Flexible and Future Power Links for Smart Grids

FLINK

Flexible and Future Power Links for Smart Grids

TESG114007

Abridged Final Project Report

01-01-2015 to 30-06-2019

Version 1.0 (public)

30-09-2019

TU/e
TKI URBAN ENERGY Topsector Energie
TU Delft Delft University of Technology
DNV·GL
alliander
EMforce
Rijksdienst voor Ondernemend Nederland
STEDIN.NET
EARLY MINUTE

Consortium Information

Consortium	Name	Type of organisation
Coordinator / Penvoerder	DNVGL Netherlands BV	Groot bedrijf
Partner 1	Technische Universiteit Eindhoven	Kennisinstelling
Partner 2	Technische Universiteit Delft	Kennisinstelling
Partner 3	EMForce	MKB
Partner 4	Early Minute	MKB
Partner 5	Alliander	Netbeheerder
Partner 6	Stedin	Netbeheerder

This project has been made possible by subsidy provided from the Dutch Ministry of Economic Affairs, within the national subsidy program *Topsector Energy* administrated by *Rijksdienst voor Ondernemend Nederland*.

Het project is uitgevoerd met subsidie van het Ministerie van Economische Zaken, Nationale regelingen EZ-subsidies, Topsector Energie uitgevoerd door Rijksdienst voor Ondernemend Nederland.

Document Information

Title: Abridged final project report intended as RVO ‘openbaar eindrapport’

Date: 30-9-2019

Authors:

Andrew Burstein	A.W.Burstein@tue.nl	TU Eindhoven
Aditya Shekhar	A.Shekhar@TUDelft.nl	TU Delft
Tiago Castelo de Oliveira	T.E.castelo.de.oliveira@tue.nl	TU Eindhoven
Erik de Jong	Erik.deJong@dnvgl.com	DNVGL Netherlands BV

Coauthors: Frank van Overbeeke vanoverbeeke@emforce.nl EMForce

The contact person for more information or to request a free digital copy of this report is Erik de Jong.

Table of Contents

1 Executive Summary

The FLINK project has performed a deep dive into the possibilities which medium-voltage direct-current (MVDC) technology could bring to a distribution network operator (DNO) in its struggle to keep up with the increasing electricity demand and its growing volatility. The rationale being that the power transfer capacity of an existing cable link, when operated under DC conditions, could be significantly higher, providing the DNO with an efficient tool to alleviate temporary or seasonal overloading situations without the need for immediate investment in grid reinforcements, while the power electronics converters could provide much needed ancillary services for local grid support when the link is operating in AC conditions.

It was framed in the context of repurposing an existing medium-voltage alternating current (AC) cable link, with the possibility to switch operation from AC to DC, and if found feasible, back to AC operation depending on DNO operational needs. Such operational needs could vary over time, which the technology should be able to take advantage of above static grid reinforcement alternatives.

As will become clear from the research outcomes reported here: the hypothesized advantages of power transfer capacity increase, the effect of operating under DC conditions on the cable reliability and lifetime; the ancillary services - provided by the power electronics converters - envisioned for local grid support and the switching of operation from AC to DC and vice versa are not trivial and comes with a very distinct operating range – at some parts solely governed by physics alone - and its own peculiarities (the introduction of space-charge build up in MV cables, for example); which makes the usefulness of such a technology depend heavily on the deployment use case and urgency of the need to solve the technical issue at hand at the DNO.

This research has succeeded in:

- finding and describing the theoretical boundary conditions and application limitations of the proposed technology;
- created useful engineering and analysis tools for assisting with grid planning and operation questions for evaluating grid reinforcement alternatives in particularly the transmission section of medium-voltage AC distribution grids using a wide range of medium-voltage DC solutions;
- Identifying best practices for the design and testing of such a technology on a component and system level; and
- delivering proof-of-concept laboratory demonstrations and measurement results that prove the fundamental functionality and technical feasibility of the technology as anticipated.

2 Introduction

Distribution network operators (DNO) today are challenged to maintain a (very) high level of availability as well as reliability and quality of supply (QoS) throughout its entire operation, despite major changes in the way power is generated, transmitted and used.

The anticipated problem of localized limited capacity and unacceptable voltages is prevalent in the lower voltage levels of the electricity grid due to the lack of enough power flow and voltage control. As a result, the risk of structural problems occurring is much higher at these lower voltage levels. DNOs are aware of these upcoming issues and are particularly searching for means to make their distribution voltage levels smarter and more flexible. Introducing smart solutions to the grid is appealing as it, if done properly, could be more economical than adding additional cable connections within the system.

There are several options to realize this flexibility, e.g. demand response at end users or electricity storage. However, next to these service options the DNO needs solutions that are fully controllable by themselves. Power electronic devices with advanced control and protection algorithms can fulfill those needs of the DNO to actively control power flows in their own distribution grids and be able to control the power flow between two neighboring distribution networks. This is a very attractive option for a DNO to get the required flexibility, as it does not require any consumer engagement.

In this context, the FLINK project has performed a deep dive into the possibilities which medium-voltage direct-current (MVDC) technology could bring to a distribution network operator (DNO) in its struggle to keep up with the increasing electricity demand and its growing volatility. The rationale being that the power transfer capacity of an existing cable link, when operated under DC conditions, could be significantly higher, providing the DNO with an efficient tool to alleviate temporary or seasonal overloading situations without the need for immediate investment in grid reinforcements, while the power electronics converters could provide much needed ancillary services for local grid support when the link is operating in AC conditions.

It was framed in the context of repurposing an existing medium-voltage alternating current (AC) underground cable link (Figure 1), with the possibility to switch operation from AC to DC, and if found feasible, back to AC operation depending on DNO operational needs. Such operational needs could vary over time, which the technology should be able to take advantage of above static grid reinforcement alternatives.

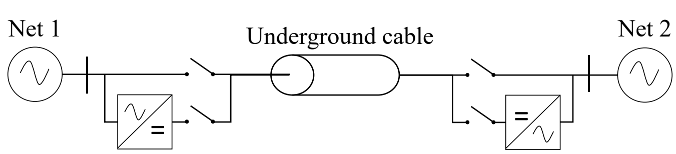

Figure 1 Basic concept of the fundamental FLINK proposed solution

This report highlights the major project results and how it contributes to the Topsector Energy ambitions.

3 Project goals and ambitions

The main project goal was to provide DNOs with a proven means to increase the flexibility – temporarily or permanent - and to simultaneously unlock additional system control measures within particularly the lower voltage levels of their distribution grids by providing the technology and tools necessary to repurpose existing medium-voltage assets in favorable grid scenarios. This to allow more efficient use of the available grid assets considering the actual loading and avoid costly passive grid reinforcement that would only be necessary for short periods of time. All of this without the direct need for consumer engagement.

The project set out to:

- Investigate the fundamental principles and theories underlying the possibility to operate an existing medium-voltage AC cable under DC conditions with enhanced transfer capacities, looking specifically into:
    - what the possible increase in transfer capacity could potentially be under ideal conditions,
    - what factors influence the transfer capacity when operating under DC conditions;
- define innovative (ancillary) services that can be offered to a future market for electricity services, such as (but not limited to):
    - Power Quality enhancement during DC operation, by decoupling two grid segments, for example
    - Grid enhancement during AC operation, by applying the available control possibilities of the shunt-connected power electronics converters as reactive power support, flicker mitigation, harmonic distortion compensation, etc.
- identify best practices in terms of design requirements and testing procedures of such utility-interactive power electronic systems
- identify whether the concept, including its capability to provide a range of ancillary services and integrate with other smart energy services will be interesting enough for commercial parties to offer such flexibility services on the smart energy market.

The project realized a scaled-down, demonstration setup in the laboratory to demonstrate proof-of-principle of the concept, both on component and system level, and thereby acquire confidence in the concept as well as initial measurements to provide initial performance estimations and validate simulation models and tools of the developed technology.

4 Project results

The project focused on a specific use case of the proposed technology, which was identified as most promising for application in the Dutch distribution grid by the grid operators themselves, namely that of the transmission section of the distribution grid. In this section of the grid:

- there usually are multiple cables, which is favorable for the use of conductors when operating at DC,
- the need for voltage regulation is prevalent, which could be supported or perhaps even totally replaced by the power electronics converters envisioned in the concept
- power congestion is most likely to happen, but usually only for limited time periods.

This use case that has been adopted and used extensively for the research is shown in Figure 2 and in more detail in Figure 3.

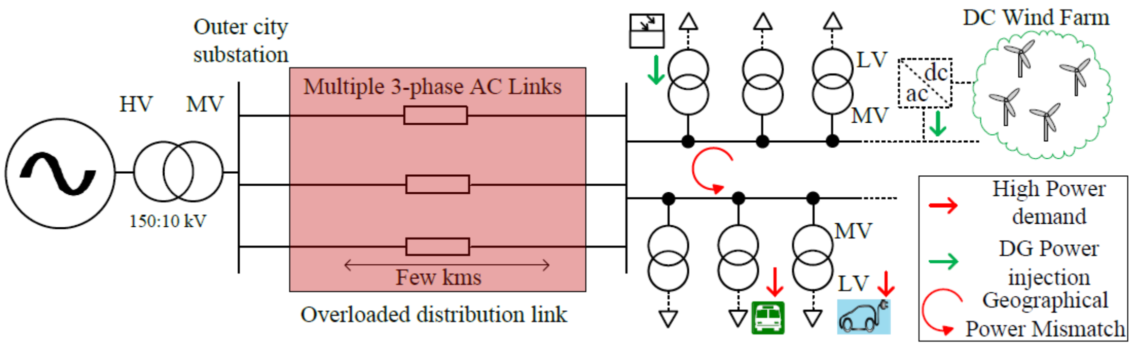

Figure 2 Interesting DNO use case: bulk power transmission into the city collection center.

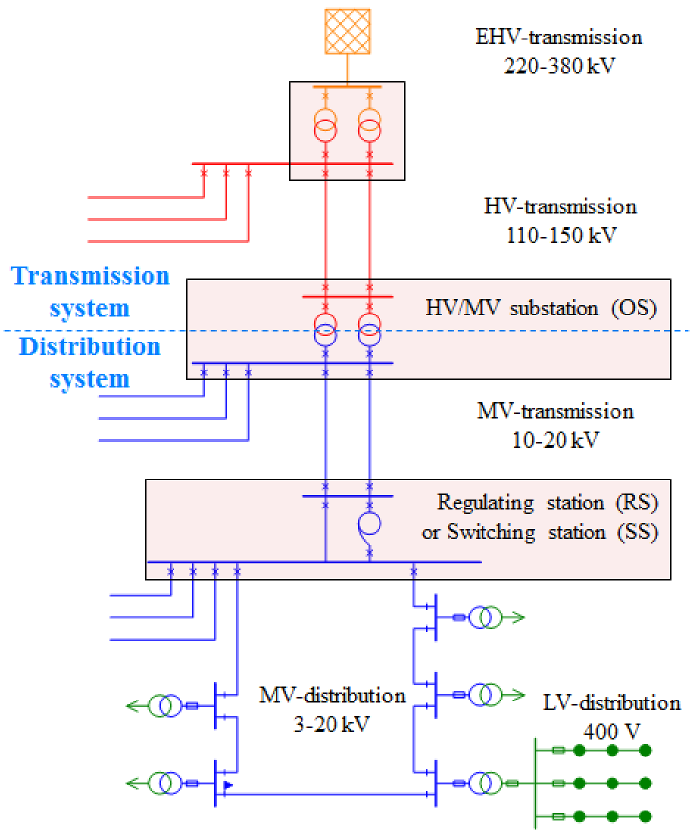

Figure 3 Detailed single-line diagram of FLINK application case

Applying the concept of a reconfigurable medium-voltage cable link to the use case results in a case study as shown in Figure 4.

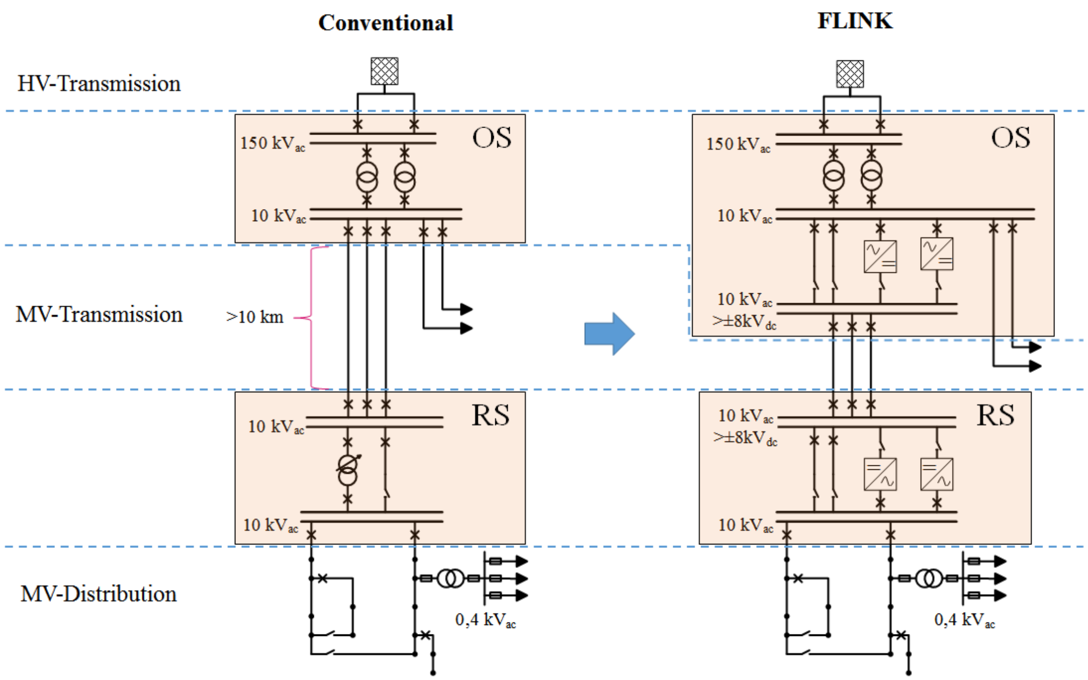

Figure 4 Introduction of the FLINK concept into the use case grid environment

By introducing voltage source converters (VSCs) into the AC medium-voltage network (MV-Grid) it is possible to operate the cable segment on either AC or DC voltages, with the premise that operating under DC conditions provides more transport capacity over the same cable link. Furthermore, a more active control is given to the distribution network operator (DNO), thus making it possible to provide services aiming at the optimization of the MV-grids operation [1]–[4].

In the AC operation, the VSCs are connected in shunt to the medium voltage point common coupling (MV PCCs) of the primary High-Voltage/Medium-Voltage (HV/MV) substation, thus regulating the Medium-Voltage/Medium-Voltage (MV/MV) substation as well as at the regulation substation (RS). The most important objective of the power electronics at the RS is to replace and improve the functionality of the regulation transformers (RT). The effectiveness of the power electronics was determined when it's being used for voltage regulation at the RS, specifically looking if they could potentially replace the RTs altogether. The ancillary services that could be provided at this location using the foreseen connection topology is interesting for future market services [1], [3], [4].

The main purpose of the DC operation is to provide an enhanced transmission capacity in the medium voltage transmission link (MV-T link). The primary substation VSC thus acts as a rectifier, controlling the DC voltage, while the RS VSC acts as a grid forming converter, providing and controlling the medium voltage distribution grid's (MV-D grid) voltage magnitude and network frequency. Due to this topology, the system must be reliable or poses sufficient redundancy, since the loss of the power electronic units would result in a blackout of the entire MV-D grid.

In the DC operation, part of the ancillary services that can be provided is power quality improvement [2]–[5]. Thus, at the RS, the control of the grid-forming inverters already regulates the frequency and voltage and can therefore also assist in reducing any harmonic distortion, within the capabilities of the power electronics converters.

The project has delivered two scaled demonstrators for laboratory experimentation purposes, that was used as proof-of-principle and testbench to provide measurement results to validate the models and theories developed herein. One demonstrator focused on the component aspects when deploying advanced power electronics converter topologies, such as multi-modular converter (MMC) in this case; while the other demonstrator focused on the system aspects associated with operating the concept in a realistic distribution grid environment.

Figure 5 shows the demonstrator used for component level studies and to validate key control concepts, and Figure 6 the demonstrator used for system studies, including the provision of ancillary services.

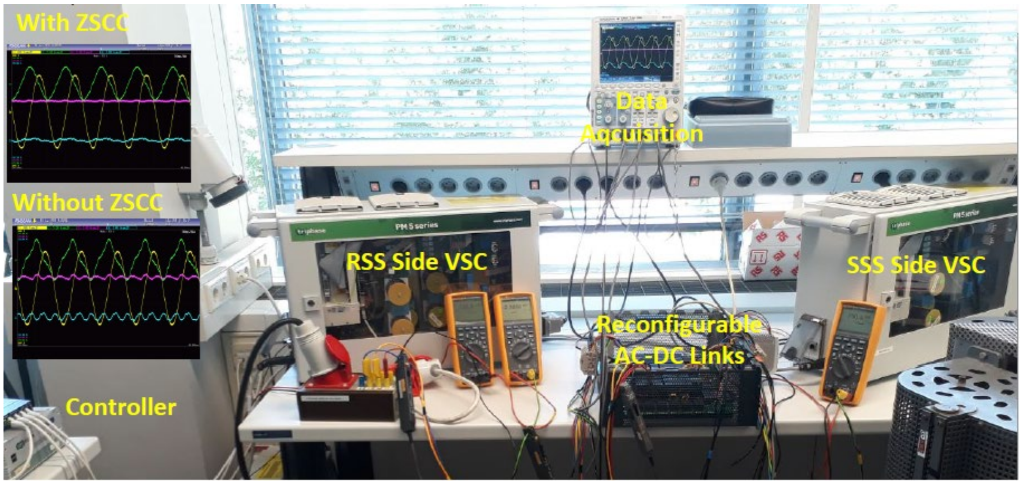

Figure 5 Demonstrator developed for component level studies of the concept and technology (MMC topology)

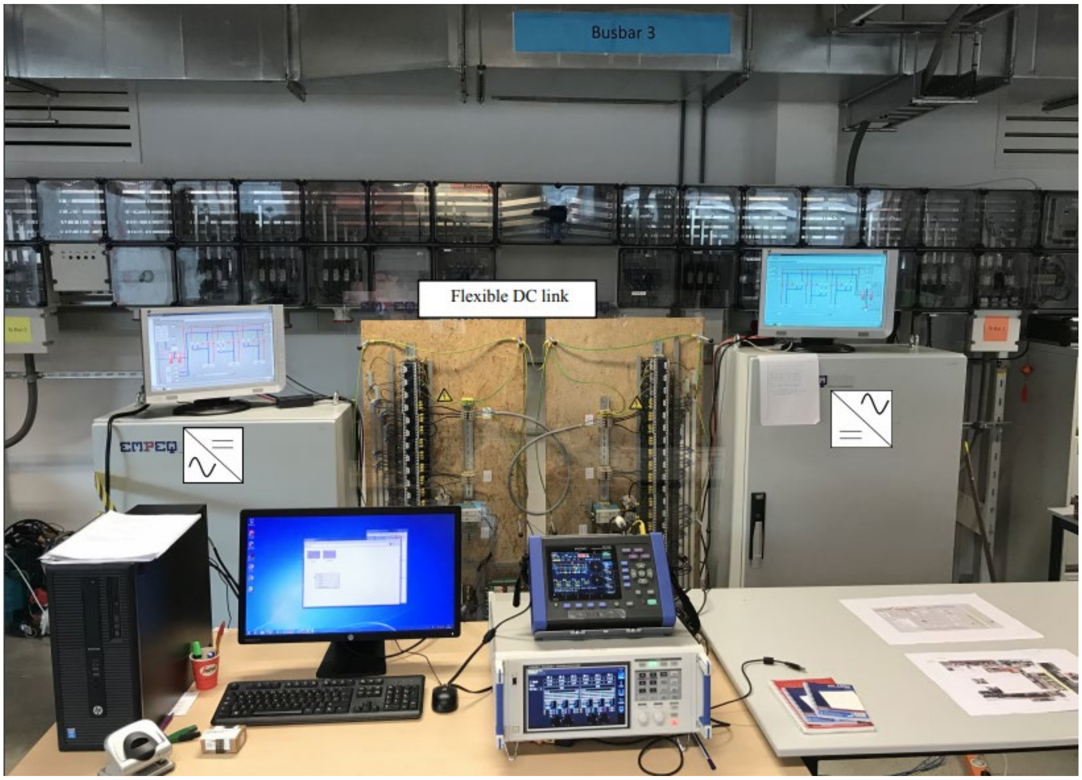

Figure 6 Demonstrator developed for system level studies of the concept and technology (Two-Level VSC topology)

The answers to the main research questions associated with this project are given here.

How much capacity enhancement can be achieved by refurbishing existing ac link infrastructure to operate under dc conditions?

Key Challenges:

- The achievable dc capacity gain is influenced by various factors that must quantified as compared to ac in relation to varying system parameters. For example, the impact of factors such as voltage rating and regulation, capacitive currents, dielectric effect, skin effect, thermal proximity reactive power demand and the system topology, can vary with grid voltage, link length, conductor type and cross-sectional area.
- Determining a fair assumption on dc voltage enhancement is not so straightforward. The magnitude by which the imposed dc voltage can be increased while ascertaining comparable insulation performance as under ac operating voltages can significantly influence the achievable capacity gains. In this context, the partial discharge behaviour can be a possible insulation lifetime performance indicator.
- There is a decrease in power delivery capacity that can be maintained during single component failure in the system (referred to as (n-1) contingency). Contingency analysis related to maximum capacity of the proposed architecture during different fault conditions must be considered.

Findings:

The computed results prove that a capacity enhancement of at-least 50–60 % can be achieved with dc operation based on the considered assumptions for different configurations. The factors include increase in imposed dc voltage as compared to ac (41 %), better voltage regulation (2-5 %), current rating enhancement (0-3 %) and reactive power support by the converters at the receiving end of the dc link (10-15 %). There is an interesting potential of enhancing the operating dc voltage for similar or superior insulation performance as compared to ac over the cable lifetime. It is empirically shown that the repetition rate of partial discharges in the prepared cable samples are much lower with dc. Based on this partial discharge behavior as insulation lifetime indicator, the dc voltage enhancement factor is conservatively assumed to be $\sqrt{2}$ times the rated r.m.s ac voltage. While it is possible to choose a higher dc voltage enhancement factor, particularly for overhead lines, the inception voltage should be considered as an indicator of insulation performance.

Contingency analysis shows that even though a much higher power can be delivered with dc for the same conductor area during healthy system operation, this is not necessarily achievable during fault conditions. This is because (n-1) contingencies result in either sub-optimal utilization of remaining infrastructure due to topology constraints, or loss of a critical component performing specific operational function.

What are the advantages of developing a flexible architecture with ac-dc distribution link reconfigurability?

Key Challenges:

- System aspects such as number of link conductors, whether they are overhead lines, single cored or three cored underground cables, rating, topology and number of substation converters can influence the viability of the proposed technology.
- The trade-offs associated with infrastructure and operational complexity should be identified and weighed against the capacity, efficiency, availability and economic benefits of the reconfigurable architecture.

Findings:

Using a specific case-study of an actual distribution link system in The Netherlands, it is shown that 50 % enhanced power delivery capacity achieved with refurbished dc operation may not be maintainable during certain fault conditions unless reconfigurability is introduced in the system architecture. A parallel ac-dc reconfigurable link architecture is proposed to improve the infrastructure utilization during different (n-1) contingencies to suggest that a post-fault system capacity of 100 % is achievable. For example, ac bypass can be used during substation converter fault to improve link conductor utilization, and thus increase the power delivery capacity during such contingencies.

The various trade-offs associated with reconfigurability are discussed, such as efficiency, availability, cost, reliability and operational complexity. For example, it is highlighted that the dc link converter capacity can be significantly lowered for the same system capacity, thus reducing installation cost. However, this can increase the number of necessary reconfigurations during fault condition, thus influencing the operational complexity. At the same time, converter downsizing can be detrimental to the operating efficiency during normal operation. These considerations are explored in detail for different system aspects such as number of link conductors, whether they are overhead lines, single cored or three cored underground cables, rating, topology and number of substation converters. The main advantages of developing a flexible architecture are therefore: enhanced system capacity during (n-1) contingencies, potential converter downsizing and relatively higher operating efficiency.

What are the design criteria for ac/dc converter used in grid connected medium voltage high power applications?

Key Challenges:

- Half-bridge based modular multilevel converters (MMCs) can improve converter efficiency with superior harmonic performance but the selection of number of levels is a trade-off between conduction and switching losses for a fixed medium voltage dc link.
- The trade-offs associated with the five degrees of freedom: switch blocking voltage, sub-module capacitance, modulation technique, arm inductance and reliability factors can influence design choices in terms of size, cost, reliability, efficiency and harmonic performance of the converter.
- The design choice must ensure acceptable capacitor voltage balancing and high frequency ripple in the internal circulating currents.

Findings:

A detailed design of a half-bridge IGBT submodule based modular multilevel converter is presented for medium voltage high power grid connected applications considering the five available degrees of freedom: switch blocking voltage, submodule capacitance, modulation technique, arm inductance and reliability factors. It is highlighted that for a fixed dc link voltage, higher number of sub-modules can reduce switching losses for the required harmonic performance but increase the conduction losses. Correspondingly, it is numerically shown that there is an optimal number of submodules for a given dc link voltage.

As an example, a 17 kV, 10 MVA dc link with back to back MMC based system integrated to a 10 kV grid is used. The comprehensive design considerations indicate that a MMC with 3 mH arm inductance and 9x half-bridge submodules of 3.3 kV IGBT switches operating with a switching frequency of 353 Hz can comply with required harmonic performance at relatively higher efficiency as compared to IGBTs of either higher (4.5 kV, 6.5 kV) or lower (1.2 kV, 1,7 kV) switch ratings. Note that higher switch rating would correspondingly result in lower number of submodules (7,5), while lower switch rating will result in higher number of submodules (17, 25) for a given dc link voltage. The optimized load dependent converter efficiency curve is derived to vary between 99.2-99.4 % for 10-100 % of the full load.

In which configuration should the distribution link architecture be operated during healthy system conditions?

Key Challenges:

- The operating losses vary based on several dimensions such as the receiving end active and reactive power demand, power sharing between ac and dc links in the system, grid voltage, dc link voltage, converter efficiency, link length and conductor area. Therefore, the system configuration with optimal efficiency must be determined by accounting for the sensitivity to all these aspects simultaneously.
- The economic viability is governed by differences in link conductor and converter installation costs for maintaining the required capacity with different configurations in trade-off with associated efficiency gains. The break-even boundaries for parallel ac-dc operation as compared to completely ac or completely dc solutions must be determined based on the related payback time involved.

Findings:

It is shown that the proposed parallel ac-dc reconfigurable link architecture can be operated under different configurations during normal conditions. A sensitivity analysis is performed for different operating power demand, power factor, ac grid voltage, converter efficiency, link length and conductor area to prove that parallel ac-dc operation can be more efficient as compared to either completely ac or dc operation within defined boundaries. Based on the quantified results, it is possible to determine the boundaries for which it is the most economically viable to refurbish the existing ac system and operate as parallel ac-dc links compared to other available solutions of equivalent capacity enhancement. For example, a payback time of 10 years is achievable for the added dc link converter cost even for short link lengths of 10-20 km for power transfer of few tens of MVA in a 10 kV grid if parallel ac-dc link is used.

By how much can the substation converter be derated while maintaining the required system capacity during different (n-1) contingencies?

Key Challenges:

- The dc link voltage, active power sharing between the ac and dc link, reactive power support by the receiving end converter and full load rating of substation converters are tightly tied in the dimensioning problem formulation.
- Reducing the substation converter rating can reduce the operating efficiency during healthy condition and increases the operational complexity for maintaining the required capacity during different (n-1) contingencies.
- The economic viability of converter downsizing is influenced by demand profile at receiving end, grid voltage, link length and conductor area. The payback time due to the system operation at sub-optimal efficiency as a consequence must be computed.

Findings:

For the same system capacity, it is shown that there is potential of reducing the installed substation converter size by almost 75 %. This increases the number of dc to ac reconfigurations in case a fault occurs in the link system, thus increasing the operational complexity. However, a more pertinent challenge is that of sub-optimal efficiency of the system during normal operation if the converter is downsized. For example, it is quantified for case-specific load profiles and system parameters that downsizing the converter by 5-10 % can give a 10-year payback on installation cost savings only for link lengths greater than 10-15 km. The de-rating potential becomes less economically viable with increasing ac grid voltage and link conductor area.

What are the control challenges involved in the dynamic operation of parallel ac-dc distribution links?

Key Challenges:

- Zero sequence currents (ZSC) circulate between the 3-line ac link and the back to back converter-based dc link in the absence of isolating transformer. Depending on the converter parameters and link length, the magnitude of these currents can result in additional losses in the system. The output current controller of the link converter should be designed to mitigate the ZSC.
- If modular multilevel converters are used, the implementation of output current 3^{rd} harmonic ZSC controller results in 4^{th} harmonic ripple in internally circulating currents in the MMC phase arms. Therefore, an additional resonator tuned to mitigate this fourth harmonic ripple is needed.
- The sending end converter must control the dc link voltage at its rated value while the converter at the receiving end of the dc link must be responsible for active power steering between the ac and dc links in the system while supporting the full reactive power demand at the substation.
- The optimal efficiency that the parallel ac-dc link system can operate varies with the receiving end power demand and must be dynamically estimated specifically to system parameters such as grid voltage, dc link voltage, load dependent converter efficiency, link length and conductor area.

Findings:

It is shown through simulations and experiments that it is possible to operate the back to back converter-based dc link in parallel with ac link with active power steering capability. The results indicate that a path exists for the circulation of zero sequence currents between the three lines of the ac link and common dc link which can be mitigated using a feedback controller. Further, it is shown that the active power shared between the ac and dc link can be controlled depending on the operating conditions to improve the system efficiency. An algorithm is developed to determine this dynamically varying optimal efficiency point and implemented in both simulation model and test set-up for the parallel ac-dc link.

Where can the dc interlink be placed in the radial distribution grids and what is its proper sizing for effective active power redirection?

Key Challenges:

- For a n-bus radial distribution network, there are n x n possible combinations for the placement of a point-to-point dc interlink. Depending on the node from where it draws and the receiving end where it injects active power, the system distribution losses can be influenced.
- Depending on the capacity of the dc link, the distribution losses, reverse power flows, power redirection needs with distributed generation and high-power loads can vary.

Findings:

Using a test 33-bus radial ac distribution network, it is shown that dc interlinks can be used to weakly mesh the system to achieve active power redirection at relatively high efficiency while improving the system capacity. The sizing and location problem of such a dc interlink is addressed for distributed generation and high-power loads installed at different buses of the system. Results indicate that geographical power mismatch can be avoided to prevent local branch overloads and the system efficiency can be improved by as much as 10-15 %.

The demonstrated concept of a reconfigurable medium-voltage DC link is a transitional technology to aid in the transition of the grid from a fully passive to a more actively controlled system. The main function of this technology, as placed in the MV-T link, is to reinforce the link during times of expected overloading without the need of installing new cables. Due to the complexity of reconfiguration, however, other solutions which achieve the same goal may be more economically and technologically feasible. One of the major impediments of the reconfigurability is the accumulation of space charges and their potentially disastrous effect upon switching to nominal AC voltage. This is suggested as better avoided, by engineers, such as a permanent VSC DC-link, or with a very-low-frequency voltage. Therefore, depending on the desired qualities of the link by the DNO, a more suitable option may be to either install a permanent DC-link, or a flexible AC/VLF-link.

The installation of reconfigurable DC links in an existing AC distribution grid offers four important key aspects: flexibility of operation, redundancy, reliability and better power flow through loss minimization. Besides these aspects, the DC link provides better viability and performance during faults and power quality concerns. This research has identified that once the link is operating in DC mode, going back to AC cannot be convenient for technical aspects, such as the timing procedure and response to faults on the downstream network. On the other hand, the system could operate in AC mode in respect to voltage regulation variations which depends on the network's conditions. These conditions are directly connected to technical and climate aspects, such as PV production during some portions of the year or even wind generation. It is up to the DNO to decide, through further analysis and predications, which portion of the year the system should be operating in either AC or DC. In this case, further analysis is required throughout the time window of a year for climate and technical conditions.

This research has also shown that the notable gain of capacity through the DC operation, as well as its stability in relation to sudden load and generation changes, is technically feasible. In DC-operation the link was able to supply a secure power supply, as well as offer high robustness. Moreover, the power electronics in DC-mode presented better performance to ride-through transient events such as voltage dips and swells, as well the link has been checked its resilience to longer duration under- and over-voltages.

It is strongly recommended te revisit the concept to quantify and test the assertions made in this work of the expected benefits and challenges of a flexible AC/DC-link for use cases not covered in this project.

5 Contribution towards the goals of the TKI Urban Energy

Power electronics, control and protection as well as DC are regarded as key technologies for operating and guaranteeing stability of Smart Grids with a large amount of embedded fluctuating renewable generation. The addendum for TKI Smart Grids mentions DC interfaces and its controls as one of the interesting options for the future. The development and critical evaluation of new concepts based on power electronics increases the acceptance of the DNOs for these new technologies as a possible alternative for increasing the grid flexibility as opposed to reinforcement.

The impact of this project on the Dutch future sustainable energy supply lies mainly in the accommodation of increased amounts of fluctuating renewable energy sources at low- and medium voltage level, as well as creating more flexibility in the physical distribution grid capacity at times when short-term overloading is imminent, without excessive investments that might not be recovered due to uncertainties in generation and load development. This study has quantified the theoretical gain in transport capacity and the boundary conditions in which it can be applied.

The ancillary services identified in this study that can be offered with the power electronic converters of a reconfigurable DC-link concept can directly support the implementation of more renewable energy sources as it can provide voltage support and grid resilience services.

The general public / electricity end users will not notice if this technology is employed or not, because it is inside the network. For the general public it will support the implementation of new energy technologies and renewable energy sources.

The collaboration established between academic institutions on an international level has improved the visibility of Dutch academia and its role in the knowledge economy.

6 Spin-off potential

The potential for spin-off of this project in terms of (academic and industrial) research and knowledge accumulation is significant. The fundamental research performed in this project has contributed significantly to the scientific literature on the topic of medium-voltage distribution grids as well as the fundamental principles[1] of operating a power cable using DC (see publication list in Chapter 7). Follow up research activities include the statistical analysis - using laboratory testing methods - on aged cable system samples, including the cable, joints and terminations to quantify the impact of DC operation on the lifetime; reliability and dielectric integrity of the cable system, as well as investigate the impact cable relaxation (removal of space charge accumulation in the dielectric material of a cable system) will have on the feasibility of the entire concept in practice.

Dutch service providers can benefit from the knowledge that was generated in The Netherlands and have direct contacts to this consortium and its partner network.

The DNOs, besides the direct knowledge and access to the DC experts, now have a valuable toolset to be able to evaluate whether the proposed concept provides the expected benefits for individual congestion cases, as they appear.

The Dutch test and certification business, followed closely by the standardization activities, will profit from the experience of using power hardware in the loop to assess and certify ancillary services from advanced components in a realistic and cost-effective manner.

The potential for spin-off of this project in terms of a commercial product or service in the short-term is limited, as the TRL ultimately achieved with the project is limited to level 5. The manufacturing industry will still need to develop the technology further before commercialization of a product or service can take place.

[1] This topic was researched for the last time in the 1970'ies

7 List of publications

The results of the project have been disseminated via different channels throughout the project execution. An overview of the major contributions towards the scientific literature is given here.

List of PhD thesis contributions.

- A. Shekhar, "Restructuring medium voltage distribution grids – Parallel AC-DC reconfigurable links, PhD dissertation, Technical University of Delft, 7 January 2020.

List of publications that appeared in international peer-reviewed journals.

- A. Shekhar, L.M. Ramirez-Elizondo, T. B. Soeiro and P. Bauer, "Boundaries of Operation for Refurbished Parallel AC-DC Reconfigurable Links in Distribution Grids," in IEEE Transactions on Power Delivery, 2019.
- A. Shekhar; X. Feng; A.Gattozzi; R.Hebner; D.Wardell; S. Strank; A. Rodrigo-Mor; L. Ramírez-Elizondo; P. Bauer, "Impact of DC Voltage Enhancement on Partial Discharges in Medium Voltage Cables—An Empirical Study with Defects at Semicon-Dielectric Interface" Energies 2017, 10, 1968.
- A. Shekhar, E. Kontos, L. Ramírez-Elizondo, A. Rodrigo-Mor, P. Bauer, "Grid capacity and efficiency enhancement by operating medium voltage AC cables as DC links with modular multilevel converters, " International Journal of Electrical Power & Energy Systems, Volume 93, 2017, Pages 479-493, ISSN 0142-0615.
- A. Shekhar, L. Ramírez-Elizondo, X. Feng, E. Kontos, P. Bauer, "Reconfigurable DC Links for Restructuring Existing Medium Voltage AC Distribution Grids," Electric Power Components and Systems, 2017, 45:16, 1739-1746.
- [Under review] A. Shekhar, T. B. Soeiro, Y. Wu and P. Bauer, "Optimal Power Flow Control in Parallel Operating AC and DC Distribution Links," in Transactions on Industrial Electronics, 2019.
- [Under review] A. Shekhar, T. B. Soeiro, L. M. Ramirez-Elizondo and P. Bauer, "Offline Reconfigurability based Substation Converter Sizing for Hybrid AC-DC Distribution Links," in IEEE Transactions on Power Delivery, 2019.

List of publications that where presented and appeared in the conference proceedings of (inter)national conferences:

- de Oliveira, T.E.C; van Overbeeke, F.; Cúk, V.; de Jong, E.C.W.; MVDC Application: Switching Processes AC-to-DC, DC -to- AC and Imbalance Mitigation through DC Mode. 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), Bucharest, 2019;
- de Oliveira, T.E.C; van Overbeeke, F.; Cúk, V.; de Jong, E.C.W., Design of a Flexible AC/DC-Link: AC vs DC Active Power Capacity. 2019 IEEE PES Innovative Smart Grid Technologies Europe (ISGT-Europe), Bucharest, 2019;
- de Oliveira, T.E.C; van Overbeeke, F.; Cúk, V.; de Jong, E.C.W., Research on the Switching Process for Re-purposing an AC Cable with DC-link in Distribution Network. 2nd International Conference on Smart Energy Systems and Technologies, Porto, 2019.;

- A. Shekhar, T. B. Soeiro, L. Ramírez-Elizondo and P. Bauer, "Zero Sequence Currents Externally-Circulating between the Back to Back Modular Multilevel Converters in Parallel AC-DC Distribution Links," IEEE 10th International Conference on Power Electronics – ECCE Asia (ICPE 2019-ECCE Asia), Busan, South Korea, 2019.
- A. Shekhar, L. Beloqui Larumbe, Y. Wu, T. B. Soeiro and P. Bauer, "Number of Levels, Arm Inductance and Modulation Trade-offs for High Power Medium Voltage Grid-Connected Modular Multilevel Converters," IEEE 10th International Conference on Power Electronics – ECCE Asia (ICPE 2019-ECCE Asia), Busan, South Korea, 2019.
- A. Shekhar, T. B. Soeiro, L. Ramírez-Elizondo and P. Bauer, "Weakly Meshing the Radial Distribution Networks with Power Electronic Based Flexible DC Interlinks," IEEE Third International Conference on DC Microgrids (ICDCM), Matsue, Japan, 2019.
- A.W. Burstein, V. Cuk, and E. C. W. de Jong, "Effect of Network Protection Requirements on the Design of a Flexible AC/DC-link," 14th Int. Conf. Dev. Power Syst. Prot., vol. 2018, no. DPSP, pp. 1291–1296, 2018.
- A.W. Burstein, V. Ćuk, and E. C. W. de Jong, "Design of a Flexible AC/DC-Link," Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf., vol. 2018–April, 2018.
- A. Shekhar, T. B. Soeiro, Z. Qin, L. Ramírez-Elizondo and P. Bauer, "Suitable Submodule Switch Rating for Medium Voltage Modular Multilevel Converter Design," IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 3980-3987.
- A. Shekhar, L. Ramírez-Elizondo, Z. Qin and P. Bauer, "Modular Multilevel Converter Performance with Dynamic MVDC Distribution Link Voltage Rating," IEEE 18th International Power Electronics andMotion Control Conference (PEMC), Budapest, 2018, pp. 1000-1004.
- A. Shekhar, L. Ramírez-Elizondo and P. Bauer, "Reliability, Efficiency and Cost Trade-offs for Medium Voltage Distribution Network Expansion using Refurbished AC-DC Reconfigurable Links," International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, 2018, pp. 242-247.
- E.C.W. de Jong, A.W. Burstein, and V. Cúk, "Determining potential capacity gains when repurposing MVAC cables for DC power transportation," in the proceedings of the CIRED conference, vol. 2017, no. June, pp. 1691–1694, 2017.
- A. Shekhar, E. Kontos, L. Ramírez-Elizondo and P. Bauer, "AC distribution grid reconfiguration using flexible DC link architecture for increasing power delivery capacity during (n-1) contingency," IEEE Southern Power Electronics Conference (SPEC), Puerto Varas, 2017, pp. 1-6.
- A. Shekhar et al., "Thermal modelling and experimental validation for research on medium voltage DC cables," IEEE Power & Energy Society General Meeting, Chicago, IL, 2017, pp. 1-5.
- A. Shekhar, E. Kontos, L. Ramírez-Elizondo, A. R.Mor and P. Bauer, "Power transfer computations for medium voltage AC link by imposing rated current at sending end," IEEE International Power Electronics and Motion Control Conference (PEMC), Varna, 2016, pp. 425-429.
- A. Shekhar, E. Kontos, A. R. Mor, L. Ramírez-Elizondo and P. Bauer, "Refurbishing existing mvac distribution cables to operate under dc conditions," IEEE International Power Electronics and Motion Control Conference (PEMC), Varna, 2016, pp. 450-455.
- A.W. Burstein, V. Cúk and E.C.W. de Jong, "Determining the theoretical maximum capacity gain of refurbishing MVAC cables as reconfigurable DC-links", IEEE Young Research Symposium, Eindhoven, May 2016, pp. 1- 6

8 References

[1] E.C.W. de Jong, A.W. Burstein, and V. Cuk, "Determining potential capacity gains when repurposing MVAC cables for DC power transportation," vol. 2017, no. June, pp. 1691–1694, 2017.

[2] J. King, J. Berry, and N. Murdoch, "Steady-state modelling for the integration of a bi-directional AC – DC – AC flexible power link," vol. 2017, no. June, pp. 445–449, 2017.

[3] A. W. Burstein, V. Cuk, and E. C. W. de Jong, "Effect of Network Protection Requirements on the Design of a Flexible AC/DC-link," *14th Int. Conf. Dev. Power Syst. Prot.*, vol. 2018, no. Dpsp, pp. 1291–1296, 2018.

[4] A. W. Burstein, V. Ćuk, and E.C.W. de Jong, "Design of a Flexible AC/DC-Link," *Proc. IEEE Power Eng. Soc. Transm. Distrib. Conf.*, vol. 2018–April, 2018.

[5] A. A. Van Der Meer, *Offshore VSC-HVDC Networks Impact on Transient Stability of*. 2017.