AC Distribution Grid Reconfiguration using Flexible DC Link Architecture for Increasing Power Delivery Capacity during (n-1) Contingency

Shekhar, Aditya; Kontos, Epameinondas; Ramírez-Elizondo, Laura; Bauer, Pavol

DOI
10.1109/SPEC.2017.8333559

Publication date
2018

Document Version
Accepted author manuscript

Published in
Proceedings - 2017 IEEE Southern Power Electronics Conference, SPEC 2017

AC Distribution Grid Reconfiguration using Flexible DC Link Architecture for Increasing Power Delivery Capacity during (n-1) Contingency

Aditya Shekhar, Epameinondas Kontos, Laura Ramírez-Elizondo and Pavol Bauer

***Abstract*—A practical issue faced by today's ac grid is the rapidly growing power demand on its aging infrastructure. One possibility to maximize the capacity of the existing infrastructure is to refurbish the ac links to operate under dc conditions using modular multilevel converters. In this paper, the idea is applied to restructure an actual medium voltage distribution system. Further, a systematic reconfiguration strategy is proposed to maintain high power delivery capacity even during (n-1) contingency. Contingency analysis is carried out for faults in different system components of the distribution grid. Towards this goal, novel concepts such as reconfigurable switch, dc link converter bypass and flexible dc to ac operational transition are proposed.**

***Index Terms*—breakers, capacity enhancement, contingencies, dc links, distribution, flexible, medium voltage, reconfiguration, system faults, switch minimization.**

I. Introduction

A. Problem Description

There is an increasing reliance on electrical power to carter for the energy needs of the society [1], [2]. This trend has put pressure on the utility grid infrastructure, particularly at critical locations at medium voltage level as illustrated in Fig. 1.

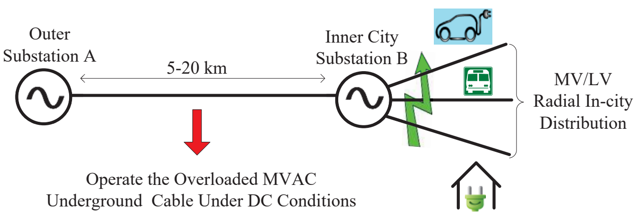

Fig. 1: Critical medium voltage ac link overloaded by the emerging energy consumers.

Conventional way of increasing the system power delivery capacity has been to lay additional 3 phase ac cable links. The architecture is simple and operational knowledge makes it an attractive choice for the distribution network operators (DNOs). The installed components are robust and reliable. However, a massive digging operation to install the underground cable infrastructure is required, which maybe undesirable at certain locations. Need for compact, socio-economically viable and efficient operation has led to pursuit of research on alternate ways of tackling this problem [2], [3]. A good discussion on anticipated challenges in restructuring medium voltage ac grids and the roadmap for the role of reconfigurable dc links is offered in [4].

Demand side management, installing distributed sources of generation (DGs) at the consumer side and storage have been explored as possible solutions [5]–[7]. Architecture is such that the base load can be supported by the utility grid and the peak load by the DGs. However, the intermittent nature of these resources as well as seasonal variation in generation needs careful planning and operational optimization. For example, in the case study presented in this paper, installation of solar PV may not be an ideal solution, considering that the peak demand breaches the available capacity during winter months.

Further, the increased power delivery capacity is usually an important consideration during (n-1) contingency arising when one of the various distribution system components undergoes a fault. In such situations, adequate redundancy is necessary to ensure that the load demand is met until the healthy system is restored. Under economic constraints, wherein desired redundancy is costly to achieve, load shedding mechanism is considered [8]. But this solution is not always favourable.

B. Proposed Solution and Challenges in Implementation

An interesting possibility is to refurbish the existing underground ac cables to operate under dc conditions, as explored in [2]. The idea can also be applied for converting high voltage ac overhead lines to dc, as proposed in [9], [10].

A generalized quantification of capacity and efficiency enhancement in refurbishing underground cables from ac to dc operation is offered in [3] using the equations derived in [11]. An empirical study exploring the consequences of imposing enhanced dc voltage on insulation performance of underground cables designed for ac operation is described in [12].

A sample result from the comprehensive mathematical consideration of all influencing factors such as voltage enhancement, regulation, dc current enhancement and load power factor is shown in Fig. 2.

For even number of converted ac conductors, at least 50 % enhancement of power transfer capacity can be achieved. While, if three conductors of ac are converted to a bipolar dc link (resulting in one redundant conductor), the capacity

The authors are with the Department of Electrical Sustainable Energy in the DCE&S Group, Delft University of Technology, The Netherlands. **Email:** a.shekhar@tudelft.nl, p.bauer@tudelft.nl.

This work is funded by tki switch2smartgrids under the project Flexible and Future Power Links (FLINK) for Smart Grids by Rijksdienst voor Ondernemend, Nederland.

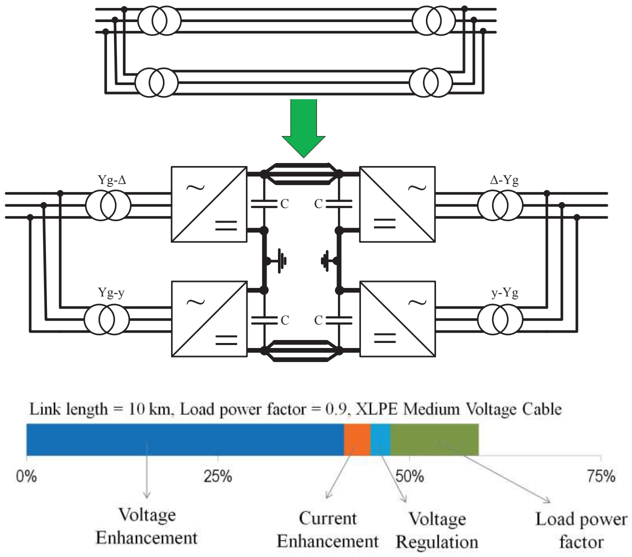

Fig. 2: Sample result for capacity enhancement due to various contributing factors by refurbishing underground double circuit ac cable link to operate under dc conditions (Proposed Topology 0) [3].

remains the same. This rule will be used during analysis in this paper.

The refurbishment topology of Fig. 2 shall be referred henceforth as 'proposed topology 0'. Even though clear system capacity gains can be obtained during normal operation, this is not always true from operational point of view. The failure of any one component should still guarantee the same enhancement in capacity. This is not the case in proposed topology 0.

To address this challenge, adequate topology design and reconfiguration strategy should be in place. Modularity and redundancy in system would help, but the trade-offs with costs should be considered. Further, the operational safety should be guaranteed.

C. Research Contributions

Based on an actual distribution network case-study, the following are the research contributions of this paper:

- Four different ac to dc system refurbishment typologies are proposed and their capacity during (n-1) contingency is discussed.
- The concept of reconfigurable switch is developed in order to use the redundant conductor for capacity enhancement during cable faults.
- Bypass strategy for dc to ac operational transition during converter faults is developed.

Section II describes the topology of the existing medium voltage ac distribution system and highlights the problem necessitating capacity enhancement.

Section III presents a simple ac to dc system refurbishment architecture for capacity enhancement (topology 1). Here, it is discussed how system capacity would change to different contingencies such as single line to ground, three core and converter faults.

In Section IV, a novel concept of reconfigurable switch is proposed to impart greater redundancy in the system. Using this concept, topologies 2 and 3 are proposed and similar contingency analysis is carried out. The advantage over topology 1 is highlighted.

Section V discusses a dc to ac hardware reconfiguration strategy by bypassing the faulty converters. It is highlighted how further capacity enhancement can be achieved by choosing this system architecture.

Section VI puts forth an alternate system architecture, making use of the concept of 'shared hybrid breaker'. A discussion on trade-offs between modularity, costs and system efficiency is carried out.

Finally, in Section VII, the conclusions on the main contributions of this paper are presented.

II. System Description

A. Existing Layout

The line diagram for the studied section of a typical dutch distribution network is shown in Fig. 3. The system consists of 3x thre phase medium voltage ac underground cable power transfer links (x1, x2 and x3) between two 10 kV substations (SS1 and SS2).

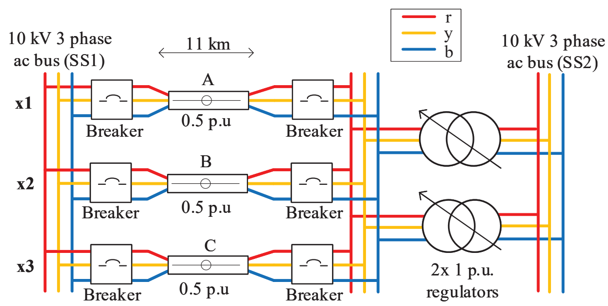

Fig. 3: Original medium voltage ac distribution link between two 10 kV substations (Sample layout of a dutch distribution network provided by Alliander).

Each transfer link x1, x2 and x3 consists of a 3 phase, crosslinked polyethylene (XLPE) 3x1x630 A aluminium cored cable A, B and C respectively. Conductors corresponding to each phase red (r), yellow (y) and blue (b) are colour coded accordingly. This will be helpful when the proposed system refurbishment is explained in subsequent sections.

Since the link length is about 11 km, 2x 1 p.u. voltage regulators are employed at SS2 ac bus. Links x1, x2 and x3 with 0.5 p.u. power transfer MVA capacity each, bring the bulk power to SS2 at the city center. The maximum transfer MVA capacity between SS1 and SS2 is, therefore, 1.5 p.u. during normal operation.

Considering that this is a critical link catering to the energy needs of the entire locality, a certain demand level should be reliably ensured with (n-1) contingency. From Fig. 3, it can be inferred that removal of any one system component due to fault would ensure a MVA power transfer capacity of 1 p.u. For example, if 3-cored 3-phase cable A of link x1 fails, links x2 and x3 can deliver a total of 1 p.u. power from healthy 3 phase cables B and C. Similarly, if one voltage regulator fails, the other can operate at 1 p.u.

B. Operational Demand Profile

Fig. 4. shows the measured maximum and minimum total MVA demand of SS2 for each day of the year 2015 (Day 1 is the 1st of January).

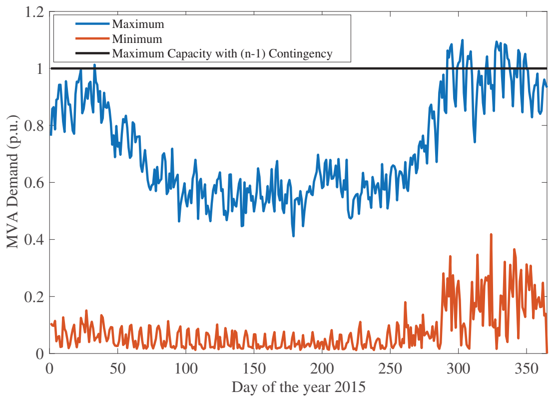

Fig. 4: Maximum and minimum daily MVA Demand from the critical medium voltage link in the year 2015 (data provided by Alliander).

Seasonal variation can be observed with lower MVA demand during summer as compared to winter months. Minimum demand, however, does not show similar seasonal variation. It can be observed that the maximum MVA demand limit of 1 p.u. during (n-1) contingency is breached several times between day 270 and 365 (winter months from October to December).

This situation is unacceptable from reliable power delivery point of view. Therefore, the utility operators were forced to increase the capacity of this system. The projected near future requirement pegged the minimum MVA capacity of 1.5 p.u. during (n-1) contingency.

While the previous paper [3] discusses the possibility of capacity enhancement and highlights the consequences of reusing existing XLPE ac cables with dc voltage, the actual implementation of this concept for system level refurbishment is not so straightforward. Even though a capacity enhancement of at least 50 % is possible during normal operation when the contributing factors are considered, the guaranteed uninterrupted power demand that can be met during (n-1) contingency is relevant. In the subsequent section of this paper, the proposed refurbishment topologies address this issue.

III. Refurbishing double circuit ac to 3x bipolar dc links (Proposed Topology 1)

The most straightforward refurbishment strategy is depicted in Fig. 5. The topology similar to proposed topology 0 in Fig. 2, except that the three conductors on each pole are segregated to form three distinct bipolar dc links. The system is more modular but the trade-off is in cost and space requirements due to larger number of switches.

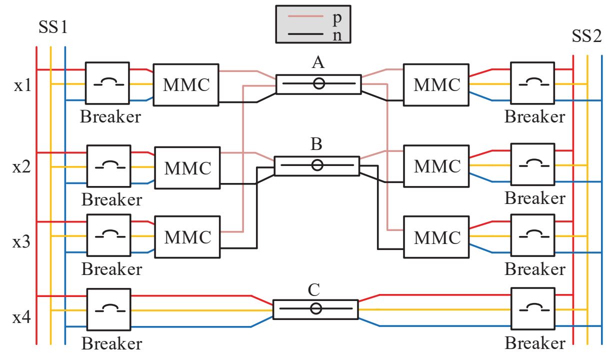

Fig. 5: Schematic for proposed topology 1.

The three conductor cores of cables A and B are refurbished to form 3x bipolar dc links (x1, x2 and x3). Modular multilevel converters (MMC) of 0.5 p.u. capacity are used at both sides of each dc link in order to have higher efficiency and lower harmonics. The breakers on the ac side of the links may need to be redesigned to handle higher short circuit currents. Cable C operates as ac link x4, while the role of the voltage regulator can be carried out by one of the parallel dc link MMC connected to the SS2 ac bus in order to enable power flow through x4.

From the theory offered in [3], it can be quantified that each link (x1 - x4) would have a MVA capacity of 0.5 p.u., giving a system MVA power delivery capacity of 2 p.u. under normal conditions as compared to 1.5 p.u. for original system.

During single line to ground faults in one of the links, or during converter failure, 1.5 p.u. MVA power delivery capacity is achievable with the remaining three healthy links of proposed topology 1. This is a 50 % capacity enhancement during (n - 1) contingency as compared to the original system.

However, considering that 3 cored ac cables were refurbished, during certain contingencies 3 conductors need to be removed from the system. For example, during maintenance activity on conductors of cable associated with link x1, link x3 might need to be detached as it shares a conductor core of cable 'A'. A way around this would be to schedule the maintenance activities during off-peak hours. However, this may not be an acceptable solution for utility operators. Further, in case of 3-conductor fault in any of the cables, the situation of 2 inactive bipolar dc links cannot be avoided. In such cases, the MVA capacity during (n - 1) contingency is 1 p.u., same as the original system, thus offering no improvement.

IV. Reconfigurable switch for redundant conductor utilization

A. Proposed Topology 2

In order to avoid the rare situations leading to no capacity enhancement during (n-1) contingencies, a new topology is proposed, shown in Fig. 6.

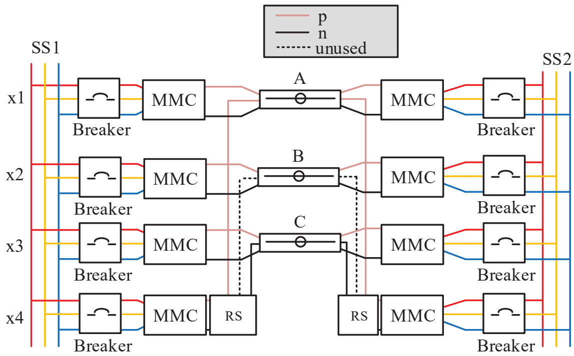

Fig. 6: Schematic for proposed topology 2.

The system is similar to proposed topology 1, with cable C also refurbished to operate under dc. Each link (x1-x4) has a MVA power transfer capacity of 0.5 p.u. during normal conditions.

Out of the 9 original conductors, one is unused and is connected to reconfigurable switch block RS. The schematic of RS is shown in Fig. 7.

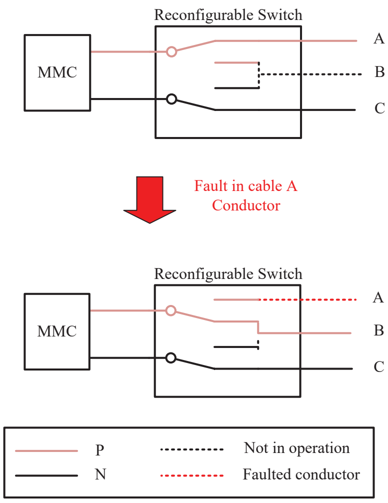

Fig. 7: Structure of an offline reconfigurable switch (RS).

For proposed topology 2, when all three conductors of cable A are nonoperational, the ac side breaker disconnects links x1 and x4. The RS switch reconfigures the connection such that the unused conductor from cable B becomes the positive pole for link x4. The system capacity during (n-1) contingency is enhanced by 50 %, to 1.5 p.u. The proposed reconfiguration is carried out offline so that the contacts of the RS switch do not have to make or break the dc fault current. For online reconfiguration, either a dc breaker or a solid state switch would be needed, adding to the cost and losses of the system.

B. Proposed Refurbished DC Topology 3

Extending the previous topology, the offline reconfigurable switch can be used in each of the dc link (x1-x4), while sharing the same unused conductor from cable ‘B’ as shown in Fig. 8.

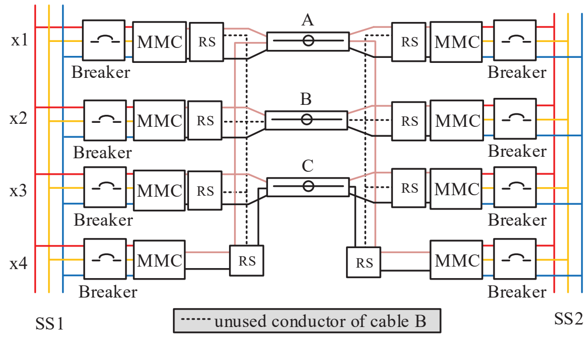

Fig. 8: Schematic for proposed topology 3.

The advantage of this topology is that during single conductor to ground faults, the MVA capacity of the system is 2 p.u. (a 100 % increase over the original system capacity during n-1 contingency). Since single conductor to ground are the most common type of faults, this solution could be attractive, particularly in the offline case where cost of the proposed reconfigurable switch is negligible.

The thermal stresses imposed on the conductors of the healthy links due to temporary overloading immediately after the ac breaker operation is an important consideration in deciding the acceptable time available for switching operations to restore the reconfigured system. The thermal inertia provides few minutes of overloading capacity without breaching the temperature limit [13]. Further, it is possible to operate the cable above its rated current capacity for a short duration. A novel idea looks into dynamic dc link voltage enhancement for temporarily increasing the capacity of healthy links [2]. However, the available time for reconfiguring the system must be ascertained if downtime for the system is to be minimized.

V. DC To AC Hardware Reconfiguration (Proposed Topology 4)

During converter fault at any of the links, the capacity of topology 3 would be 1.5 p.u. (a 50 % enhancement). This is good, but another strategy can be applied to further modify the system topology by bypassing the converters. The dc to ac hardware reconfiguration strategy for bypassing the faulty converter is shown in Fig. 9.

In this scheme, the dc path for links x1 - x4 are similar to topology 3. All three cables (A, B and C) are connected to the ac bus of the substations SS1 and SS2, forming a redundant three phase ac path x5, shared by links x1-x4. Two extra normally open ac breakers are needed at the sending and receiving end of the system. Additionally, three phase normally open isolators (offline connectors) are needed at both sides of each dc link (I12-I41) and (I12-I42) respectively.

In case of a converter fault in link x1 the following sequential reconfiguration steps are to be followed:

1) Fault cleared through ac side breakers of link x1.
2) ac side breaker of x4 is opened.

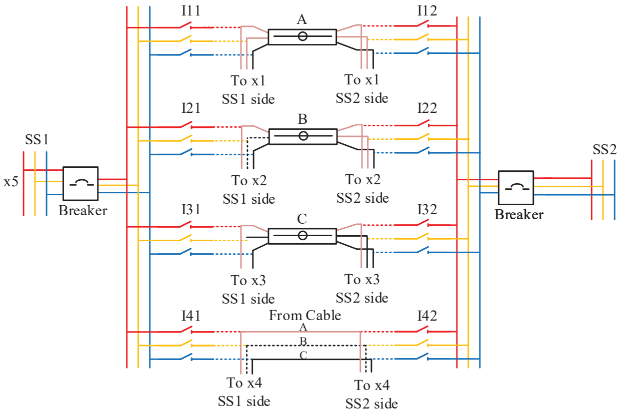

Fig. 9: Schematic for dc to ac hardware reconfiguration (Topology 4).

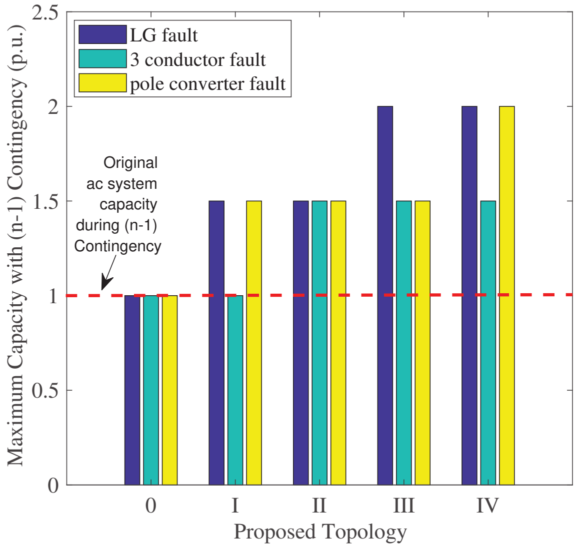

Fig. 10: Summary of maximum capacity with (n-1) contingency.

3) Reconfigurable switch connects unused conductor of cable B as positive pole of link x4 instead of cable A conductor.
4) Isolators I11 and I22 are closed while x5 is still inactive.
5) ac breakers for x4 and x5 are closed.

After this system hardware reconfiguration, the links x2, x3 and x4 of the reconfigured system operate under dc, while x5 works as a three phase ac link using the conductors of cable A. In this way, the system MVA capacity during converter faults is improved to 2 p.u. (a 100 % increase over the original system) by using this strategy. One of the remaining healthy converters connected to SS2 can be assigned the role to regulate the voltage at ac bus to ensure power transfer through ac link x5. Once the faulty converter is replaced by a healthy one, the system can revert back to topology 3 sequentially.

Note that this dc to ac reconfiguration would not be possible without the RS block in each of the refurbished dc link (x1-x4). Further, it is reiterated that offline reconfiguration strategy is considered keeping in mind the cost and efficiency trade-off with allowable downtime in the system. The summary of system capacity for different (n-1) contingencies is shown in Fig. 10 for each proposed topology.

Topology 0 does not offer any capacity enhancement during (n-1) contingency as compared to the original system assuming that monopolar system with ground return is not allowed during faulted condition. Topology 1 offers 50 % capacity enhancement, but is unfavourable if 3-cored cables are refurbished. Using strategies such as reconfigurable switch in topology 2 and 3 and dc to ac hardware reconfiguration for faulty converter bypass in topology 4, as much as 100 % capacity gains can be achieved over the original system.

VI. Alternate Strategy with Shared Parallel Path Hybrid DC Breaker

A major drawback of choosing topologies 1-4 over topology 0 is the cost of sending and receiving end converters. Using multiple converter links achieves greater modularity, but since the cost of solid state switches is more dependent on blocking voltage than capacity, using 3 to 4 times the number of switches would incur proportionally high costs. On hindsight therefore, such a strategy might be undesirable from economic point of view.

With use of modular multilevel converters, enough modularity can be achieved for submodule level contingencies. Together with dc to ac reconfiguration by converter bypass, topology 0 could guarantee at least 1.5 p.u. capacity during converter faults. However, one of the issues with topology 0 proposed in Fig. 2 is that a single conductor to ground fault would lead to the disconnection of 3 conductors of a dc pole from the ac side circuit breaker. This leads to no capacity enhancement over the original system.

One of the ways is to employ dc breakers at each of the interconnected conductors of the dc pole so that the faulty conductor could be isolated. With use of hybrid breaker, conduction losses during normal operation can be avoided [14]. This is because the semiconductors in conduction path only need to develop a voltage enough to commute the conductor fault current to the main solid state breaker path (which have normally zero current) and then the line is opened using mechanical disconnector.

Nevertheless, even if the on-state conduction losses are just 1 % of the transmitted power, the cost of the breaker is high [15]. An interesting possibility is to share the main solid state breaker (MSSB) among the three interconnected conductors of the dc poles as shown in Fig. 11. This strategy is based on the idea proposed in [16].

Here the low cost, low loss current commutation devices (CCD) are installed at each of the conductors, that share a common MSSB and an energy absorption path (EAP). Reverse blocking (RB) is required to prevent healthy conductors from shorting through the common MCCB connection during ground faults.

Even though a discussion on operating principles of this strategy is beyond the scope of this paper, from contingency

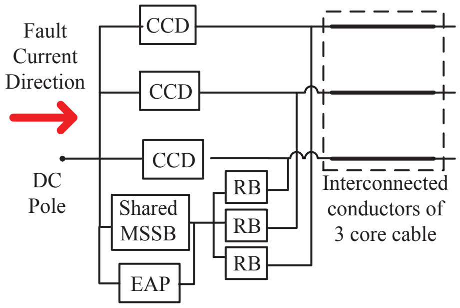

Fig. 11: Alternative topology with hybrid dc breaker sharing common parallel paths.

point of view, it can be inferred that the ability to isolate single conductor to ground fault could boost the capacity of this system to 1.5 p.u. Reconfiguration strategy similar to the ones proposed in topology 3 and 4 could further enhance the capacity.

From economic point of view, the shared MCCB strategy would have lower cost than having a dc breaker at each conductor. However, this strategy has a trade-off against proposed topology 1-4, in terms of cost and lower operating efficiency due to losses in CCD.

VII. Conclusion

It was highlighted that even though a capacity enhancement of 50 % is achievable during normal operating by refurbishing underground ac cable infrastructure to operate under dc conditions, the system design is challenging, particularly to guarantee a similar enhancement during (n-1) contingencies.

Five different typologies of increasing complexities were proposed to enhance the system capacity during (n-1) contingency by upto 100 % as compared to the original ac system. It is recommended to refurbish the system systematically from topology 1 to topology 4 in a step-wise fashion.

A novel integration of offline reconfigurable switch resulted in greater use of infrastructure and a significant capacity enhancement during single line to ground faults.

The system architecture is designed with ability to bypass the dc link converters during faults so that the faulty dc link can be reconfigured to operate as three phase ac link. This boosted the contingent system capacity to 2 p.u. (a 100 % gain).

An alternate architecture was discussed based on shared hybrid dc breaker that minimized the breaker costs. This strategy has lower cost than installing dc breaker for each conductor. However, it is costlier and less efficient than the offline reconfigurable architectures.

Future work involves a study on economic viability of the suggested schemes. The space required to install the components is an important consideration. The time needed in implementing all the reconfiguration switching actions is also a relevant consideration. Consequently, the thermal stresses on the remaining healthy cables during a temporary overload immediately after the fault must be taken into account.

Acknowledgements

The authors would like to acknowledge the help from Teunis Brand, Frans Provoost and Pieter Kropman from Alliander as part of the FLINK Consortium.

References

[1] Sacha Silvester, Satish Kumar Beella, Arjan van Timmeren, Pavol Bauer, Jaco Quist, Stephan van Dijk, "Exploring design scenarios for large-scale implementation of electric vehicles; the Amsterdam Airport Schiphol case," Journal of Cleaner Production, June 2013, Pages 211-219.

[2] 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.

[3] Aditya Shekhar, Epameinondas Kontos, Laura Ramírez-Elizondo, Armando Rodrigo-Mor, Pavol Bauer, "Grid capacity and efficiency enhancement by operating medium voltage AC cables as DC links with modular multilevel converters," In *International Journal of Electrical Power & Energy Systems,* Volume 93, 2017, Pages 479-493.

[4] Aditya Shekhar, Laura Ramírez-Elizondo, Xianyong Feng, Epameinondas Kontos, Pavol Bauer, "Reconfigurable DC Links for Restructuring Existing Medium Voltage AC Distribution Grids," *Electric Power Components and Systems.*

[5] C. Vivekananthan, Y. Mishra, G. Ledwich and F. Li, "Demand Response for Residential Appliances via Customer Reward Scheme," in IEEE Transactions on Smart Grid, vol. 5, no. 2, pp. 809-820, March 2014.

[6] Xianyong Feng, Aditya Shekhar, Fang Yang, Robert Hebner, and Pavol Bauer "Comparison of Hierarchical Control and Distributed Control for Microgrid," Electric Power Components and Systems, 2017.

[7] A. S. A. Awad, T. H. M. EL-Fouly and M. M. A. Salama, "Optimal ESS Allocation and Load Shedding for Improving Distribution System Reliability," in IEEE Transactions on Smart Grid, vol. 5, no. 5, pp. 2339-2349, Sept. 2014.

[8] S. Abdelwahid, A. Babiker, A. Eltom and G. Kobet, "Hardware Implementation of an Automatic Adaptive Centralized Underfrequency Load Shedding Scheme," in IEEE Transactions on Power Delivery, vol. 29, no. 6, pp. 2664-2673, Dec. 2014.

[9] D. Marene Larruskain, Inmaculada Zamora, Oihane Abarrategui, Zaloa Aginako, Conversion of AC distribution lines into DC lines to upgrade transmission capacity, Electric Power Systems Research, Volume 81, Issue 7, July 2011.

[10] D. Marene Larruskain, Inmaculada Zamora, Oihane Abarrategui, Araitz Iturregi, VSC-HVDC configurations for converting AC distribution lines into DC lines, International Journal of Electrical Power Energy Systems, Volume 54, January 2014.

[11] 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.

[12] Shekhar, A.; Feng, X.; Gattozzi, A.; Hebner, R.; Wardell, D.R.; Strank, S.; Rodrigo-Mor, A.; Ramirez-Elizondo, L.M.; Bauer, P. "Impact of DC Voltage Enhancement on Partial Discharges in Medium Voltage Cables - An Empirical Study with Defects at Semicon-Dielectric Interface," Preprints 2017, 2017100009 (doi: 10.20944/preprints201710.0009.v1).

[13] Shekhar, A.; Feng, X.; Hebner, R.; Gattozzi, A.; Strank, S.; Rodrigo-Mor, A.; Ramirez-Elizondo, L.M.; Bauer, P. "Thermal Modelling and Experimental Validation for Research on Medium Voltage DC Cables," in *IEEE PES General Meeting,* Chicago, 2017.

[14] Magnus Callavik, Anders Blomberg, Jrgen Hfner, Bjrn Jacobson; "The Hybrid HVDC Breaker: An innovation breakthrough enabling reliable HVDC grids ," *ABB White Paper,* Nov 2012.

[15] M. K. Bucher, M. M. Walter, M. Pfeiffer and C. M. Franck,"Options for ground fault clearance in HVDC offshore networks," 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, 2012, pp. 2880-2887. doi: 10.1109/ECCE.2012.6342371

[16] E. Kontos, T. Schultz, L. Mackay, L. Ramirez-Elizondo, C. M. Franck and P. Bauer, "Multi-Line Breaker for HVDC Applications," in *IEEE Transactions on Power Delivery,* vol. PP, no. 99, pp. 1-1. doi: 10.1109/TPWRD.2017.2754649