1. General	
Project title	High voltage modular arbitrary waveform generator for testing power components to increase reliability of an inverter rich flexible power grid (HV-AWG)
Project leader(s)	Dr. ir Mohamad Ghaffarian Niasar
Affiliation(s)	Electrical Sustainable Energy Department, Delft University of Technology
Researcher(s) employed	ir. Weichuan Zhao
2. Financial report	
Start date	1-10-2019
End date	11-11-2023
Total budget	566517 Euro
Realisation - Personnel - Materials - Equipment	*See the attachment*
3. Project & results a) Aims and objectives of the research project b) New insights and remarkable scientific results, bottlenecks and setbacks c) Changes with respect to the original research plan	**a) Aims and objectives of the research project** The objective of the project is to design and construct a PE based HV-AWG for medium voltage equipment testing. This is to assess and ensure long term reliability of the medium voltage components exposed to high level of harmonics and transient created by PE present in a flexible future electric grid. The specific objectives are defined as follows: WP1: Specification and topology choice Specification of the test generator and selection of the best topology suitable for the desired voltage class and bandwidth. Different topologies (MMC, Cascaded H-bridge) will be compared from the complexity, performance and cost point of view. WP2: Sub-module design Power electronic circuit design, which can be half-bridge or full-bridge configuration with desired current rating capability for impulse operation and proper electromagnetic interference shielding for reliable operation. Power supply for each sub-modules, suitable gate driver and choice of communication method are some of important aspects of this objective. WP3: Main power supply design. Design of main power supply for the test generator. This might be either isolated high frequency transformers, cascaded high frequency high power transformer, or dc source; depending on the selected topology. Suitable driver of the high frequency transformer is needed in case that architecture is chosen. WP4: Control and communication system Development of suitable control algorithm to generate different type of arbitrary waveform as well as hardware implementation of the communication system. Fast, stable, reliable and immunity of the control system from electromagnetic interferences are the main challenges of this objective. WP5: Structure design Structural design of the test generator and the necessary design consideration for electromagnetic shielding and operation of oil-immersed power electronics circuit used in the test generator. WP6: Prototyping and testing Construction of a scaled down model of the test generator. A demonstration model of the test generator with five stages will be built and tested with the developed hardware and software of the control algorithm. Here the sub-module's design must fulfil all requirements of a full scale test generator (voltage class and bandwidth)

b) New insights and remarkable scientific results, bottlenecks and setbacks

*Parts of the answers provided below are taken from reports/theses of PhD and Master students who contributed to this research.

Our original plan was to develop a power electronics-based high voltage test source capable of handling all the test conditions associated with testing medium voltage devices. However, as our research progressed, it became evident that implementing such a generalized test source was not the most optimum solution and would result in a very expensive test source. It was concluded that the space of voltage, frequency, and test object capacitance needed to be partitioned. For each section, a specific design of HV-AWG would offer an optimum solution.

It is important to highlight that the equivalent load during a dielectric test is capacitive. Hence, there will not be any intended active power transfer in the PE based HV-AWG. This significantly differs from the kW to GW (HVDC converters) range of active power transfer occurring in the typical PE converter. Furthermore, the power efficiency of the converter is of utmost importance in energy transmission, whereas voltage accuracy is paramount in HV testing. With these differences in mind, the main specifications of the test generators are defined to be voltage and current capability (load capacitance), and bandwidth (frequency).

Both topologies of MMC and CHB were investigated in detail. Additionally, various pulse transformer and resonant transformer-based solutions for generating high frequency high voltage waveforms were explored. The utilization of series-connected MOSFETs to generate pulses with very fast rise time has also been studies throughout this research project.

Our findings indicated that the MMC topology, providing complete modularity, is capable of achieving very high voltage output. However, its bandwidth is limited to a few kilohertz due to presence of arm inductors. Moreover, for the MMC topology the complexity of the startup procedure and capacitor voltage balancing necessitates special attention. To address startup challenges, auxiliary power supplies with very similar response time are required. An alternative solution involves using larger submodule capacitances, but this increases the size and cost of each submodule. It was also observed that because the auxiliary power supply starts operating at a specific voltage level (in our case, it starts operating at ~100 V), the input voltage must be abruptly applied to the MMC, resulting in a sudden output voltage at the output of the test source. This is undesirable for high voltage testing, and precise control of the output voltage from zero to any voltage level is essential. The proposed solution, though not yet implemented in our prototype, involves incorporating a battery storage system for each submodule. This allows independent control and operation of each submodule, regardless of the applied voltage. When the applied voltage exceeds a certain level, the auxiliary power supply activates and charges the battery storage of each submodule. This ensures a continuously charged submodule battery storage system, eliminating the need for frequent removal and recharging submodule batteries.

The Cascaded H-Bridge (CHB) topology, offers easier controllability and a bandwidth in the range of tens of kilohertz. However, it requires transformers with high isolation level, capable of taking the full voltage level on each submodule, making it unsuitable for very high voltage applications due to increased transformer size and higher submodule cost. Consequently,

	a considerable amount of effort was allocated in designing such high frequency high isolation level transformer. Achieving the desired transformer performance involves meticulous considerations, including proper design of the bobbin, windings configuration, spacing between the winding and the core, appropriate termination of the winding, utilization of stress grading methods, and precise casting with materials such as epoxy, silicon rubber, or immersion under oil. These factors collectively contribute to the creation of a high voltage high frequency (HVHF) transformer. Epoxy casted high frequency transformers emerges as a viable solution, offering a clean and compact design for voltage levels below 10 kVrms, with reasonable dimensions of approximately (~15*15*15 cm). For the frequency range from a few kHz to hundred kHz, an amplifier with a properly designed step-up pulse transformer emerges as the most suitable solution. The complete procedure of designing such pulse transformer with high bandwidth is illustrated in two of our master theses, both of which are accessible on the TUD repository. Relatively small size pulse transformer (~25*20*10 cm) at voltage level of more than 10 kVrms could be constructed. An H-bridge combined with an air-core resonant transformer can cover even higher frequency range, though constrained to generating sinewaves at those frequencies. Proper tuning of the resonant circuit is essential in this configuration. Moreover, the H-bridge at the primary side of the transformer must be equipped with fast overcurrent protection to prevent failure of MOSFETs and potential damage to gate drivers and isolated DC/DC converters present on the H-Bridge boards. Achieving pulses with very fast rise time, in order of 100 ns or less, is feasible through the use of series-connected MOSFETs. However, the main switching frequency is typically limited to several kHz due to issues related to switch overheating. A comprehensive literature review of series connected MOSFETs was carried out throughout this project and it was identified that pulse transformer-based isolated gate driving technique is the most promising solution for effectively managing high voltage series-connected switches. Additionally, our investigation reveals that utilizing non-isolated gate drivers, combined with optocouplers and isolated dc/dc converters, present another viable method for series connection of MOSFETs. This alternative method is particularly suitable for series-connected MOSFETs operating up to a voltage level of approximately 10 kV, the voltage level for which commercially available components (isolated dc/dc converter and optocoupler) can be leveraged. For both MMC and CHB, the significance of submodule board design cannot be overstated. This includes implementing fault protection mechanisms, utilizing suitable gate drivers, and choosing MOSFETs with adequate current and voltage ratings. A critical consideration in the prototyping phase is the availability of desired components. Shortage and unavailability of electronics components may significantly impact the prototyping process. While a professional PCB designer can design the PCB of submodules in a relatively short time, it is important to acknowledge that at the university level, students may require considerable amount of time to learn how to design and optimize these boards. Despite this additional time investment, this learning process is valuable, as it equips students with skills that have broader applications and can contribute to societal advancement in the future.

The project also delved into the investigation of lifetime of various insulation materials using the produced high-frequency pulse stress. It was found that different insulation materials exhibit accelerated ageing under higher frequencies at different rates.

It was also found that the PSC modulation technique provides additional advantages over NLC by shifting the carrier harmonics to Nth of the switching frequency without changing any baseband harmonics present due to non-sinusoidal wave shape.

For MMC topology the arm inductance and series resistance filter the undesirable voltage harmonics and determine the available small- and large-signal bandwidth and slew rate. To obtain higher bandwidths and slew rate, lower values of arm inductance should be used. However, it demands a higher switching frequency to attenuate the carrier harmonics, and a higher switching frequency needs higher accuracy from the controller hardware. Hence, SiC MOSFETs seems to be the most suitable solution with the possibility of higher switching frequency. Apart from this, the analytical expression of submodule capacitor voltage ripple is derived from selecting the value of submodule capacitance using the averaging principle. This derivation is based on the fact that the HV AWG application does not need a large circulating current. This is the reason why submodule capacitor voltages are well balanced even when complex wave shapes are generated.

The down-scaled MMC prototype can provide voltage waveforms with reasonable accuracy for the design value of voltage, current, bandwidth, and the control system. These waveforms include bipolar, unipolar, and mixed polar waveforms to show the performance of MMC-based AWG. The THD of most waveforms is less than or around 1% except for unipolar complex waveform and unbalanced sinusoidal waveform where it is around 3 %. Furthermore, the theoretical assumption of negligible circulating current and the derived submodule capacitor voltage expression are proved with MATLAB-Simulink simulations and experimentally with the down-scaled prototype. The ripple in the submodule capacitor voltages suggests that the submodule capacitance requirement for HV AWG application is much smaller than that for the traditional energy transmission application of MMC.

Among many possible control methodologies available for the MMC topology, active damping control methodology was investigated to eliminate the losses occurring in the arm resistor. Even though active damping methodologies have been implemented for converter topologies, it is verified that the bandpass filter based active damping methodology can be implemented when non-sinusoidal complex waveforms are generated from the MMC. It is observed that the losses have been significantly reduced by implementing the active damping methodology. However, considering the involved computation cost and accuracy of measurement, passive damping methodology was used in this project.

Since the HV-AWG application have reference waveform at high-frequency in the kHz range, it is crucial to have the simulation step in hundreds of nanoseconds. The selected commercial device in this project is Typhoon-HIL 404, and it can withstand the harsh EMC environment in the HV testing facility. The performance of the Typhoon HIL is demonstrated with the scaled-down prototype, where large-signal bandwidth of 5kHz is achieved with THD within 5 %. The importance of filter design and choice of frequency is showcased, and shown that it is critical when the frequency of the reference waveform increases in the kHz range. These experimental results prove that the MMC-based AWG can go up to 5 kHz to generate accurate waveforms.

Generating lightning impulse directly with a power electronics based HV-AWG, demands substantial oversizing of the test generator, rendering it cost ineffective and defeating the original purpose of the project, to create a test source with reasonable price to encourage adaptation by testing companies. Therefore, a hybrid solution was proposed, combining a traditional Marx generator with the HV-AWG generator. Simulation and experimental results for low voltage levels demonstrated successful operation. However, implementing a high voltage arrangement for this combined HV-AWG and Marx generator requires additional investment, time and research to address issues related to interference and other potential unforeseen effects.

c) Changes with respect to the original research plan

The PhD student was hired approximately 10 months after the start of the project. Later, due to some personal issues, the student took a 3 months unpaid leave, resulting in a delay of the project for more than one year. In agreement with TKI, the project leader (Mohamad Ghaffarian Niasar) dedicated additional hours to the project to ensure its successful completion on time. Fortunately, this adjustment did not have a negative impact on the overall outcome of the project. Although the project has now officially ended, our PhD student still has another year remaining to continue working on this research topic and to publish new findings.

According to the original plan, our intention was to create a power electronics-based high voltage test source capable of handling all the test conditions associated with testing medium voltage devices. However, during the course of this research, it became evident that implementing such a generalized test source is not the most optimum solution and would result in a very expensive test source. Consequently, it was decided to design a PE based HV-AWG that covers a reasonable range of voltage, frequency, and load capacitance, and to address the extremes of the spectrums, alternative solutions were introduced.

3. Valorisation Importance of the results for the industrial partners and/or industry and/or society in general	The knowledge and insights created by this research project is of great value for relevant industry and in particular for both our industry partners, KEMA and VSL. KEMA laboratories not only actively participated in this project but also independently funded one additional PhD student on the same topic. They also provided support for several of our master students undertaking theses on various aspects of this research topic. This collaborative effort has significantly enhanced their readiness for testing medium/high voltage power electronics-based components of the future electric grid and increased their understanding of the intricacies of power electronics-based test sources. VSL offered valuable feedback throughout the project and presented scenarios how a HV-AWG could be utilized to test specific components under conditions that conventional test sources are unable to replicate. Apart from industrial partners, the project has laid the foundation for a new research line within the High Voltage Technology (HVT) group of TU Delft. Over the past four years, 26 students have performed their master theses, extra projects, and PhD theses, either fully or partially related to this project. This has had a significant positive impact on society by equipping the new generation of engineers with the skills needed to address the challenges of the future electric power grid.
4. Output a) Posters and presentations during congresses with reference to TKI Urban Energy b) (Draft) publications c) (Draft) patent applications	Despite no patent was filed, this research project has yielded significant outcome including: 14 master thesis (13 completed, 1 ongoing), 8 extra project completed. 3 PhD thesis, (one student will defend her PhD thesis in January 2024, another student is projected to finalize his PhD by the end of 2024, and a third student is expected to conclude his work and submit his PhD thesis by the end of 2025). The following papers have been published/submitted based on this research topic. (*resulted from the fund provided by TKI, # resulted from the fund provided by KEMA for the second student): 1. Guangyao Yu, Mohamad Ghaffarian Niasar, Dhanashree Ganeshpure, Thiago Batista Soeiro, Pavol Bauer, "A Transformer Isolated Driving Method for SiC MOSFETs with a Constant Negative Off Voltage", 2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC).* 2. Mohamad Ghaffarian Niasar, Weichuan Zhao, "Aging of oil-impregnated paper at different frequencies", 2021 IEEE International Conference on the Properties and Applications of Dielectric Materials (ICPADM).* 3. Weichuan Zhao, Tianming Luo, Mohamad Ghaffarian Niasar, "Ramp sinusoidal breakdown of epoxy resin under high voltage waveforms at different frequencies", 22nd International Symposium on High Voltage Engineering (ISH 2021).* 4. T Luo, W Zhao, M Ghaffarian Niasar, "Experimental study of epoxy surface discharge under different frequencies", 2021 IEEE Conference on Electrical Insulation and Dielectric Phenomena (CEIDP).* 5. Philip Mathew, Mohamad Ghaffarian Niasar, "Lifetime of oil-impregnated paper under pulse stress at different frequencies", Proceedings of the Nordic Insulation Symposium, 2022.* 6. P. Mathew, M. G. Niasar, and P. Vaessen, "Design of High-frequency Fast-rise Pulse Modulators for Lifetime Testing of Dielectrics ", IEEE transaction on dielectric and insulation material, 2023.* 7. Weichuan Zhao, Mohamad Ghaffarian Niasar, Peter Vaessen, Gert Rietveld, "Voltage Sharing Improvement Methods in Series Connected Mosfets for Future Grid High Voltage Applications", 23rd International Symposium on High Voltage Engineering, ISH 2023.* 8. Gijs Lagerweij, Mohamad Ghaffarian Niasar, "Design of a high-frequency

	transformer based on amorphous cut cores for insulation breakdown testing", submitted to IET journal, 2023.* Suraj Jagannath, Reza Mirzadarani, Mohamad Ghaffarian Niasar, "High Voltage, Wireless Power Transfer based DC Power Supply", submitted to IEPMC 2023.* 9. Sohrab Ghafoor, Mahesh Kulkarni, Reza Mirzadarani, Peter Vaessen, Mohamad Ghaffarian Niasar, "A Scalable Pulse Transformer Based Isolated Gate Driving Technique for Open-Loop Voltage Balancing of Series-Connected SiC MOSFETs to Generate High Voltage Arbitrary Switching Function", submitted to IEEE Open Journal of Power Electronics.* 10. Gijs Lagerweij and Mohamad Ghaffarian Niasar, "High-Frequency Insulation Test System using a Ferrite-Based Resonant Transformer", ready to be submitted to IEEE, Transaction on Dielectrics and Insulation Material. 2023.* 11. Gijs Lagerweij and Mohamad Ghaffarian Niasar, "Ageing of Insulated Metal Substrate PCBs under High-Frequency Voltage Stress", ready to be submitted to IEEE, Transaction on Dielectrics and Insulation Material. 2023.* 12. Dhanashree Ashok Ganeshpure, Luis Carlos Castro Heredia, Mohamad Ghaffarian Niasar, Peter Vaessen, Thiago Batista Soeiro, Pavol Bauer, "Analysis of partial discharge behaviour under staircase-based sinusoidal voltage waveforms", 2020 IEEE 3rd International Conference on Dielectrics (ICD).# 12. Dhanashree Ashok Ganeshpure, Thiago Batista Soeiro, Mohamad Ghaffarian Niasar, Peter Vaessen, Pavol Bauer, "Modular multilevel converter-based arbitrary wave shape generator used for high voltage testing", 2021 IEEE 19th International Power Electronics and Motion Control Conference (PEMC).# 14. Dhanashree Ashok Ganeshpure, Thiago Batista Soeiro, Mohamad Ghaffarian Niasar, Peter Vaessen, Pavol Bauer, "Design trade-offs of modular multilevel converter-based arbitrary wave shape generator for conventional and unconventional high voltage testing", IEEE Open Journal of the Industrial Electronics Society.# 15. Yiming Zang, Mohamad Ghaffarian Niasar, Dhanashree Ashok Ganeshpure, Yong Qian, Gehao Sheng, Xiuchen Jiang, Peter Vaessen, "Partial Discharge Behavior of Typical Defects in Power Equipment under Multilevel Staircase Voltage" IEEE Transactions on Dielectrics and Electrical Insulation, 2022.# 16. Dhanashree Ashok Ganeshpure, Ajeeth Phrassanna Soundararajan, Thiago Batista Soeiro, Mohamad Ghaffarian Niasar, Peter Vaessen, Pavol Bauer, "Comparison of Pulse Current Capability of Different Switches for Modular Multilevel Converter-based Arbitrary Wave shape Generator used for Dielectric Testing of High Voltage", 2022 24th European Conference on Power Electronics and Applications (EPE'22 ECCE Europe).# 17. Xiaochuan Zhou, Dhanashree Ashok Ganeshpure, Thiago Batista Soeiro, Mohamad Ghaffarian Niasar, Yang Wu1and Peter Vaessen, "Implementation of Active Damping Control Methodology on Modular Multilevel Converter(MMC)-Based Arbitrary Wave Shape Generator Used for High Voltage Testing", 25th European Conference on Power Electronics and Applications EPE 2023.# 18. Dhanashree Ashok Ganeshpure, Thiago Batista Soeiro, Mohamad Ghaffarian Niasar, Peter Vaessen, Pavol Bauer, Nitish Kulkarni, "Design of Integrated Hybrid Configuration of Modular Multilevel Converter and Marx Generator to Generate Complex Waveforms for Dielectric Testing of MV and HV Grid Assets", ready to submitted to IEEE Industrial Open Access.

5. Follow-up a) career staff b) research	*The research performed in this project, and in general research on insulation system design, diagnostics and monitoring, and testing of medium/high voltage power electronics-based components plays a crucial role for ensuring the reliable operation of the future power grid. As a result, these areas of research are now recognized as one of the main research lines of High Voltage Technology (HVT) group of TUD. This research line is led by assistant professor Mohamad Ghaffarian Niasar.* *The main PhD student who works on this project still has another year to complete his PhD studies. We also have an additional self-funded PhD student who is actively contributing to this research topic with two more years ahead. Furthermore, a master student is currently working on his master thesis related to this project, and several new MSc students have expressed interest in contributing to different aspects of this ongoing research.* *Significant knowledge has been accumulated throughout this project. Prototypes of MMC and CHB based AWG, several resonant and pulse transformer as well as high voltage switch using series connected MOSFETs were constructed during the course of this project. During these activities new ideas have flourished which we plan to explore further in future projects.* *The next step is to write a continuation research proposal to provide guideline for insulation system design of medium/high voltage power electronics-based grid components.*
6. Results for general public	The project's primary objective is to design and build a power electronics (PE) based High Voltage Arbitrary waveform Generator (HV-AWG) for testing medium voltage (MV) equipment. This aims to evaluate and ensure long-term reliability of MV components exposed to high levels of harmonics and transient created by PE in a flexible future electric grid. Several specific objectives were investigated during the project, including specification and topology selection, sub-module and main power supply design, control and communication system implementation, prototyping and testing. Initially a comprehensive review of HV testing performed on MV equipment was conducted. From that review the specification of the HV-AWG was defined. It was concluded that the space of voltage, frequency, and test object capacitance needed to be partitioned. For each section, a specific design of HV-AWG would offer an optimum solution. The Multilevel Modular Converter (MMC) topology, providing complete modularity, was identified as capable of achieving HV output. However, its bandwidth is limited to a few kilohertz due to existence of arm inductors. The Cascaded H-Bridge (CHB) topology with easier controllability and a bandwidth in the range of tens of kilohertz, requires isolated transformer capable of taking the full voltage level on each submodule, making it unsuitable for very high voltage applications due to increased transformer size and higher submodule cost. For the frequency range from a few kHz to hundred kHz, an amplifier with a properly designed step-up pulse transformer emerges as the most suitable solution. Meanwhile an H-bridge together with an air-core resonant transformer can cover even higher frequency range, though limited to generating sinewaves of such frequencies. Pulses with very fast rise time in order of 100 ns or less, can be achieved using series connected MOSFETs. However, the main switching frequency is typically limited to several kHz due to issues of switch overheating. The project also delved into the investigation of lifetime of various insulation materials using the produced high-frequency pulse stress.

7. Illustrations	*See the attachment*
8. Signature	Completed truthfully and signed: Surname and initials: M. Ghaffarian Niasar Date: 20-12-2023 Place: Delft