THE EFFECTIVENESS OF USING IEC61660 FOR CHARACTERISING SHORT-CIRCUIT CURRENTS OF FUTURE LOW VOLTAGE DC DISTRIBUTION NETWORKS

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ABSTRACT

Low voltage direct current (LVDC) distribution systems have the potential to be considered as an enabler of increased penetration of distributed renewables, electric vehicles, and heat pump systems. They do however present significant challenges for understanding fault behaviour and effective protection systems. This paper presents these challenges, and investigates the effectiveness of using IEC61660 for the short-circuit characterisation of LVDC networks.

INTRODUCTION

Low voltage direct current (LVDC) distribution systems have been used for many years in different applications. They have been widely used in auxiliary installations in power plants and substations. LVDC systems are also considered a good solution for many transport applications such as electric traction systems due to the wide usage of DC motors, and also as a good solution for aircraft power systems and electric ships due to the enhanced controllability of DC [1]. Recently, the move toward using DC devices in utilities has been rapidly growing, and LVDC distribution systems have been used for new applications such as powering different sized data centres [2]. With the help of modern power electronics and advanced smart grid technologies, it is believed that LVDC power systems have the potential to be considered as a valuable component of future smart grids [1]. More intelligent monitoring and controls, and better generation and use of energy could be offered by LVDC systems [2]. The potential benefits of LVDC systems will be discussed further, in the next section of the paper.

However, the implementation of LVDC systems introduces new components that can make power systems more complex [3]. A new complex arrangement of mixed AC and DC will emerge. And in order to make LVDC distribution systems technically feasible and compatible with existing AC systems, an understanding of other behaviour under different operating conditions is necessary. For example, as the system becomes more complex new forms and types of faults will be introduced, and different system responses are anticipated [4]. Consequently, characterising LVDC short-circuits is significantly important, as appropriate equipment ratings and correct protection operation in terms of settings and selectivity are highly based on accurate short-circuit characterisation.

To date, there are no comprehensive standards for how to characterise LVDC short-circuit currents, and how to protect LVDC networks optimally [1]. The most widely used standard for DC short-circuits characterisation is IEC 61660 [5]. This standard has been mainly introduced for providing a calculation method for DC short-circuit currents in auxiliary DC installations in power plants and substations. IEC 61660 introduced an approximate DC short circuit current form to identify the transient and steady-state courses of a DC fault current profile in such auxiliary DC systems. LVDC power networks will have different and larger configurations and several different sources in comparison to these auxiliary systems. Consequently, it may not be appropriate to use IEC 61660 to calculate the values and forms of short-circuit currents in LVDC networks. Inaccurate short-circuit estimation would have a negative impact on the system performance under faults. Therefore, this paper evaluates the effectiveness of using IEC 61660 to characterise DC short-circuit currents in an LVDC network. The paper also investigates the potential benefits that LVDC distribution systems will offer for future power systems.

POTENTIAL BENEFITS OF AN LVDC

Due to its better controllability, and the possibility of implementing a higher voltage as allowed by EU (LVD) 2006/95/EC [7], an LVDC system has the potential to overcome some of the traditional LV system constraints [6]. Using LVDC with a higher voltage will reduce the impact of thermal limits, and increase the transmission power capacity of the networks [4]. This in turn will increase the possibility of expanding an existing system to supply a higher load without uprating the MV/LV transformer or adding new cables. The results of the research in [8] have shown that with the same voltage drop and the same cables (as used for 3-phase AC), a unipolar 1.5kV LVDC system can transmit 16 times more power than a 0.4kV AC system. Also, with a higher voltage rating, smaller losses in voltage and power will be experienced in DC feeders. In DC systems, the inductances have no effect on the voltages during normal operation, and the reactive current component which increases the magnitude of the current resulting in more losses, does not exist. In addition, the skin effect that normally increases the cable resistance in AC networks has no impact in DC cables. For new installation, all these positive points would increase the opportunity of using smaller cables with lower costs, and indirectly reduce the environmental impact of energy production. For example, up to 20% cable cross section can be reduced in each conductor when the cable is used to deliver the power by a DC grid instead of AC [9]. As another example of LVDC potential benefits, the very recent research conducted by the Electric Power Research Institute (EPRI) has concluded that using 380V LVDC to supply small and medium sized data centres instead of traditional distribution systems will improve the electrical efficiency up to 15% and with 36% lower lifetime cost [2][10]. Also, ABB has reported that the recent 1MW 380V DC network which was built in 2012 to supply a medium sized data centre was 10% less than the AC system in terms of capital costs [2].

An LVDC distribution system will also facilitate in a better way the connection of microgeneration and storage devices in comparison to traditional LV systems [11]. Most microgeneration and energy storage devices generate DC outputs. These devices can be connected directly or by DC/DC converters to LVDC networks. An LVDC network is also more suitable for the connection of large numbers of DC power consuming devices. The need for using large numbers of adapters to convert 230V AC to lower voltages and then convert into DC can be removed, resulting in reduced losses and saved cost [9]. The transformers used for the adaptors of consumer electronic equipment can cause considerable losses during stand-by mode. As stated in [9]and , according to the International Energy Agency (IEA), in the EU, the total domestic consumption of electronic equipment in stand-by mode has been estimated to be more than 36 TWh/year [9]. Therefore, many conversion steps for sources and loads can be reduced, and the losses and costs can also be reduced in comparison to the equivalent AC system [12].

TEST NETWORK

A typical LV distribution network based on actual data has been selected as the test network. The network data has been derived from information provided within distribution long term development statements (LTDS) by the distribution network operators and manufacturers of distribution equipment [13]. The AC medium voltage (MV) 11kV network has been modelled using an ideal voltage source and impedance with X/R=5 scaled in accordance to IEC60909 [14] to provide a fault level of 156MVA at the ring main unit (RMU) supplying the secondary substation. An impedance of 4.5% and rating of 0.5MVA has been taken for the secondary substation transformer (11/0.433kV). The LVDC network is interfaced to the AC system by IGBT-based Voltage source converter (VSC) with smoothing capacitor C=6750µF. The VSC has the ability of allowing the transfer of the power in two directions between AC and DC systems. This is important when LVDC is integrated with local generation, and the power is exchanged between the AC and DC system. However, the VSC will introduce new losses to the network, and its configuration has a direct influence on the AC and DC system performance during fault conditions [15]. The VSC normally consists of controllable IGBT switches and uncontrollable antiparallel diodes plus smoothing capacitor. The smoothing capacitor on the DC side will also contribute to the DC short-circuit. The LVDC test network is assumed to be unipolar network providing 612V DC between the two poles. The parameters of the used LV cables are Rdc=0.164Ω/km, and L=0.24mH/km.

Figure 1 shows the single line diagram of the test network used for the studies. A short-circuit fault between the two DC poles is applied at four different locations on the DC feeder. Fault1, shown as F1 in Figure 1, is applied at the terminals of the converter, and the other faults F2-F4 are applied at 500m, 1km, and 2km away from the converter terminals respectively. These fault scenarios have been applied to capture DC fault current features for different fault locations and because the correction factors used in IEC61660 change when the fault path impedance is changed. At each fault location, the DC fault is characterised in accordance with the IEC61660 standard and by simulation studies, and a comparison is thus made to evaluate the effectiveness of using IEC61660 for the short-circuit characterisation of LVDC.

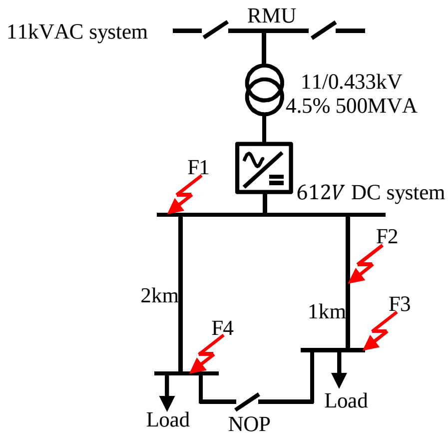

Figure 1: LVDC network model

LVDC SHORT-CIRCUIT CHARACTERISATION IN ACCORDANCE WITH IEC 61660

IEC61660 takes into account the following components as DC fault sources; rectifier bridge, stationary batteries, smoothing capacitors, and DC motors [4]. Each DC source will supply a different profile of fault current. However, IEC61660 has introduced a typical short circuit current form as given in equations (1) and (2) to represent approximate transient and steady-state features of DC short-circuit current that could be supplied by all such sources [4][5].

$$i_1(t) = i_p \frac{1-e^{-t/\tau_1}}{1-e^{-t/\tau_1}} \qquad 0 \le t \le t_p \qquad (1)$$

$$i_2(t) = i_p[\left(1 - \frac{I_k}{i_p}\right) e^{\frac{t-t_p}{\tau_2}} + \frac{I_k}{i_p}] \quad t \ge t_p \qquad (2)$$

Where I_k is the steady-state short-circuit current, i_p is the peak current, t_p is the time to peak, and $\tau_1$and τ_2 are the rise and decay time constants. In the case of faults, the above equations can be directly used to identify the DC fault current supplied by each individual source. The total DC fault current is then the aggregate of the individual fault contributions.

When IEC61660 is used to characterise the DC short-circuits current of the test network in Figure 1, there are no DC motors or batteries, and only the main converter and smoothing capacitor are considered. The DC fault current contributions from the converter and the capacitor to each fault location as shown in Figure 1 are calculated by IEC61660 as follows, and the total DC short-circuit current is calculated by adding both currents are included in figures (2-4).

Converter characterisation

By using the equivalent circuit diagram given as figure 6 in the IEC61660 to represent the test network shown of this paper, the DC steady-state fault current I_k supplied by the converter can be calculated from the following formula [5].

$$I_k = \lambda_D \frac{\sqrt{2} C_v V_n}{\sqrt{3}\sqrt{R_g^2 + X_g^2}} \quad (3)$$

R_g and X_g are the equivalent resistance and reactance of the upstream AC grid. V_n is the nominal rms AC L-L voltage, and C_v is the voltage factor. The voltage factor as explained in IEC61660 is used in accordance to IEC60909 [14]. $C_v = 1.1$ to give the highest short circuit [14]. λ_D is a corrective factor that reflects the impact of DC resistance on the steady-state fault current. The value of λ_D at each fault location can be obtained from the curves of figure 7 in IEC61660 [5]. λ_D depends on the values of R_{dc}/R_g and R_g/X_g. R_g/X_g of the AC system equals to 0.2. R_{dc} changes in accordance to the fault location on the DC side. When $R_{dc} = 0$ for the fault F1 as shown in Figure 1, $\lambda_D = 1$, and for remote faults F2, F3, and F4 as the R_{dc} increases, the values of $\lambda_D < 1$. The value of I_k is calculated from (3) for each value of λ_D. The peak short-circuit current $i_p = K_D I_k$, where the factor K_D depends on L_{dc}/L_g, and $\frac{R_g}{X_g}(1 + \frac{2R_{dc}}{3R_g})$ and can be obtained from the curves of figure 8 in IEC61660 [5]. Using the test network parameters, the values of K_D have been found for all the faults to be larger than one. If $K_D \geq 1.05$ and $L_{dc}/L_g < 1$ as mentioned in IEC61660 standard, the time to the peak t_p can be calculated from this formula $t_p = (3k_D + 6)ms$. Based on the K_D values, the peak current i_p for each fault location is calculated. The rise and decay times of the converter transient fault current have been calculated from the following equations [5]:

$$\tau_1 = 2 + (K_D - 0.9)\left(2.5 + 9\frac{L_{dc}}{L_g}\right) \quad ms \quad (4)$$

$$\tau_2 = 2/\left[(R_g/X_g)\,(0.6 + 0.9\,R_{dc}/R_g)\right] \quad ms \quad (5)$$

Based on this information, the DC short-circuit current profile supplied by the converter has been calculated from equations (1) and (2).

Capacitor characterisation

The steady-state fault current of the capacitor $I_{kc} = 0$. The capacitor peak fault current can be obtained from $i_{pc} = K_C(V_C/R_{dc})$, where V_C is the capacitor voltage before the fault, and is equal to the $V_{dC} = 612V$. The factor K_C and the peak time of the capacitor fault current t_{pc} have been calculated from the curves of figure 12 and 13 in IEC61660 for each fault location, and i_{pc} has been determined. The rise and decay time constants can be calculated from $\tau_{1c} = K_{C1} t_{pc}$, and $\tau_{2c} = K_{C2} R_{dc} C$. C is the capacitance of the smoothing capacitor and equals to 6750µF, and K_{C1} and K_{C2} have been obtained from figure14 and 15 in IEC61660. Then the transient current contribution from the capacitor has been calculated from equations (1) and (2).

MODELLING AND SIMULATION STUDIES

The PSCAD/EMTDC simulation programme was used to model the same test network. When the fault is initiated, the IGBTs are normally blocked for self-protection, and the charged smoothing capacitor will immediately act as a significant DC fault source, and starts feeding the fault. When the current peak is reached, the capacitor is completely discharged, and the capacitor current reduces to zero. Then the antiparallel diodes act as a bridge rectifier and continue supplying the fault during the transient [15]. After the transient dies out, the steady state DC fault current will be supplied by the grid. Therefore, in order to model these three short circuit phases (i.e. the capacitor discharge phase, the anti-parallel diodes conduction phase, and the grid current-fed phase), the converter has been modelled as six pulse rectifier with smoothing capacitor on the DC side, since the IGBTs switches will be inoperative during the short circuit on the DC side. Such a model will also give the worst DC fault scenario where no converter control action is implemented, and the highest DC short circuit can be identified. The same fault scenarios as shown in Figure 1 are considered in the simulation studies, and the output results are included in Figure 2 to Figure 4 with those calculated by application of IEC61660.

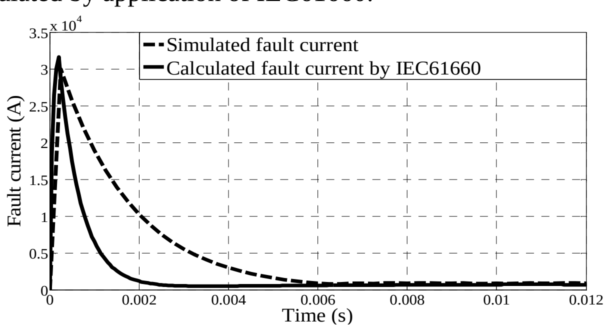

Figure 2: DC fault at the terminals of the converter

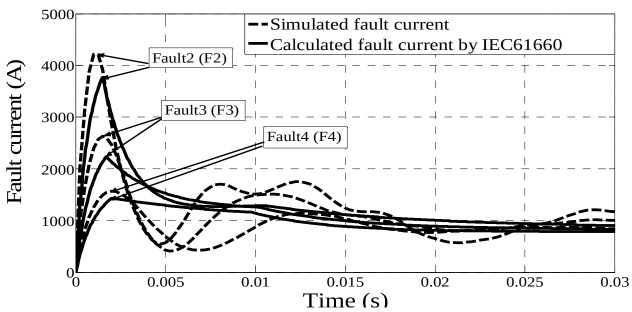

Figure 3: DC remote faults at different locations

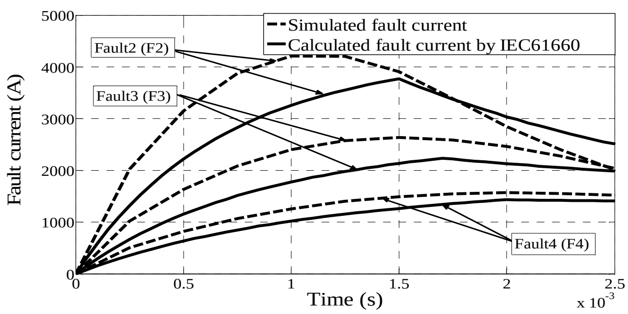

Figure 4: The rise times of DC remote faults

ANALYSIS OF THE RESULTS

For the fault at the converter terminals which is equivalent to the main DC bus of an auxillary system in IEC61660, the fault path impedance is zero ($R_{dc}/R_g = 0$), and the corrective factor $\lambda_D = 1$. In this case the approximate mathematical model provided by IEC61660 is still effective for calculating the peak of the capacitor discharging current as shown above in Figure 2. However, the decay time of the calculated transient current is noticeably faster than the simulated value.

For remote faults ($R_{dc}/R_g > 0$ and $\lambda_D < 1$) when corrective factors as recommended by IEC61660 are applied, the discharging peak currents as given in Figure 3 are lower than the actual values by almost 10%. Also the results from the simulation for remote faults have shown that the DC fault current has a sinusoidal form decaying exponentially due to the nonlinear RLC circuit with decay time larger than the calculated value. The damping factor and the resonant frequency of the equivalent RLC circuit which depend on the capacitor, and the equivalent resistance and inductance from the VSC to the fault point determine the type of the transient response of the discharge current. For all applied remote fault scenarios the calculated and simulated steady-state values are very close with error less than 8%. This means that IEC61660 could be still effective for calculating the steady-state of the DC short-circuit faults in LVDC networks, and less accurate for characterising the capacitor discharging currents. Therefore, if an LVDC network is designed in accordance to IEC61660 calculations, the network in reality will experience a higher current with longer decay time. This can be an issue in terms of power electronics and equipment rating. Also, the rise time constants of the simulated results as shown in Figure 4 are smaller than the calculated values. This can lead to fault detection issue if the detection threshold values are based on the IEC61660 calculations.

CONCLUSIONS

LVDC distribution systems have the potential to bring benefits to future electricity grids. Overall cost and losses are expected to be reduced, and system efficiencies improved. Also better controllability of generation and use of energy can be offered, resulting in reducing the environmental impacts of energy usage and production. In order to conveniently understand such schemes' fault behaviour and support design, the use of IEC has been evaluated in this paper. The evaluation is conducted by comparing the obtained results from IEC61660 with the results from detailed simulation in PSCAD/EMTDC. The output results have shown that the IEC 61660 is still effective for calculating the steady-state DC short circuit, and it is less accurate for characterising the transient DC short-circuit current when the LVDC network is faulted. The calculated results from IEC61660 are more conservative compared to the simulated results, where the peak of the discharging current is almost 10% less than the simulated value, and the decay time is faster than the simulated oscillating decay time. The source of the error is that the IEC61660 corrective factors are derived on an experimental basis for DC auxiliary installations, and not for larger networks.

Acknowledgments

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