Chapter 57
Review of Power Electronic Transformer in Railway Traction Applications

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Abstract Being one of merging technologies, power electronic transformer (PET) is attracting more and more attentions. In this review, all the existing PET technologies for railway traction applications are comprehensively reviewed in order to provide a solid background of PET designs. Also, the basic of high-frequency transformer which is the key technology of PET is reviewed. The trend of PET is summarized as the guidelines for future researches.

Keywords Power electronic transformer · Traction transformer · High-frequency transformer

57.1 Introduction of PET

57.1.1 Principle of PET

The original purpose of PET is to replace the conventional line frequency transformer (LFT) while reducing the volume and weight of the transformer. PET is not just a simple transformer but an energy conversion system based on the combination of power electronic converters and medium-/high-frequency transformers.

The term of PET is not universal. Alternative terms can be found as medium-frequency transformer, high-frequency transformer, e-transformer, solid-state transformer, or intelligent universal transformer for various applications. The basic principle of PET is expressed in Fig. 57.1. The line frequency or DC input voltage is transfer into a high-frequency voltage by the front end converter. Through the HFT, this voltage is transferred to the secondary side with the amplitude being stepped up/down. The high-frequency voltage is shaped again by the output converter to obtain the required voltage.

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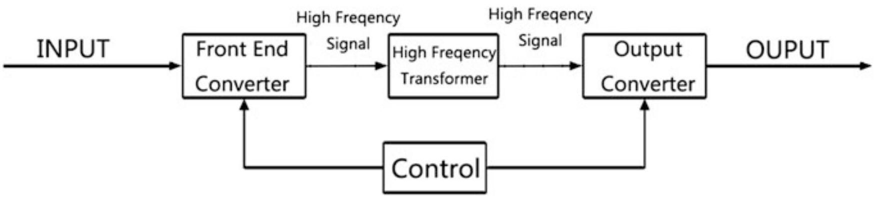

Fig. 57.1 Basic system configuration of PET

The operating frequency of the power electronic devices is decided by both technically and economically. The higher the frequency to operate, the smaller the size can achieve. However, with higher frequency, extra losses will lead to a lower efficiency.

57.1.2 Applications of PET

The first concept of PET was introduced in 1970. However, at that time, PET was limited by voltage and power rating of the power switches and available circuit topologies, and hence not penetrated into various applications.

With the development of power switches, circuit topologies, and new high-frequency ferrimagnet materials, PET has become one of the major emerging technologies. Various companies and universities, such as ABB and Alstom, University of Minnesota, University of Missouri, and Texas A&M University, have been doing research on PET.

Based on the previous analysis, PET is promising for following applications:

The weight and volume of the transformer system are critical to whole system performance, such as on-board electric tractions, battery charger, off-shore wind farm, and tidal power;

The system has high requirements on the power quality, such as smart grid and renewable energy;

The system requires additional functions besides of isolation and voltage regulation, such as smart grid.

57.2 Railway Traction Applications

It is possible that PET replaces the conventional line frequency transformer (LFT) in railway traction applications for several reasons:

Compared with massive and bulky LFT, PET reduces the transformer system size and weight. With higher power density, the train performance will improve.

The current LFT is optimized for maximum power per weight. However, the typical efficiency is about 92 % due to other key parameters. The PET can improve the efficiency of transformer system [1–3].

PET can improve the power quality and provide more functions, such as power factor, current harmonics, voltage sag/swells/flicker compensation, and fault current limitation.

For traction applications, the PET requires special design [4, 5]:
Be compact both in size and weight;
High tolerance with vibrations and shocks;
Multiple windings (output windings contain auxiliary windings);
Relatively high short-circuit impedances and high reliability levels;
Deal with multiple voltages and frequencies if cross the different electrification.

All the railway tractions use single-phase system; however, the rated voltage and frequency vary in different areas. The PET must be able to deal with multiple voltages and frequencies due to the different electrification systems used across Europe, sometimes even within one country. The catenary standard in European market [6] is listed in Table 57.1. Furthermore, it should be always considered the proportion of the 2nd harmonic ripple in the THD of DC voltage in traction applications because of the single-phase configuration [4].

In the following sections, various PET designs for traction applications are comprehensively reviewed.

57.2.1 ABB

ABB is one of the first companies starts the high-power medium-voltage MFT for railway tractions and has the world's first-ever 1.2-MVA PET tested in a locomotive. According to the report of PET application of ABB company, there are mainly three prototypes: A laboratory-scale prototype [2, 7, 8], 1.2 MVA PET developed later

Table 57.1 List of the voltage and frequency standard in European market [6]

System type	Lowest non-permanent voltage	Lowest permanent voltage	Nominal voltage	Highest permanent voltage	Highest non-permanent voltage
600 V DC	400 V	400 V	600 V	720 V	800 V
750 V DC	500 V	500 V	750 V	900 V	1 kV
1.5 kV DC	1 kV	1 kV	1.5 kV	1.8 kV	1.95 kV
3 kV DC	2 kV	2 kV	3 kV	3.6 kV	3.9 kV
15 kV AC, 16.7 Hz	11 kV	12 kV	15 kV	17.25 kV	18 kV
25 kV ac, 50 Hz	17.5 kV	19 kV	25 kV	27.5 kV	29 kV

with all the IGBTs being 3.3 kV [5], and another 1.2-MVA PET with 6.5-kV IGBTs on the high-voltage side and 3.3-kV IGBTs on the other side [2, 7–11] which makes it the world's first-ever full-scaled MFT tested in a locomotive.

57.2.1.1 Laboratory-Scale Prototype [2, 7, 8]

The laboratory-scale PET prototype is the fundamental research for the full-scale PET. The full-scale PET developed few years later use the same control hardware and strategies.

The main parameters of the transformer are listed in Table 57.2.

The cell is modularized as power electronic building blocks (PEBBs) because there is no much need for insulation. The PEBB is applied in AFE and DC/DC stages for simplicity. The PEBB is composed of water-cooling heat sink, 4 half-bridge IGBT modules of 600 V/150 A with accompany drivers, capacitors, and supervisory circuits. Due to the low voltage and current ratings, the short-circuiting device is a simple relay in each cell. The resonant tank adopted an off-the-shelf transformer with an series-connected inductor to get Lr needed at the bottom of the cabinet. The auxiliary power for cabinet is supplied with off-the-shelf switch-mode power supplies (SMPS).

An 30-mH line inductor is used to connect the 700-Vrms AC source at 50 Hz in laboratory which is provided by an three-phase generator. The input voltage source is the line voltage of the generator. So the input harmonic performance is unable to analyze.

Table 57.2 Main parameters of laboratory-scale prototype [7]

Overall rating		
Rated power	kW	54
Line current	A	36
Line frequency	Hz	50
Line inductor	mH	30
Per AFE converter		
Rated power	kW	6
DC link voltage	V	360
Switching frequency	Hz	350
Per DC/DC converter		
Rated power	kW	6
DC link voltage	V	360
Switching frequency	Hz	1500
Transformer turn ratio	–	1
Resonant inductor Lr	mH	0.135
Resonant inductor Lm	mH	13
Resonant capacitor Cr	μF	60
Rated power	kW	6

The output is variable: A 10-kW resistive load and a DC machine are connected by a 2-phase braking chopper. The machine can controlled the input power by adjusting the excitation current which can take 130-kW power. Thus, the machine is able to perform continuous load experiments. The chopper can generate the situation when load disturbances appear. The parameters of this prototype are shown in Table 57.2.

1.2-MVA PET with All the IGBTs Being 3.3 KV [5]

This PET demonstrator is developed for EMU railway specification of the 15 kV/16.7 Hz. The output of the PET rated at 1.2 MVA is 1.8 kV DC link voltage. The PET is capable of bidirectional power flow. It is expected that the power density could achieve 1 kg/kVA.

The system topology is shown in Fig. 57.2. It has 16 cells, each having a cycloconverter, MFT, and rectifier. All the 16 cycloconverters on the grid side are series connected, and all the 16 rectifiers on the secondary side are parallel connected. All the cycloconverters and rectifiers are designed using 3.3 kV/2 × 400A IGBTs.

The catenary voltage is 18 kV. There are several challenges for system design, such as medium-frequency transformers, cooling, and insulation.

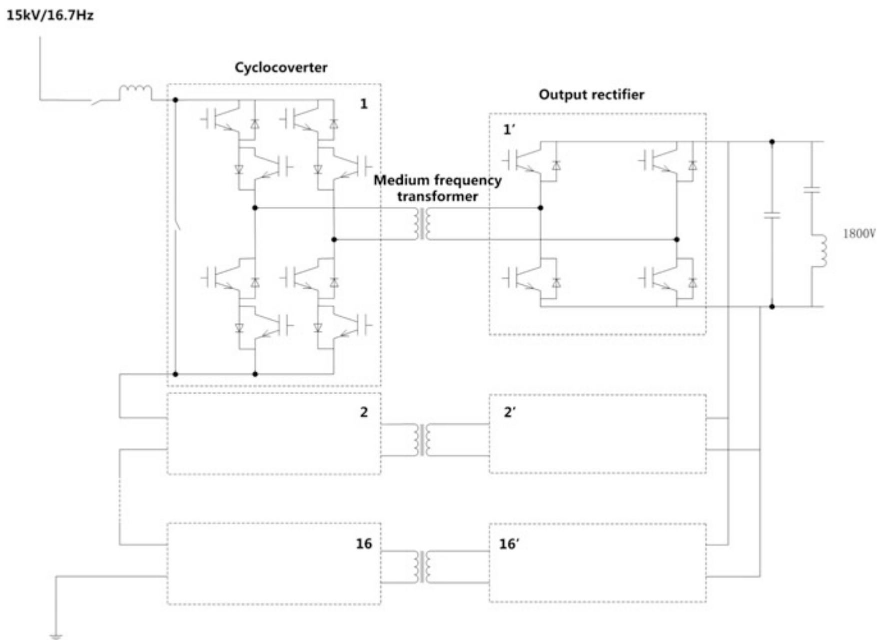

Fig. 57.2 Topology of 1.2-MVA PET demonstrator using 3.3 kV IGBTs

The same cooling oil is adopted for the converters and transformers to reduce the size and costs. A HV-insulated source is used to supply the gate drivers. With specific design rules, the short-circuit impedance could be very low. Moreover, the core weight is optimized too.

Compared to the conventional line frequency traction transformer, this MFT has 50 % less weight and 20 % less volume. What's more, the efficiency at nominal power is improved by 3 % which reduces the cost.

It is also pointed out that with new high-power SiC semiconductor which has higher operating frequency and blocking capability further works and optimization could be achieved [5]. Once the SiC semiconductor is available on the market, an new solution with an increased operating frequency and a reduced number of cascaded modules is expected.

1.2-MVA PET with 6.5-KV IGBTs and 3.3-KV IGBTs

This is the first-ever PET tested on a shunting locomotive in the area of Geneva, Switzerland, since February 2012. With growing need for EMU traction drives, the PET demonstrator has 1.2 MVA rated power with 1.8 MVA peak capability. The shutting locomotive is provided by Swiss Federal Railways (SBB). The detailed test results will be shown later.

Instead of using single PET, modularization is the trend for the simplicity of maintenance. As shown in Fig. 57.3, the cascaded topology of identical cells can support higher grid such as 15-kV railway grid working at 16.7 Hz. Due to the parallel connection on the output side, the full power is the sum of the power each cell provides. For this medium-voltage (MV) PET, each module on the AC side contains a startup circuit which enables the power to flow from the grid. In other situation, it could be bypassed.

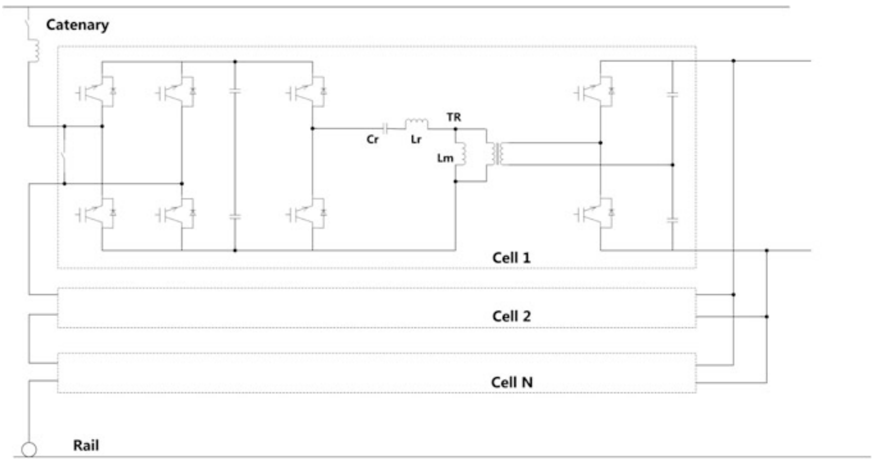

Fig. 57.3 Topology of 1.2-MVA PET demonstrator with 6.5- and 3.3-kV IGBTs

To achieve the minimum number of cells on the AC side, the 6.5-kV IGBT modules are used, and the number of cell rating 150 kVA is nine for the 15-kV railway grid.

The cell can be distinguished as follows: the HV PEBBs, the LV PEBBs, and the MFT. Based on the functionalities, the PEBBs also can be classified into active front end (AFE) converter on the AC side and DC–DC converter [2].

The HV PEBB converts the high-voltage AC source to several 3.6-kV DC. The LLC resonant converter is adopted in DC–DC converter.

The MFT provides the galvanic isolation between the HV and LV sides. The leakage and magnetizing inductances should be carefully designed to satisfy the need of proper working zone of LLC resonance converter. The LV PEBB adopts 3.3-kV IGBT of 800 A, and the LV DC link is 1.5 kV.

As shown in Fig. 57.3, the topology is capable of bidirectional power flow. When the vehicle works at regenerative braking, the power could be fed back from the LV side, which enhances the efficiency of the converter.

57.2.2 Alstom

The PET application for railway traction by Alstom is shown in Fig. 57.4 [12]. It is based on the phase-controlled multilevel converter. It contains a current source inverter, a MFT and a voltage source inverter. The current source inverters are series connected to the grid, and the voltage source inverter are parallel connected to the LV DC bus. Also instead of high-voltage IGBTs, high-voltage silicon carbide devices are employed aiming for a 2 MVA 12-stage PET for a 25-kV 50-Hz network.

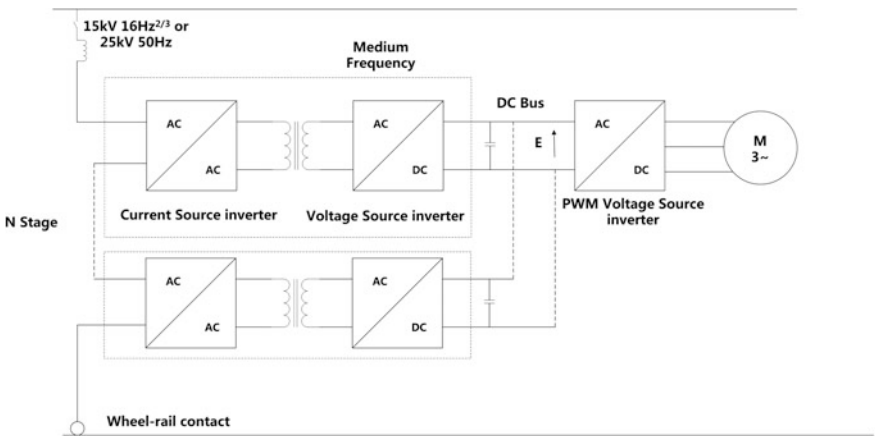

Fig. 57.4 The multilevel converter with phase-controlled method [12]

The investigation is focused on the converter losses, switching frequencies, and limitations under soft switching mode, which is carried out on a test bench. Theoretical analysis of conduction and switching losses also are calculated [12, 13]. According to the experiment, the switching frequency is limited by the snubberless operation at 2 kHz. Experimental results presented in papers [14] show a switching frequency up to 5 kHz and is realized with huge losses and limited output voltage range. The influence of losses on the thermomechanical stresses on Si and SiC power switches is further investigated [15].

57.2.3 Bombardier

The first PET prototyped developed by Bombardier is shown in Fig. 57.5 [16]. At least, 8 subsystems are series connected to the grid to achieve 15-kV line voltage with the consideration of redundancy.

In the DC/DC converter, the leakage inductance of transformer is low. The converter works in series resonant mode. The transformer ratio is 1:1, which enables the use of the same IGBT for both bridges. Once the voltage of the primary differs from the secondary, the series resonance excites which leads to self-balance.

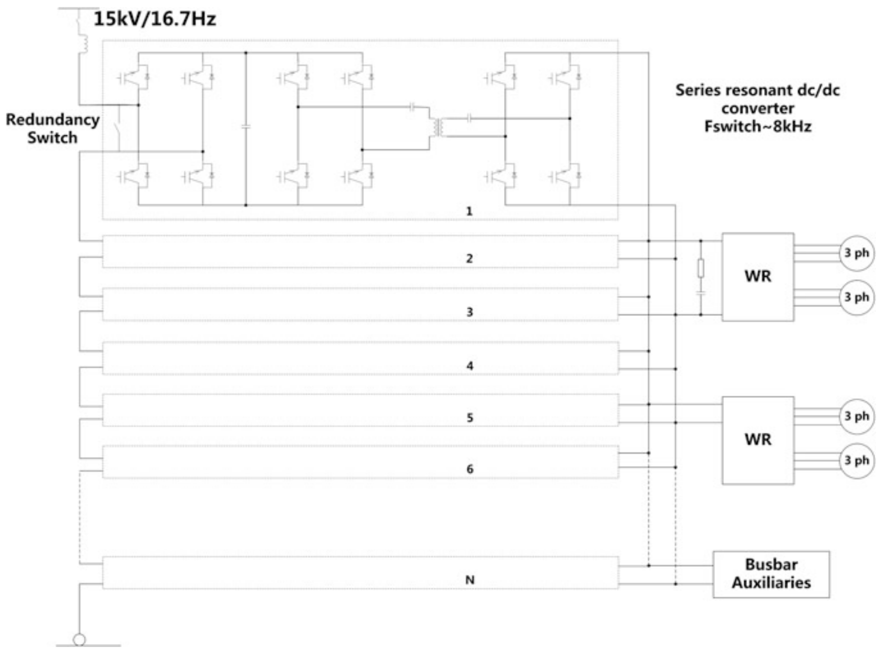

Fig. 57.5 Medium-frequency topology of bombardier

For the MFT, 8-kHz switching frequency is a compromise between losses, costs, and sizes, as well as acoustic noise. The windings are directly cooled by deionised water through rectangular aluminum profiled tubes. The transformer is made of nanocrystalline metal having 1T maximum flux density to reduce the losses. The flat water coolers are adopted to cool the cut cores from both sides.

With encapsulated winding arrange design, a low leakage inductance of the transformer is realized, which enables the zero-voltage switching for the converter and a homogenous electrical field distribution between windings.

An prototype transformer has passed the insulation, partial discharge, and 500 kW test with 8-kHz frequency. The weight is only 18 kg, and the leakage inductance is measured to be 2.3 μH.

On the other hand, the soft switching strategies of full bridge series, parallel, and series–parallel resonant converters are investigated [17, 18]. For transportation application, an LCC inverter is reported as well [19, 20]. In urban transit, the linear induction motor is powered by the inverter.

57.2.4 Siemens

Siemens and University of München investigate the PET based on the concept of modular multilevel converter (M2LC). As shown in Fig. 57.6, the single-phase M2LC contains four identical arms. Each arm contains same amount of identical submodules. It also needs one concentrated MF transformer with multiwindings.

The system is chosen considering the cost, system efficiency, power-to-weight ratio, maintenance, and redundancy. It is predicted that at nominal power, an efficiency of nearly 98 % is possible. [21, 22]. About M2LC configuration, Siemens

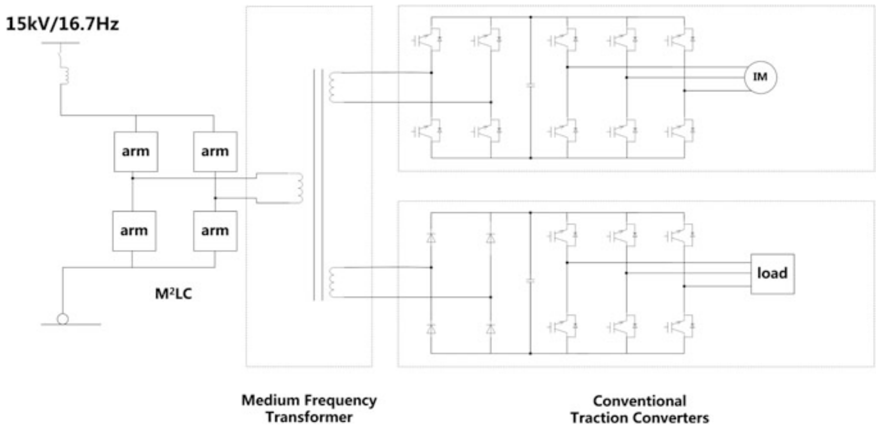

Fig. 57.6 Traction converter concept for the operation on the 15-kV/16.7-Hz power line by Siemens

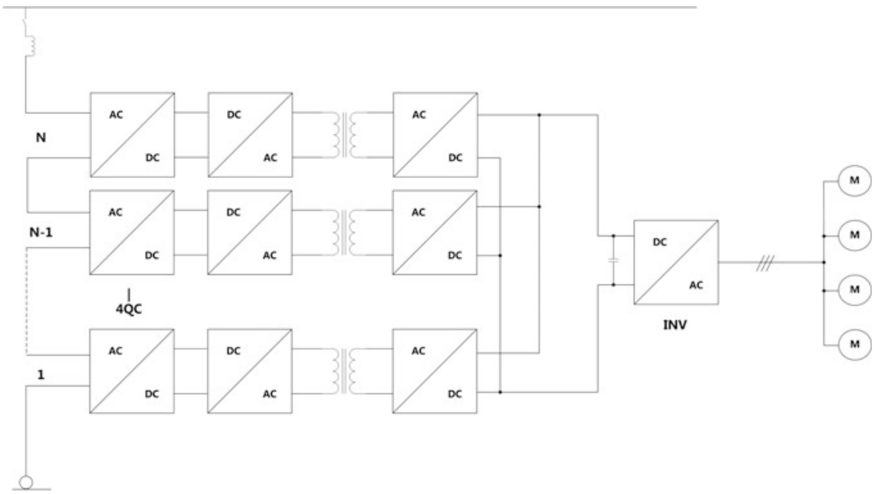

Fig. 57.7 Topology of a railway power supply with stacked single-phase 4-quadrant converters (4QC) using MF dc/dc converters

did research on 5 MW applications [21, 22] and 2 MW 17-level applications [23] using the same topology.

Siemens also works with University of Erlangen on another PET of the series-input and parallel-output configuration [3, 24–26] as shown in Fig. 57.7. Also, multitransformers are used instead of single transformer.

57.2.5 Summary

In previous parts, all the PET prototypes developed by leading companies are thoroughly reviewed in group of companies. In this part, several trends and common features can be highlighted as follows.

For the system level:

1. Series connection adopted to achieve high voltage for the LV side and parallel connection for the output is common configuration;
2. Modular and redundancy features are desirable;
3. The system switching frequency is not the higher the better. It is due to that when the switching frequency increases, both the transformer volume and loss will be stabilized. But the converter loss may be increased. It is a compromise between volume, cost, and efficiency, also between converter and transformer;
4. To increase the efficiency and achieve high switching frequency (few thousand Hz), soft switching methods such as ZVS and ZCS are necessary.

For the converters:

1. Two-stage configuration is preferred than the three-stage configuration. Half-bridge is preferred than the full bridge. The main reason of this is to reduce the cost and complicity;
2. High-voltage switches are also essential to reduce the power switching number and modular number and thus improve the reliability. Therefore, SiC switches are desirable.

For the MFT:

1. Instead of single transformer having multiwindings, multi- and identical transformer having single input and single output is preferred;
2. Oil is a good option to achieve cooling and insulation at the same time and thus save cost;
3. For the core material, nanocrystalline is preferred. For the windings, Litz or hollow wires are preferred.

57.3 High-Frequency Transformer

In PET system, the major functions of HFT are galvanic isolation between the source and load and fixed voltage amplitude adaptation. Since the design of HFTs varies significantly with the power rating, the review is focused on the high-power medium-voltage HFTs.

57.3.1 Topologies

The transformer topology is an important design issues. According to the core geometry and winding type, various transformers can be classified as four categories [27–31] as shown in Fig. 57.8. The core- and shell-type transformers are conventional topologies widely used in distribution and power transformers. The matrix and co-axial transformers are relevantly new. The matrix transformer is proposed [32] in order to integrate several transformers and use for low-profile applications. The co-axial transformers are commonly used in low leakage inductance and radio frequency applications [33, 34].

All the basic features, pros and cons for these four transformer topologies, are summarized in Table 57.3 [27–41]. It can be seen that for the high-power and medium-voltage applications, the conventional core- and shell-type transformers are the main choice.

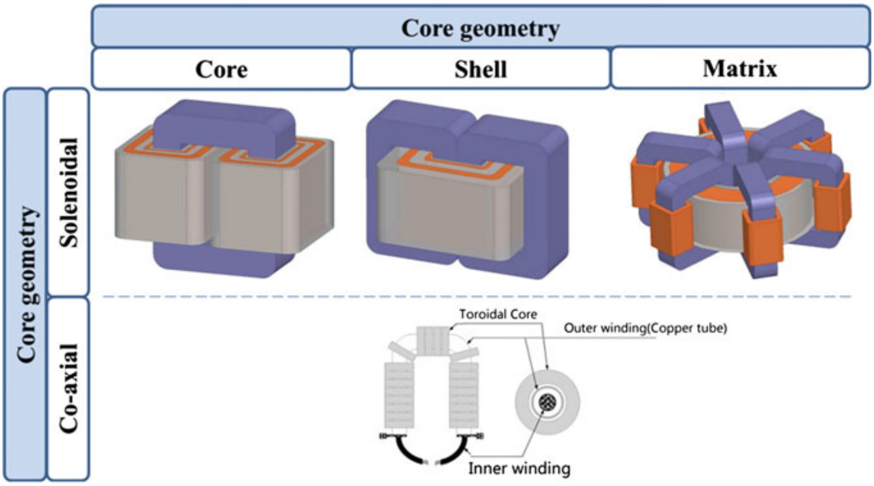

Fig. 57.8 Topologies of HFT

57.3.2 Thermal and Cooling

One of the major challenges in HFTs especially the high-power applications is the thermal issues. It is mainly due to two simultaneous effects of high-frequency operation. The total cooling surface is greatly reduced due to the extensive reduction of the transformer's volume. The loss density is significantly increased. In actual HFTs, their power capability is determined by its maximum allowed operating temperature. So it is requisite and vital to run a simulation on the temperature distribution with a proper accuracy.

In general, there are two ways of thermal investigations. One is based on FE analyses [42–44], and the other one is based on equivalent thermal circuits [45, 46]. Their pros and cons are briefly summarized in Table 57.4.

The cooling method is another important thermal issue. The cooling system has three main purposes: to effectively remove the heat, improve the power density, and easy the thermal managing system. Therefore, when comparing various cooling systems, following criterions should be considered: cooling capability, weight, volume, complexity, reliability, and cost. All the cooling systems can be divided into two groups: passive and active. For the active cooling system, the cooling medium can be air or liquid, such as water, de-iron water, coolant, and oil. Compared with the passive cooling systems, the active systems, especially the water or oil, are able to carry large amount of heat over long distance. For example, 55 percent reduction could be achieved with oil for the maximum temperature. However, the active cooling systems also have various drawbacks, such as extra cost, weight, volume due to the pump and other components, higher system complexity, lower reliability, risk of leakage, and regular maintenances. From this

Table 57.3 Comparison of different transformer topologies [30, 31, 34–37]

Topology	Basic features	Pros	Cons	Applications
Core	Single magnetic core Windings on both legs	Easiest manufacturing Better insulation capability	Higher leakage inductance	High voltage
Shell	Two magnetic cores encircle the single winding	Lower leakage inductance than core type Better mechanical protection Better thermal performance	Better thermal performance Low insulation capability	Relative low voltage
Matrix	Several parallel magnetic cores LV windings on the outer legs One HV winding on middle legs	Split current in secondary windings Improve thermal performance Better MMF distribution	Higher volume and weight Higher total loss and cost Higher leakage inductance	High frequency and low profile
Co-axial	Co-axial winding with an outer conducting tube and an inner tube/Litz wire Toroid magnetic cores	Low leakage inductance Low copper and core loss	Limited current capability Limited turn ratio Difficult to make Expensive	Radio frequency

Table 57.4 Comparison of thermal analyses based on FE and equivalent thermal circuit

	Pros	Cons
Equivalent circuit	Link the results to detailed design parameters Good for design optimization at the preliminary stage It is much faster to obtain the results The conclusions can be more general	The results is approximated Only the temperatures at nodes are available Accuracy of the model is largely determined by the researcher
FE	It is able to consider every details of the design It is able to obtain the whole picture of temperature distribution even inside of each component Can be very accurate	Very complicated to build the FE model It is timeconsuming It is case based and good for the final check for the design

point of view, forced air cooling systems are better than the liquid cooling systems. However, in the large power transformers, de-iron water or oil cooling systems are more popular. It is partly due that de-iron water and oil also are used as insulation.

57.3.3 Summary

Furthermore, in order to achieve better system performance, additional features for HFT include the following:

High power with low weight and volume;
High efficiency and low loss at high power and frequency;
Controllable inductance and capacitor, and resonant switching.
Due to this features and the nature of high-frequency operation, it is much more complicated to design and optimize the HFTs. The main challenges are as follows:
High power and voltage while low volume, which makes the insulation and cooling very difficult to design;
Highly coupled multiphysic system including electromagnetic, thermal, and mechanical, which makes the modeling very challenging;
Complicated multiparameter system, such as switching frequency, number of turns and dimensions of wires, core material and shape, and current density and maximum flux density, which makes the optimization very challenging;
Parasitic effects due to high frequency and nonlinearity, such as magnetic saturation, non-sinusoidal waveforms, skin- and proximity-effect, leakage inductance, and stray capacitor, which make the design very complicated.
Thus, the design consideration of HFT is different from the one of LFT;
More likely, new core materials are preferred to maintain low core loss at high frequency. However, less data for these materials are available. Even for the existing materials for insulation and cooling, their properties under high-frequency operation are still not comprehensive;
The requirement of designable leakage inductance and stray capacitance for the resonant switching makes the design of HFT more different form LFT;
In order to compete with LFT, it is better to have low cost as much as possible.

57.4 Trends

For the future railway tractions, the trends can be summarized as follows [4, 16, 29, 35, 41]:

1. High-power conversion system with reduced weight and volume due to several reasons. To increase passenger comfort is a strong trend, and it needs more space for passenger, more effective load, low floor accessing, and increased levels of auxiliary power on trains;

2. Higher efficiency, which is a global trend. The current LFT is optimized for maximum power per weight. However, with the consideration of cost, compromise on key parameters is made such as the efficiency is only about 92 % for the LFT [1–3];
3. Better reliability and easier maintenance. For the power module, A 150-k-hour mean time between failure(MTBF) is a must. Depending on the project, the product lifetime is expected to be 15 to 30 years. There is also a concern about life cycle cost, which aims to minimize the maintenance cost.

References

1. Dujic Z, Steinke G, Bianda E, Lewdeni-Schmid S, Zhao C, Steinke JK (2013) Characterization of a 6.5 kV IGBT for medium-voltage high-power resonant DC-DC converter. In: 2013 twenty-eighth annual IEEE applied power electronics conference and exposition (APEC), pp 1438–1444
2. Dujic D, Zhao C, Mester A, Steinke JK, Weiss M, Lewdeni-Schmid S, Chaudhuri T, Stefanutti P (2013) Power electronic traction transformer-low voltage prototype. IEEE Trans Power Electron 28:5522–5534
3. Hoffmann H, Piepenbreier B (2011) Medium frequency transformer for rail application using new materials. In: Electric Drives Production Conference (EDPC), 2011 1st International, pp 192–197
4. Dujic D, Kieferndorf F, Canales F, Drofenik U (2012) Power electronic traction transformer technology. In: Proceedings of International Power Electronics & Motion Control Conference, vol 1, pp 636–642
5. Hugo N, Stefanutti P, Pellerin M, Akdag A (2007) Power electronics traction transformer. In: 2007 European conference on power electronics and applications, pp 1–10
6. Energy conversation program for commercial equipment, distribution transformers energy conversation standards. CFR Standard 431, Oct. 2007
7. Besselmann T, Mester A, Dujic Z (2014) Power electronic traction transformer: efficiency improvements under light-load conditions. IEEE Trans Power Electron 29:3971–3981
8. Dujic D, Mester A, Chaudhuri T, Coccia A, Canales F, Steinke JK (2011) Laboratory scale prototype of a power electronic transformer for traction applications. In: Proceedings of the 2011-14th European conference on power electronics and applications (EPE 2011), pp 1–10
9. Zhao C, Dujic Z, Mester A, Steinke JK, Weiss M, Lewdeni-Schmid S, Chaudhuri T, Stefanutti P (2014) Power electronic traction transformer-medium voltage prototype. Ind Electron IEEE Trans 61:3257–3268
10. Zhao C, Lewdeni-Schmid S, Steinke JK, Weiss M, Chaudhuri T, Pellerin M, Duron J, Stefanutti P (2011) Design, implementation and performance of a modular power electronic transformer (PET) for railway application. In: Proceedings of the 2011-14th European conference on power electronics and applications (EPE 2011), pp 1–10
11. Zhao C, Weiss M, Mester A, Lewdeni-Schmid S, Dujic D, Steinke JK, Chaudhuri T (2012) Power electronic transformer (PET) converter: design of a 1.2 MW demonstrator for traction applications. In: International symposium on power electronics power electronics electrical drives automation & motion, pp 855–860
12. Martin J, Ladoux P, Chauchat B, Casarin J, Nicolau S (2008) Medium frequency transformer for railway traction: soft switching converter with high voltage semi-conductors., In: International symposium on power electronics, electrical drives, automation and motion, SPEEDAM 2008, pp 1180–1185

13. Casarin J, Ladoux P, Chauchat B, Dedecius D, Laugt E (2012) Evaluation of high voltage SiC diodes in a medium frequency AC/DC converter for railway traction. In: 2012 international symposium on power electronics, electrical drives, automation and motion (SPEEDAM), pp 1182–1186
14. Casarin J, Ladoux P, Martin J, Chauchat B (2010) AC/DC converter with medium frequency link for railway traction application. Evaluation of semiconductor losses and operating limits. In: 2010 International symposium on power electronics electrical drives automation and motion (SPEEDAM), pp 1706–1711
15. Escrouzailles V, Castellazzi A, Solomalala P, Mermet-Guyennet M (2011) Finite-element based comparative analysis of the thermo-mechanical stresses affecting Si and SiC power switches. In: ICPE 2011-ECCE Asia, pp 1077–1082
16. Steiner M, Reinold H (2007) Medium frequency topology in railway applications. In: European conference on power electronics & applications, pp 1–10
17. Youssef MZ, Jain PK (2007) Series-parallel resonant converter in self-sustained oscillation mode with the high-frequency transformer-leakage-inductance effect: analysis, modeling, and design. IEEE Trans Industr Electron 54:1329–1341
18. Youssef MZ, Pinheiro H, Jain PK (2006) Self-sustained phase-shift modulated resonant converters: modeling, design, and performance. Power Electron IEEE Trans 21:401–414
19. Youssef M, Qahouq JAA, Orabi M (2010) Analysis and design of LCC resonant inverter for the transportation systems applications. In: Applied power electronics conference and exposition (APEC), 2010 twenty-fifth annual IEEE, pp 1778–1784
20. Youssef M, Qahouq JAA, Orabi M (2010) Electromagnetic compatibility results for an LCC resonant inverter for the transportation systems. In: Applied power electronics conference and exposition (APEC), 2010 twenty-fifth annual IEEE, pp 1800–1803
21. Glinka M, Marquardt R (2003) A new AC/AC-multilevel converter family applied to a single-phase converter. In: The fifth international conference on power electronics and drive systems, PEDS 2003, pp 16–23
22. Glinka M, Marquardt R (2005) A new AC/AC multilevel converter family. IEEE Trans Industr Electron 52:662–669
23. Glinka M (2004) Prototype of multiphase modular-multilevel-converter with 2 MW power rating and 17-level—output-voltage. In: PESC record—IEEE annual power electronics specialists conference, vol 4, pp 2572–2576
24. Weigel J, Ag ANS, Hoffmann H (2009) High voltage IGBTs in medium frequency traction power supply. In: EPE European conference on power electronics & applications, pp 1–10
25. Hoffmann H, Piepenbreier B (2010) High voltage IGBTs and medium frequency transformer in DC-DC converters for railway applications. In: Power Electronics Electrical Drives Automation & Motion International Symposium on, pp 744–749
26. Hoffmann H, Piepenbreier B (2011) Medium frequency transformer in resonant switching DC/DC-converters for railway applications., In: Proceedings of the 2011-14th European conference on power electronics and applications (EPE 2011), pp 1–8
27. Lu J, Dawson F (2006) Analysis of Eddy current distribution in high frequency coaxial transformer with faraday shield. IEEE Trans Magn 42:665
28. Rauls MS, Novotny DW (1995) Multiturn high-frequency coaxial winding power transformers. IEEE Trans Ind Appl 31:112–118
29. Mermet-Guyennet M (2010) New power technologies for traction drives. In: Power electronics electrical drives automation and motion (SPEEDAM), pp 719–723
30. Agheb E, Hoidalen HK (2012) Medium frequency high power transformers, state of art and challenges. In: 2012 International conference on renewable energy research and applications (ICRERA), pp 1–6
31. She X, Huang AQ, Burgos R (2013) Review of solid-state transformer technologies and their application in power distribution systems. Emerg Sel Top Power Electron IEEE J 1:186–198
32. Herbert, E. (1986). Flat matrix transformers.US Patent 4665357
33. Kheraluwala MH, Novotny DW, Divan DM (1992) Coaxially wound transformers for high-power high-frequency applications. IEEE Trans Power Electron 7:54–62

34. Tao H, Duarte JL, Hendrix MAM (2007) High-power three-port three-phase bidirectional DC-DC Converter. In: Industry applications conference, 42nd IAS annual meeting. Conference record of the 2007 IEEE, pp 2022–2029
35. Drofenik U, Canales F (2014) European trends and technologies in traction. In: Power electronics conference (IPEC-Hiroshima 2014—ECCE-ASIA), 2014 international, pp 1043–1049
36. Huang D, Ji S, Lee FC (2014) LLC resonant converter with matrix transformer. IEEE Trans Power Electron 29:4339–4347
37. Interior UDO (2012) Transformers: basics, maintenance, and diagnostics: CreateSpace independent publishing platform
38. Bortis D, Biela J, Kolar JW (2010) Transient behavior of solid-state modulators with matrix transformers. IEEE Trans Plasma Sci 38:2785–2792
39. Ngo KDT, Alpizar E, Watson JK (1995) Modeling of losses in a sandwiched-winding matrix transformer. IEEE Trans Power Electron 10:427–434
40. Heinemann L (2002) An actively cooled high power, high frequency transformer with high insulation capability. In: Applied power electronics conference and exposition, APEC 2002. Seventeenth annual IEEE, pp 352–357
41. Taufiq J (2007) Power electronics technologies for railway vehicles. In: Power conversion conference—Nagoya, PCC '07, pp 1388–1393
42. Hwang CC, Tang PH, Jiang YH (2005) Thermal analysis of high-frequency transformers using finite elements coupled with temperature rise method. Electr Power Appl IEE Proc 152:832–836
43. Tomczuk BZ, Koteras D, Waindok A (2014) Electromagnetic and temperature 3-D fields for the modular transformers heating under high-frequency operation. IEEE Trans Magn 50:317–320
44. Xu J, Kubis A, Zhou K, Ye Z, Luo L (2013) Electromagnetic field and thermal distribution optimisation in shell-type traction transformers. IET Electr Power Appl 7:627–632
45. Susa D (2005) Dynamic thermal modelling of power transformers. Power delivery IEEE Trans 20:197–204
46. Susa D, Lehtonen M (2006) Dynamic thermal modeling of power transformers: further Development-part I. Power Delivery IEEE Trans 1961–1970