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Offline Reconfigurability based Substation Converter Sizing for Hybrid AC-DC Distribution Links

Aditya Shekhar, Thiago Batista Soeiro, Laura Ramírez-Elizondo and Pavol Bauer

Abstract—Hybrid ac-dc distribution systems with multiple parallel operating ac and dc links are being developed to maximize system capacity during (n-1) contingencies. This paper shows that offline reconfigurability between such ac and dc links post-fault clearance allows an additional design flexibility of reducing the required substation converter rating to maintain the same required capacity by maximizing the utilization of healthy infrastructure. The associated variation of system capacity with power rating and number of substation converters is determined for different types of component faults. It is discussed that while converter downsizing is possible, as a consequence the parallel ac-dc link system is forced to operate at a sub-optimal efficiency during normal conditions. Using case-studies, the economics of this trade-off is quantified for determining the optimal de-rating factor for varying grid voltage, link length and conductor area.

Index Terms—capacity enhancement, dc links, distribution network, efficiency, expansion, flexible, medium voltage, reconfiguration, reinforcement, reliability.

NOMENCLATURE

A_{con}	Cross-sectional area of a single link conductor.
F_{1LG}, F_{3LG}	Single and three conductor to ground fault.
F_{conv}	Single substation converter fault.
$i_{\text{ac}}, i_{\text{dc}}$	Single ac and dc conductor current respectively.
k_{cr}	Ratio of the rated active power of the substation converter to the total dc conductor current rating.
$k_{\text{cr,min}}$	Minimum achievable k_{cr} .
$k_{\text{cr,n-1}}$	Converter active power capacity factor after F_{conv} .
k_e	Operating voltage ratio between dc & ac conductor.
k_{ins}	Voltage ratio based on dc & ac insulation.
k_{opr}	Correction factor for converter operating limit.
$k_{\text{q,n-1}}$	Converter reactive power capacity factor after F_{conv} .
l	Distance between sending and receiving substation.
N_{ac}	Number of conductors under ac operation.
$N_{\text{ac, n-1}}$	Number of ac conductors during (n-1) contingency.
N_{conv}	Total number of converters per substation.
N_{dc}	Number of conductors under dc operation.
$N_{\text{dc, n-1}}$	Number of dc conductors during (n-1) contingency.
N_{ori}	Total number of link conductors.
$P_{\text{cap,ac,n-1}}$	$P_{\text{max,ac}}$ during (n-1) contingencies.
$P_{\text{cap,conv,n-1}}$	Total active power converter capacity of dc link during (n-1) contingencies.
$P_{\text{cap,dc,n-1}}$	$P_{\text{max,dc}}$ during (n-1) contingencies.
$P_{\text{cap,dc-con,n-1}}$	Total active power conductor capacity of dc link

$P_{\text{L,sys}}$	Total operating power loss of the system.
$P_{\text{max,ac}}$	Maximum active power capacity of ac link at upf.
$P_{\text{max,dc}}$	Maximum active power capacity of dc link.
$P_{\text{max,RSS,n-1}}$	Maximum active power demand met at RSS during (n-1) contingencies.
$P_{\text{r,conv}}$	Installed active power rating of substation converter.
$P_{\text{r,cond,dc}}$	Maximum achievable $P_{\text{max,dc}}$.
Q_{rated}	Reactive power rating of the substation converter.
$r_{\text{ac}}, r_{\text{dc}}$	Single ac and dc conductor resistance in Ω/km .
$S_{\text{cap,n-1}}$	Total apparent power capacity of the system during (n-1) contingencies.
S_{RSS}	Apparent power demand at receiving substation.
$S_{\text{RSS,max}}$	Maximum S_{RSS} .
$S_{\text{RSS,peak}}$	Daily peak apparent demand at receiving substation.
$S_{\text{RSS,opt}}$	Maximum S_{RSS} that can be met at the optimal efficiency point.
$T_{\text{ac}}, T_{\text{dc}}$	Single ac and dc conductor operating temperature.
$V_{\text{LL,rms}}$	Line to line r.m.s. substation ac bus voltage.
V_{dc}	Voltage of the dc link.
y	Ratio of active dc power flow to that of the total active power demand at system receiving end.
y_{con}	y computed based on the ratio of active power capacity of the dc and ac link conductors.
$y_{\text{min}}, y_{\text{max}}$	Minimum and maximum y , respectively.
y_{opt}	y for optimal system operating efficiency.
$\cos \theta$	Receiving end operating power factor.
$\cos \theta_{\text{R}}$	Receiving end $\cos \theta$ operating at $S_{\text{RSS,max}}$.

I. INTRODUCTION

Load growth will accelerate in the coming years with increasing reliance on the electrical grid to serve the energy needs of the society. Distribution network operators (DNO) face the challenge of meeting the increasing demand due to mismatch between intermittent distributed generation (DG) (example: wind, solar) and energy intensive loads (example: electric vehicles (EV)). A typical radial ac distribution network supplying is shown in Fig. 1.

In such systems, bulk power transfer between the Sending-end Substation (SSS) and Receiving-end Substation (RSS) is accomplished with multiple medium voltage (1-66 kV) 3-phase ac links at short link length (0-50 km) with high power (few tens of MVA). The critical grid section (highlighted in red) is expected to see a significant rise in power demand from the down-line radial network and must guarantee the minimum required capacity even if a single component at this location fails (referred to as (n-1) contingency).

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Fig. 1: Typical medium voltage distribution network.

In a previous work [1], it was proved that refurbishing the existing ac distribution links to a converter based hybrid ac-dc architecture is an economically viable opportunity as compared to installing additional three-phase ac links to improve the system capacity by at least 50 %. The basis for the expected system capacity enhancement is due to higher power delivery capacity with dc for equivalent conductor area as compared to ac [2]. The work in [1] showed that even though complete dc refurbishment is viable for relatively long distances and high voltages as suggested in [2]–[4], hybrid ac-dc solution can offer the same benefits of dc power distribution. Therefore, with increasing need for grid infrastructure reinforcement due to increasing demand, application of hybrid ac-dc distribution is concomitant [5]–[9].

Conventionally [10], the ac network capacity augmentation is achieved by (a) Adding multi-circuit lines with addition of new links (b) Re-conductoring to higher cross-sectional area (c) Series compensation (d) Reactive power support at receiving end. In [11], the optimal conductor is selected for feeder reinforcement by minimizing the operating losses in trade-off with investment cost. In [12], optimal operation of DG is coordinated with upgradation of distribution lines and high/medium voltage transformers with an objective to minimize the investment, operational loss and reliability cost. A dynamic improvement of inter-area power transfer capability is suggested in [13] for under-utilized HVDC grid infrastructure under low wind conditions. Reference [14] maximizes the hosting capacity of distribution network (DN) by optimizing the chargeable region of EVs given the power quality constraints and uncertainty in demand. The concept of reliability enhancement of DN with EVs as active components in vehicle to grid applications is extended in [15]. Use of energy storage for peak shaving to avoid installing under-utilized medium voltage grid infrastructure for network reinforcement is explored in [16]. Such avenues of strategic DN reinforcement combined with smart operation must take into account the ownership of grid assets. For example, it is discussed in [17] that DNOs may be prohibited from owning generation units due to regulations aiming to separate the business interests associated with concerned entity. The coordinated planning of DG, EV and storage placement and sizing for efficient DN reinforcement can be difficult with decentralized ownership.

Power supply reliability is a challenge for DNOs, particularly with emerging grid assets and forecasted exponential rise in demand [18]. The necessity of maintaining the minimum

supply capacity for (n-1) contingency is the bedrock of DN planning. That is, the system level reliability is determined from the availability of the supply in meeting this minimum required power demand even if a single component fails. For example, the importance of network reconfiguration and component rating of DN in relation to daily load curves is highlighted in [19]. The concept of reconfiguration can be seen as a method to maximize the utilization of remaining healthy infrastructure in a post-fault clearance scenario and can be viewed as a way to reduce the need for redundancy in the system. This is because the added cost of redundancy has limited use during normal conditions where the system spends the majority of its operational lifetime.

The main contribution of the present paper is to quantify the advantage of introducing reconfigurability in the hybrid ac-dc distribution link architecture post-fault clearance. It is shown that such a reconfigurability between ac and dc links allows additional design flexibility of reducing substation converter rating while maintaining the same required capacity during (n-1) contingencies. The specific contributions are as follows:

- Determining the impact of the dc link voltage, rating and number of substation converters on the system capacity during (n-1) contingencies in consideration to different offline reconfigurations post-fault clearance. (Section III)
- Developing insight on the system loss minimization during normal operation by optimally selecting the dc link active power share and highlighting the associated constraint of converter rating (Section IV).
- Quantifying the trade-off between converter downsizing and loss minimization during normal operation with a economic viability case-study using adapted substation load profile data and sensitivity to parameters like ac grid voltage, link length and conductor area (Section V).

II. PARALLEL AC-DC LINK DIMENSIONING ASPECTS

A. AC-DC Reconfiguration strategy

The offline reconfiguration strategy post-fault clearance is depicted in Fig. 2.

While ac to dc reconfiguration is shown here, the sequential principle can be applied for dc to ac reconfiguration as well. Fig. 2(a) shows three link conductors (x_1 - x_3) connecting the SSS and RSS via the ac feeder switches and three-phase circuit breaker CB1. An alternate path (in open condition) exists for each conductor using the dc feeder switches.

There are a total of N_{on} link conductors (highlighted as dotted line) out of which states of only three conductors are shown. The other conductors in the system may be connected via the dc path with the ac path bypassed, thus the depicted converter is not offline during the operating condition depicted in Fig. 2(a). One or multiple VSCs can be used in the system as per the redundancy requirements highlighted in Section III-C. Modular Multilevel Converter (MMC) topology is used and a complete design and selection process specific to this application, including loss model, operating performance and number of levels, is given in [20], [21].

Since the link conductor reconfigurations are carried out offline using the ac and dc feeder switches once the relevant

Fig. 2: Offline reconfiguration strategy post-fault clearance (a) Normal Operation (b) Fault clearance in a single link conductor (c) Reconfigured system operation.

circuit breakers have isolated the faulty component, the dynamics of the system during the fault is not studied in this paper. Some considerations on dynamic operation during fault protection of components in such systems can be found in [22], [23]. Post-reconfiguration, the healthy MMCs are expected to run in grid connected mode as back-to-back VSC based point-to-point dc link in parallel with the ac link, as shown in [24].

Fig. 2(b) shows a single line to ground fault occurring in conductor x_3 , which is cleared by CB1 as per conventionally used ac protection methodology. Thereafter, Fig. 2(c) shows the offline ac to dc reconfiguration using the feeder switches to connect the remaining healthy conductors x_1 and x_2 for dc operation. When the faulty component is replaced, the normal operation depicted in Fig. 2(a) can be restored in reverse sequence.

One of the drawbacks of this strategy is the increase in operational complexity. Further, it can be seen that more number of feeder switches are necessary for achieving the reconfiguration, thereby increasing the system complexity. However, lack of this flexibility offered by the reconfigurable architecture will increase capital costs due to need for adequate redundancy and higher converter capacity in the system. The impact of the reconfiguration on the system insulation must be considered at the design stage. Some discussion on the insulation performance under ac and dc voltages is provided empirically in [25]. The challenges associated with ac-to-dc and dc-to-ac switching processes on the system operation with the purpose of using the VSC based flexible ac-dc links to provide ancillary services to medium voltage distribution grids are explored experimentally in [26].

B. Service Restoration and Protection

In [27], it is discussed that distribution feeder reconfiguration for post-fault service restoration has three objectives (i) isolate the fault using protection devices (ii) minimize the unavoidable load shedding (iii) change the open/close status of switches to restore supply for healthy regions. Based on the field trial results shown in [28], the maximum service restoration time corresponding to the sequence of events suggested in Section II-A, including fault isolation, switch motion and system reconfiguration is taken as 1 s. Assuming a high system component failure rate of one per week (52 per year), the worst case loss of 217 kWh/year is incurred if an average load shedding of 30 MVA per fault event occurs. Considering energy cost of 0.1 €/kWh, this amounts to about 0.003 % of installation costs for a 30 MVA converter station. Therefore, the added service restoration costs due to proposed ac-dc reconfigurability are significantly lower than the expected savings with achievable converter downsizing and hence, are neglected.

Based on discussions with the DNOs in [29], the researchers working with a 10 kV reconfigurable ac-dc distribution link system suggest that proper protection selectivity can limit the number of customers experiencing outage in the downstream network. A possible design is suggested by introducing modularity such that every two dc conductors operate as an independent point-to-point symmetrical monopolar link and the fault is isolated in each with ac-side CB. Emphasizing the importance of proper protection design in future hybrid ac/dc medium voltage links, a recent study [30] compares three possible solutions (i) ac circuit breakers (ii) dc circuit breakers (iii) fault blocking converters with a focus on dynamic operation, fault protection and post-fault restoration. While further research on different protection schemes can potentially influence the magnitude and duration of load shedding during (n-1) contingencies, this aspect is not the focus of the current paper.

C. System Description

In Fig. 3, an illustration of the generalized system diagram is shown for a parallel ac-dc link of a given length ' l ' between SSS and RSS. The specific connection diagram can be reconstructed from Fig. 2. Such an arrangement can be present in transmission and DNs as suggested in [31], [32].

Fig. 3: Generalized illustration of a parallel ac-dc reconfigurable link system.

Using ac and dc feeders, the number of conductors N_{ac} and N_{dc} can be strategically selected to operate as ac and dc links respectively. Since the ac link has to be three-phase while the dc link is symmetric monopole without ground return, the former must be a multiple of three and the latter a multiple of two. Furthermore, the possible reconfiguration strategies are constrained by the total link conductors (N_{ori}) based on the relation (1), with an objective of maximizing the utilization of available conductor area.

$$N_{ac} + N_{dc} \leq N_{ori} \quad (1)$$

The cross-sectional area (A_{con}) and operating temperature (T_{ac}, T_{dc}) dependent per kilometer conductor resistances are r_{ac} and r_{dc} . In this study, A_{con} of both ac and dc link are considered equal because the system is developed using the refurbishment strategy for a completely ac link system described in [32], [33]. However, the presented equations can be generically applied for any magnitude. Note that for the same A_{con} , r_{ac} is slightly higher than r_{dc} as it includes the skin and proximity effects associated with the link conductors at the fundamental frequency (50 Hz in this paper). The single conductor currents i_{ac} and i_{dc} depend on the respective ac and dc operating power. η is the operating power dependent efficiency of the substation ac/dc converters at both ends of the dc link.

D. DC Link Voltage Ratio (k_e)

For a three-phase line to line rms voltage ($V_{LL,rms}$), the dc link voltage V_d is given by (2).

$$V_d = \frac{2k_e V_{LL,rms}}{\sqrt{3}} \quad (2)$$

where,

$$k_e = k_{opr} k_{ins} \quad (3)$$

The voltage enhancement factor k_e is defined by (3). k_{ins} describes the dc to ac voltage ratio in consideration to the insulation performance of the link conductor infrastructure. For example in case of underground cables, k_{ins} is conservatively $\sqrt{2}$ for ac and dc cables of similar technology and cross-section according to the discussion in [25]. For overhead lines, k_{ins} can be chosen considerably higher [3], [4]. This constraint is particularly relevant if the capacity enhanced reconfigurable ac-dc architecture is developed by refurbishing a purely ac link system [33]. On the other hand, if the design process involves newly installed link conductor infrastructure, k_{ins} can be more freely chosen based on the capacity and operational requirements of the system in trade-off with higher costs related to the converter semiconductor and link insulation.

The factor k_{opr} corrects for the minimum operating dc voltage limit of the converter depending on the reactive power requirements, fault current limiting and filter inductance, availability of grid connecting transformer tap and the modulation technique. Based on these considerations, the value of k_e must be adjusted in relation to k_{ins} with k_{opr} typically between 1-1.15. Considering the value of k_{opr} at its minimum of 1, $k_e \geq \sqrt{2}$ is an important dimensioning constraint in this paper.

E. Share of DC Link Active Power (y)

The dc link converters can be used to steer the active power (P_{dc}) by controlling the power sharing ratio (y) for a given RSS apparent power demand (S_{RSS}) at power factor $\text{pf}=\cos\theta$ as described by (4).

$$y = \frac{P_{dc}}{S_{RSS} \cos \theta} \quad (4)$$

Assuming that the dc link converter supports the full load reactive power demand at RSS, the ac link sees unity power factor (upf) at its RSS side and thus the maximum active power capacity of the ac link ($P_{max,ac}$) is given by (5).

$$P_{max,ac} = \sqrt{3} \left(\frac{N_{ac}}{3} \right) V_{LL,rms} I_{cond,rated} \quad (5)$$

Assuming that the current rating ($I_{cond,rated}$) of the link conductors under ac and dc conditions is the same and substituting V_d from (2), the maximum active power capacity of the dc link ($P_{max,dc}$) is given by (6).

$$P_{max,dc} = \frac{N_{dc} k_{cr} k_e V_{LL,rms} I_{cond,rated}}{\sqrt{3}} \quad (6)$$

k_{cr} is the converter de-rating factor which will be discussed in Section II-F. Note that N_{dc} is a multiple of 2 corresponding to a symmetric monopole dc link system without ground return. The minimum dc active power share (y_{min}) and maximum dc active power share (y_{max}) for a given S_{RSS} at $\text{pf}=\cos\theta$ is described by (7) and (8) respectively.

$$y_{min} = \begin{cases} 0, & \text{if } S_{RSS} \cos \theta \leq P_{max,ac} \\ 1 - \frac{P_{max,ac}}{S_{RSS} \cos \theta}, & \text{if } S_{RSS} \cos \theta > P_{max,ac} \end{cases} \quad (7)$$

$$y_{max} = \begin{cases} 1, & \text{if } S_{RSS} \cos \theta \leq P_{max,dc} \\ \frac{P_{max,dc}}{S_{RSS} \cos \theta}, & \text{otherwise} \end{cases} \quad (8)$$

Herein, (7) implies that the share of dc active power can be zero only if the active power demand at RSS is less than or equal to the maximum capacity of the ac link in the system. In other words, y_{min} can either be zero or positive, depending on the actual RSS power demand. The selection of the appropriate y between y_{min} and y_{max} can influence the operating efficiency during healthy operating conditions, as shall be explored in Section IV.

F. Substation Converter Rating (k_{cr})

k_{cr} is defined as the ratio of the rated active power of the substation converter ($P_{r,conv}$) to the total thermally limited active power rating of the dc link conductors ($P_{r,cond,dc}$) for the given N_{dc} . It is constrained by $k_{cr} \leq 1$, signifying that if $P_{r,conv} > P_{r,cond,dc}$, no further improvement in system capacity can be achieved with increasing $P_{r,conv}$ for given configuration of N_{ac} & N_{dc} .

Maximizing k_{cr} may be of interest from maximum achievable system capacity point of view, however, it also increases the converter cost and size. Further, if k_{cr} is low, reconfiguration can be used to increase system capacity by decreasing N_{dc} and directing a higher active power flow through the ac path.

This method of capacity enhancement can be advantageous during (n-1) contingency corresponding to converter faults (as explored in Section III). Physically, dc to ac reconfiguration increases the utilization of the installed converter capacity (by increasing the effective k_{cr}). On the other hand, the thermally limited power capacity of the link conductors is higher for dc operating conditions as compared to ac at least by a factor of k_e . Thus the installation cost driven minimization of k_{cr} is a trade-off between the optimal converter and conductor utilization for achieving the required system capacity.

It can be inferred that the minimum converter derating for the given configuration of N_{ac} & N_{dc} is obtained at $y_{max} = y_{min}$ when the system is delivering the maximum apparent power demand $S_{RSS,max}$ with power factor $\cos \theta_R$. Therefore, by equating (7) and (8) and substituting $P_{max,dc}$ from (6), the minimum value of converter de-rating factor ($k_{cr,min}$) can be estimated based on (9), where, $P_{max,ac}$ can be computed from (5).

$$k_{cr,min} = \frac{S_{RSS,max} \cos \theta_R - P_{max,ac}}{\left(\frac{(N_{dc}) \cdot (k_e)}{N_{ac}}\right) P_{max,ac}} \quad (9)$$

Equation (9) is valid only for $N_{ac} > 0$ where the definition of y is relevant, within the constraint that $k_{cr,min}$ takes a positive value less than one. The minimization of k_{cr} can decrease the operating efficiency of the system during healthy operation even if the system capacity requirement during (n-1) contingency is met, as shall be discussed in Section IV.

G. Problem Formulation

The purpose of this paper is to highlight that the main challenge in the dimensioning of reconfigurable ac-dc links is the trade-off involved in selecting k_e , y and k_{cr} . Subsequent sections will show that with design constraint of achieving constant system power capacity during (n-1) contingency, the competing dimensioning objectives for k_e , y and k_{cr} will influence the operational complexity (Section III), operating efficiency during normal operation (Section IV) and installation cost (Section V). Table I lists the test parameters used for the presented results, unless specified otherwise. The six dc conductors can be connected either to common dc bus at the converter station to give a single symmetrical monopole MMC based link or form three separate dc links based on the trade-offs discussed in [32].

TABLE I: Test Parameters

$V_{LL,rms}$	10 kV
Type of conductor	Aluminum
A_{con}	630 mm ²
$I_{cond,rated}$	590 A
N_{ac}, N_{dc}	3, 6
Capacity during (n-1) contingencies	3 p.u. at $pf=0.9$
Base Power	10.2 MVA

The studied system represented in Table I is developed by converting six conductors of the overloaded 3x three-phase ac links (refer Fig. 1, highlighted in red) for dc operation during normal conditions. The viability of this ac to dc

conversion is explored in detail in [1]. The base power can be calculated from (5) at $N_{ac} = 3$ and physically describes the rated capacity of a single 3-phase ac link. Therefore, it will vary for the presented sensitivity analysis with $V_{LL,rms}$ and A_{con} . k_e is initially assumed at minimum possible value of $\sqrt{2}$ and k_{cr} is considered at maximum possible value of 1. Consequently under normal operating conditions, it can be estimated from (5) and (6) that $P_{max,ac} = 1$ p.u and $P_{max,dc} = 2.8$ p.u respectively. The dc active power share y can be varied between 0.63 to 1 under these conditions. The rated active power of the installed substation converter is given by $P_{r,conv} = P_{r,cond,dc} = 2.8$ p.u corresponding to $k_{cr} = 1$.

The current paper explores the potential benefit of post-contingency reconfigurability between the ac and dc conductors in minimizing k_{cr} in trade-off with y_{opt} for different k_e and fault conditions.

III. RECONFIGURATION DURING (N-1) CONTINGENCIES

The maximum active power demand at RSS during (n-1) contingencies ($P_{max,RSS,n-1}$) is given by (10).

$$P_{max,RSS,n-1} = P_{cap,ac,n-1} + P_{cap,dc,n-1} \quad (10)$$

The active power capacities of the ac link ($P_{cap,ac,n-1}$) and dc link ($P_{cap,dc,n-1}$) are given by (11) and (12) respectively.

$$P_{cap,ac,n-1} = \frac{k_q N_{ac,n-1} V_{LL,rms} I_{cond,rated}}{\sqrt{3}} \quad (11)$$

$$P_{cap,dc,n-1} = \frac{k_{cr,n-1} k_e N_{dc,n-1} V_{LL,rms} I_{cond,rated}}{\sqrt{3}} \quad (12)$$

Here, $N_{ac,n-1}$ and $N_{dc,n-1}$ are the number of actively operating ac and dc link conductors respectively during a given (n-1) contingency in the system. $k_{cr,n-1}$ describes the ratio of active power that the substation converter can deliver ($P_{cap,conv,n-1}$) with respect to the dc link thermal capacity ($P_{cap,dc-cond,n-1}$) corresponding to $N_{dc,n-1}$ conductors during fault conditions. It is limited by the maximum value of 1, signifying that $P_{cap,conv,n-1} > P_{cap,dc-cond,n-1}$ cannot increase $P_{cap,dc,n-1}$. The factor k_q depends on the reactive power support provided by the RSS converter and is equal to 1 if the full load reactive power (Q_{rated}) is supported by the RSS converter. The total apparent power capacity of the system $S_{cap,n-1}$ is given by (13).

$$S_{cap,n-1} = \sqrt{P_{max,RSS,n-1}^2 + Q_{rated}^2} \quad (13)$$

A. Capacity during Single-Conductor to Ground Fault (F_{ILG})

Consider a single line to ground fault in a practical distribution link system with $N_{ori} = 9$ described in [33]. This fault can be in either ac or dc link conductor and can be cleared by the active circuit breaker CB1 or CB2. The remaining 8 conductors can be reconfigured offline within the constraint (1) to give different active power capacity based on (11) and (12). The operating states of the link conductors before and after offline reconfigurations post F_{ILG} fault clearance is shown in Fig. 4.

It can be seen that three possible system configurations are possible with a single faulty conductor. Depending on the number of conductors operating under ac and dc conditions,

Fig. 4: Conductor operating status before and after offline reconfiguration post F_{ILG} fault clearance.

the unused healthy conductors in the system can be minimized. Further, since dc has inherently higher power delivery capacity as compared to ac conductors of the same cross-sectional area, the maximum achievable capacity during (n-1) contingencies varies with each configuration as described by (13), constrained by the installed converter capacity factor k_{cr} .

Fig. 5 shows the $S_{cap,n-1}$ that can be met during F_{ILG} with respect to $P_{r,conv}$ for different link configurations and k_e .

Fig. 5: RSS apparent power demand capacity during (F_{ILG}) for different link conductor configurations with varying active power capacity of converter and k_e .

The full reactive power needs at the RSS can be met by the healthy substation converter. It can be seen that the maximum capacity is limited by k_e for the given $N_{ac,n-1}$ and $N_{dc,n-1}$, corresponding to the thermal limit of the link conductors associated with the specific configuration. While the achievable capacity reduces with the active power rating of the substation converter, an increase in $N_{ac,n-1}$ using system reconfiguration can achieve the required capacity for a lower converter rating. For example, 3 p.u. apparent demand at RSS with $pf=0.9$ can be met for F_{ILG} with 0.7 p.u., 1.7 p.u. and 2.7 p.u. active power converter rating for $N_{ac,n-1} = 6, 3$ and 0 respectively. Though minimization of converter rating can reduce installation cost, the required number of offline reconfigurations post-fault clearance increase, therefore increasing the operational complexity of the system [32]. Furthermore, a

lower converter rating can reduce the system efficiency during normal operation as shown in Section IV.

B. Capacity during Three-Conductor to Ground Fault (F_{3LG})

The (n-1) contingency analysis associated with achievable system capacity during link conductor faults with F_{ILG} is sufficient if the system consists of overhead lines or single cored cables. However, if the system consists of 3-cored cables, the possibility of F_{3LG} can occur. In such case only $N_{ori}-3$ healthy conductors are available for offline reconfigurations post-fault clearance (6 in this case). The operating states of the link conductors before and after offline reconfigurations post F_{3LG} fault clearance is shown in Fig. 6.

Fig. 6: Conductor operating status before and after offline reconfiguration post F_{3LG} fault clearance.

Similar to the discussion in Section III-A, the link conductor area utilization and number of operating ac and dc links determine the achievable system capacity, constrained by k_{cr} . Fig. 7 shows the $S_{cap,n-1}$ that can be met during F_{3LG} with respect to $P_{r,conv}$ for different link configurations and k_e .

Fig. 7: RSS apparent power demand capacity during F_{3LG} for different link conductor configurations with varying active power capacity of converter and k_e .

It can be observed that unlike with F_{ILG} , reconfigurability post F_{3LG} fault clearance provides limited opportunity to derate the active power capability of the converter. This is because the the maximum achievable system capacity is significantly limited by the thermal capacity of the remaining healthy

conductors. Maximizing the number of conductors operating under dc conditions is important as the dc power delivery capacity for the same conductor area is inherently higher [2].

C. Capacity during Converter Faults (F_{conv})

If a substation converter fault (F_{conv}) occurs, the total ac and dc link capacity reduces according to (11) and (12), respectively. With varying number of converters (N_{conv}) per substation for a fixed installed converter capacity $P_{r,\text{conv}}$, an increase in N_{conv} results in improved modularity of the system. This results in a reduced loss in total converter capacity during a single F_{conv} , as mathematically described by (14) and (15).

$$k_{\text{cr},n-1} = \frac{P_{\text{cap,conv},n-1}}{P_{\text{cap,dc-cond},n-1}} = \frac{P_{\text{conv, rated}} \left(1 - \frac{1}{N_{\text{conv}}}\right)}{P_{\text{cap,dc-cond},n-1}} \quad (14)$$

$$k_{\text{q},n-1} = \sqrt{1 - \left(\frac{\sqrt{3}Q_{\text{rated}}}{N_{\text{conv}}N_{\text{ac},n-1}V_{\text{LL,rms}}I_{\text{cond,rated}}} \right)^2} \quad (15)$$

The correction factor $k_{\text{q},n-1}$ is relevant when the F_{conv} is on the RSS side converter, leading to a increase in reactive power flow in the ac link. The operating states of the link conductors before and after offline reconfigurations post F_{conv} fault clearance is shown in Fig. 8.

Fig. 8: Conductor operating status before and after offline reconfiguration post F_{conv} fault clearance.

The impact of these conductor reconfigurations maximize the utilization of the remaining healthy system converters with an objective of meeting the required system demand. For example, with $N_{\text{conv}} = 1$, active dc link power transfer is not possible during F_{conv} . In such a scenario, maximum $S_{\text{cap},n-1}$ can be achieved with $N_{\text{dc},n-1} = 9$ and $N_{\text{ac},n-1} = 0$. On the other hand, if $N_{\text{conv}} > 1$, some dc active power transfer as well as reactive power support at RSS is possible when a single converter in the system fails.

Fig. 9 shows the $S_{\text{cap},n-1}$ that can be met during F_{conv} with respect to N_{conv} for different link configurations and k_e . The active power rating of the converter is considered constant for all configurations considered, corresponding to the maximum achievable capacity with $N_{\text{dc},n-1} = 6$. This value is $P_{r,\text{conv}} = 2.8 \text{ p.u.}$ for $k_e = \sqrt{2}$ and $P_{r,\text{conv}} = 4 \text{ p.u.}$ for $k_e = 2$.

It can be observed that if $N_{\text{conv}} = 1$, no active power can be transferred by the dc link conductors. In the worse case scenario, if F_{conv} is on the RSS side, the entire reactive power

Fig. 9: RSS apparent power demand capacity during F_{conv} for different link conductor configurations and k_e with respect to number of substation converters with maximum rated active power of the substation.

flows through the ac link. Therefore, the $S_{\text{cap},n-1}$ for a given configuration corresponds to the capacity of the $N_{\text{ac},n-1}$ ac link conductors. With increasing N_{conv} , the active and reactive power support by the dc link during single converter fault improves. It can be observed that the required capacity of 3 p.u. at 0.9 can be met without the necessity of dc to ac reconfiguration with $N_{\text{conv}} = 3$ for $k_e = \sqrt{2}$. Thus there is a trade-off between modularity and operational complexity in terms of system reconfigurations post-fault clearance.

While link conductor reconfigurations are carried out by the ac and dc feeders, substation converter connections have consequences on factors such as cost, protection, operational and architectural complexity. For example, multiple ac/dc converters connected in parallel between a common ac and dc bus can simplify the reconfigurable ac-dc feeder architecture. However, in case of a dc conductor fault, the full dc link system may need to be isolated if ac-side circuit breaker is employed for protection. On the other hand, if individual ac/dc converter is employed for each dc link comprising of two conductors, dedicated ac protection system can be designed for the faulty dc link conductor. However, each converter must then have a three-phase ac bypass, leading to a more complicated reconfiguration architecture. Some case-specific as well as generalized discussions on these aspects are offered in [32], [33].

If the active power rating of the converter is minimized for F_{ILG} according to Fig. 5, the $S_{\text{cap},n-1}$ during F_{conv} for different configurations is shown in Fig. 10 for varying number of converters.

$P_{r,\text{conv}}$ for all three configurations is considered equal to 0.7 p.u. corresponding to $k_e = \sqrt{2}$. It can be observed that even if higher N_{conv} is chosen, reconfiguration towards a system with $N_{\text{ac},n-1} = 9$ is necessary during any F_{conv} . This is because the converter capacity is such that it cannot fully utilize the available thermally limited capacity of the dc link conductors even with $N_{\text{dc},n-1} = 2$ and $N_{\text{conv}} = 10$.

Therefore, the main conclusion from the contingency analysis performed in this section is that the required RSS apparent power demand capacity of 3 p.u. at $\text{pf}=0.9$ can be met with

Fig. 10: RSS apparent power demand capacity during F_{conv} for different link conductor configurations and k_e with respect to number of substation converters with minimum rated active power of the converter for $k_e = \sqrt{2}$.

either with 3x converters with cumulative capacity of 2.8 p.u. per substation or 1x converter with a capacity of 0.7 p.u. per substation if single-cored link conductors are used. Though the latter is beneficial from installation cost point of view, greater number of reconfigurations are required in case a fault occurs in the system. Note that the direction of reconfiguration (ac to dc or dc to ac) is case-specific depending on the chosen pre-fault system configuration and post-contingency capacity requirements. This is not the focus of this paper.

IV. LOSS MINIMIZATION DURING NORMAL OPERATION

Although the reconfigurable dc link in parallel with the ac link can be dimensioned with considerably low converter rating to achieve the same system capacity during (n-1) contingencies, this can increase the losses during normal operation. This section shows the constraint that substation converter rating puts on the operating efficiency of the system.

In the previous work [1], it is discussed in detail that an optimal point exists for the active power share of the dc link (y_{opt}) depending on the several factors such as RSS power demand, power factor, ac grid voltage, dc link voltage, converter efficiency, link length and conductor area. For relatively high power demand, y_{opt} is close to the value y_{con} governed by the thermal limit of the ac and dc link conductors, given by (16).

$$y_{\text{con}} = \frac{k_e N_{\text{dc}}}{N_{\text{ac}} + k_e N_{\text{dc}}} \quad (16)$$

It can be construed from (6) that $k_{\text{cr}} < 1$ can impose a constraint on $P_{\text{max,dc}}$ for a given link conductor current limit $I_{\text{cond,rated}}$. In other words, converter downsizing associated with a decreasing k_{cr} can reduce the y_{max} described by (8). As a consequence, the system may be forced to operate at a y lower than y_{opt} , thus incurring higher losses during normal operating conditions. While it is desirable to operate the system at its optimal efficiency point y_{opt} , selecting a lower k_{cr} can be advantageous in reducing the installation costs corresponding to the converter rating. The immediate trade-off of these competing requirements necessitates the system to operate at sub-optimal efficiency under specific operating conditions as

illustrated in Fig. 11. The y_{opt} as a function of S_{RSS} at $\text{pf}=0.9$ with $k_{\text{cr}} = 1$ is shown for link length of 5 km and 15 km. The approximation, y_{con} , is also highlighted.

Fig. 11: Constraint of converter rating on the operating active power ratio between ac and dc link.

The dotted black lines in Fig. 11 correspond to the y_{max} as a function of S_{RSS} at $\cos \theta = 0.9$ for different Δk_{cr} . The highlighted values of Δk_{cr} as a percentage of $k_{\text{cr,min}}$ can be used to determine the system k_{cr} using (17).

$$k_{\text{cr}} = k_{\text{cr,min}} + \Delta k_{\text{cr}} \quad (17)$$

As an example, the highlighted point 'P1' in Fig. 11 represents the optimal efficiency operation for $S_{\text{RSS}} = 3 \text{ p.u.}$ at $\cos \theta = 0.9$ for a 15 km link. If the substation converters are de-rated so that $k_{\text{cr}} = k_{\text{cr,min}}$ with $\Delta k_{\text{cr}} = 0\%$, the link system is forced to operate at point 'P2'. It can be inferred that by operating the system at $y = 0.63$ (point P2) instead of $y_{\text{opt}} = 0.77$ (point P1), additional losses are incurred. On the other hand, to avoid these losses at the specific operating point, the converter has to be overrated corresponding to 20-25% higher Δk_{cr} . Fig. 11 shows that with decreasing link length (see for 5 km; blue line) and increasing Δk_{cr} , operating range, for which the described trade-off is valid, shortens. It can be inferred that for a given link length and Δk_{cr} , the intersection between the demand dependent plot-lines for y_{opt} and y_{max} define the maximum apparent power demand for which the system can operate at the highest efficiency that is achievable unconstrained by the converter rating. The payback associated with the additional incurred losses, cumulative for $S_{\text{RSS}} > S_{\text{max,opt}}$ over the given RSS load profile, in relation to the investment costs for the installed converter rating governs the appropriate choice. Consequently, the selection of k_{cr} is case specific as shall be explored further in Section V.

V. ECONOMIC VIABILITY OF CONVERTER DOWNSIZING

Section III shows that the same system capacity can be maintained using reconfigurations even though the dc link converters are significantly downsized. Section IV highlights that as a consequence of such a converter downsizing, the system cannot operate at its optimal efficiency (y_{opt}) during normal operation. Since the reconfiguration post-fault clearance is temporary and the system is expected to revert back

to its original configuration once the faulted part is fixed, the impact of converter downsizing on the additionally incurred losses over the operational lifetime must be determined. In this section, the economics of this trade-off will be explored with case-study using examples of two adapted RSS demand profiles.

A. System Losses and Converter Downsizing

Fig. 12 shows the effect of this trade-off on system losses with varying S_{RSS} at pf=0.9 for different link lengths (l) and Δk_{cr} . The calculated system losses include both conductor and converter losses for different operating scenarios as per the mathematical model described in [1]. The system parameters used for the computations are listed in Table I, with $N_{ori} = 9$ single-cored link conductors operating with $k_e = \sqrt{2}$.

Fig. 12: System losses with varying converter rating and RSS power demand at pf=0.9 for different link lengths.

The highlighted cutlines $x_{cut,0}$, $x_{cut,10}$ and $x_{cut,20}$ show the variation in $P_{L,sys}$ with link length dependent $S_{max,opt}$ for $\Delta k_{cr} = 0\%$, 10% and 20% respectively. Here, $S_{max,opt}$ is defined as the maximum S_{RSS} that can be met at the optimal efficiency point. It is obtained at the intersection between the link length dependent y_{opt} and the Δk_{cr} dependent y_{max} from Fig. 11. For a given link length, it can be observed from Fig. 12 that $P_{L,sys}$ can significantly decrease for $S_{RSS} > S_{max,opt}$ as Δk_{cr} increases from 0% to 20% , particularly for relatively longer l . On the other hand, for power demands below $S_{max,opt}$, $P_{L,sys}$ slightly increase with Δk_{cr} .

B. Case-study Showing Trade-off of Converter Downsizing with Optimal Efficiency System Operation

The energy savings over the operational life of the system is a function of the RSS load profile shown in Fig. 13 for two test cases.

Both the described load profiles are adapted from the annual power demand data shown in [33] such that the maximum peak in power demand is consistent with the test system parameters listed in Table I. In Case I (Fig. 13a), the shaded area in red corresponds to the period where daily peak demand is greater than $S_{max,opt}$ at $k_{cr,min} = 0.607$ and $l = 10$ km. Considering the RSS power demand with per hour resolution,

(a) Case I.

(b) Case II.

Fig. 13: Daily peak RSS power demand and maximum optimal power limit for a parallel ac-dc link system with converter derating factor of $k_{cr} = k_{cr,min}$.

20.6 MWh/year savings can be achieved if the the converter rating is 10 % higher. However, this has an additional incurred cost of 0.16 M€ at 50 €/kVA as per the installed converter cost trends mentioned in [34], giving exceedingly high payback time if energy costs are assumed at 0.1 €/kWh [1]. Therefore, it is economically viable to downsize the converter to $k_{cr,min}$ for Case I (that is, $P_{r,conv} = 1.7$ p.u), even though it operates at sub-optimal efficiency for RSS power demand in the shaded red region of Fig. 13a.

For Case II load profile shown in Fig. 13b is modified such that the average power demand of the system is 1.71 p.u. compared to 1.16 p.u. in Case I while the maximum peak demand is maintain constant at 3 p.u. The highlighted red area represents RSS power demand which cannot be met at optimal efficiency for $l = 20$ km if the converter is downsized to $k_{cr,min} = 0.607$. A 10 % increase in converter size can offer energy savings of 239.4 MWh/year, with a payback of 6.6 years. Therefore in this case, the optimal converter size depends on its cost trade-off with higher power losses associated with sub-optimal system operation due to converter downsizing, even though the power delivery capacity during (n-1) contingencies can be maintained constant. Fig. 14 shows the payback for different Δk_{cr} with varying link lengths.

Fig. 14: Payback due to variation in derating factor and link length for Case II.

C. Sensitivity Analysis with Grid Voltage and Conductor Area

The $V_{LL,rms}$ and A_{con} of the system is varied while keeping the p.u. values of the Case II load profile (Fig. 13b) constant.

Therefore, the base power associated with the presented results of this section varies in accordance to (5). The heat-map of minimum link length for which a payback of 10 year can be achieved for varying converter derating factor as a function of $V_{LL,rms}$ and A_{con} is shown in Fig. 15a and 15b, respectively.

Fig. 15: Link lengths giving 10 year payback for converter downsizing in Case II.

The contour lines show the variation of optimal converter de-rating factor with $V_{ll,rms}$ and A_{con} for given link length. It can be observed that greater converter downsizing is possible with increasing $V_{LL,rms}$, A_{con} and decreasing link length, because these parameter tendencies decrease the efficiency of dc link operation in relation to the ac link. If k_e is increased from $\sqrt{2}$ to adjust k_{opt} and/or to increase the capacity of the system further, the losses in the dc link conductors will decrease for the given power. It is inferred that an increase in k_e will limit the economic viability of converter downsizing from optimal efficiency perspective.

VI. CONCLUSION

DC link dimensioning involves interrelated trade-offs between dc voltage, substation converter rating and optimal dc active power share. The reconfigurability between ac and dc link converters is shown to offer potential for converter downsizing by as much as 75 %, for example, in the range of 0.7-2.8 p.u. active power while maintaining the same power

transfer capacity during different (n-1) contingencies. However, this de-rating is detrimental to system efficiency during normal operation. Furthermore, a lower converter rating will result in increased number of offline reconfigurations post-fault clearance.

Using a case-study with adapted substation load profile data, the trade-off between operating efficiency and converter sizing is quantified to suggest a economically viable solution. Sensitivity analysis is performed for different grid voltage, link length and conductor area to determine the appropriate converter rating giving a 10-year payback time.

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