Reliability, Efficiency and Cost Trade-offs for Medium Voltage Distribution Network Expansion using Refurbished AC-DC Reconfigurable Links

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Reliability, Efficiency and Cost Trade-offs for Medium Voltage Distribution Network Expansion using Refurbished AC-DC Reconfigurable Links

Aditya Shekhar, Laura Ramírez-Elizondo and Pavol Bauer

***Abstract*—The role of MVDC links for distribution network expansion is important. The distribution network operators (DNOs) can maximize the power transfer capacity of existing grid infrastructure during (n-1) contingencies using reconfigurable parallel ac-dc architecture. In addition this concept involves a range of efficiency, reliability and economic trade-offs. The object of this paper is to present a discussion on the emerging choices involved in adopting a parallel ac-dc reconfigurable link architecture in designing future and flexible power grids.**

***Index Terms*—dc links, distribution networks, grid expansion, flexible, medium voltage, MVDC, parallel ac-dc, power router, reconfiguration, reconfigurable, refurbishing**

I. Introduction

A. MVDC in Distribution Network Expansion

The generation and loading patterns in the medium voltage girds are creating local pockets of excess or deficit energy. The distribution network operators (DNOs) are looking to maximize the capacity of their ageing infrastructure in meeting the emerging requirements.

Our project explores the potential of flexible dc links in restructuring existing medium voltage ac grids [1]. The increasing focus of dc in medium voltage distribution is evident in recent projects across the world [1]–[6]. For example, a Whitepaper by Siemens [7] presents their interest in adopting dc based technologies for designing future and flexible distribution grids.

B. Background

Medium voltage distribution systems are usually dominated by relatively short distance power transfer at 10-66 kV ac [1]. The role of dc is important in capacity enhancement of refurbishing existing grid infrastructure [8]. It was shown in [9] that every two cable conductors under dc operation can approximately deliver power equivalent to three conductors under ac with the same cross-sectional area, giving a dc capacity enhancement factor of 1.5. The key assumption contributing to this number is the operating voltage ensuring similar or better insulation performance of the system over its lifetime. Some empirical evidence for supporting an assumption of operating dc voltage rating equal to peak of the rated cable ac voltage is offered in [10]. In [11] however, it was shown that this enhancement factor is achievable only under normal operating conditions. During (n-1) contingencies, some reconfiguration techniques maybe necessary to maintain the enhanced capacity of the refurbished dc system. Different system architectures and the corresponding capacity with contingency analysis is presented in [11].

C. Structure of this paper

Section II describes the system studied in this paper. The importance of understanding the various reliability, efficiency and cost trade-offs in influencing the available choices is highlighted. In Section III, the link conductor trade-offs are discussed based on whether the system conductors are overhead lines or underground cables, 3-cored or 1-core and number of link conductors available for operation. In Section IV, different configuration cases are explored in terms of reconfigurability in maintaining high capacity during (n-1) contingency. Trade-offs between conductor utilization, converter rating and number of necessary reconfigurations are inferred. Further, the benefits of parallel ac-dc operation are explored in an attempt to understand the factors governing which system configuration is optimal based on operational complexity, efficiency and cost. In Section V, choices related to minimizing substation converter power rating, system architecture and topology are highlighted. In Section VI, the main conclusions of the paper are revisited.

II. System Description

The main design goal is to enhance the power transfer capacity of the distribution grid during different (n-1) contingencies. The original system consists of 'N_{ori}' conductors forming a medium voltage ac link between two substations as shown in Fig. 1. Considering that its a 3-phase system, n_{ori} is a multiple of three.

In this system, the receiving-end substation (RSS) supplies high power to an urban locality which is expected to experience a steep increase in demand. Consequently, the conductors linking it to the sending-end substation(SSS) are overloaded and an adequate capacity up-gradation is necessary. In [8], it was proposed that refurbished operation of these conductors under dc could possibly increase the power transfer capacity. In [9], it was mathematically proved in a comprehensive analysis that refurbished dc operation could enhance the power

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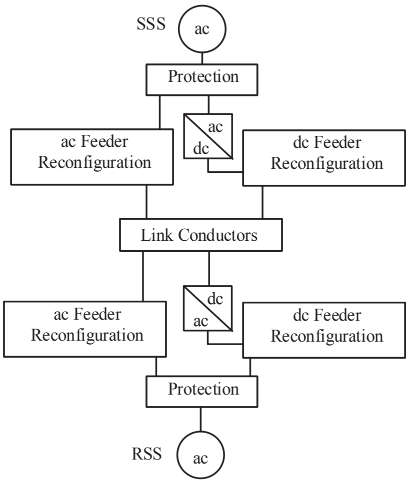

Fig. 1: Parallel ac-dc reconfigurable link architecture.

transfer capacity to atleast 1.5 p.u. as against 1 p.u. for the original system.

Even though the physical capacity of the link conductors increases under dc operation, it was shown in [11] that during (n-1) contingencies, this is not necessarily true. Adequate reconfiguration strategies were developed that could maintain the power transfer capacity enhancement at 1.5 p.u and even improve it to 2 p.u. under certain circumstances.

Blocks such as protection, ac/dc converters, ac-dc feeder reconfiguration switches and conductors for power transfer link are shown. Different choices for essential components of each block results in different implications for the reliability, efficiency and cost of the distribution system. A detailed discussion on these choices is the object of this paper.

The goal of power transfer capacity up-gradation can be achieved in several ways. Choice of components in the refurbished system and the reconfiguration strategies employed influence the operational efficiency, reliability and incurred capital cost for achieving this goal. Therefore, it is important to know the possible choices and the inevitable trade-offs that accompany these choices.

III. Link Conductor Trade-offs

The SSS and RSS may be connected using overhead lines or underground cables with three cored or single cored conductors. Furthermore, multiple link conductors maybe available for power transfer. This section discusses the corresponding influence of link conductors on the choices and trade-offs pertaining to the system operation.

A. Overhead and Underground Conductors

In case of overhead lines, economics of compact power transmission plays a role in choosing dc distribution links [3]. For underground cables, avoiding digging and installation of new insulated conductors could be an important consideration [1]. The dc voltage enhancement factor is more liberally chosen in case of overhead lines leading to 2-3 times increase in capacity, even though some modifications in the towers and supporting structure maybe necessary [12]. A comparison on the solutions for capacity enhancement with overhead lines is illustrated in [13]. Even though we have conservatively considered dc capacity enhancement factor at 1.5 in our work [9], primarily based on the empirical evidence of cable insulation performance under ac and dc conditions [10], other studies consider higher capacity gains for underground cables [14]. The reasoning behind this anticipation is, possibly, lower partial discharges under dc operation as compared to ac for the same cable insulation [15]. It is important to note that it is difficult to estimate the accurate dc voltage enhancement factor ensuring safe operation without detrimental effect to insulation lifetime. Therefore, it is discouraged to implement an one step increase in operating dc voltage and a gradual increase in system capacity is recommended [16].

The role of space charges becomes important in case of dc operation of cables [17]–[21]. It is known that space charge accumulation can result in local electric field enhancement and even inversion within the insulation. On the contrary, space charges may also reduce the imposed electric field at some locations. Based on qualitative understanding, the detrimental effect on insulation lifetime in case of frequent and sudden polarity reversal may encourage minimization of dc to ac reconfiguration during (n-1) contingencies. However, many aspects need further investigation, such as: (i) magnitude of accumulated space charges at medium voltage levels (translated to imposed electric fields on the insulation) [22] (ii) time and temperature dependence of space charges when dc voltage is imposed or removed [23] (iii) insulation performance under the expected space charge accumulation at different locations in cable insulation system over its entire operational lifetime [10] (iv) understanding of impact on insulation with dc to ac reconfiguration based on a) reconfiguration frequency b) timelag after each such reconfiguration. On one hand it is difficult to measure the accumulated space charges during on-site operation; On the other, it is even harder to quantify their precise effects on the insulation lifetime. Such performance indicators are further complicated when different insulation systems (example: XLPE, EPR) are compared [24]. Keeping these considerations in mind, incrementally gathering operational knowhow as recommended in [16] is particularly important.

B. 3-cored or 1-cored Cables

3-cored cables are vulnerable to 3-conductor to ground faults. Since the refurbished dc system uses two conductors per link, four conductors of two dc links could go out of service if 3-core fault occurs in the system [11]. Not only this, even a single conductor to ground fault could result in the removal of all three cores during maintenance activity. With single core cables, only the dc link corresponding to the faulty conductor fails. Correspondingly, it is easier to maintain the (n-1) contingency capacity of the system with 1-core cables as compared to 3-cored cables.

C. Number of Conductors

The number of conductors in the original ac system (N_{ori}) available for refurbishment is an important consideration for the network upgradation goals. The ac and dc feeder reconfiguration blocks shown in Fig. 1 consists of isolating switches that connect the link conductors to the ac and dc substation buses respectively. These switches can either be normally open or normally closed, resulting in different number of operational ac conductors (N_{ac}) and dc conductors (N_{dc}). Consequently, the position of feeder switches physically govern the ratio of ac and dc power flow capacity between the two substations. Based on a certain N_{ori}, the number of conductors operating under ac (N_{ac}), dc (N_{dc}) and redundant (N_{red}) condition can have different combinations. Each consideration results in its own opportunity and associated challenges. Let the maximum achievable (n-1) criterion driven capacity enhancement factor be CEF_3 for system with 3-cored and CEF_1 for system with single-cored conductor. A summary of possibilities resulting with different N_{ori} is listed in Table I.

TABLE I: Impact of number of conductors of original system on the maximum achievable capacity enhancement

N_{ori}	N_{ac}	N_{dc}	N_{red}	CEF_3	CEF_1
3	0	2	1	0	50 %
6	0	6	0	0	50 %
6	3	2	1	0	50 %
9	0	8	1	50 %	100 %
9	3	6	0	0/50 %	50/100 %
9	6	2	1	0/50 %	50/100 %

If the original ac distribution system with $N_{\text{ori}} = 3$ conductors is refurbished to operate as dc link with $N_{\text{dc}} = 2$ and one redundant conductor, no capacity enhancement is possible during (n-1) contingency if the link conductors are 3-cored. This is because all three conductors must be removed even during single line to ground fault. One the other hand, with single-cored cables, a 50 % capacity enhancement is possible (i.e. a factor of 1.5) because the redundant conductor can be reconfigured to replace the faulty one. Similar concept can be used to deduce the CEF_3 and CEF_1 for $N_{\text{ori}} = 6$ and $N_{\text{ori}} = 9$. In order to maintain the system capacity, ac to dc or dc to ac conductor reconfigurations may also be necessary, as discussed in the subsequent section.

IV. Operational Trade-offs

In this section, the example of $N_{\text{ori}} = 9$ is used to describe the various choices available. Similar principles can be applied when the SSS and RSS are connected using different number of link conductors. The available choices result in N_{ac} as a multiple of 3 (due to 3-phase ac) and N_{dc} as an even number (2 conductors per dc link) with the sum $N_{\text{ac}} + N_{\text{dc}} \leq N_{\text{ori}}$. For example, for $N_{\text{ori}} = 9$, four combinations are possible: (i) $N_{\text{ac}} = 9$, $N_{\text{dc}} = 0$ (Case A), (ii) $N_{\text{ac}} = 6$, $N_{\text{dc}} = 2$ (Case B) (iii) $N_{\text{ac}} = 3$, $N_{\text{dc}} = 6$ (Case C) and (iv) $N_{\text{ac}} = 0$, $N_{\text{dc}} = 8$ (Case D).

The system architecture and feeder switch connections for SSS in case of Case C is shown in Fig. 2. The same system can be connected for other configuration cases by changing the state of switches shown in ac and dc reconfiguration feeders.

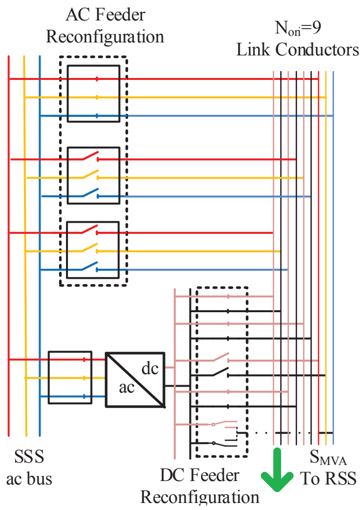

Fig. 2: SSS connected for Case C.

A. Reconfiguration Strategies

Fig. 3 shows the conductor status and system capacity with different configurations during normal operation as well as a single conductor to ground fault. Conductors operating under ac conditions are depicted in blue, dc conditions in green and faulty/removed conductors in red. Those that are healthy but redundant are depicted in white.

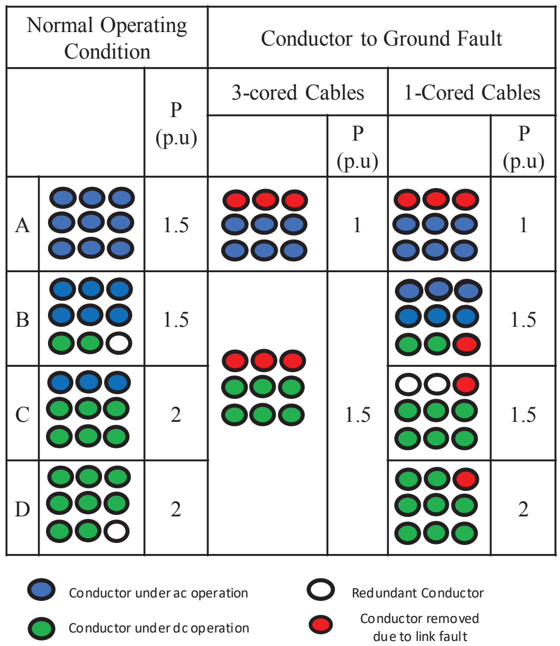

Fig. 3: Configurations of $N_{\text{ori}} = 9$ link conductors during normal and single conductor to ground faults with ac (blue), dc (green), redundant (white) and faulty (red) conductor states.

For any system configuration, every 2x dc conductors (green) have 0.5 p.u power transfer capacity, equivalent to 3x ac conductors (blue) corresponding to a dc enhancement factor of 1.5 as proved in [9].

Case A depicts the original system, wherein, 9x ac conductors (blue) have a total capacity of 1.5 pu under normal operating conditions. With a single conductor to ground fault, one ac link with 3x conductors (red) is isolated from the system. This leads to a (n-1) contingency capacity of 1 p.u. with remaining 6x healthy ac conductors (blue) for both 3-cored and 1-cored cables. In the subsequent discussions, Case A will be considered as the baseline system.

In Case B, 6x ac conductors (blue) and 2x dc conductors (green) operate with a total 1.5 p.u. capacity under normal operating conditions. There is one redundant conductor (white) in the system during normal operation. During single conductor to ground fault, the system retains its enhanced power transfer capacity of 1.5 p.u as compared to baseline Case A using reconfigurations described as followed:

1) 3-cored Cable in Case B: If the fault occurs in one of the ac conductors, 3x conductors of the corresponding ac link are removed (red). 3x ac to dc conductor reconfigurations and 1x redundant to dc reconfigurations are required to achieve the maximum capacity of 1.5 p.u. If the fault occurs in one of the dc conductors, 6x ac to dc reconfigurations are needed. Therefore, with both ac and dc faults, the reconfigured system operates with 6x dc conductors (green), thus requiring a minimum converter rating of 1.5 p.u per substation.

2) 1-cored Cable in Case B: The faulty conductor has to be isolated from the system and replaced by the healthy redundant conductor during either of ac or dc single conductor to ground fault. The system requires neither ac to dc nor dc to ac reconfiguration. Minimum converter rating of 0.5 p.u is required for the system.

Case C shows the conductor configuration when the same system is operated with 3x ac conductors and 6x dc conductors with a maximum capacity of 2 p.u during normal operation. During single conductor to ground fault, the system maintains an enhanced power transfer capacity of 1.5 p.u as compared to baseline Case A using reconfigurations described as followed:

3) 3-cored Cable in Case C: In either of ac or dc conductor fault, the system must be reconfigured to operate with 6x dc conductors. If the fault is in the ac link, all three conductors must be isolated. If the fault is in one of the dc link conductors, 3x cores of the faulty cable must be removed and 3x ac conductors should be reconfigured for dc operation. The substation converter should be rated to deliver at least 1.5 p.u.

4) 1-core cable in Case C: If a minimum converter rating of 1.5 p.u is available per substation, it is possible to isolate the entire link associated with either ac or dc faulty conductor. As an example, in case the fault is in one of the ac link conductors, the system is reconfigured to operate with 2x redundant (white), 1x removed (red) and 6x dc (green) conductors as shown in the Fig. 3. Similarly, it is possible to operate the system with 1x redundant, 1x removed, 4x dc and 3x ac conductors in case the fault is in one of the dc link conductors. This is not shown in the system, but can easily be deduced. On the other hand, with a reduced converter rating of 1 p.u per substation, the system can still maintain 1.5 p.u capacity during the fault with a trade-off for more number of reconfigurable switching actions.

Case D shows the situation where eight conductors are used to form 4x dc links with a total capacity of 2 p.u during normal operation. There is one redundant conductor in the system.

5) 3-cored Cable in Case D: During conductor to ground faults, 3-cores of the faulty cable must be removed, The redundant conductor must be connected to the system to form a total of 6x healthy dc conductors with a capacity of 1.5 p.u. Therefore, the minimum converter rating is 1.5 p.u.

6) 1-core Cable in Case D: When a conductor to ground fault occurs, the faulty conductor can be replaced with the redundant conductor to maintain the 2 p.u capacity with equivalent converter rating available per substation as shown in Fig. 3. With a lower converter rating of 1.5 p.u, the system can be reconfigured to operate with 2x redundant, 1x removed and 6x dc conductors. This is not shown in the figure but can easily be deduced.

Two important conclusions emerge from above discussion: i) Under normal operating conditions, different combinations of ac, dc and redundant conductors can deliver the required power demand at RSS. This will be explored more in Section IV-B. (ii) For each configuration, there is a trade-off between substation converter rating and number of reconfiguration switch actions. This will be explored more in Section V-A.

B. Parallel AC-DC Operation

The goal of this section is to highlight the possible trade-offs in choosing between Cases A-D during normal operation assuming that 1.5 p.u capacity can be ensured during (n-1) contingencies. It is possible to achieve this capacity in baseline Case A only by installing three additional conductors, increasing the total number of available link conductors to $N_{\text{ori}} + 3 = 12$. For cases B, C and D, the capacity of 1.5 p.u can be maintained with $N_{\text{ori}} = 9$ using various reconfiguration techniques mentioned in Section IV-A. The question arises: which is the best system configuration among the various cases under normal operation?

On one hand, different N_{ac}, N_{dc} and N_{red} influences the conduction losses in the link conductors because (i) The conductor utilization is different, with 12 operational conductors under Case A, 9 in Case C and 8 in Case B and D. (ii) dc link conductor losses are lower than ac mainly due to higher dc operating voltage imposed on the cable. On the other hand, the converter losses vary for each configuration due to different ratio of dc and ac power flow in the system to deliver the required demand at RSS. Consequently, the system efficiency vary with link length, ac-dc power share and the power factor at RSS as derived in [25]. The findings in [25] suggest that parallel ac-dc operation such as Case C may offer some efficiency benefits as compared to fully ac or dc operation within the defined boundary of operation.

The added investment on the requirement of substation converters in Cases B, C and D must be compared against that of laying additional cables for capacity enhancement in Case A. Considering the efficiency enhancement, the payback time must be considered. Further, the possibility of power derating of the converter as a trade-off for greater number of reconfigurable switching actions is an important consideration which is explored in Section V-A.

Finally, the consequences of the necessary reconfiguration strategies during (n-1) contingencies on the system reliability and availability must be considered. For example, increasing the number of reconfigurations may increase the operational complexity and impact the reconfiguration time. Furthermore, dc to ac reconfigurations may cause undesirable stresses on the cable due to space charges as cautioned in III-A.

V. Link Converter Trade-offs

A. Power Rating

The substation converters must be rated according to the maximum demand that they are expected to deliver during normal operation as well as (n-1) contingencies. This value can differ based on the operational mode selected such as parallel ac-dc operation and the reconfiguration strategy employed when a fault occurs. The advantage of de-rating is reduced investment for the same capacity enhancement. Converter derating is possible when the system employs 1-cored cables may result in increase in number of reconfigurations to maintain the required capacity post-fault as described in Section IV-A. Table II summarizes an example of variation in reconfigurable switching operation with converter rating for ac and dc faults with different configuration cases (B, C and D).

TABLE II: Number of reconfiguration switching operations for maintaining 1.5 p.u capacity during single conductor to ground (CG) fault for 1-core cable based system with different configuration cases for varying substation converter ratings.

Configuration	Fault	Substation Converter Rating		
		0.5 p.u.	1 p.u.	1.5 p.u.
Case B	ac CG	2	2	2
	dc CG	2	2	2
Case C	ac CG	-	4	3
	dc CG	-	2	2
Case D	ac CG	-	-	-
	dc CG	-	-	2

In this analysis, whenever a conductor is reconfigured from either ac to dc or dc to ac operation, two offline switching actions are necessary. On the other hand, removing the faulty conductor or connecting the redundant conductor requires a single switching operation.

As explained in Section IV-A4, if a ac conductor to ground fault occurs for Case C with 1.5 p.u converter per substation, three ac conductors have to be removed from the system to maintain the system capacity when the operation resumes, leading to a total of three offline switching actions. On the other hand, if the converter is derated to 1 p.u, one faulty ac and one healthy dc conductor must be removed, while one healthy dc conductor must to be reconfigured to operate under ac condition. As a result, four offline switching actions are required to maintain the capacity when the operation resumes. Further derating the converter rating to 0.5 p.u is not possible for Case C, as this particular configuration cannot maintain 1.5 p.u system capacity during normal operating with the corresponding converter. Hence, the number of reconfigurations is highlighted in Table II with (-) for this unacceptable operating condition. Similarly, the number of reconfigurations can be calculated for other cases and faults.

B. Substation Converter Architecture

Once the rating of the converter is decided, it is necessary to chose whether modularity is required at substation converter level. A single, fully rated ac/dc converter between the ac and dc buses in the substation shown in Fig. 1 and Fig. 2 can meet the power needs during normal conditions as well as link conductor faults. The system can maintain enhanced power delivery capacity if this converter fails, however, all the dc conductors must be reconfigured for ac operation. In such a case, all switches in the dc feeder reconfiguration block of Fig. 2 are opened and those in ac feeder reconfiguration block are closed.

With selection of multiple converters between the substation ac and common dc bus, the dc to ac link conductor reconfiguration requirements can be minimized or even eliminated in case of converter faults. However, the investment cost as well as space requirements in the substation may increase.

Another possibility is to have a dedicated converter for every dc link operating in the system. With such an architecture, as described in [11], each converter must have an individual ac bypass switches if reconfigurability to ac is required. The advantage of this method is that each dc link can individually be protected using dedicated ac side circuit breaker.

C. Number of Levels

The link converters are expected to operate at a medium dc link voltage above 10 kV at a power rating of 10-50 MVA. In this range voltage sourced converters (VSC) with more than two levels are appropriate. Topologies such as neutral point clamped (NPC-VSC) have acceptable performance upto three to five levels [26]. Further, with superior harmonic performance and higher efficiency due to reduced switching, modular multilevel converters (MMC) can be an interesting solution [27]–[30]. Most importantly, the possibility of modular operation with ability to bypass one or more faulty submodules without rendering the entire converter inoperative is particularly advantageous. The optimal design of the required medium voltage dc link MMC considering number of levels, switch rating, redundancy, efficiency, submodule capacitance and investment costs is discussed in [28].

D. Operational Opportunities

The optimal value of ac-dc link load share for maximizing system efficiency is dependent on operating conditions and can be actively controlled using the dc link converters. Therefore, a dynamic power steering in Case B and C depending on RSS demand and power factor can be beneficial. A competing objective of active power steering in the parallel ac-dc link system could be to decrease the thermal cycling at the junction of the dc link converter switches to improve the reliability of power electronic components [31], [32]. However, increasing or decreasing the ac link power share in order to minimize the dc link converter thermal cycling can move the system away from the optimal efficiency point.

With dc operation, the system efficiency and capacity can further be enhanced by dynamically enhancing the dc cable voltage as suggested in [9]. In order to achieve this without increasing the MMC submodule component voltage rating, an interesting solution is proposed in [33]. In this method, the average arm energy is controlled while enhancing the dc link voltage taking advantage of the sum capacitor voltage ripple.

VI. Conclusion

It was discussed that a parallel ac-dc link architecture could provide opportunities for improving the capacity, efficiency, reliability and availability of medium voltage distribution grids. It is more favourable to enhance the system capacity with dc operation if the link conductors are single-cored as compared to 3-cored. As number of link conductors increase, different combinations of ac-dc configurations can be used. Different reconfigurable techniques for maximizing the flexibility of the system to (n-1) contingencies are explored. It is shown that minimum dc link converter rating can be achieved using Case B (half as compared to Case C and one third of Case D) for the same (n-1) system capacity, but it was emphasized that efficiency boundaries can be different.

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