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# Scalable Solid State Transformers (SSTs) for DC railway substations

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The Power Point Presentation will be made available after the conference.

## Abstract

DC railway substations may require different rated powers, input AC voltages and output DC voltages. Hence, current substation technology needs to be adapted to each application. To overcome this issue, the Solid State Transformer (SST) topology, which is inherently modular, can address the different applications with a single elementary power electronic building block (PEBB). In this paper, a methodology is proposed to define the optimal rated power and number of PEBBs. It results in a 94 kW PEBB with a 3.6 kV intermediate DC bus which leads to an oversizing ratio regarding normal operation comprised between 3.38 and 5.7 and a number of PEBBs per MW comprised between 36 and 60. A topology of the PEBB with a reconfigurable secondary bridge to address both 750 V urban and 1.5 kV suburban applications is also proposed. The power losses are similar to those obtained with dedicated secondary inverters sized specifically for either urban or suburban applications.

## 1 Introduction

Several voltage levels coexist for DC railway overhead lines or third rails, e.g. in Europe, either 3 kV or 1.5 kV for regional and suburban supplies, and either 1.5 kV, 750 V or 600 V for urban supplies [1]. These lines or rails are fed by railway substations connected to the distribution network, and supplied typically by voltages from 7.2 kV to 36 kV at either 50 Hz or 60 Hz, according to the country and the related standards [2]. The power levels of the substations varies also according to the application: typically from 1 MW to 4 MW for tramway or subway, and from 3 MW to 6 MW, for regional and suburban trains.

Current substations are generally composed of a low frequency transformer (LFT) and either a diode or thyristor rectifier [3]. The main advantages of these topologies are their high efficiency and reliability. However, these topologies are unidirectional and they are not modular. They have to be redesigned for each substation application, i.e. for each combination of power, input and output

voltage levels. Recently, new topologies, such as *HESOP<sup>TM</sup>* substations [3], were developed with an IGBT converter for energy recovery in braking mode.

To address bidirectionality and modularity issues, solid state transformer (SST) topologies, previously studied for on-board applications [4], are proposed to replace the LFT and rectifier [5] in urban and suburban substations. The general diagram of a three-phase to DC SST, formed by three single-phase SSTs with a common neutral point, is illustrated Fig. 1. Each single-phase SST is constituted by power electronic building blocks (PEBBs), in series on the AC side to withstand the medium voltage, and in parallel on the DC side to transmit the power to the DC railway line, i.e. in ISOP configuration. A PEBB is composed of a single-phase AC/DC converter, supplying a DC bus and connected to an isolated DC/DC converter, typically a dual active bridge (DAB) or a LLC resonant converter [5], [6]. The galvanic isolation is provided by a medium frequency transformer (MFT)

operating typically between a few hundreds of hertz and a few kilohertz.

The objective of this paper is to propose an elementary PEBB, sized to address all the main combinations of voltage and power of DC substations. It should also present a good compromise between efficiency, reliability, modularity and footprint.

The paper is organised as follow: in section 2, the use cases addressed in this study are presented. The methodology to choose the optimal power of a PEBB to address all the considered cases, and the results are developed in section 3. In section 4, a reconfigurable variant of the secondary bridge on the low voltage side of the PEBB is proposed and compared to a design with two inverters sized for each applications. Some conclusions and perspectives close the paper.

## 2 Studied cases

Both urban and suburban applications are considered in this paper. The parameters of the DC infrastructures and substations are listed in Table 1 according to European standards EN 50163 [1] and EN 50329 [7]. According to European standard [7], urban and suburban substations should be able to handle respectively 4.5 times their nominal current during 15 s and 3 times their nominal current during 60 s. The railway supplies are currently fed by substations connected to the distribution network. Depending on their locations, the substations can be supplied by various voltage. In this study, the most common values of equipment voltage ratings, i.e. either 12 kV, 24 kV or 36 kV are considered on the AC side of the SSTs [2], [8]. Both 50 Hz and 60 Hz distribution grid can be addressed by the same SST structures. Subsequently, the AC grid frequency will not be specified.

The considered PEBB topology is illustrated Fig. 2. A two level full bridge active front end (AFE) converts the input AC voltage into an intermediate DC voltage. An isolated DC/DC converter ensures galvanic isolation between the intermediate DC bus and the output DC bus connected to the overhead railway line, thanks to a MFT. In order to minimise the number of semiconductor devices, half bridges are considered both on the primary and secondary

Tab. 1: Parameters for the railway substations

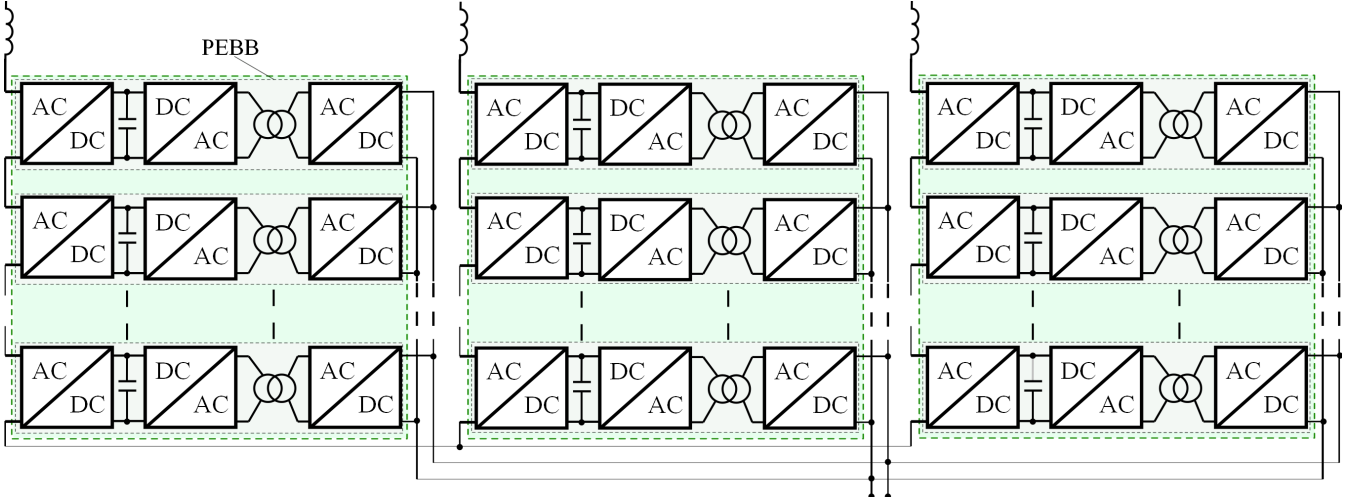
	Urban supplies	Suburban supplies
<b>DC voltages [1]</b>		
- Nominal values	750 V	1500 V
- Minimum values	500 V	1000 V
- Maximum values	1000 V	1950 V
<b>Railway substation nominal power</b>	1 MW 2 MW 2.5 MW	3 MW 4 MW
<b>Duty class &amp; overload factor [7]</b>	Class VII 4.5	Class VI 3
<b>Equipment voltages for distribution grids [2], [8]</b>		12 kV 24 kV 36 kV

side of the MFT. To address both urban and suburban applications, a MFT with two secondary windings and two inverters are considered. For urban applications, the two secondary windings of the MFT are connected in parallel (see Fig. 3a) and the DC/DC secondary bridges is composed of 1.7 kV Si IGBTs, to withstand output DC voltages between 500 V and 1000 V [1]. For suburban applications, the two MFT secondary windings are connected in series (see Fig. 3b) and the secondary bridge of the DC/DC converter is constituted of 3.3 kV Si IGBTs to withstand DC voltages from 1 kV to 1.95 kV [1].

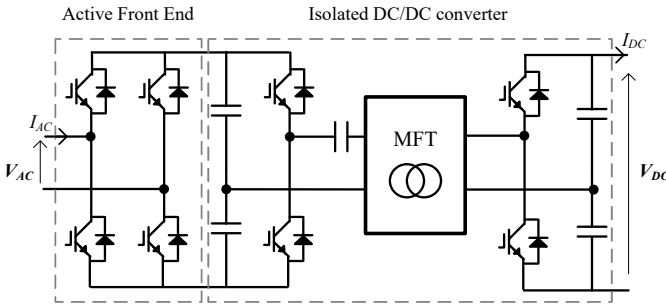
On the primary side of the MFT, i.e. for the AFE and the primary bridge of the isolated DC/DC converter, either 3.3 kV or 6.5 kV Si IGBTs are considered. Respectively, 1.8 kV and 3.6 kV intermediate DC buses are thus investigated.

## 3 Optimisation of the number and of the power rating of PEBBs

The first step to design an elementary PEBB addressing the various cases listed in Table 1 is the definition of its installed semiconductor power. It is determined by the minimum value, in every configuration, of the ratio between the installed power in the converter and its power in normal operation.



**Fig. 1:** General diagram of a three-phase solid state transformer railway substation (star connection)



**Fig. 2:** Diagram of the considered PEBB topology

To do that, the minimum number of PEBBs is calculated for every configuration in a wide range of PEBB powers. Each configuration is defined by four parameters listed in Table 1:

- the input AC voltage, related to the distribution network supplying the substation;
- the application, either urban or suburban, which defines the output DC voltage and the overload factor of the substation;
- the intermediate bus voltage, linked to the voltage rating of the semiconductor devices;
- the power in normal operation of the SST.

To withstand the AC medium voltage, a minimum number of PEBBs,  $N_s$ , should be connected in series.  $N_s$  depends on the intermediate bus voltage

$V_{int}$ , the AC voltage and the connection, either star or delta connection. It is calculated thanks to Eq. (1), where  $\widehat{V}_{AC}$  is the peak value of the AC voltage either phase-to-phase in delta connection and phase-to-neutral in star connection and  $m$  is a margin. One PEBB per phase is added for redundancy.

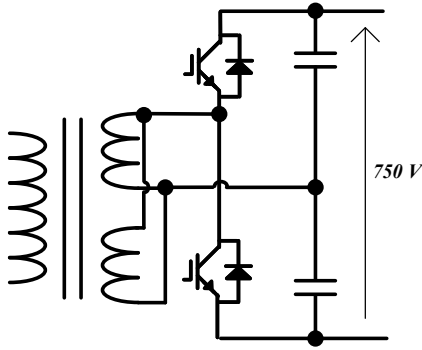
$$N_s = \text{ceil} \left( m \frac{\widehat{V}_{AC}}{V_{int}} \right) \quad (1)$$

Once the number of PEBBs in series per phase calculated, the number of SSTs in parallel,  $N_p$ , required to handle the maximum currents in overload is calculated in function of the power of a PEBB,  $P_{PEBB}$ , thanks to Eq. (2).  $P_n$  is the power of the substation in normal operation,  $k_{overload}$ , the overload factor and  $P_{PEBB}$ , the power of a PEBB. The total number of PEBBs in a SST, including redundancy,  $N_{tot}$  and the oversizing ratio,  $k_P$ , i.e. the ratio between the installed power and the power in normal operation of the substation, are then calculated using Eq. (3) and Eq. (4), respectively.

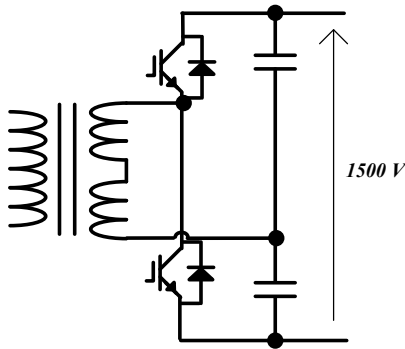
$$N_p = \text{ceil} \left( \frac{P_n k_{overload}}{3N_s P_{PEBB}} \right) \quad (2)$$

$$N_{tot} = 3N_p (1 + N_s) \quad (3)$$

$$k_P = \frac{N_{tot} P_{PEBB}}{P_n} \quad (4)$$



(a) In parallel MFT secondary windings for urban applications

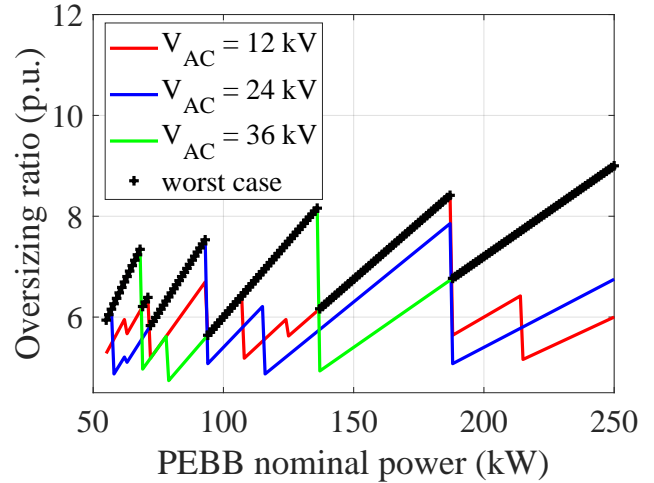


(b) In series MFT secondary windings for suburban applications

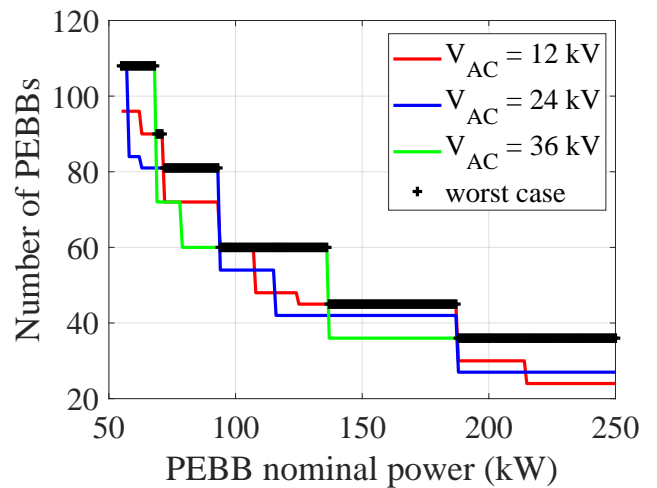
**Fig. 3:** Secondary bridges of the isolated DC/DC converter for 750 V and 1500 V applications.

For each configuration, the AC connection, either star or delta, is selected to minimise the number of PEBBs and the oversizing ratio. Then, the envelope curve of the maximum oversizing ratio in all configurations is drawn. Its minimum corresponds to the optimal power of a PEBB to globally minimise the installed power.

An example of the minimum oversizing ratios between star and delta connections and the corresponding numbers of PEBBs in a 1 MW urban substation with 3.6 kV intermediate buses is given Fig. 4 for the three input AC voltages and a power of a PEBB varying from 50 kW to 250 kW. The envelope curves are drawn in black. They represent the maximum oversizing ratio and maximum number of PEBBs in a 1 MW urban substation with a 3.6 kV intermediate bus.



(a) Oversizing ratio vs power of a PEBB

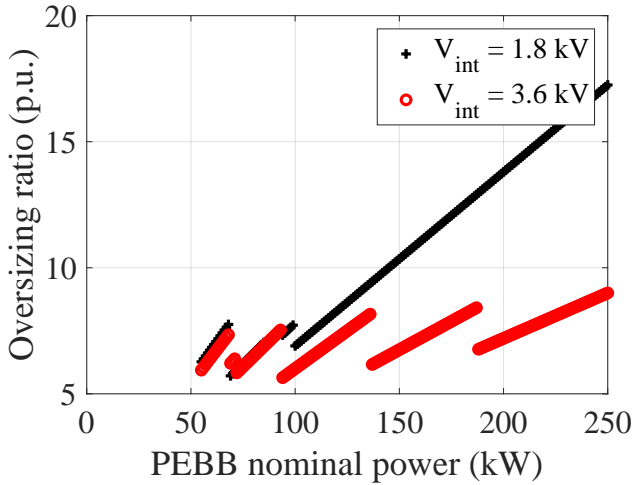


(b) Number of PEBBs vs power of a PEBB

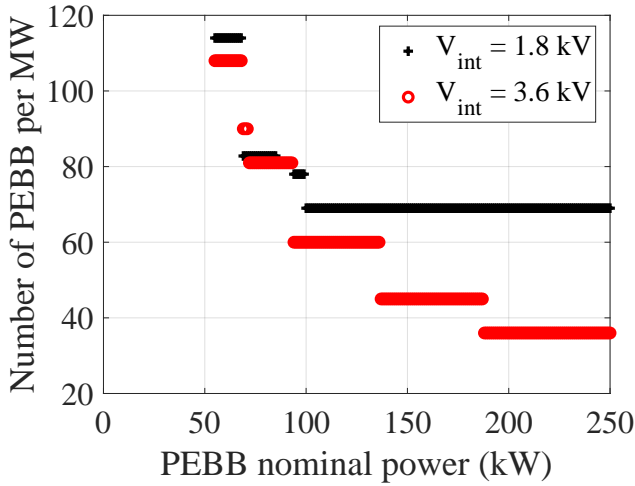
**Fig. 4:** Results for a 1 MW urban substation with 3.6 kV intermediate buses and 750 V output DC voltage.

To select the optimal power of the elementary PEBB, the same process is repeated for every substation configuration. For both intermediate bus voltage values, the resulting envelope curve of the maximum oversizing ratio for all configurations is drawn Fig. 5a. As the power of the substations varies from 1 MW to 4 MW, the maximum number of PEBBs per SST is divided by the nominal power of the substation (see Fig. 5b).

For a 1.8 kV intermediate bus, with 69 kW PEBBs, the oversizing ratio and the number of PEBBs per megawatt are insured inferior or equal to, respectively, 5.71 and 82.8, in every configuration. For a 3.6 kV intermediate bus, with 94 kW PEBBs,



(a) Maximum oversizing ratio for all configurations vs power of a PEBB



(b) Number of PEBBs per MW vs power of a PEBB

**Fig. 5:** Results for 1.8kV and 3.6kV intermediate DC buses including all configurations listed in Table. 1.

the oversizing ratio and the number of PEBBs per megawatt are insured inferior or equal to, respectively, 5.64 and 60, in every configuration. In the best configurations, the minimum oversizing ratios and numbers of PEBBs per megawatt are 3.31 and 48 for 69kW PEBBs with 1.8kV intermediate buses and 3.38 and 36 for 94kW PEBBs with 3.6kV intermediate buses.

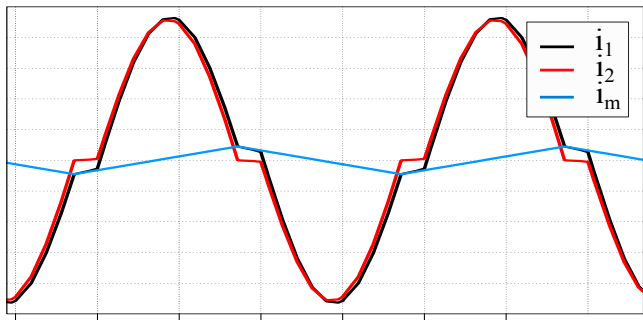
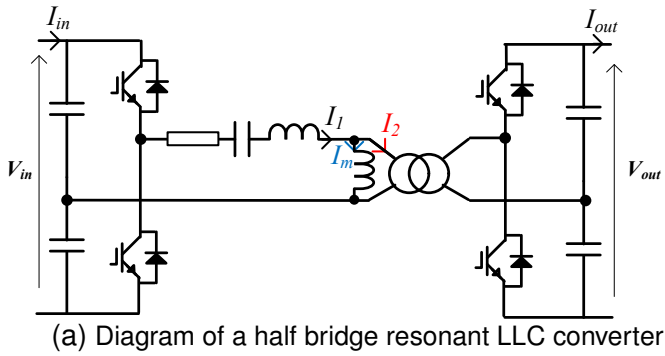
## 4 Comparison of two PEBB designs

In order to minimise the oversizing and the number of PEBBs in every SST configuration, a 94 kW PEBB with an intermediate bus at 3.6 kV is selected. As precised in section 2, two different bridges are designed for the secondary of the MFT, in order to avoid oversizing the semiconductor devices, either in voltage for urban applications, or in current for suburban applications.

The considered isolated DC/DC converter topology is a resonant LLC converter with half bridges to handle the low current ratings (see Fig. 6a). It has been chosen to maximise the efficiency, based on previous studies [6], [9]. In this topology, only one bridge is controlled by square waves (primary bridge in normal operation and secondary bridge for energy recovery), the second one operates as a diode bridge. The resonant frequency of the circuit formed by a capacitor and the leakage inductance of the MFT is set slightly higher than the switching frequency in order to operate in discontinuous conduction mode (DCM) (see Fig. 6b). Both zero voltage switching (ZVS) and zero current switching (ZCS) can be achieved with this topology. However, special care must be dedicated to the magnetising inductance of the transformer, in order to ensure a magnetising current sufficient supporting ZVS during turn-on [6], [10].

A variant of the DC/DC converter, illustrated Fig. 7, is proposed for a more modular PEBB. It consists in replacing the two secondary bridge designs by two half bridges using 1.7 kV Si IGBTs, connected to each secondary winding of the MFT and each supplying a 750 V output DC bus. For urban applications, they are connected in parallel on the DC side (see Fig. 7a). For suburban applications, they are connected in series on the DC side (see Fig. 7b). Thus, only half the power of the PEBB goes through each half bridge and only two different semiconductor devices (6.5 kV Si IGBTs between the AC input (distribution grid medium voltage) and the MFT, and 1.7 kV Si IGBTs between the MFT and the DC output (railway overhead line)) are necessary.

Technically, the hardware can be highly simplified as both configurations could be realised only by



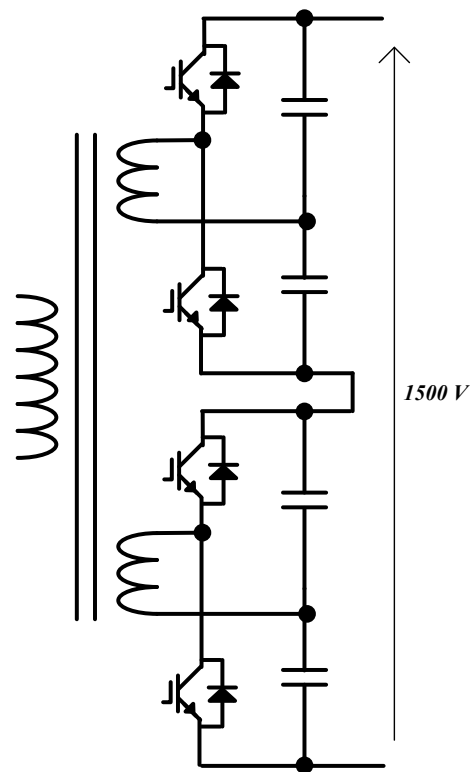
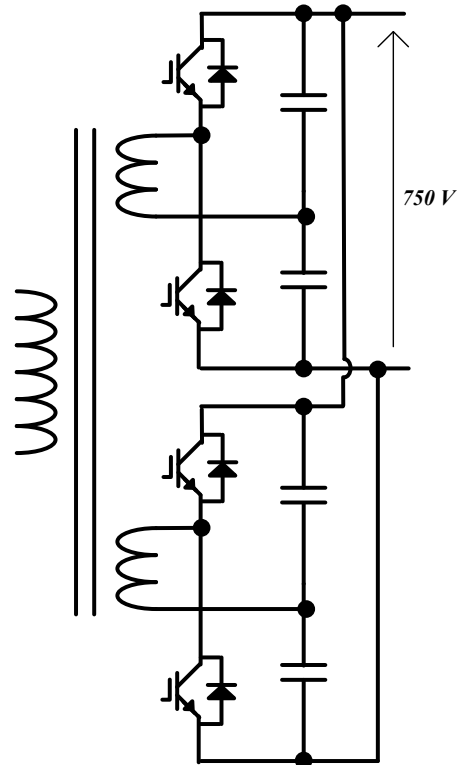
**Fig. 6:** Resonant LLC converter

changing the busbar or its connections instead of the whole inverter.

The impact on the losses, with the variant (hereafter named *variant 2*) compared to the PEBB with two inverters (hereafter named *variant 1*) is estimated. As the primary bridge and the MFT are identical, only the losses in the secondary bridges are compared. As the DC/DC converter operates in soft switching, only the conduction losses in the diodes are considered. The selected semiconductor devices are referenced in Table. 2. Respectively 2 kHz and 2.3 kHz are considered for the switching and resonant frequencies.

The losses at nominal power have been calculated with the two variants for both urban and suburban applications. The results are listed in Table. 3.

It should be noticed that, as the overload factors considered for suburban and urban applications are different (see Table. 1, [7]), the powers in normal operation in both cases are also different. This explains the variation between the losses obtained with *variant 2* in both applications. However, the percentage of the losses regarding the nominal power of the PEBB are the same. One can see



**Fig. 7:** Variants of the secondary bridge of the isolated DC/DC converter.

**Tab. 2:** Considered Si IGBT for the two variants

	Variant 1		Variant 2
	Urban	Suburban	Urban/suburban
<b>Supplier</b>	Infineon	Infineon	Infineon
<b>Supplier reference</b>	FF300R17KE4P	FF200R33KF2C	FF150R17KE4
<b>Blocking voltage</b>	1.7 kV	3.3 kV	1.7 kV
<b>Current rating</b>	300 A	200 A	150 A
<b>Diode on-state resistances at 125 °C</b>	2.52 mΩ	6.48 mΩ	3.96 mΩ
<b>Diode thermal resistance</b>	0.177 K/W	0.108 K/W	0.160 K/W

**Tab. 3:** Losses in normal operation in the secondary bridges for the two variants in both urban and suburban applications

	Losses	
	in W	in %
<b>Variant 1 - urban</b>	65.7 W	0.31 %
<b>Variant 1 - suburban</b>	68.5 W	0.22 %
<b>Variant 2 - urban</b>	61.7 W	0.3 %
<b>Variant 2 - suburban</b>	97.9 W	0.3 %

that the losses in both variants are similar. Thus, thanks to the variant of the secondary bridge design shown in Fig. 7, both DC supply voltages can be addressed by a simple reconfiguration of the busbar in output, without degrading the losses compared to two inverters designed for each application.

## 5 Conclusion

In this paper, an elementary PEBB for modular and scalable SSTs is sized for multiple configurations of DC railway substations. The optimal rated power of the elementary PEBB, minimising the oversizing ratio in all configurations (DC line or rail voltage, AC grid voltage and substation rated power), and the resulting number of PEBBs to address every substation rated powers and distribution network configuration are determined. A variant of the PEBB design, with a reconfigurable secondary, has been proposed for a more modular PEBB.

A 94 kW PEBB can be used for every railway substation configuration listed in Table. 1, i.e. for every distribution network voltage in input, every

nominal power and every railway DC voltage. It ensures an oversizing ratio and a number of PEBB per MW comprised between, respectively, 3.38 and 5.7 and 36 and 60 in all the applications. Same efficiency can be reached with the reconfigurable secondary bridge to address both urban and suburban applications, compared to two inverters sized for urban and suburban infrastructure.

## 6 Perspectives

The optimal power of the PEBB for modular railway substation has been determined. The next step consists in sizing the PEBB, and particularly the isolated DC/DC converter. In this paper, Si IGBTs, switching at 2 kHz, have been considered. However, a higher frequency of the transformer could lead to a higher power density of the MFT and a reduction of potential acoustic noise issues. In this case, SiC MOSFETs could also be considered to limit the losses in the isolated DC/DC converter. As the highest voltage ratings currently available for such devices are 3.3 kV, a NPC topology would be necessary on the primary side of the transformer to withstand the intermediate bus voltage.

A proper control of the topology should also be developed, for instance to ensure the balance of voltages in half bridges and the balance of the power in the two secondary windings of the MFT when using the proposed variant of the secondary bridges.

A prototype of a PEBB would then be necessary to validate the design and the feasibility of a reconfigurable busbar.

## 7 Acknowledgement

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