PROTECTION AND EARTHING REQUIREMENTS OF LV AC AND DC DISTRIBUTION NETWORKS INTERFACED BY A SMART TRANSFORMER

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ABSTRACT

Electrification of more transport and heat will place increasing demand on LV networks for which they have not been designed. This can potentially overload MV/LV transformers and LV cables, and may result in voltage drops outside statutory voltage limits. Deployment of solid state smart transformers (STs) at secondary substations has recently been considered as an alternative approach to address such challenges. However, their deployment will lead to a radical change in the operation of associated LV networks and, in particular, protection systems. Therefore this paper investigates in detail the impact of a smart transformer deployment at a secondary substation on the performance of conventional MV/LV protection, and provides recommendations on suitable earthing and protection for LVDC and hybrid AC/DC distribution networks interfaced by a smart transformer.

INTRODUCTION

The growth of low-carbon technologies (LCTs) such as distributed renewables, electrical storage, and electrical vehicles (EV) has increased the need for improving the infrastructure and operation of existing low voltage (LV) distribution and their associated substations [1][2]. Key operational parameters such as substation loading, fault levels, and LV voltage profiles are likely to be impacted. This is because LV distribution networks operate within relatively tight voltage limits, and electrification of more transport and heat will place increasing demand with the potential to overload MV/LV transformers and LV cables.

In response to such challenges, SP Energy Networks' LV Engine project has a key objective to design and trial the deployment of an electronic smart transformer (ST) within power distribution secondary substations [3]. In comparison to conventional transformers, STs have the potential to provide more effective voltage control, independent real and reactive power control, and bidirectional real power control. The ST deployment will be trialled within five different schemes, three of which will provide conventional 0.4kV AC supply with different network configurations, while the remaining two provide LV direct current (LVDC) and hybrid DC/AC supply.

From protection perspective, the ST will provide reduced fault currents and potentially enable the use of equipment with lower ratings. However, its deployment at secondary substations will fundamentally change fault profiles on the associated LV networks. STs with suitable controls and configuration can have the ability to limit and block fault currents from the AC grid for the purpose of self-protection against internal and downstream faults. Since the majority of existing LV networks are protected by simple overcurrent protection, reduced LV fault levels caused by the ST may impact fault detection, operating time, and selectivity of the overcurrent-based protection. Therefore, it is important to understand the impact of ST installation on existing MV/LV networks' protection. This paper investigates through detailed discussion and simulation studies the impact of an ST deployment on the performance of conventional MV/LV protection. The paper provides recommendations on suitable earthing and protection for LVDC and hybrid AC/DC networks interfaced by an ST.

IMPACT OF SMART TRANSFORMER ON LV PROTECTION PERFORMANCE

Impact on fault level and protection coordination

STs normally operate with reduced fault levels due to their power electronics limited short-circuit capabilities. Such constraints can potentially impact overcurrent protection operating time and coordination [4]. Another issue related to a reduced protection speed is the cause of severe voltage sags with increased duration. This can create a power quality issue on the customer side and stability issue on the ST side. Severe voltage sags can also be a problematic to any distributed generation connected to the network.

Impact on LV earthing schemes

When an ST is installed, the earthing requirements will be different in accordance to the ST outputs. For STs with only AC outputs, typical TN-S or TN-C-S earthing can be used, and the PE can be connected to the mid-point of the ST last stage inverter. But, for STs with LVDC outputs, the earthing will be different, and the following aspects should be considered. (1) Safety: on the customer side, TN-S system can only be used with certain voltage levels (<±380Vdc if electronic DC-RCDs are used) [5]. Above these voltages, it may require double isolation or floating IT earthing systems. (2) Corrosion: it is important to consider the avoidance of corrosion impact on any metal surfaces connected to the LVDC earth. (3) Common-mode noise and parasitic capacitors: when one ST provides AC and DC, common PE between the two systems could potentially lead to common-mode noise currents [6].

ST immunity levels to remote faults

There is a need to understand the compatibility between existing protection performance and immunity levels of the ST to remote faults. The BS EN50328 [7] has identified a number of immunity levels associated to converters installed at AC-DC substations for traction systems [7]. These include: redundancy, functional (no performance), and tripping (disconnection of services). These may also be useful to consider for the control design of the ST. Remote faults on adjacent circuits may impact the functional level of the ST, but should not trip the ST. Due to the lack of standards and studies, ST immunity levels to remote faults remain an open question. This may require further stability studies and it is out of this paper scope.

EARTHINGS OF ST-INTERFACED DISTRIBUTION NETWORKS

This section discusses earthing arrangements for different distribution networks interfaced by an ST. These include ST with AC outputs, DC outputs, and hybrid AC/DC outputs. A typical non-modular three-stage ST is used in this paper for the network with AC outputs, and two-stage ST is considered for the dedicated DC outputs [4]. A two-level voltage source converter (VSC) is used for stage one to convert 11kV AC to 20kV DC, and a DC-DC dual active bridge (DAB) converter with a galvanic isolation is considered for stage two to provide an LVDC. The last stage uses two-level VSC to convert LVDC to LVAC.

Earthing of an ST-interfaced LVAC network

Figure 1 presents a layout of the ST connected to a 3-phase LVAC network with a TN-C-S earthing. The LV system earth point will be connected to the mid-point of the ST stage-three inverter. When a fault occurs on the customer side of the LVAC, the fault current will flow in the ST through controlled electronic switches, and will be limited by the controller to the ratings of the switches. The high frequency transformer (HFT) of the DC-DC converter will ensure the circulation of the fault currents within the LV networks and not to be passed to the MVDC and MVAC sides of the ST.

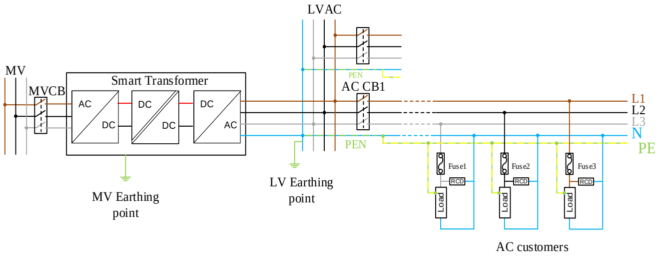


Figure 1: ST-interfaced AC network earthing

Earthing of an ST-interfaced LVDC network

In this case, three key earthing criteria have to be met. (1) Enabling LVDC earth fault detection. (2) Providing suitable earth for the substation metal surfaces (e.g. ST tank). (3) Preventing DC current leakage and stray currents under normal operation to avoid electrolytic corrosion to metal surfaces [8]. These are similar requirements provided by BS7430:2011 for DC traction systems [9]. To meet such criteria, two different earthing systems can be considered, an IT or a TN configuration. The IT earthing has been used in a number of existing LVDC trials in Finland and South Korea [10][11]. However, with IT earthing is difficult to protect against earth faults, and an insulation monitoring device (IMD) to monitor the insulation between the poles and the earth is required.

To use LVDC TN earthing and eliminate stray currents, only TN-S system can be used. The PE cannot be directly connected to the negative pole (L-) in 2-wire LVDC system and to the mid-point (M) in 3-wire LVDC system. The earth fault path needs to be provided only during the fault to enable earth faults detection. This can be achieved by using earthing diodes as in traction systems [12] or through capacitive earthing [13], or by using both diodes with a capacitor in parallel (see Figure 2.)

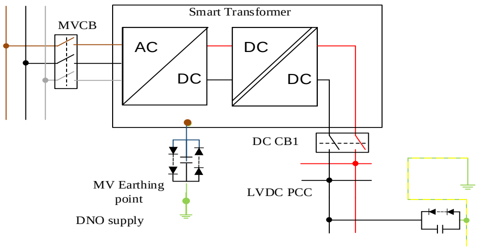


Figure 2: 2-wire (uni-polar) LVDC earthing

Earthing of an ST-interfaced AC/DC network

The earthing of an ST-interfaced hybrid AC/DC network is a combination of the two previous earthing schemes. The LVAC can be configured as a TN-C-S and the LVDC as a TN-S as illustrated in Figure 3.

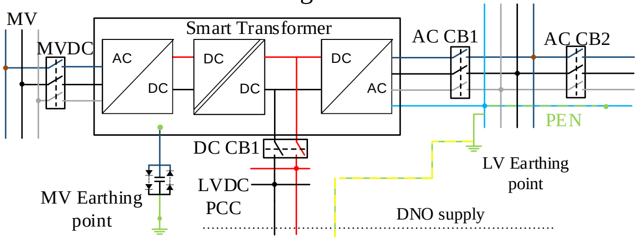


Figure 3: Earthing of a hybrid LVAC/LVDC

TEST NETWORK MODEL

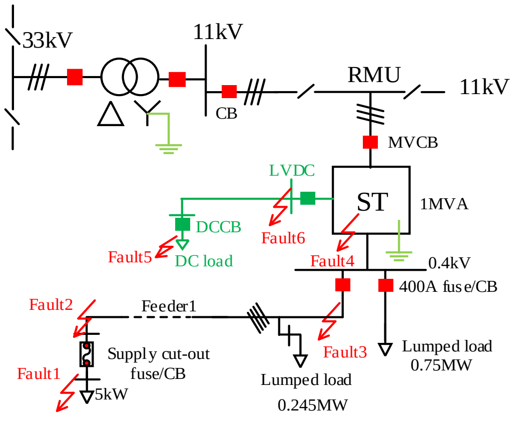


Figure 4: Test network layout

This section investigates through modelling and simulation studies the impact of the ST deployment on existing protection of MV/LV distribution networks, and identifies the required changes that need to be adopted for secure and safe operation. A test network is presented in Figure 4 and developed using PSCAD tool as follows.

AC grid supply point (GSP) model

The AC grid is modelled as a 33kV voltage source behind an equivalent impedance to provide equivalent fault level of an actual urban network example. 15MVA transformer is selected to step down the 33kV GSP to 11kV at the ring main unit (RMU). The transformer short circuit impedance (Zpu) is calculated to provide 9.14kA current at the RMU. See Table 1 for the parameters.

Table 1: AC grid supply parameters [14]

	V	MVAsc	Isc	X/R	Zs
GSP	33kV	1074.57MVA	17.79kA	10	1.013Ω
RMU	11kV	182.47MVA	9.14kA	8.6	0.66314Ω

Smart transformer model

The ST is modelled as a 1MVA non-modular three-stage Figure 5 [4][19]. The rectifier AC-DC stage-one and the inverter DC-AC stage-three are modelled using a typical two-level VSC. The rectifier and the inverter are interfaced by a DC-DC dual-active-bridge (DAB) stage-two converter with an isolation transformer.

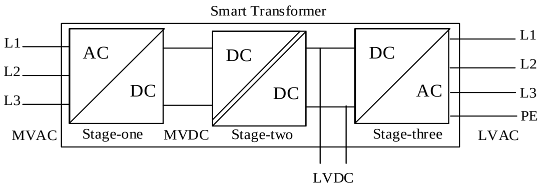


Figure 5: Layout of a three-stage smart transformer

Each converter is modelled as a detailed switching model and fully controlled using vector control in the synchronously rotating d-q reference as given in Figure 6. The stage-one VSC is modelled as a DC voltage and reactive power regulator. Whilst stage 3 VSC is modelled as a real power and AC voltage regulator. The stage-two DC-DC DAB converter is modelled to regulate the DC voltage on the LVDC link. A simplified PI-based DC voltage controller as presented in Figure 7 is used for controlling the DC-DC DAB converter. The key ST model parameters are listed in Table 2 and Table 3.

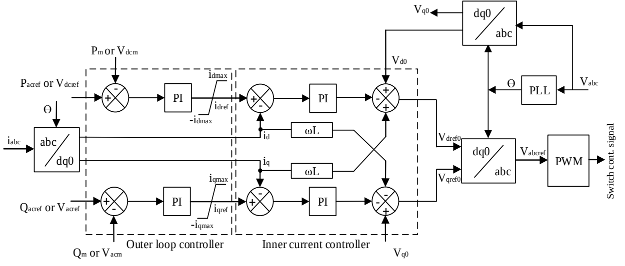


Figure 6: Block diagram of VSC vector control

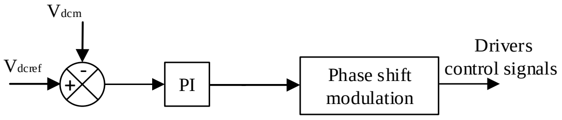


Figure 7: Simplified control of the DC-DC DAB [15]

Table 2: ST stage 1 and stage 3 parameters

	Vin	Vout	$L_{\_phase}$	$C_{\_smoothing}$	$F_{\_switching}$
Stage1	11KVac	20kVdc	0.15H	250 µF	2kHz
Stage3	1.5Vdc	0.4kVac	0.88mH	10mF	2kHz

Table 3: ST DC-DC DAB converter parameters

	Vin	Vout	$L_{\_HFT}$	$F_{\_switching}$
Stage2	20Vdc	1.5Vdc	0.2pu	20kHz

Overcurrent protection model

The LV protection is modelled as an overcurrent using extreme inverse time-current characteristic for modelling LV fuses and inverse time-current characteristics for mechanical CBs. An integrating function of the current passing through the breaker/fuse with respect to time is used to calculate the total operating time of the protection device in accordance to the IEC60909 [16].

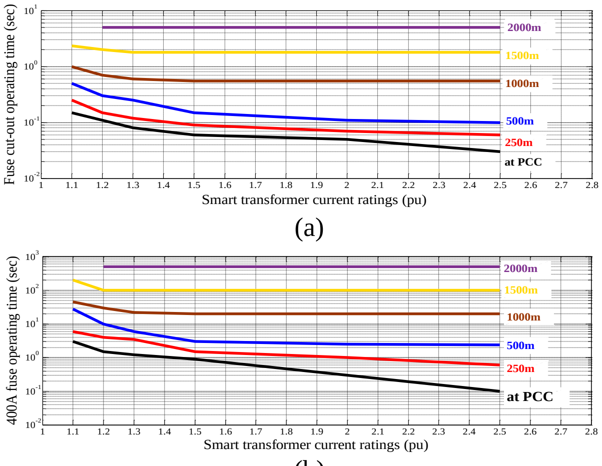
SIMULATION STUDIES

Protection against short circuit faults on the LVAC network of the smart transformer

This simulation task achieves three main objectives. (1) To identify the minimum required prospective fault current (PFC) that the ST with different fault current ratings should provide to operate downstream overcurrent protection. According to [17], the allowable disconnection time of the supply must not exceed 5sec. (2) To identify the maximum ST PFCs for faults at the end of main LV feeders (before the customer connection). (3) To identify the impact of the ST PFC contributions on the protection speed of the main feeders' protection (e.g. 400A fuse/CB).

In this case, a 0.75MW lumped load is connected to the LVAC main bus and one feeder shown as feeder 1 in Figure 4 is modelled in detail and rated to 0.25MVA. The feeder is assumed to be fully loaded and supplies 0.245MW lumped load and a three-phase 5kW customer load. A solid three-phase-to-earth fault (shown as fault1 in Figure 4) is applied, and the maximum length of the LV cable to ensure the operation of the supply main cut-out fuse/CB (100A rating) within 5sec is identified. The fault is then applied at different locations, and the maximum PFCs of the ST with different short-circuit current ratings are identified. The ST is set to provide 1.1 per unit (pu), 1.2pu, 1.3pu, 1.5pu, 2pu, and 2.5pu of the base current (1.443kA), and the fault locations are assumed to be at the main LVAC point of common coupling (PCC), 0.25km, 0.5km, 1km, 1.5km, and 2km to represent different distances of the customer in respect to the ST location.

As shown in Figure 8, ST with current ratings >=1.2pu can provide enough current (0.63kA) to operate supply cut-out fuses/CB within 5sec for a network with feeders up to 2km in length. However, this will require up to 500sec for the main feeder 400A fuse/CB to operate. Having a fault with such relatively long time may create safety issues close to the customer side. This can also lead to rise of voltage unbalance on the customer side for almost 8 minutes. The capability of the ST to operate under such faulted condition for such period of time depends the thermal limitation of the ST electronic switches. The thermal limitation factor is not considered in the studies, but in general power electronics can operate with currents >1pu of their full load for a few seconds but this depends on the ST rating [4].



(a)

(b)

Figure 8: Protection speed vs different ST current ratings: (a) 100A fuse/CB, (b) main feeder 400A fuse/CB

Protection of ST against internal faults

Conventional MV/LV transformers are protected against internal electrical faults by breakers located on their MV side. To test the suitability of the MV breaker to protect the ST against internal faults, a pole-to-pole fault is applied on the internal MVDC and LVDC links of the ST. The response of the breaker is then simulated for each case. For the MVDC link internal fault and as shown in Figure 9, the stage-one VSC converter allows the flow of fault current high enough to operate the breaker on the MV side within standard time. However, for faults on the ST LVDC internal link, the current on the primary side of the high frequency transformer (HFT) of the DAB converter will flow through the converter controlled switches. This has reduced the currents on the secondary side of the HFT (see Figure 10) to the level that cannot operate the MV CB.

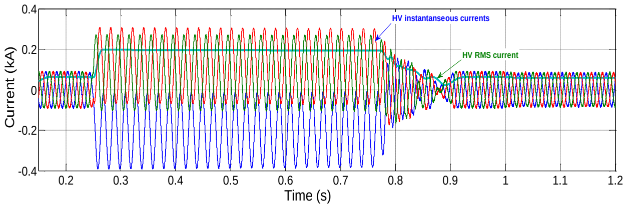


Figure 9: MVDC internal link fault profiles

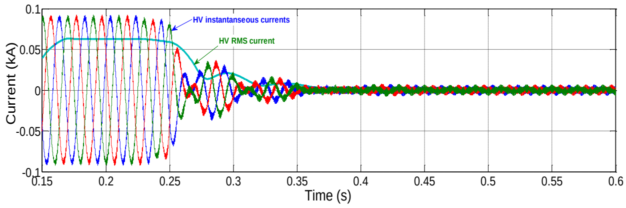


Figure 10: LVDC internal link fault profiles

Testing the performance of proposed earthing

ST-interfaced network with AC outputs only

A single-phase-to-earth fault shown as fault 1 in Figure 4 is applied on the customer side. The customer is assumed to be located 250m far from main LVAC bus, and the ST is selected to provide up to 120% of the full load current for downstream faults. The simulation results are presented in Figure 11. In this case, 1.6kA fault current flows in the PEN conductor, and this allows the supply fuse/CB to operate within 120ms. It is important for the control design of the ST to minimise the impact of any resultant unbalanced AC voltages caused by a single-phase-to-earth fault or due to the trip a single-phase customer following the fault to avoid increased levels of harmonics in the system.

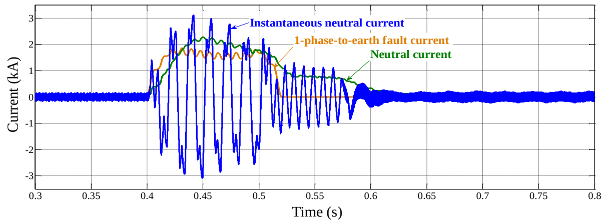


Figure 11: Earth and neutral current profiles against AC single phase earth fault applied on the AC customer side

ST-interfaced network with DC outputs only

A pole-to-earth fault is applied at two locations. One is on the customer side shown as fault 5 in Figure 4 and the other is on the supply side shown as fault 6 on the same figure. In each case, the fault is applied at 0.25sec and the DC breakers are set to clear the faults within 100ms to provide enough window to capture the key features of the LVDC fault profiles against the following requirements: no DC current leakage during normal operation, the earth fault path is provided only during earth fault conditions, and earth faults on the customer side circulate locally and do not propagate to the supply side and vice versa.

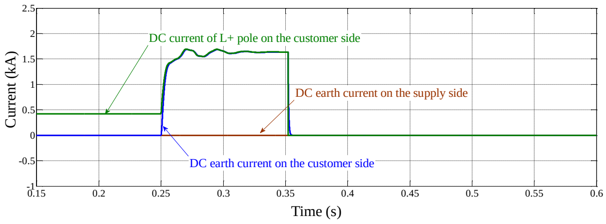


Figure 12: DC current profiles against pole-to-earth fault on the customer side

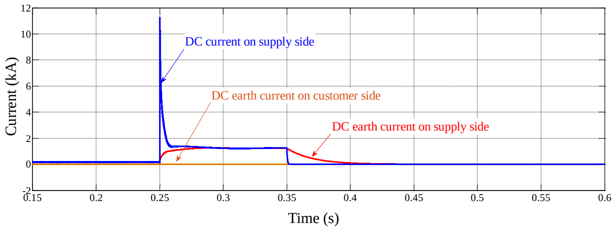


Figure 13: DC current profiles against pole-to-earth fault on the supply side

The simulation results as presented in Figure 12 and Figure 13 demonstrate that before the fault occurs, there is no DC earth current leakage due to the reverse-biased operation of the earthing diodes. When the fault is applied at 0.25sec and as shown in Figure 12, 1.64kA DC fault current flows in the earth path and circulates locally on the customer side. The results have also proven that the earth current on the supply side remains zero during the whole duration of the fault on the customer side. This is because the isolation transformer of the customer's DC-DC converter splits the customer earthing path from the supply earthing as required. This also ensures limited impact on the LVDC supply voltages and currents where the impact on the DC current on the supply side is insignificant during Fault 5.

CONCLUSIONS

The paper has investigated through detailed fault and protection simulation studies the impact of deployment of smart transformer at a typical distribution secondary substation on existing conventional overcurrent protection. It has been demonstrated that such deployment can impose a radical change in the nature of faults on the associated LV networks. Typical 1 MVA smart transformer with fault current rating ranges from 1.1 to 2.5 per unit of its full load current will reduce prospective fault levels at the point of common coupling (PCC) 8 to 15 times in comparison to a conventional substation. Such a significant change in the fault level has made a significant reduction in the speed of inverse time-current protection of the main feeders of the LV networks.

The paper studies have also proven that overcurrent-based MV CB is unlikely to trip for faults on the LVDC internal links of the smart transformer. More advance protection will be required to detect internal faults within the smart transformer and provide reliable and selective protection operation. For example, parameters such as under-voltage, rate of change of DC voltage, or rate of change of internal DC current may be considered.

In addition to these challenges, there is a need to radically change the earthing arrangement of LV networks on the supply and customer sides for smart transformers with LVDC outputs. The paper has provided and demonstrated a number of different earthing arrangements which can be considered to provide protection for safety, eliminate the risk of corrosion, and minimise the common mode noise.

Acknowledgments

This research work was supported by the SP Energy Networks as a part of the Ofgem Electricity Network Innovation Competition (NIC) LV Engine project.

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