss	226W	1357W	
Reverse diode switching losse	107W	645W	
Total H-bridge losses per conve	756W	4536W	1,36%

Hbridges	**DABp**	**DABs**
1572V	1572V	700V
35A	35A	79A
55556W	55556W	55556W
8144W	21079W	33605W
5465W	3734W	2159W

	Per DAB	**All DABs**	
DAB conduction losses	591W	3548W	
DAB switching losses	61W	365W	
Reverse diode conduction losses	290W	3478W	
Reverse diode switching losses	73W	880W	
Total DAB losses per converter ar	1015W	8271W	2,48%

No-load losses?	5679W	97%
Conduction losses	14037W	
	19716W	

$P_{IGBT\ COND}$
$P_{IGBT\ SW\ lo}$
$P_{Diode\ CONI}$
$P_{Diode\ SW\ l}$
$P_{MOSFET\ CO}$
$P_{MOSFET\ SW}$

				H-bridges		**DABs (primary)**		**DABs (secondary)**							
		P per stacl	I per stack	Conductic	Switching	Conductic	Switching	Conductic	Switching	SST load	η H-bridges	η DABs primary	η DABs seco	Efficiency vs load	
0%	0 VA	0 VA	0,0A	1W	1W	0W	0W	0W	0W	0%	100,00%	100,00%	100,00%	0,0%	5679
2%	6667 VA	1111 VA	0,7A	54W	36W	1W	2W	2W	3W	2%	99,97%	99,97%	99,97%	0,0%	4734,854
4%	13333 VA	2222 VA	1,4A	109W	73W	3W	4W	7W	6W	4%	99,95%	99,94%	99,94%	0,0%	3932,901
6%	20000 VA	3333 VA	2,1A	163W	109W	6W	5W	16W	10W	6%	99,92%	99,91%	99,91%	0,0%	3254,037
8%	26667 VA	4444 VA	2,8A	217W	146W	11W	7W	29W	13W	8%	99,89%	99,89%	99,87%	88,4%	2681,404

Figure 5 Snapshot of the tool made for component and rating selection

The result of this conceptual design was a topology that has six modules per phase.

The total amount of modules is 18, for a three-phase SST. Another nice outcome of this evaluation phase is that the output of the modules, still needs an inverter to make the LV. This inverter does, however, not have to be a single unit. And as opposed to a conventional power transformer, the SST can have many LV outputs, one for each street in a neighborhood. Thus, avoiding the typical problems of having a voltage increase in one street due to PV-panels and a low voltage in another street due to many electric cars being charged. A grid situation that a conventional power transformer cannot solve, whereas an SST with multiple inverters could.

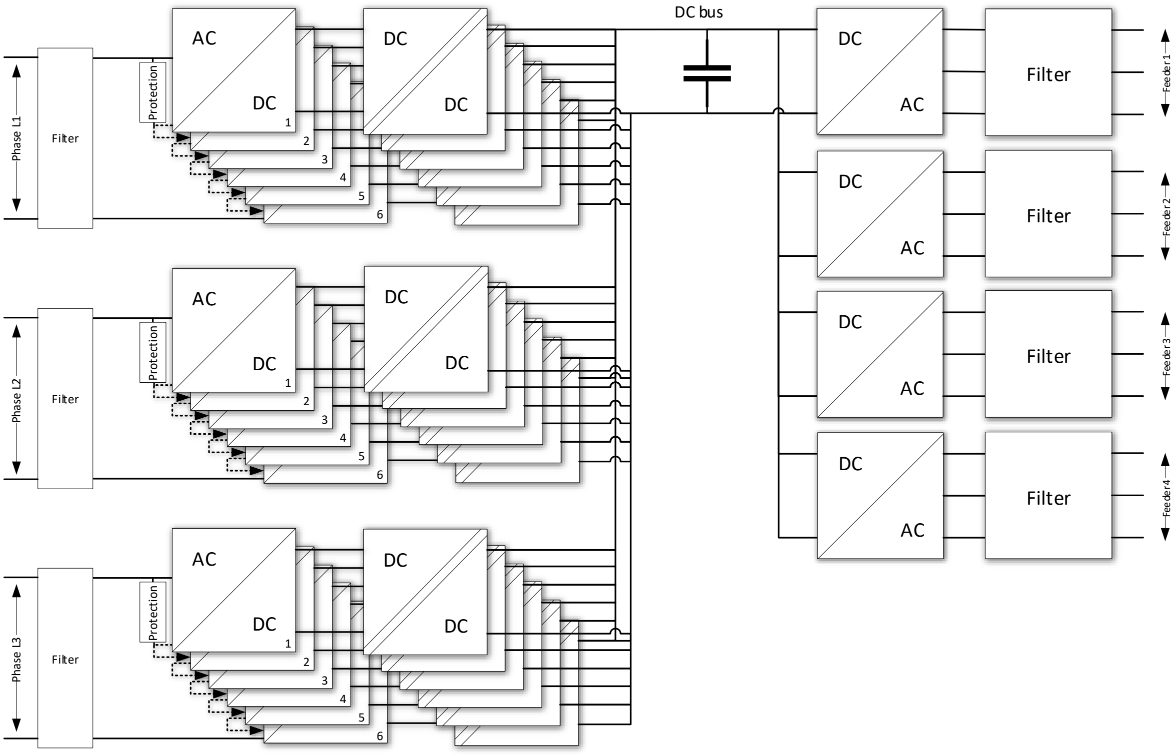


Figure 6   The final concept of the SST's power electronics architecture

2.3.2 Simulation model of the SST

A detailed EMT model of the complete solid-state transformer has been created in simulation software MATLAB/Simulink using the PLECS toolbox. This to verify the operational principles, investigate the control functionalities within the system as well as the interaction with the connected power system, on both MV and LV levels.

The model encompasses the full-scale primary power part of solid-state transformer system in terms of complexity, components and bandwidth and is intended as a first step towards creating a model object for inclusion in typical grid operator planning tool libraries. The simulation model still needs to be validated with the available hardware prototype before external parties can start to port the model into the intended (planning) tools (out of scope). It also serves as a basis for a real-time simulation model, that can in time be used in a hardware-in-the-loop test configuration as part of a larger grid test to show complex, realistic and dynamic behaviour of the SST in future distribution grids.

The overall simulation model is shown in Figure 7. It contains the three-phase cascaded H bridge modules, dual-active bridge, the output inverter and all the low- and high-level control algorithms required for its operation.

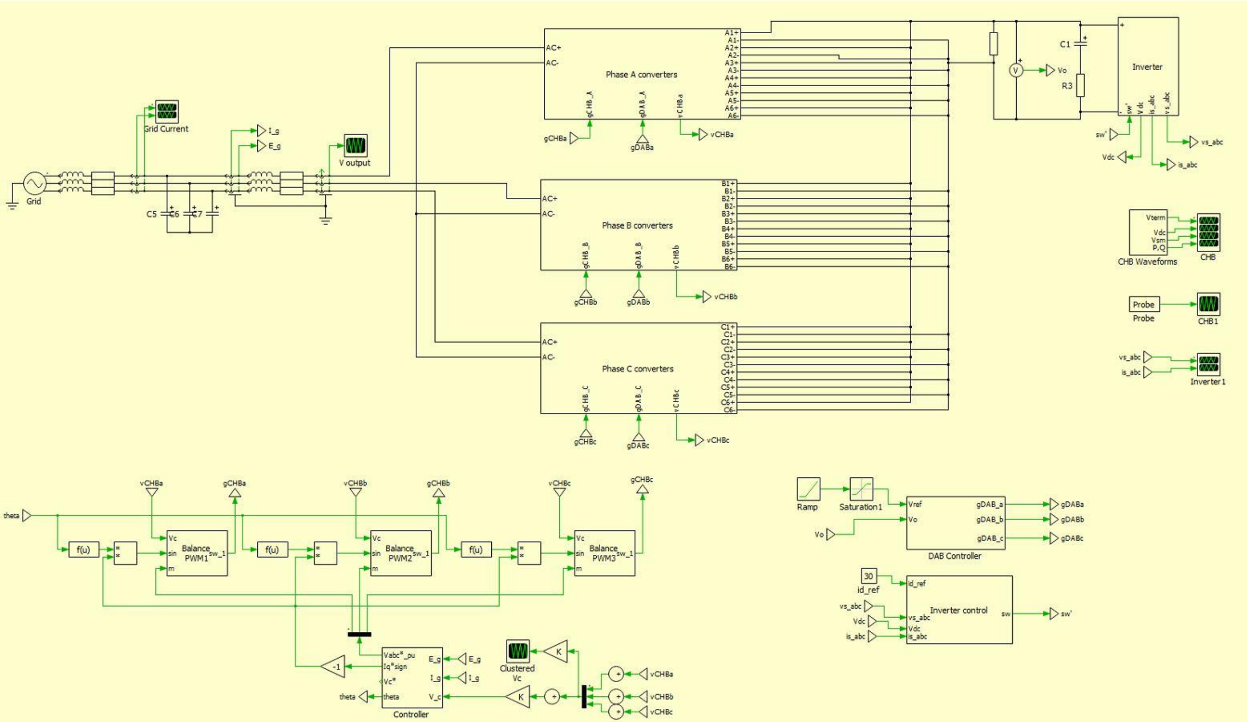


Figure 7 Simulation model of the solid-state transformer – system overview

Each of the three phases comprise 6 modules. Figure 8 shows a closer view of how the 6 modules of one phase, labelled as Phase A converters, Phase B converters and Phase C converters in Figure 7, is modelled. It shows the individual CHB and DAB components and its communication with the overlaying control (control blocks not shown in Figure 8).

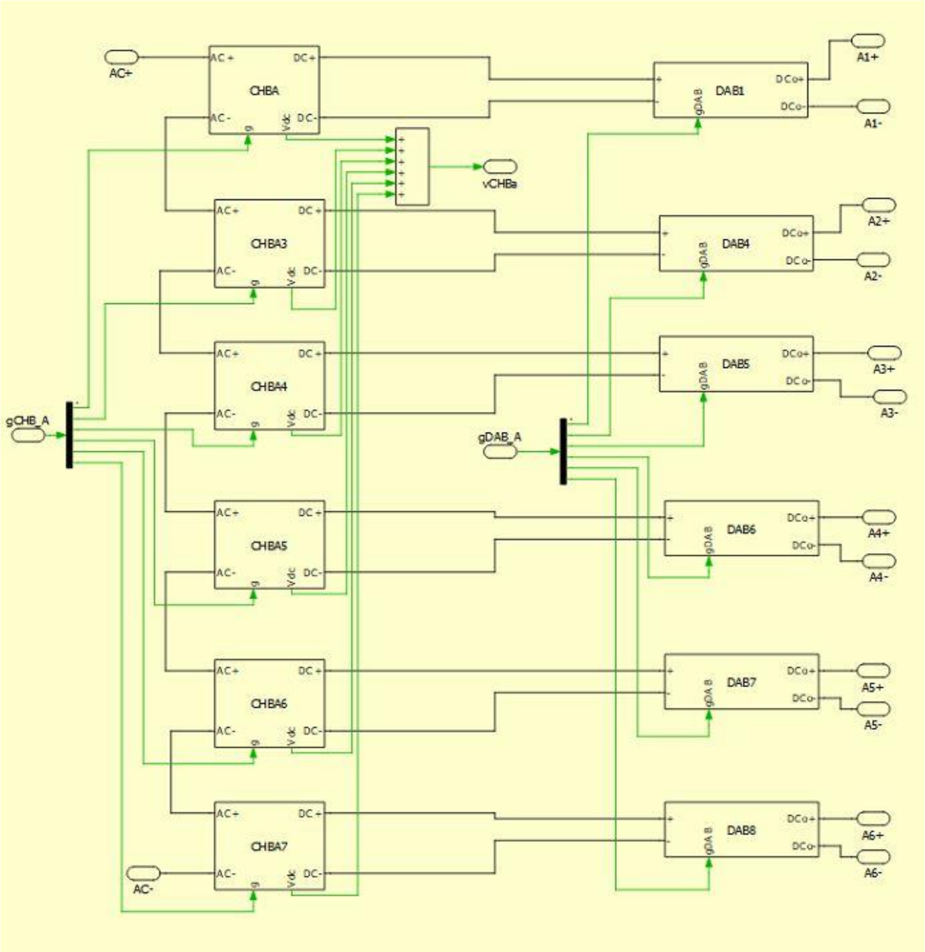


Figure 8 Simulation model of the solid-state transformer-Single phase zoom in (all CHB and DAB modules shown for 1 phase)

Each of the six modules comprise 1 CHB and 1 DAB module. Figure 9 shows a closer view of how one of the CHB modules is modelled, showing the individual semiconductor switches (IGBTs). The DAB modelling is also modelled down to the individual semiconductor switches (IGBTs, picture not shown here). This level of complexity allows the highest bandwidth for dynamic performance and transient analysis of the system model, but also comes at a significant resource burden when running the simulation. The remaining challenge for creating the libraries for use in grid operator (planning) tools, is how to retain the high fidelity of the model but reduce the processing power burden enough to allow it to be run on more typical PC platforms. One solution for this issue could be replacing the individual semiconductor blocks with pre-made sub-cycle average power modules. This replicates the switching behaviour of the semiconductors using controlled voltage and current sources, thus decreasing the calculation time needed.

For the intended real-time application in a laboratory or academic environment, this model will be able to run on a real-time digital simulator platform, such as OPAL-RT or RTDS, which has enough calculation capacity to solve the high-fidelity model and honour the real time criteria at the same time.

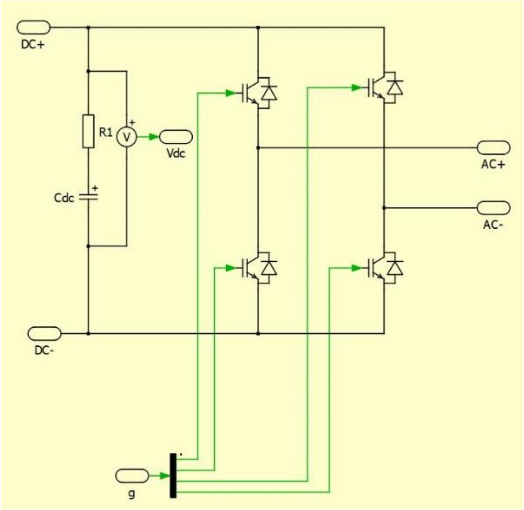


Figure 9 Simulation model of the solid-state transformer-Single CHB zoom in (Individual semiconductor switches shown for 1 CHB)

The next figures show simulation results from the above model for the SST application, processing 5 MVA of power from a 10kV MV grid into a 400V LV grid. The MV converter is grid-following, and the LV converter is grid-forming. A power frequency of 50Hz has been chosen for this simulation.

Figure 10 shows the input MV grid voltage (top oscillogram), being 10kVrms line-line, the MV grid current (second from top oscillogram), the total DC voltage level across all cells (second from bottom oscillogram) as well as the active and reactive power flow from the MV grid (bottom oscillogram). It shows a balanced and stable three-phase power system, with minimal distortion operating at rated power of the SST and close to power factor of 1.

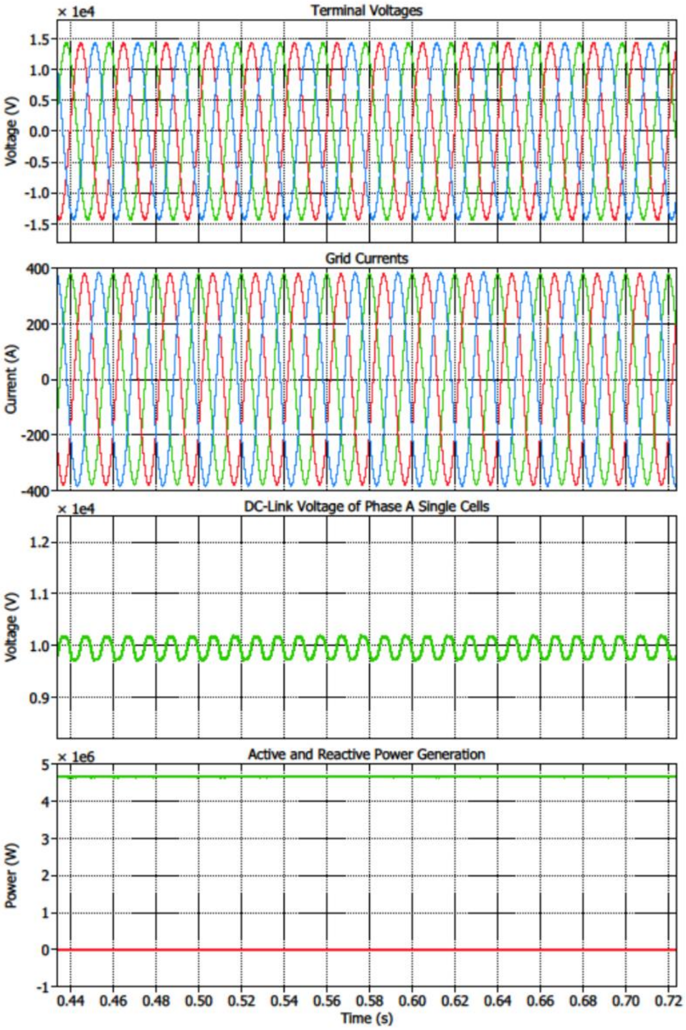


Figure 10 Simulation model results – CHB stage

The CHB transforms the input AC voltage into a myriad of internal DC voltages that are individually fed to the respective DABs. Figure 11 shows the DC voltage created by all the parallel connected DAB modules.

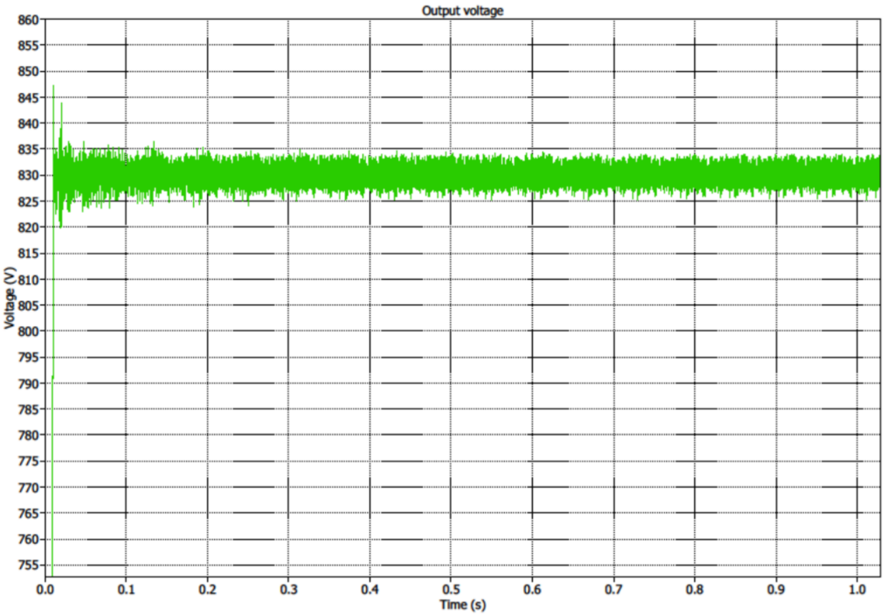


Figure 11 Simulation model results – DAB stage

This DC voltage from all the 18 parallel DAB modules is the input for the LV output inverter that interacts with the 400V LV grid. Figure 12 shows the 400Vrms LV grid voltage at a given load current (not the same as the current setpoint above). As a test a load change has been implemented after 0.54 seconds to show that the control system keeps the SST and LV grid parameters stable during a load reduction as well as a load increase event. All transient phenomena have decayed within a half cycle.

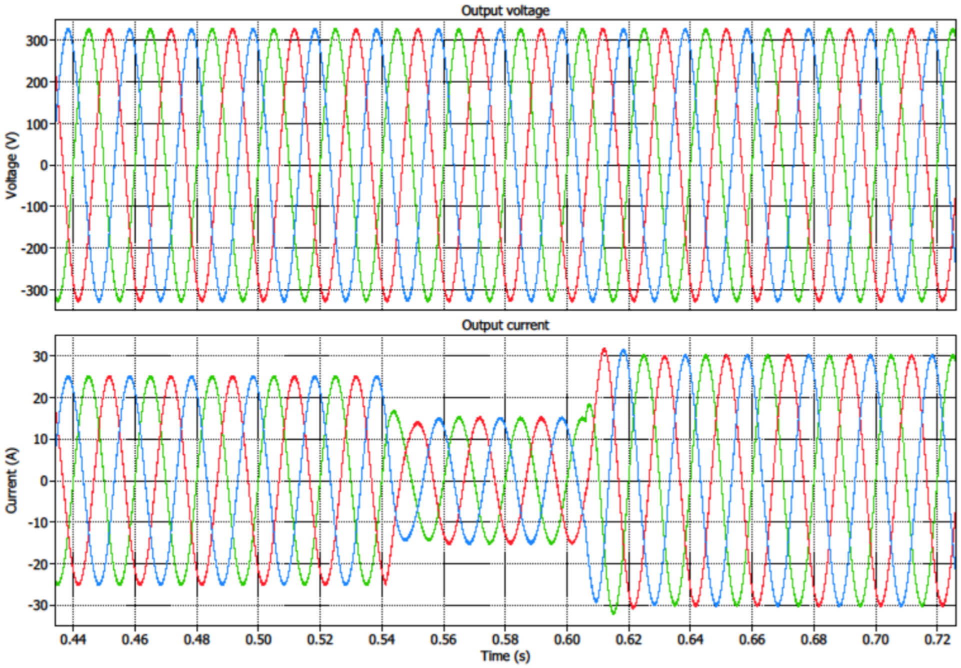
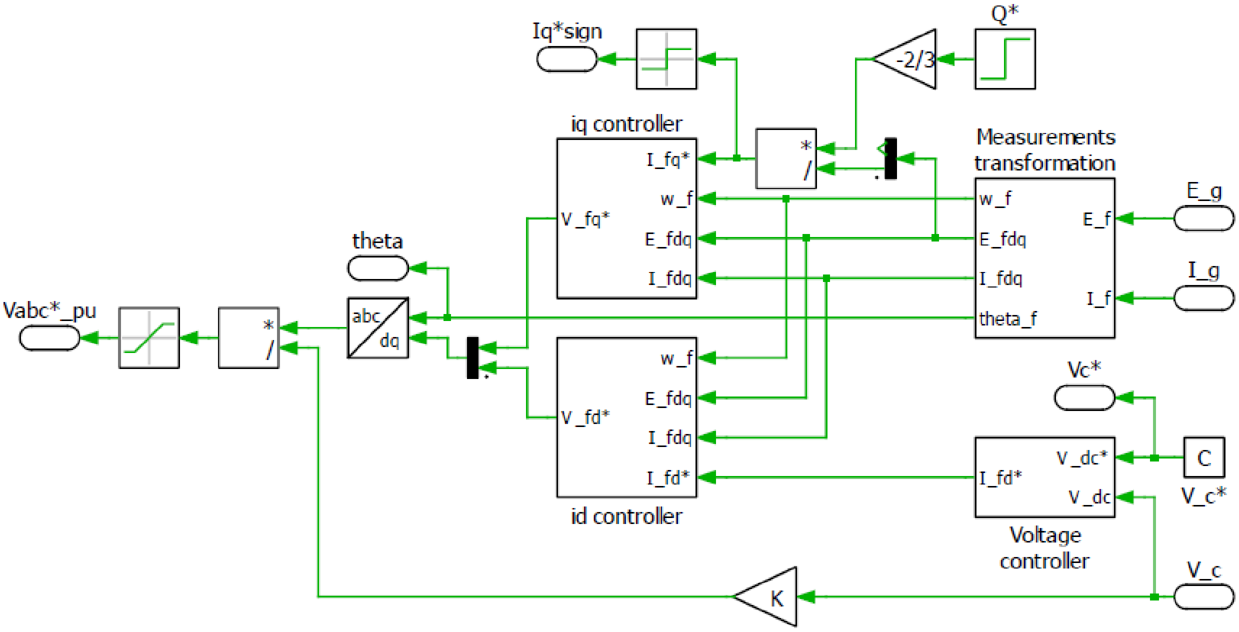


Figure 12 Simulation model results – Output inverter stage

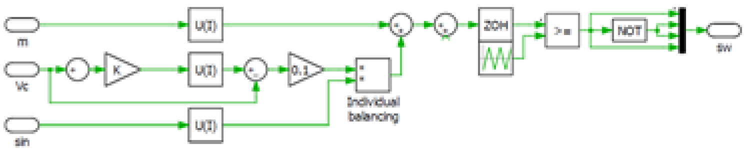
Although only results for the power delivery use case (MV→LV) of the SST is shown, the model is bidirectional in power flow, as is the SST hardware itself. The model is also suitable for grid compliance and power quality analysis.

2.3.3 Control strategy for the SST

The global control strategy of the solid-state transformer can be divided into two parts: 1) control strategies of three phase cascaded H-bridges (CHBs) at MV side and 2) control strategies of the Dual active bridge (DAB) at LV side. Three phase CHBs utilize the dc-link voltage control to maintain the power balance between the MV and LV. The output of dc-link voltage control is fed into the inner current control as the reference in the dq frame. The synchronization control is used to generate the phase reference to control injected grid current at MV side as sinusoidal waveforms that in phase with the grid voltage, as shown in Figure 13 (a). The Pulse Width Modulation (PWM) is also implemented to control the switches the CHB, as shown in Figure 13 (b). The dual active bridge employs the voltage droop control to ensure the equal current sharing among the multiple DABs, and the output is fed into the phase-shift PWMs to control the switches in the primary side and secondary side of DAB, as shown in Figure 14.



(a) dc-link voltage control and current control



(b) PWM modulation

Figure 13 Control strategies of the CHB at MV side

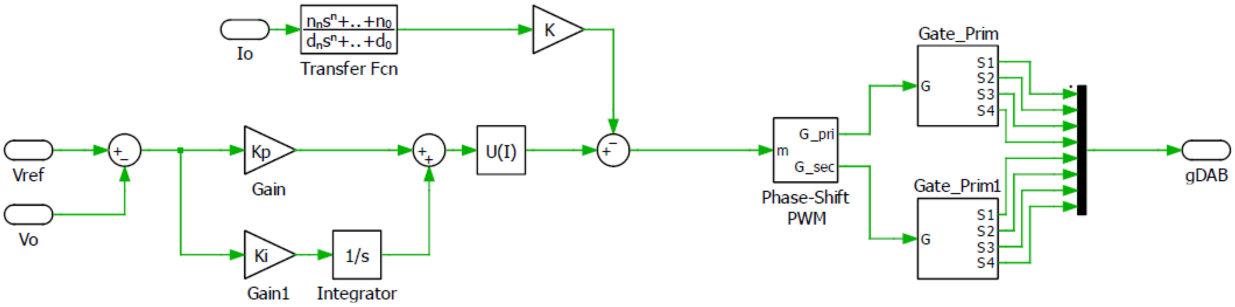


Figure 14 Control strategies of the DAB at LV side

The stability of the whole system is evaluated through analytical modelling of the CHB and DAB in the frequency domain, and the use the Nyquist stability criterion to design the control parameters to ensure the good stability margin as well as good dynamics. The bode diagram of the control system is shown in Figure 15, where the cut-off frequency is 600Hz and the phase margin is 35 degrees. The final simulation waveforms shown in Figure 11 indicate a stable operation of the whole system.

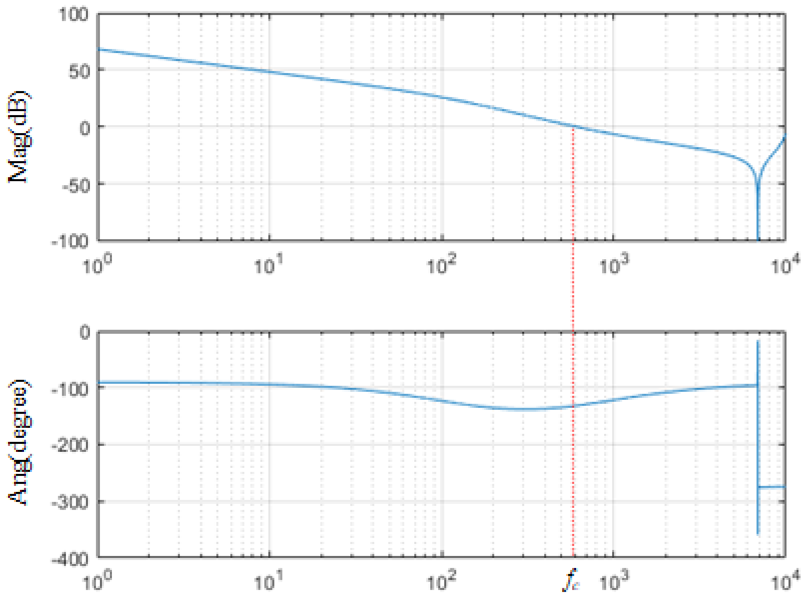


Figure 15 Bode diagram of control system

The key waveforms of solid-state transformer are shown in Figure 16, where the CHB output currents are controlled as sinusoidal waveforms in phase with the grid voltage at MV side, while the DAB voltage is controlled as a dc constant value of 830 V.

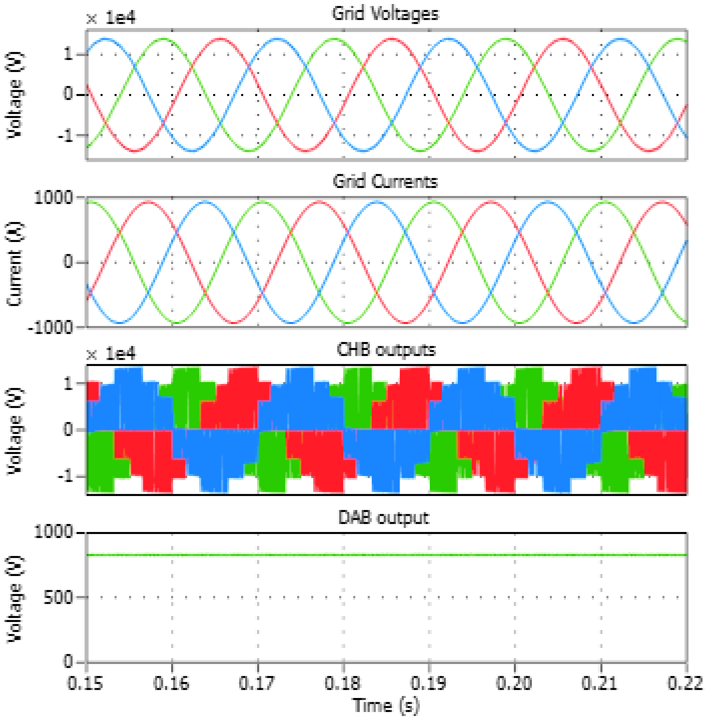


Figure 16 Key waveforms of the solid state transformer

2.4 Building and testing of the prototype

The building of the prototype was done at Prodrive and TU/e, in several phases. A view of the parts production at Prodrive can be seen in Figure 17.

The parts production included the AC/DC stage, DC/DC stage – with the high-frequency transformer and retrofitting and existing DC/AC converter setup for the use in the prototype. Due to the innovative scope of the project, where many modules are not "of the shelf" for the medium voltage operational range, many prototype part had to be manufactured specifically for this project only. As an example, the high-frequency transformer used in the DC/DC stage of the converter had to be made with a combination of standard winding and 3D printing to achieve the required insulation requirements. The high-frequency transformer can be seen in Figure 18.

The prototype was further tested in the Smart Grid laboratory of the TU/e, an impression of some of the tests are given in Figure 19 through 22.

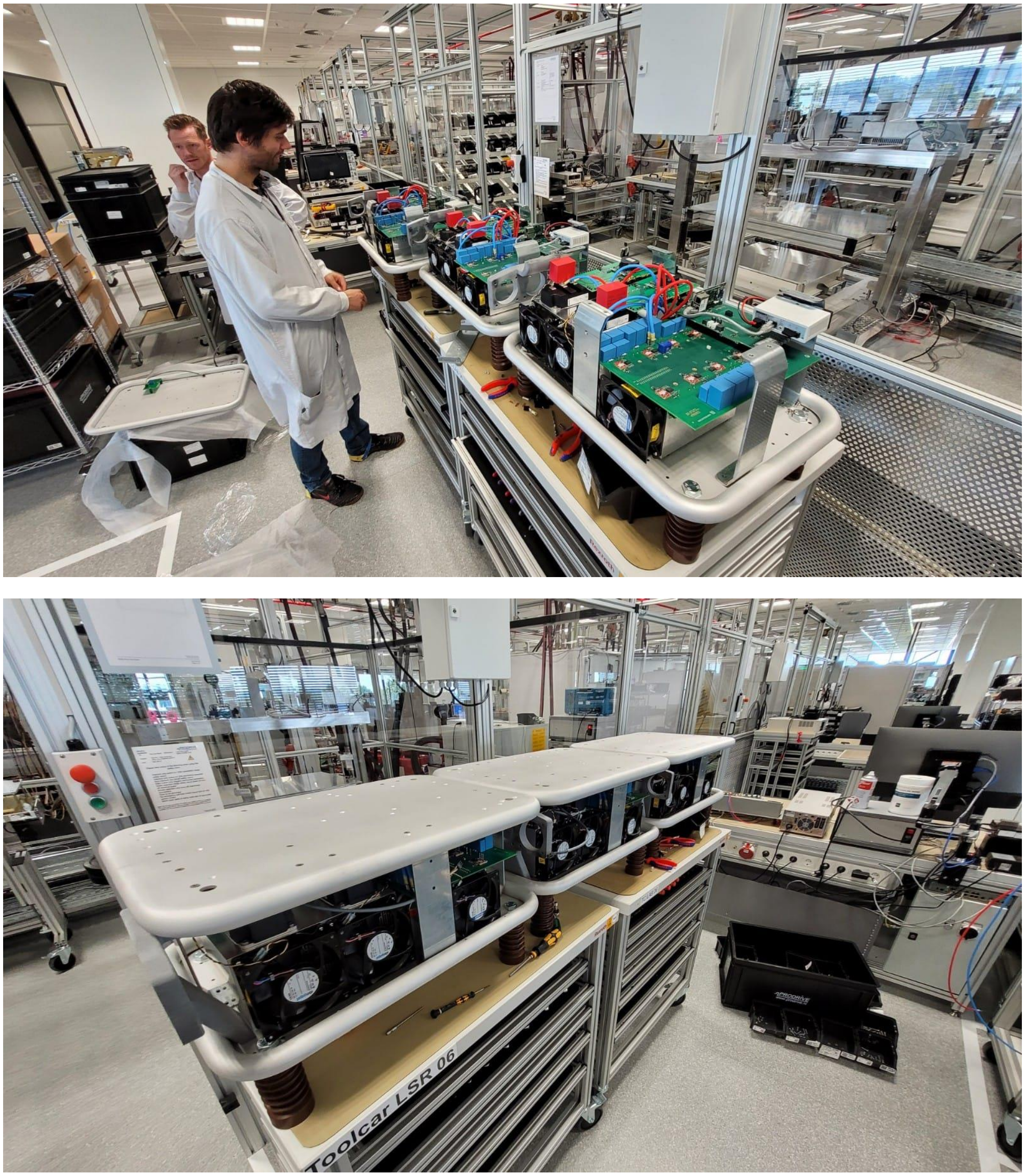


Figure 17 Assembly of the AC/DC and DC/DC stage at Prodrive

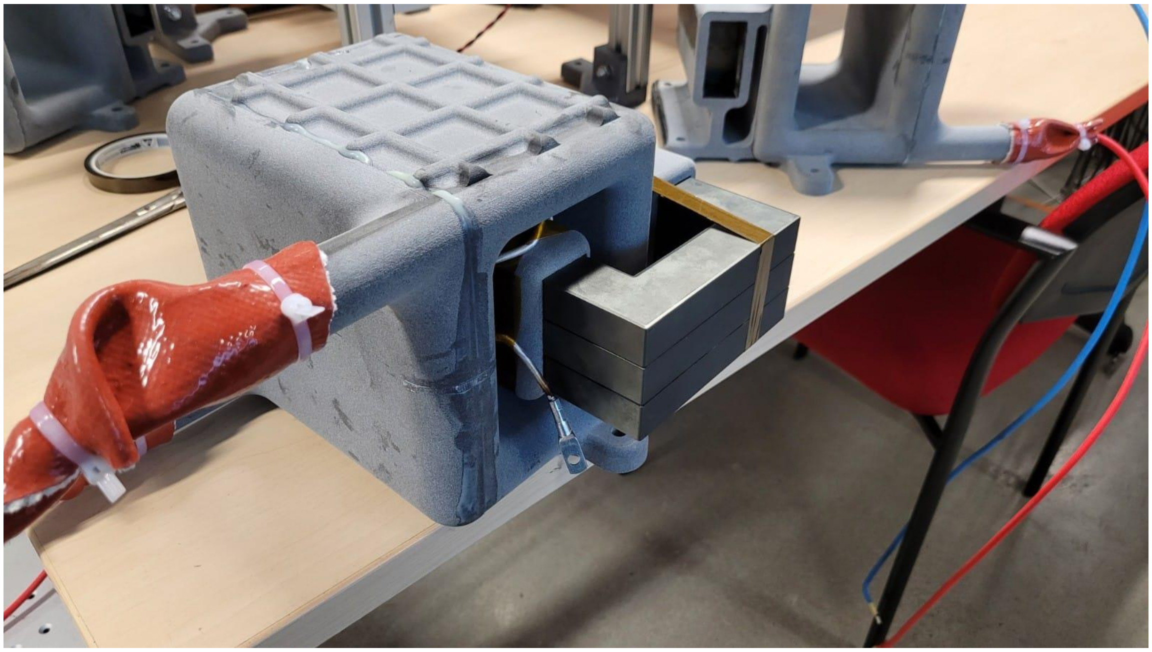


Figure 18 The high-frequency transformer manufactured and set-up for testing

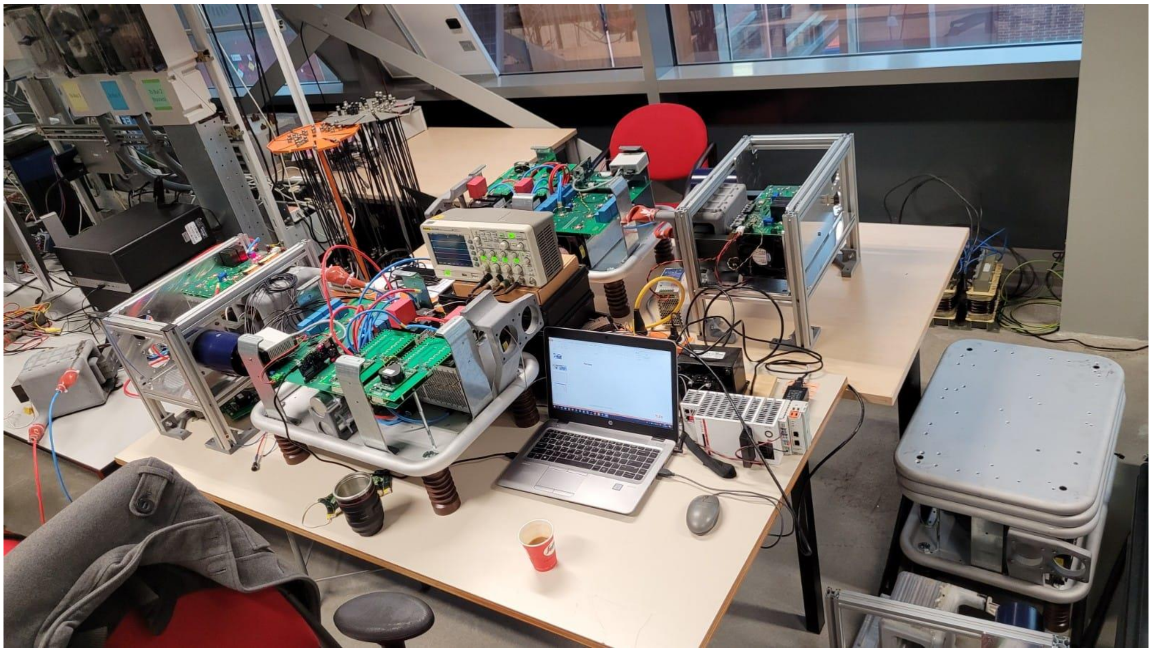


Figure 19 Prototype testing at TU/e – single AC/DC and DC/DC module

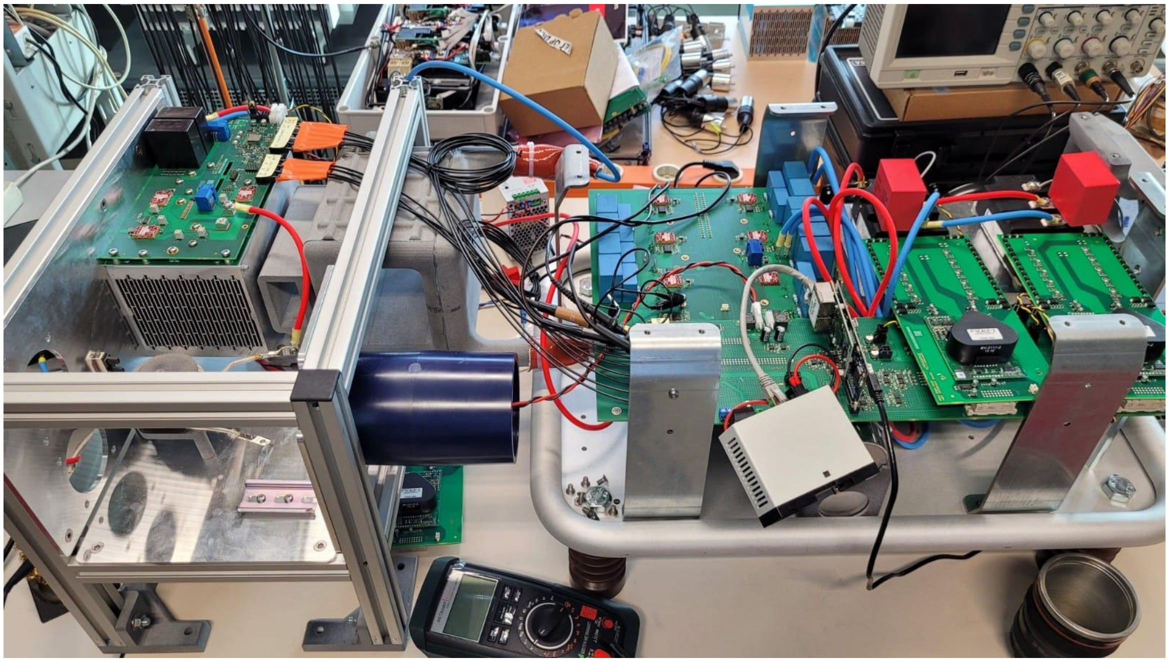


Figure 20 Prototype testing at TU/e – single AC/DC and DC/DC module

Figure 21 Prototype testing at TU/e – complete AC/DC and DC/DC stage of the converter

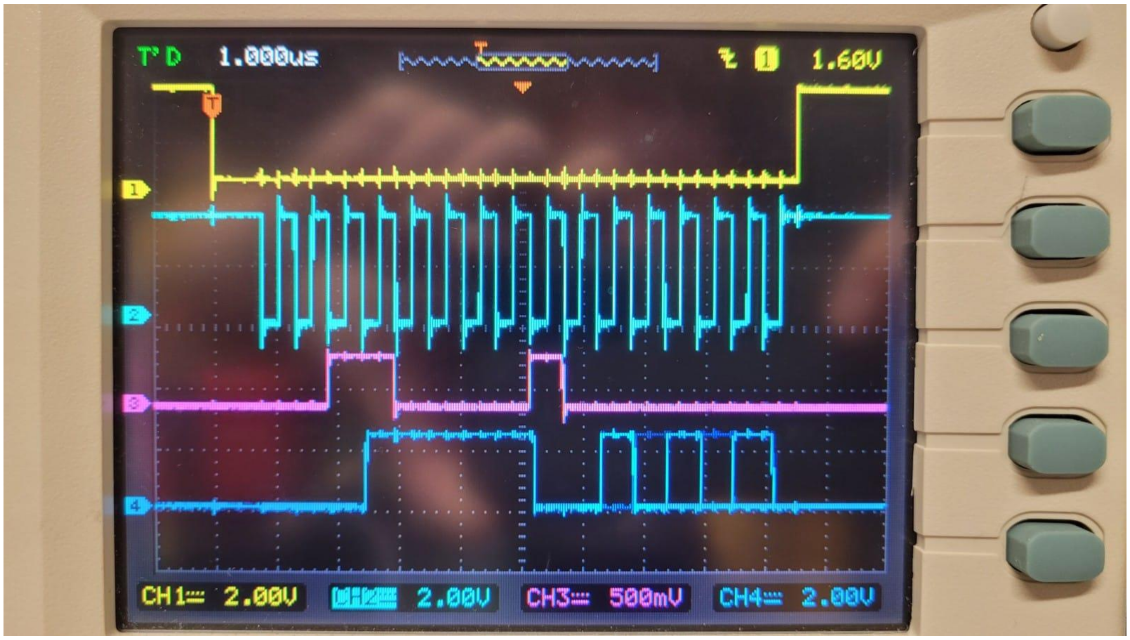


Figure22 Prototype testing at TU/e – testing of the switching control in the DC/DC converter

Based on the prototype architecture, a detailed and optimized layout which could be used in a commercial version of the device (with reduced volume) is shown in Figure 23.

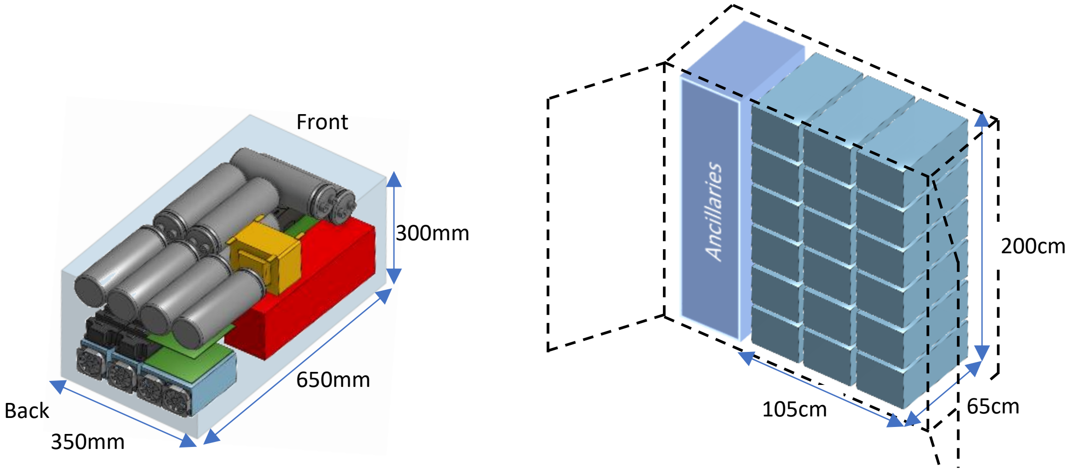


Figure 23 Concept of a commercialized version of the converter, as a module and complete converter

2.5 Optimisation of the reliability of the PES

One of the key advantages of the SST over a (conventional) electro-magnetic transformer is the possibility of modular design. This means that the converters power and voltage capabilities can be increased during its operation, which is not possible for the conventional transformers. However, one of the challenges of power-electronics based transformers is the much higher complexity of the device, which is a challenge for its reliability. To cope with this, the possibility to utilize its modularity to mitigate reliability risks was investigated and concluded that compliance with IEC 60076-3 inherently resulted in a partially redundant design.

This project considered using voltage control in the DC/AC stage of the converter as a method to influence loads to decrease demand in emergency conditions ('load shedding').

This method was tested on a lab setup of 33 kW (half of a single phase) of the low voltage side of an SST. The laboratory setup is shown in Figure 24. A controller was developed to shed load when a certain power limit is reached. Depending on the type of load, this controller managed to decrease demand up to 19% within the range of voltage that the Dutch Netcode and EN50160 standard allows. Furthermore, different types of loads and dynamic scenarios were experimented with to test the controller for stability and robustness, and to observe the behavior of the test setup and loads.

Real world effectiveness of this load shedding method is highly dependent on the connected grid composition, topology, and loads. It could be employed as an emergency procedure, protecting SST hardware from overloading and possibly preventing customers from experiencing blackouts.

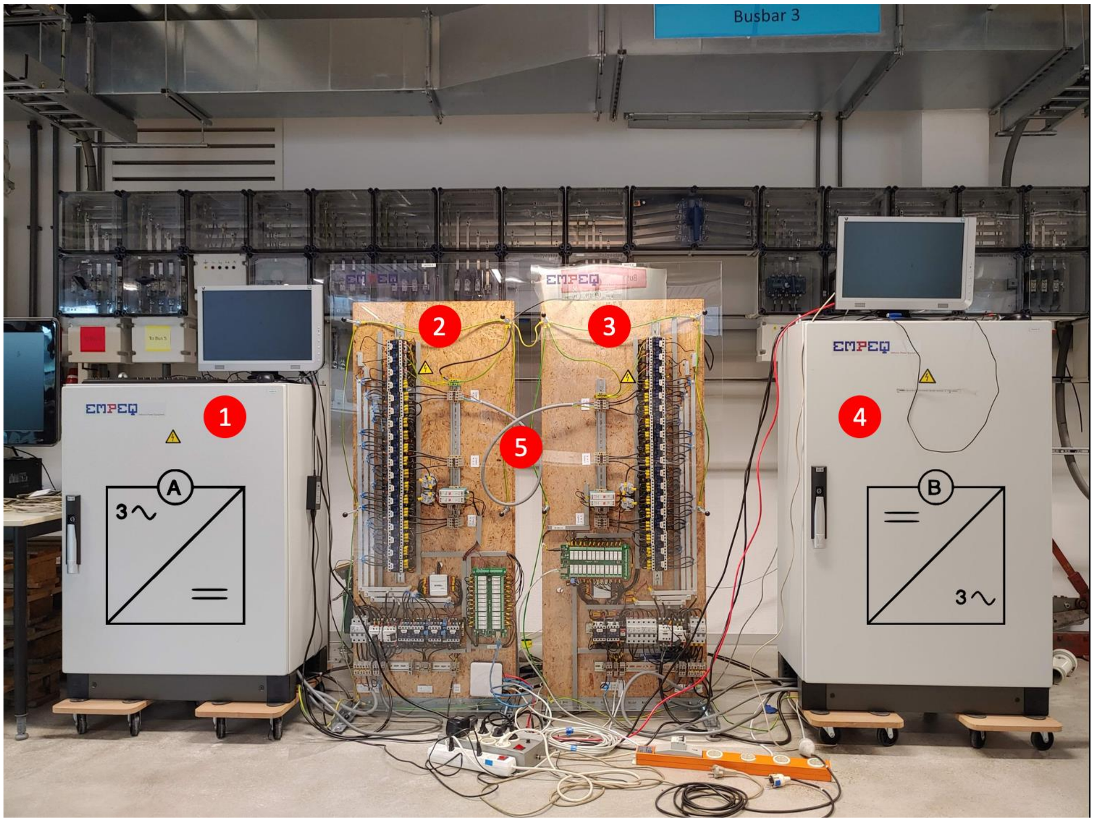


Figure 24 Laboratory setup used for the testing of the strategy; (1) Inverter A, (2) Switch Matrix A, (3) Switch MatrixB, (4) Inverter B, and (5) The cable connecting the switch matrices.

A live demonstration in the Smart Grid Lab of the TU/e was given to the consortium partners and interested others during the final hybrid event of March 15, 2022. The integration of the software/firmware was still underway. Consequently, the full SST was not demonstrated, and instead the functionality of a single module was demonstrated. The power flow through the module's DAB with its crucial galvanic isolation barrier was shown at 96~97% efficiency. As well as the hardware waveforms near-perfectly conforming to the theoretical waveforms previously established in the early stages of the project.

Figure 25 Demonstration single module in the Smart Grid Lab of TU/e

3. Contribution towards the goal of TKI urban Energy

The contribution of FlexStation project towards the goals of TKI urban Energy is in program-line 4 "Flexibele energie infrastructuur". A PES facilitates the energy transition as it enables the DSOs to integrate more fast changing generation (renewables) and loads (EVs, heat pumps) the grid without compromising the voltage limitations and preventing overload. The existence of a DC-bus enables new applications like storage and fast (DC) charging. Due to the fast controllability a PES contributes to the availability and stability of the grid. As the PES is made of modules, it allows enhancement of power handling capabilities during operation.

Although it is still a long way to go towards a reliable, acceptable and affordable medium voltage SST the developed knowledge and technology in the FlexStation project is very valuable for the partners and Dutch industry as it became clear:

- which challenges have to be solved to make a SST technically and commercially feasible.

- that existing norms and standards for distribution transformers are not one-to-one transferable for testing SSTs, new test methods must be developed and agreed upon
- that the experience gained, and solutions researched for electrical insulation in the MV power electronic environment can be reused for high voltage transformers and actuators.
- To the DSO's what features and limitations MV connected grid converters have
- To the manufacturing industry what is important for products in the power grid market.
- That apart from the two PhDs involved, many BSc and MSc students learned that there is a bright future in power electronic technology for power grids
- When looking at total system costs, the extra investment of the DSO in an SST mainly leads to financial benefits to other parties, viable business cases should be investigated and implemented

4. Spin off potential

An important rationale for the involved non-academic partners to join this research project, was to experience and learn the challenges of realizing an SST. Is it possible to build an SST? What are the benefits and what is the impact on the electricity grid?

The FlexStation project has shown that it is possible to build an SST, but it is not easy and still many challenges need to be overcome. Cost-wise an SST can (by far) not compete with a conventional distribution transformer. The typical lifetime of a conventional transformer of 40 years is hard to compete with. The efficiency, overloading capabilities and reliability are hard to realize with a power electronics converter. So commercially an SST only makes sense if other features, such as controllability or monitoring, can compensate for the short comings.

But even if an SST is not commercial feasible yet, the developed knowledge and technology in the FlexStation project is very valuable for all the partners:

- As a result of the project, it has become clear which challenges have to be solved to make a SST technically and commercially feasible.
- The existing norms and standards for power grids and transformers do not take into account devices like SST, as a consequence some requirements are not appropriate. But as long as these standards are not updated, the DSO will require compliance. It makes sense to update the standards for other solutions than conventional 50Hz transformers. All involved partners should contribute to develop test methods and procedures, as well as adaptation of the standards.
- The developed technology to connect to a MV power grid can also be used for other applications. For example, for MV connected fast chargers for vehicles, trucks and boats, for large scale electrolysis rectifiers, for high power battery storage and for large scale grid connected fuel cells and even reactive power control equipment. This could especially be interesting as these applications have different requirements on up-time, overloading and dynamic performance
- The advanced control methodologies for modular power electronic converters can be re-used in other applications. Even in low voltage applications, such as gradient amplifier for MRI, these approached are used these days.

- The experienced challenges and researched solutions for isolation in MV environment can be reused for high voltage transformers and actuators.
- The interaction between the partners has been very valuable. We have all gained a lot of insight about the possibilities and challenges of the other partners. The DSOs learned about the features and limitations of MV connected grid converters. Power electronics cannot be overloaded 2 times for 1 hour as they are used to for conventional transformers. But power electronics are capable of reactive power control, automatically, on demand or local controlled. KEMA now has a better understanding of the future needs for MV power electronics testing and possibly they can help to update the standards for design and testing of (solid state) transformer. Prodrive Technologies has learned what is important for products in the electricity market. Until standards have been updated or extensive joint and mutual agreed development tests have been performed, DSOs expect that all SST comply with the existing transformer standards, even if some of the requirement might not be applicable to SSTs. The University has achieved great scientific results. But it is also very clear that many challenges have to be solved, to make SSTs competitive with respect to conventional transformers. These challenges should be translated into new research questions which shall be used as starting point for future research.
- And last but not least, the FlexStation project has ‘delivered’ two excellent educated PhDs and many bachelor and master students. All have found or will easily find their way to an exciting job in the power industry, (semi) governmental organisations or academia.
- When looking at total system cost more closely, it appears that the extra investment of the network operator in an SST mainly leads to financial benefits to other parties, like private companies that invest in storage or fast charging stations. In the end this will of course benefit society as a whole. For a healthy business case however, the network operator may have to be compensated for the extra cost, when the SST would be implemented on a large scale.

5. Discussion, conclusion, and recommendations

One of the key trends that change the power system as we know it today is the increasingly penetration and domination of power electronics, especially in the low voltage (less than 400V) and the ultra-high voltage arena (higher than 500kV). These developments are driven by consumer applications, distributed renewables and electric vehicles on the one side and bulk power transmission, enhanced grid controllability and connection of remote renewables like offshore wind farms. Solid state or power electronic transformers have nearly completely replaced the traditional low voltage low power transformers for consumer electronics due to the very low losses and lightweight/compact design, e.g. think of a charger for mobile phones, tablets, laptops and TVs.

Due to the challenges in the electric power distribution system – increased flexibility and controllability is needed to cope with the variability of the generation caused by renewables like PV systems and changing load behavior due to e.g., EV's and electric heat pumps. Solid State transformers are promising components for the future smart distribution grid because of their superior controllability, wide range of application beyond "traditional" transformation and low losses. When stepping up the power rating for SST's from kW tot the multi-kW and fractional MW-range and touching the medium voltage (1.5kV to 24kV), the isolation realized by a high frequency transformer operating in the 10's of kHz needs special attention. Often an intermediate DC-bus is applied, in the so-called two or three stage designs, which is ideally suited for connecting "DC" generation and load and the creation of local micro-grids.

The highly modular design allows price reduction, following a learning curve of about 15% price reduction when the installed capacity doubles. Presently the price level of a SST in the distribution power range is around 600 Euro/kVA compared to 20 to 50 Euro/kVA for a conventional transformer. Despite the superior controllability, efficiencies in the same range of 96 to 98%, the reliability and (expected) lifetime of SST's is a serious issue that hinders rapid market share growth. All major manufactures like ABB, Hitachi, Siemens, GE and Schneider, Prodrive technologies allocate development capacity and pilots being realized. This indicates that although the market is virtually non-existing yet, this can change fast due to the huge replacement and expansion demand for distribution transformer capacity, power electronics price development and new business models to cope with the reliability and life-time issues. Based on a logistic growth model, a speculative indication of the market share of SST's 10 to 15 years from now could be 1% to 3% and 5% to 30% in 2050.

Modular power electronics like SSTs allow for unprecedented changes in functionality and controllability of the nodes of the power grid. The function of the future modular node can not only be dynamically adjusted to changes in load and generation but also with respect to its function e.g., acting as inverter, transformer or breaker. Due to the modular build and "programmed functionality" of the hardware the future node even allows for innovative combinations of functions, depending on grid operating conditions and/or emergencies.

6. List of Appendices and References

Appendix A – A. Nikolopoulou and M. Nijhuis, 'Flexible & Active – Power Electronic Substation: Future bottlenecks within the distribution network', project Deliverable 2.1, December 2021

Appendix B – M. Geers, Y. van Geffen and M. Hazenberg, 'Requirements PES / SST', project Deliverable 2.2 and 2.3, April 2019

Appendix C –M. Berende and S. Bhattacharyya, 'Economic analysis - Solid State Transformer', project Deliverable 3.1, July 2020

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[1] B. van Dam, K. Wijnands, D. Yang, V. Cuk, E. de Jong and G. Pemen, 'The Impact of IEC60076-3 on Solid-State Transformer Design', in proc. CIRED 2021 conference, Geneva, June 2021, paper 476

[2] S. Bhattacharyya and M. Berende, 'Feasibility of implementing MV/LV Solid State Transformers in the Dutch electricity grids – from economic perspective ', in proc. CIRED 2021 conference, Geneva, June 2021, paper 365

[3] L. Vlaar, 'Control Aspects of Solid-State Transformer Application in the Distribution Grid', November 2019

[4] B. van Dam, 'SST cabinet A4 specification', September 2020