Power Electronic Transformer Technology for Traction Applications – An Overview

Dražen Dujić, Frederick Kieferndorf, and Francisco Canales

Abstract—**Combining modern high-power semiconductor devices with constantly improving magnetic materials opens up the possibility to replace bulky low-frequency transformers with a new medium voltage medium frequency conversion structure. While there are still challenges to be addressed related to these so called power electronic transformers, a steadily increasing development effort is evident and considered in various contexts. Traction applications seem to be the first ones where proliferation of these galvanically isolated power electronic converters is expected. In this application field, substantial weight and volume reduction can be achieved while providing additional functionality at the same time. In this paper a survey of recent R&D efforts in this field is presented.**

Index Terms—**Power Electronic Transformer, Railway, Medium Frequency Transformer, Multilevel Converter.**

I. Introduction

Nowadays, conventional line frequency transformers (LFT) are widely spread in electrical systems providing basic functionalities such as voltage isolation and voltage adaptation. However, to deal with power quality problems (e.g., sags, swells, flicker and harmonics) at medium voltage (MV) levels, there is a need for the installation of additional equipment (usually some kind of power electronics converter operating at higher switching frequencies). This leads to a further increase of the installation volume, which in certain applications may not be feasible (traction, marine, wind, offshore). Recent trends in MV high power applications are replicating something that has already been achieved and put into practice in low voltage applications. There, line frequency operated transformers have mostly been replaced by medium frequency transformers (MFTs) where high frequency waveforms are applied directly to the transformer terminals, so that the overall magnetic volume is reduced and more compact converter designs are reached. Some of the results from this field are presented here, with the scope of this paper being limited to railway applications (thus, single phase).

Traction applications are recognized as one of the likely early adopters of this emerging technology. Typical single phase railway AC lines found in Europe are 15kV, 16⅔Hz (originating from the use of cycloconvertors in the past and thus being one third of 50Hz) and 25kV, 50Hz. A conventional (state-of-the-art) approach to provide DC voltage to the variable speed drive on the locomotive is illustrated in a simplified manner in Fig.1. The primary winding of the LFT is connected directly to the AC catenary and active rectifier(s) are connected to the secondary winding(s) of the transformer where the voltage is stepped down. One or more inverter and motor units are further connected to the provided DC link (not illustrated in Fig.1). Since traction LFTs are usually optimized for minimum weight (2-4kg/kVA) and are heavily loaded, the resulting efficiency is rather poor and somewhere in the range of 90%-92%. Oil is customarily used for cooling and insulation, adding to the total weight and potential environmental issues (i.e. in case of leakage). The power of the system may vary from below 1MVA up to 10MVA for large cargo locomotives.

In a classical train arrangement, where the propulsion system is concentrated in the locomotive, the weight of a LFT is not necessary a problem, since a certain weight is required in any case in order to provide sufficient traction without slipping. However, in the case of electric multiple units (EMUs), where the propulsion system is distributed throughout the train, weight becomes an issue.

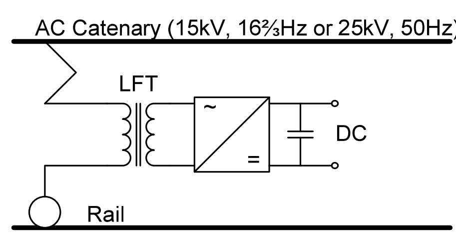

Fig. 1 AC-DC conversion with a line frequency transformer (LFT).

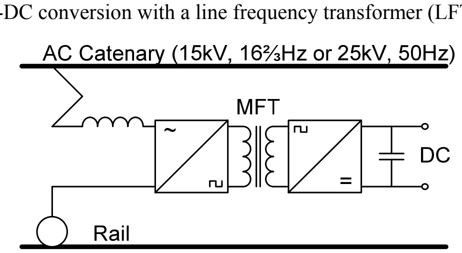

Fig. 2. AC-DC conversion with medium frequency transformer (MFT).

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An alternative to the state-of-the-art solution is the use of a so called power electronic transformer (PET), consisting of a power converter in conjunction with MFT(s), as illustrated in Fig.2. Here, some sort of power electronic converter is connected directly to the AC catenary, while the MFT is providing voltage insulation and adaptation.

Present semiconductor devices are unable to work directly with these medium voltages and thus usually some of kind of series connection of a number of cells or modules is required in order to meet the voltage level of the MV line, resulting in a multilevel converter structure. The MFT from Fig.2 is usually realized not as one single transformer (although in some implementations it is), but rather as a number of transformers rated for a fraction of the total power and operating at a higher switching frequency (several kHz). Finally, rectification is required on the secondary side of the MFT in order to provide a DC link to the inverter(s).

This type of MV technology (although still under development) is becoming a reality with the advances in semiconductor technology (faster switching actions, higher blocking voltages and higher power densities) and the development of new magnetic materials with low loss densities at higher operating frequencies. Even though early considerations regarding PET can be traced back to the seventies [1], at the present time there are still no products of this kind offered by any of the key players in the traction market.

II. State-of-The-Art: PET Architectures

Various architectures/topologies have been considered for the realization of a PET for tractions applications. Early works considered the use of thyristor based solutions [1], [2], as illustrated in Fig.3. The primary side of the MFT consists of two thyristor H-bridges connected in anti-parallel while the secondary side has a single phase forced commutated H-bridge. Thus, there is a cycloconverter at the input (HV side) and voltage source inverter (VSI) at the output (LV side).

In this implementation, the MFT is excited from the secondary side by the VSI and the MFT voltage is used to commutate the cycloconverter on the primary side. Use of thyristors limits the MFT frequency to a few hundreds of Hertz. In addition to low frequency, the circuit also generates fairly high line harmonics and improvements in this direction are reported in [3].

To mitigate some of the issues with the thyristor based approach and further increase the operating frequency of the MFT, the use of fully controllable devices such as IGBTs has been proposed [4], [5]. In [4], the cycloconverter from Fig.3 has been realized using IGBTs (series connection of two IGBTs with common emitter as a replacement for two anti-parallel thyristors) using at the same zero voltage switching (ZVS), while the VSI is realized as a standard IGBT H-bridge converter. However, to achieve the line voltage, a series connection of a number of IGBTs is required considering that, at present, the highest blocking voltage of commercially available IGBTs is only 6.5kV.

Thus, a modular structure consisting of a number of cascaded cells (which are of the same nature as those in Fig.3, but realized with IGBTs) has emerged, as shown in Fig.4. In this arrangement, thanks to the voltage clamping of the secondary side DC voltage through the MFT to the primary side, voltage sharing among the different cells is achieved. At the same time, a multilevel voltage waveform at the input of the PET helps to reduce the line harmonics and the resulting filter requirements. In contrast to Fig.3, instead of having a single MFT, there is a need for a number of MFTs, each connected to an associated cell and rated for a fraction of the full power. However, insulation requirements are not relaxed and each MFT must be designed for the same dielectric stress as before.

A PET prototype based on the topology from Fig.4 has been presented in [5], targeting 15kV, 16⅔Hz railway network and with 1.2MVA ratings (continuous operation). The implementation had a total of 16 cells each consisting of a cycloconverter, MFT and VSI (rectifier). 3.3kV IGBTs were used on both primary and secondary sides, while the MFT was operated with 400Hz (see Fig.5).

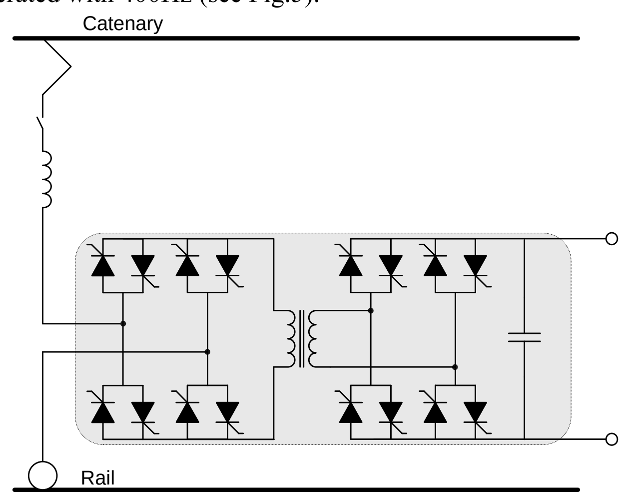

Fig. 3. PET topology with source commutated primary converter.

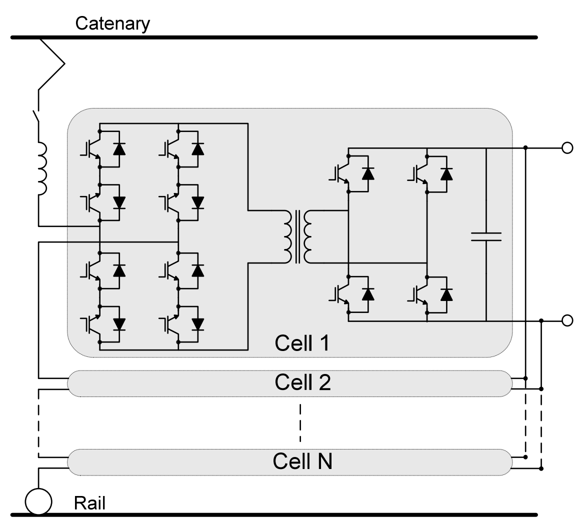

Fig. 4. PET topology with cascaded source commutated primary converters.

Fig. 5. ABB PET prototype (2006) using topology from Fig.4 [5].

To avoid the difficulties with cycloconverters on the primary side of the MFT and considering the fact that a number of cells is required anyhow, cascaded H-bridges (four quadrant converters) have been proposed by various research groups [6-10 all references]. In this way, a pure IGBT solution is achieved and the number of required cells is primarily related to the selected voltage class of the semiconductors.

In [6], a topology similar to the one shown in Fig.6, was proposed (the main difference is a lack of capacitors connected to the MFT, thus being a non-resonant converter). The input stages are realized with four quadrant converters and provide the intermediate DC links as well as a high resolution multilevel waveform at the input of the converter. DC/DC converters are connected to each of the floating DC links and provide galvanic isolation and voltage level adaptation to the secondary side (as before all converters are connected in parallel at the output). Power flow control is achieved through manipulation of the phase shift between the rectangular waveforms of the two sides of the DC/DC converter. Various reconfiguration possibilities of this kind of topology are discussed by the same group of authors in [7].

A topology identical to the one shown in Fig. 6 has been presented in [8], [9]. A series resonant DC/DC converter is proposed in order to reduce switching losses of the semiconductors (zero voltage switching (ZVS) and zero current switching (ZCS)) and allow for further increase of the MFT operating frequency. For a 15kV railway network using 6.5kV IGBTs, it was calculated that 7 cells would be required for nominal operation (although adding an extra cell for redundancy reasons is proposed) and the MFT frequency was expected to be in the range of 8-10 kHz. Some details about the control of this kind of PET can be found in [10].

More considerations regarding the topology of Fig.6 can be found in [11], [12]. Various arrangements have been analyzed and 6.5kV devices were selected as the most suitable ones, considering failure-in-time (FIT) rates and the number of devices needed. To increase the switching frequency, a soft switching series resonant DC/DC converter with half bridges on both sides of the MFT is considered. In addition to standard IGBTs, modified semiconductor devices were tested as well. In particular, standard IGBTs were irradiated with electrons in order to move the device properties on the technology curve towards the area of lower turn off energies (reduction of carrier lifetime) but at the expense of higher on-state voltage drop and thus higher static (conduction) losses. Reported results emphasized the possible increase of the switching frequency in the range of 40-50% (at rated power). However, these kinds of devices are not commercially available yet, except for limited engineering samples.

A slightly different approach has been presented in [13]-[15] where multi-winding MFTs are used. The primary side is again realized with a series connection of H-bridges providing intermediate HV side DC links from which the primary windings of the multi-winding MFT are excited by half-bridge series resonant converters operating at 5kHz. The secondary side is realized using a single H-bridge converter with bidirectional power flow. A full scale 1.5MW PET prototype was realized featuring 8 cells in total (7 without redundancy). The mass of the PET prototype was reported as 3.1T, in comparison to 6.8T for a conventional LFT, however, at the expense of 50% higher cost and jeopardized reliability due to the use of 48 6.5kV IGBTs on the primary side of the multi-winding MFT. The authors advertised upcoming field trials using the developed PET prototype, but no further results were reported.

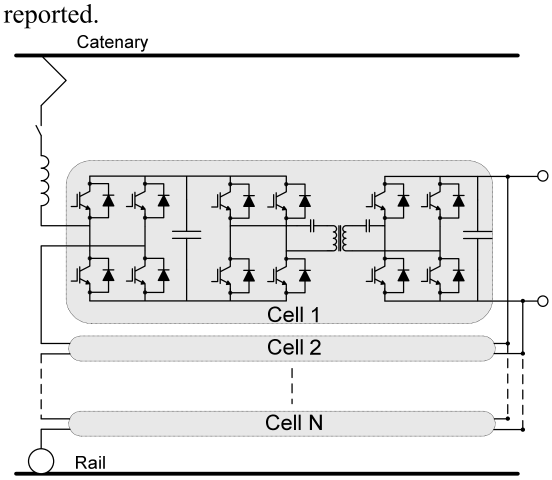

Fig. 6. PET topology with cascaded H-bridges and resonant/non-resonant DC-DC stages.

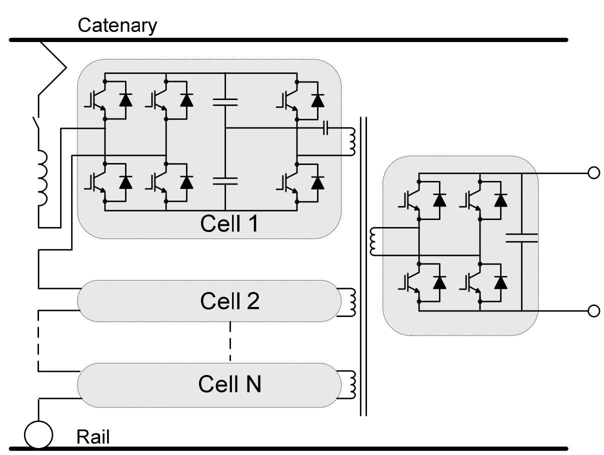

Fig. 7. PET topology with cascaded H-bridges and multi-winding MFT.

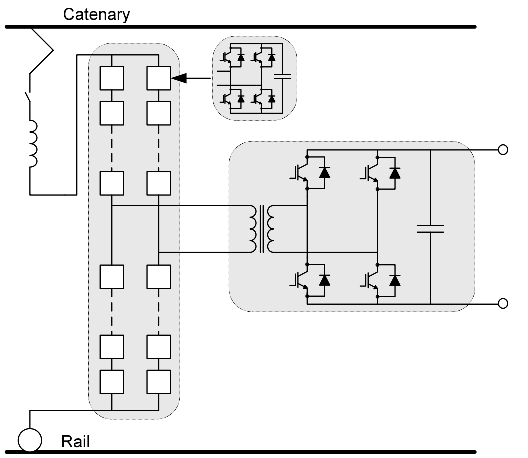

Fig. 8. PET topology using M2LC converter.

Use of a modular multilevel converter (M2LC) for traction applications has been presented in [16], [17]. A simplified layout is shown in Fig.8 (in the original publication there are multiple secondary windings of the MFT with dedicated active rectifiers, inverters and motors). M2LC is a highly modular topology and the basic building blocks (cells) for traction applications are H-bridges connected in series, each with its own DC capacitor bank, finally resembling a sort of large composite H-bridge, as shown in Fig.8. M2LCs are associated with large amounts of stored energy in each cell but with low energy density per cell, adding to the weight and volume of the whole system. So far, in real world applications M2LC has been successfully commissioned only for HVDC installations.

The most recent reports concerning PETs in traction application are reported in [18]-[20]. The topology is shown in Fig.9 and similar to the previous example it consists of cascaded H-bridges at the input and resonant DC-DC converters with the power stage realized using a half-bridge configuration. Also, in contrast to the LC series resonant tank employed in [8], [9] and [13]-[15], a LLC resonant tank is used. Thus, both the leakage inductance and the magnetizing inductance of the transformer are participating in the resonance. In this way ZVS is achieved during turn-on of the IGBTs while near ZCS is achieved during turn-off of the IGBTs. Some results regarding the design and preliminary testing of a DC/DC LLC resonant converter are presented in [18].

In [19] the development of a low voltage PET prototype is presented, focusing primarily on the control features required for characteristic operating regimes in traction applications. The LV PET, shown in Fig.10, was used as an analogue hardware simulator since the implemented control HW was identical to that used later in the full size PET reported in [20]. The full sized MV PET prototype, shown in Fig.11, is designed for a 15kV, 16⅔Hz railway network with a 1.2MVA power rating (1.5kV output voltage) and is realized with 8 cells (+1 for redundancy) and a MFT operating at 1.8kHz.

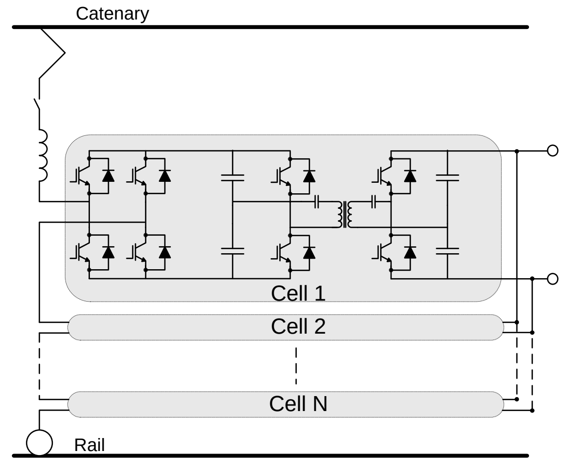

Fig. 9. PET topology with cascaded H-bridges and resonant (LLC) DC-DC stages.

Fig. 10. ABB low voltage PET prototype (2011) [19].

Fig. 11. ABB PET prototype (2011) [20].

A full set of experimental results is reported in the paper, illustrating various operating conditions in steady state and during transients as well. The PET prototype was developed for a field trial with Swiss Federal Railways and during the preparation of this paper it was already installed on the locomotive and electrically commissioned. Since February 2012, the PET prototype is in service for a one year field trial.

III. MEDIUM FREQUENCY TRANSFORMER

Details related to the MFT implementation were deliberately omitted from the previous section, since this topic is difficult enough on its own, and due to the space limitations it is discussed here on a rather general level. Therefore, the basic problems that are encountered in the design phase of an MFT are highlighted and some examples are illustrated.

The size of a transformer can typically be related to the area product, Ap, defined as [22]:

$$A_p = \frac{P_t}{K_f K_u B_m J f} \qquad (1)$$

When designing a MFT, all of the parameters present in (1) must be carefully considered. The main idea behind the PET is to replace the bulky LFT with an overall more compact MFT or MFTs operating at a higher frequency (f), normally in the range of several kHz. While increasing the operating frequency (f) leads to a reduction of transformer size (Ap), high insulation requirements have a negative effect on the window utilization factor (Ku), resulting in a low filling factor of the window area due to the required amount of insulating material. This is especially true in the case of the MFT for PET, where due to the lack of applicable standards, the MFT is usually designed to meet the same requirements as the direct AC line connected LFT. Therefore, the required level of insulation is nearly independent of all the other parameters in (1) since it is purely related to the system requirements. Considering that the MFT is driven by rectangular rather than sinusoidal waveforms, the Kf factor which relates to the waveform shape is different relative to a LFT. At the same time, the Steinmetz parameters and associated core losses for the selected material at a particular frequency are determined assuming sinusoidal excitation, which makes preliminary loss estimations rather inaccurate, and experimental characterization is often required. Materials usually considered for the MFT are: nanocrystalline, amorphous iron and/or ferrites.

The winding current density (J) is directly linked to the required cooling effort to remove generated heat from the winding, thus having a huge impact on the selection of the cooling method. On the other hand, selection of different core materials leads to different maximum operating flux density (Bm) and has an impact on the MFT size as well. Finally, combining the requirements for high power (Pt), high insulation (Ku), simple cooling (J) and lower flux densities (Bm) of suitable materials for the frequencies (f) of interest the design of a high insulation, high power, MFT is not a straightforward task. On top of that, since it is desirable to integrate elements of the resonant tank into the MFT there is a need to precisely control transformer inductances (leakage and magnetizing) for proper resonant operation, which introduces further complications into the design. The need to operate at higher switching frequencies requires low leakage inductance which is at odds with the high insulation requirements which typically results in higher leakage.

Considering selection of different core materials, silicon steel is used in [5], nanocrystalline in [20,24], ferrites in [13] while amorphous iron is used in [23]. Regarding the cooling and insulation, oil is used in both [5] and [20], de-ionized water for cooling of windings is used in [23,24], while insulation is also provided by oil in [24]. Two particular examples are illustrated in Fig.12 and 13.

The MFT shown in Fig.12 is realized using amorphous iron core material with a coaxial winding structure and active de-ionized water cooling through the space available between the primary and secondary windings. The prototype was designed for 350kW and 10kHz switching frequency. The respective insulation voltage testing is performed at 38kV and 50Hz for 60 seconds, while the rated impulse voltage is 95kV. The use of coaxial type windings limits the turns ratio to 1:1, which was acceptable in the case analyzed in [23]. Special attention was paid to properly assess the dielectric stress across the MFT in order to provide a design that could guarantee a long lifetime.

A different design is shown in Fig.13 [20]. It features an assembly with three MFTs, each rated for 150kW (with the ability to withstand 225kW overload for 60 seconds) and an operating frequency of 1.8kHz. The insulation test voltage and rated impulse voltage are similar to the previous case. The material used for the core is nanocrystalline and the oil direct air forced (ODAF) cooling method is applied (the whole structure being immersed into the oil), which solves the problem of insulation at the same time. This type of MFT was installed in the 1.2MVA PET prototype shown in Fig.11, in the oil filled tank visible at the bottom of the structure in Fig.11. The inductive elements required for proper resonant operation are realized as the leakage and magnetizing inductance of the MFT.

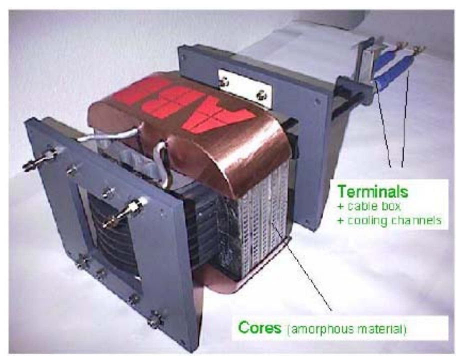

Fig. 12. ABB MFT prototype (2002) [23].

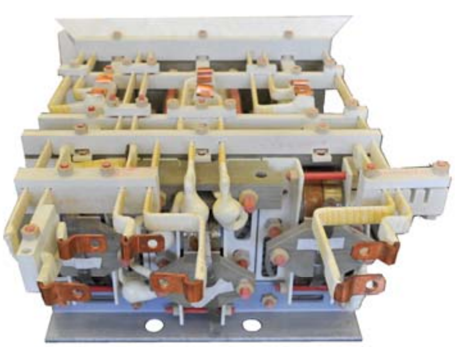

Fig. 13. ABB MFT prototype (3 pieces) (2011) [20].

IV. General Remarks

Something that is not shown in any of the figures in section 2 and should be mentioned, since it is always considered in tractions applications, is the presence of the 2nd harmonic ripple in the DC link, which is an inherent property of single phase systems. In the original publications, referenced throughout section 2, the 2nd harmonic filter (LC) is usually found on the low voltage secondary side of the MFT. As an example, in [13], the weight of the 2nd harmonic filter is 385kg, which compared to the weight of the rest of a system (around 3085kg) is more than 12%. The amount of the 2nd harmonic ripple is directly related to the power consumed during operation, and it can be partly suppressed by over-sizing of the DC link capacitors and increasing the amount of energy stored locally.

At the input of the PET, there is a need for a line inductor, since the input stage is a four quadrant converter with power factor capability, in essence a boost type converter. Taking into account the frequency cancellation due to phase-shifted operation of the power modules, the resulting size of the inductor is minimized. However two additional considerations must be taken into account. The first one is related to the use of this inductor to also filter the line harmonics, for which a higher value is usually needed than that required for boost operation. In addition, if the line inductor is used to limit short circuit in case of a fault, the required value increases even further (e.g. in [20] 180mH air core inductor is used at the input of the PET prototype).

On a more general note, the main concerns preventing PET proliferation into the market are the reliability and cost of the technology. The reliability question comes simply from the fact that in order to realize a medium voltage multilevel converter, a high number of semiconductors is needed. Even if their FIT rates are reasonably low, there are other electronics boards (e.g. gate drivers, controls hardware, etc.) which have higher FIT rates (more prone to failure). One way to tackle this issue is to provide redundancy inside the converter and thus effectively increase the availability of the system. Since availability is driven by time lost (see (2)) and, if due to the high part count, the mean time between failure (MTBF) is low (reliability is low or FIT rates are high) then by making the mean time to repair (MTTR) as short as possible, one can still maintain a high availability.

$$A = \frac{MTBF}{MTBF + MTTR} \qquad (2)$$

This implies that the converter should be as modular as possible so that the faulty part can be exchanged quickly. The philosophy behind the operation of a modular PET is that with all cells installed in the system, (minimum number +1), in the case of failure of any one cell, the faulty cell will be removed (bypassed) from the system. In this way, the system will continue operation with the remaining healthy cells. Note that while in operation with the minimum number of cells, the PET system can still deliver the full power to the output.

The cost issue is difficult to describe in simple terms since it depends on many factors. In [14] a cost increase of around 50% compared to the conventional technology, was reported. This is not the whole story though, because a PET can provide more efficient energy conversion compared to the conventional solution, and this is in the range of 2-4%. Additionally the harmonic performance is improved when compared with the low frequency transformer approach. If this is provided in a smaller installed volume and with less weight than the conventional solutions, it creates further energy savings potential besides an improvement in passenger comfort, thus giving PET technology a strong potential in railway applications. The potential savings due to improved efficiency can also partly offset the higher cost of installation and for a clear understanding the total cost of ownership (TCO) must be considered. This issue is not simple and should be studied in more detail and will be addressed by the authors in the future.

V. Conclusion

Power electronic transformers, providing a reduction in weight and volume accompanied by additional functionalities, are considered a viable solution for the replacement of bulky low-frequency transformers. This is especially true for those operating from a 16⅔Hz railway grid. Designing such a converter system is not a straightforward task, and some of the challenges that are reported in the literature are presented here in this paper. PET offers certain advantages over the conventional solution, such as a reduction of weight and volume, improved efficiency and more control flexibility towards grid disturbances. Functional properties of this kind of technology have been demonstrated previously by many authors but still more integration work aiming at cost reduction is required before a first implementation will be seen on the market. In meantime, a great milestone has been achieved recently by successfully commissioning and putting into operation a world's first ever power electronic transformer on a locomotive that is in regular service [25].

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