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# Solid State Traction Transformer Technology

Venu Kumar Sahu[1], Amit Goswami[2]
*[1]M. Tech. Scholar, Department of Electrical & Electronics Engineering, DIMAT, Raipur, India*
*[2]Assistant Professor and HoD, Department of Electrical & Electronics Engineering, DIMAT, Raipur, India*

***Abstract*: Connecting modern high-power semiconductor devices with constantly improving magnetic materials opens up the opportunity to replace the huge low-frequency transformers with a new medium-frequency arrangement. While there are still challenges to be faced associated with these so-called electronic power transformers, also called solid state traction transformers, a growing development effort is evident and is considered in several frames. Traction applications seem to be the first in which the explosion of these new galvanically isolated electronic power converters is expected. In this paper particular field of application, considerable weight and volume reduction can be achieved while providing additional functionality.**

***Keywords*: Solid State Traction Transformer, Power electronic transformer, medium voltage, converter, traction, railway.**

## 1. Introduction

Nowadays, conventional line frequency transformers are widely distributed in electrical systems that provide basic functionalities, such as voltage isolation and voltage adaptation. However, in order to deal with energy quality problems (for example, subsidence, oscillations, flicker, harmonics, etc.) at medium voltage (MV) levels, the installation of additional equipment is needed (generally some type of electronic converter). Of working power). At higher switching frequencies). This leads to an additional increase in installation volume, which in certain applications may not be feasible (for example, traction, marine, wind, offshore). Recent trends in high power MV applications are replicating something that has already been achieved and put into practice in low voltage applications. There, the line frequency transformers (LFT) have been replaced mainly by medium frequency transformers (MFT) where the high frequency waveforms are applied directly to the terminals of the transformer, so that the overall magnetic volume is reduced and more compact converter designs are achieved. Some of the results of this field are presented here, and the scope of this document is limited to railway applications (hence, a one-phase case). Traction applications are recognized as one of the first to adopt this emerging technology. The typical monophasic railway CA lines found in Europe are 15kV, 16⅔Hz (originated by the use of cyclo converters in the past and therefore are one third of 50Hz) and 25kV, 50Hz.

The conventional approach to supplying the DC voltage to the locomotive speed variator is illustrated in a simplified form Figure 1. The primary winding of the LFT is connected directly to the AC catenary and the active rectifier is connected to the secondary winding of the transformer. Where the tension is reduced and regulated. In addition to the supplied DC connection, one or more inverters and motor units are connected. Because tensile LFTs are generally optimized for a minimum weight (2-4 kg / kVA) and are heavily loaded, the resulting efficiency is rather poor and in a range of 90% to 92%. Oil is commonly used for cooling and insulation, which increases total weight and potential environmental problems (for example, in the event of leaks). The power of the system can range from less than 1MVA to 10MVA for large locomotives. In a classic train system, where the propulsion system is concentrated in the locomotive, the weight of an LFT is not a problem, since a certain weight is needed to provide sufficient traction without slippage. In the case of several electric units (EMU), where the propulsion system is distributed throughout the train, weight becomes a problem and the reduction would be advantageous. An alternative to the cutting edge solution is the use of the so-called solid state traction transformer (SSTT), which consists of a power converter together with MFT, as shown in Fig.2. Here, a certain type of electronic power converter is connected directly to the AC catenary, while the MFT provides voltage isolation and voltage adaptation.

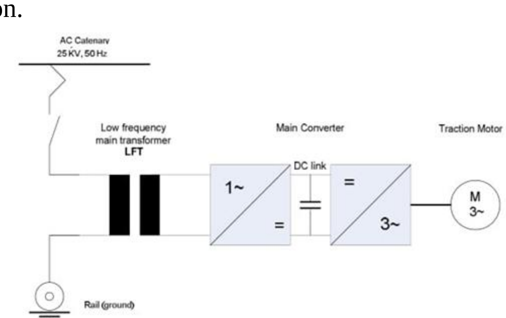


Fig. 1. Traction chain transformer with line frequency transformer (LFT)

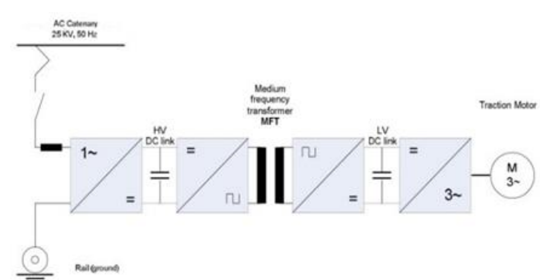


Fig. 2. Traction chain with medium frequency transformer (MFT)

The current semiconductor devices cannot work directly with these average voltages and, consequently, a certain type of serial connection of several cells or modules is necessary to comply with the voltage level of the MV AC line, resulting in a multi-converter structure. Level. The MFT of Fig. 2 is generally performed not as a single transformer (although in some implementations it is), but rather as a number of transformers evaluated for a fraction of the total power and operating at a higher switching frequency (different kHz). Finally, an adjustment is required on the secondary side of the MFT to provide a DC voltage to the inverter. This type of MV technology (although still under development) is becoming a reality with advances in semiconductor technology (faster switching actions, higher block voltages and higher power densities) and the development of new magnetic materials with low density losses at higher operating frequencies. Although initial SSTT considerations date back to the 1970s, there are currently no products offered by any of the major players in the traction market.

## 2. Solid state traction transformer topologies

Several architectures / topologies have been considered for the realization of an SSTT for traction applications. The first works considered the use of solutions based on thyristors, as illustrated in Fig. 3. The primary side of the MFT consists of two H bridges of thyristors connected in parallel, while the secondary side has an H-bridge. forced single-phase switching. In other words, there is a cycloconverter in the input (HV side) and the voltage source inverter (VSI) in the output (LV side). In this implementation, the MFT is driven from the secondary side by the VSI and the voltage from the MFT is used to switch the cycloconverters on the primary side. The use of thyristors limits the MFT frequency to a few hundred hertz. In addition to the low frequency, the circuit also generates quite high line harmonics and other improvements in this direction. To mitigate some of the problems with the thyristor-based approach and to further increase the frequency of operation of

MFT, the use of fully controllable devices such as IGBTs has been proposed. In the cycloconverter in Fig. 3, it was made using IGBT (serial connection of two IGBTs with a common emitter as replacement of two antiparallel thyristors) - dependent while switching null voltage (ZVS), during the execution of the VSI as a bridge converter H IGBT standard. However, in order to cope with line voltage, a series connection of various IGBTs is required, which, at present, the maximum IGBT blocking voltage available on the market is only 6.5 kV. Therefore, a modular structure is formed consisting of several cascaded cells (which are of the same nature as those in Fig. 3, but made with IGBT), as shown in Fig. 4. In this arrangement, thanks to the tightening voltage the tension continued on the secondary side via the primary side MFT, a suitable voltage distribution between different cells is obtained. At the same time, a multilevel voltage waveform at the SSTT input helps to reduce the line harmonics and resulting filter requirements. Contrary to Fig. 3, instead of having a single MFT, a number of MFTs, each of which is an integral part of an associated cell and is evaluated for a fraction of the total power is required. However, insulation requirements are not relaxed and every MFT must be designed for the same dielectric voltage as before. There was a prototype 1.2MVA SSTT railway network for 15kV and 16⅔Hz, based on the topology of Fig. 4. The implementation is based on 16 cells, each with a cyclo converter, MFT and VSI (rectifier) and using IGBT's 3.3 kV, while the MFT was operated at 400 Hz. To avoid difficulties with the cyclo converters on the primary side of the MFT and taking into account the fact that, in any case, a number of cells is required, different research groups have proposed cascade H bridges (four quadrant converters). Thus, a pure IGBT solution and the required number of cells (modules) is realized is mainly related to the selected semiconductor voltage class.

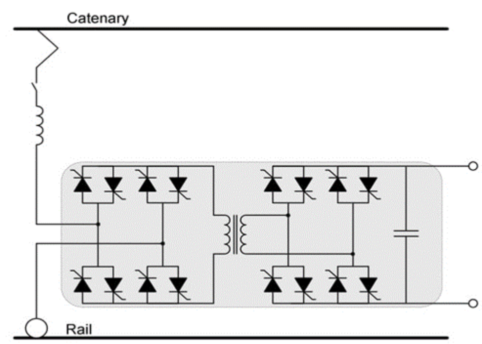


Fig. 3. SSTT topology with primary switched converter source

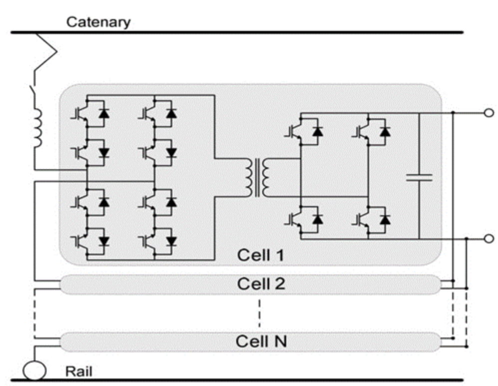


Fig. 4. Topology SSTT with cascaded source switched primary switches

In, a topology similar to the one shown in Figure 6 has been proposed (the main difference is the lack of capacitors connected to the MFT, so it is a non-resonant converter). Input stages are performed with four quadrant converters and provide intermediate DC connections as well as a high-resolution multilevel waveform at the drive input. The DC / DC converters are connected to each of the floating DC connections and provide galvanic isolation and voltage adaptation to the secondary side (as previously, all the converters are connected in parallel in the output). The power control is obtained by manipulating the phase change between the rectangular voltage waveforms on the two sides of the DC / DC converter. The same group of authors analyses different possibilities of reconfiguration of this type of topology. It presented a topology identical to that shown in Fig. 5. A DC / DC resonant converter is proposed in series to reduce semiconductor switching losses (zero voltage switching (ZVS) switching and zero current (ZCS)) and allowing an additional increase in the frequency of the MFT operation. For a 15 kV rail network and the use of 6.5 kV IGBTs, it was estimated that 7 cells would be required for nominal operation (even if it is proposed to add an additional cell for redundancy) and it was expected that the MFT would it was often in the 8-10 kHz range. You can find some details on checking this type of SSTT. Other considerations on the topology of Fig. 5 can be found, various susceptibilities discussed and 6.5 kV as the most suitable selected, considering failure rates over time (FIT) and the amount of devices needed. To increase the switching frequency, a resonant soft switching DC / DC series with a semiconductor half-bridge arrangement on both sides of the MFT is considered. In addition to the standard IGBTs, modified semiconductor devices have also been tested. In particular, the IGBT series irradiated with electrons to move the properties of the device in the curve towards technology the area of lower energies of extinction (reduction of the useful life of the carrier) but at the expense of a greater fall of tension in the state and, therefore, greater static losses (of conduction). The reported results emphasized the possible increase in the switching frequency in the range of 40-50% (at nominal power). However, these devices are not commercially available, except for limited engineering samples.

A slightly different approach has been presented when using multiple winding MFTs. The primary side is realized again with a series connection of bridges in H that provide DC links of the intermediate HV side from which the primary windings of the MFT of multiple windings are excited by half-bridge series resonant converters operating at 5 kHz. The secondary side is made using a single bidirectional H-bridge converter. A 1.5MW SSTT prototype was completed on a full scale with 8 cells in total (7 without redundancy). The mass of the prototype SSTT was reported as 3.1T, compared to 6.8T for a conventional LFT, however, at the cost of a 50% higher cost and a compromised reliability due to the use of 48 IGBT of 6.5kV on the primary side of the MFT multiwindings. The authors published the next field trials using the developed SSTT prototype, but no additional results were reported or tracked. There has been a use of a modular multi-level converter (M2LC) for traction applications. Although the simplified design is shown in Fig. 7, in the original publication there are several secondary windings of the MFT with rectifiers, inverters and dedicated active motors. M2LC is a highly modular topology and the basic building blocks (cells) for traction applications are series-connected H-bridges, each with its own DC capacitor bank, which ultimately resembles a kind of large composite H bridge, such as shown in Fig. 7. M2LCs are associated with large amounts of energy stored in each cell, but with a low energy density per cell, which increases the weight and volume of the entire system. So far, in real-world applications, M2LC has been successfully launched only for HVDC installations.

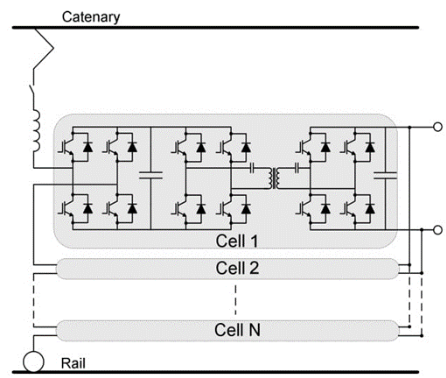

Fig. 5. SSTT topology with cascaded H bridges and resonant / non resonant DC-DC stages

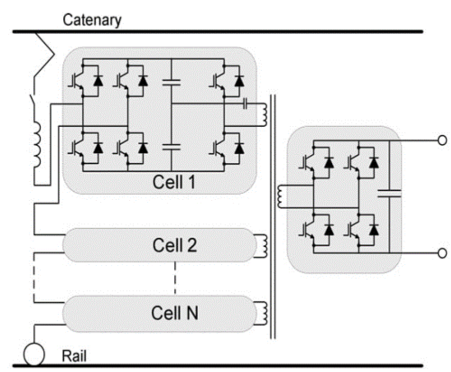

Fig. 6. SSTT topology with cascade H bridges and multi-winding MFT

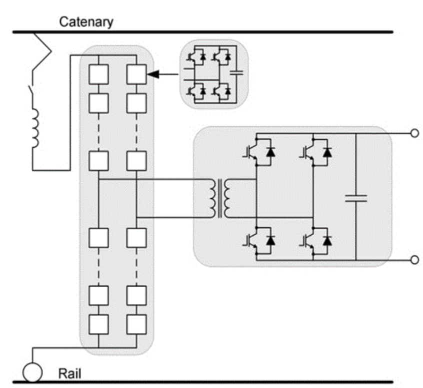

Fig. 7. SSTT topology using the M2LC converter

The most recent reports on SSTT in traction applications are reported. The topology is shown in Fig. 8 and, as in the previous example, consists of cascade H bridges on the input and resonant DC / DC converters with the power stage performed using a half-bridge configuration. Moreover, unlike the resonance tank of the LC series used, an LLC resonant tank is used. Therefore, both the leakage inductance and the magnetization inductance of the transformer are participating in the resonance. In this way, ZVS is reached during IGBT switching on, while close to ZCS is reached during the switching off of the IGBT (ie, the current is not zero, but has a low value previously determined during the IGBT design). resonant tank and DC The resonance tank gain is largely independent of the load). The results are presented with regard to the design and preliminary tests of the DC-DC resonant converter LLC.

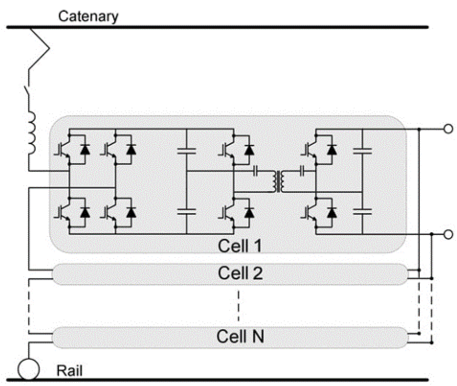


Fig. 8. SSTT topology with cascaded H bridges and resonant DC-DC stages

### 3. Medium frequency transformer

The details related to the implementation of MFT have been deliberately omitted in the previous section, since this topic is rather difficult on its own and, due to space limitations, is dealt with here at a fairly general level. Therefore, the basic problems that are found in the design phase of an MFT are highlighted and some examples are illustrated. The size of a transformer can generally be related to the area product, Ap, defined as:

$$A_p = \frac{P_t}{K_f K_u B_m J_f} \quad (1)$$

When designing an MFT, all parameters in (1) must be carefully considered. The main idea behind the SSTT is to replace the bulky LFT with a more compact MFT or MFT in general, operating at a higher frequency (f), usually in the range of several kHz. Although the increase in the operating frequency (f) leads to a reduction in the size of the transformer (Ap), the high insulation requirements have a negative effect on the window utilization factor (Ku), which results in a low fill factor of the window area due to the required amount of insulating material. This is particularly true in the case of MFT for SSTT, where due to the lack of applicable standards, the MFT is generally designed to meet the same requirements as the AC direct line connected to LFT. Therefore, the required level of isolation is almost independent of all other parameters in (1) since it is purely related to the system requirements. Taking into account the fact that the MFT is controlled by rectangular waveforms instead of sinusoidal, the Kf factor that is related to the waveform is different from an LFT. At the same time, the Steinmetz parameters and losses in the core associated material selected at a particular frequency are determined by hypothesizing a sinusoidal excitation, which makes estimate the preliminary losses are rather inaccurate and often an experimental characterization is required. The materials considered in general for MFT are: nanocrystalline, amorphous iron and / or ferrites. The current density of the winding (J) is directly related to the cooling effort required to eliminate the heat generated by the winding, which has a great impact on the choice of the cooling method. On the other hand, the selection of different base materials leads to a different density of operating flow (Bm) and also has an impact on the size of the MFT. Finally, combining the requirements of high power (Pt), high insulation (Ku), simple cooling (J) and low flow density (Bm) of materials suitable for the frequencies (f) of interest, the design of a high insulation, High power, MFT is not a simple task. Furthermore, since it is desirable to integrate resonant tank elements into the MFT, there is a need to accurately control the transformer inductances (losses and magnetization) for proper resonance operation, which introduces further complications in the design. The need to operate at higher switching frequencies requires a low dispersion inductance, which is in contrast to the high isolation requirements that generally result in greater losses. Considering the selection of different base materials, silicon nanocrystalline steel, ferrites are used, while amorphous iron is used. As far as cooling and insulation are concerned, the oil is used both in deionized water and to cool the windings, while the oil also provides insulation. The MFT shown in Fig. 9 is made using amorphous iron core material with a coaxial winding structure and active cooling with deionized water through the space available between the primary and secondary windings. The prototype was designed for a switching frequency of 350kW and 10kHz. The respective insulation voltage test is performed at 38 kV and 50 Hz for 60 seconds, while the nominal pulse voltage is 95 kV. The use of coaxial windings limits the ratio of the turns to 1:1, which was acceptable in the case analysed.

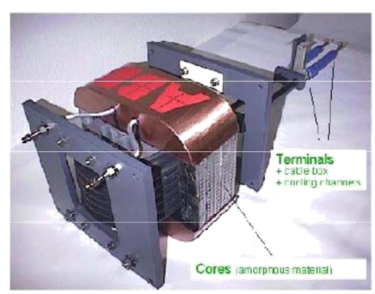


Fig. 9. ABB Medium Frequency Transformer prototype

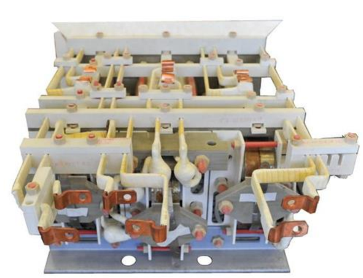

Fig. 10. ABB Medium Frequency Transformer prototype (3 pieces)

Special Attention was paid to adequately assess dielectric stress throughout the MFT in order to provide a design that could guarantee a long life. A different design is shown in Fig. 10. It has a set with three MFTs, each rated for 150 kW (with the ability to withstand an overload of 225 kW for 60 seconds) and an operating frequency of 1.8 kHz. The test voltage of the insulation and the nominal voltage of the impulse are similar to those of the previous case. The material used for the core is nanocrystalline and the forced air cooling method (ODAF) is applied (the whole structure is immersed in oil), which solves the problem of insulation at the same time. The inductive elements necessary for a correct resonance operation are realized as an inductance of dispersion and magnetization of the MFT. The most recent discussion on the problems related to the optimization of the multi-parameter configuration of a 150 kW medium-frequency transformer is available, which highlights the coupling effects of several parameters, in particular different cooling scenarios, as discussed in relation to (1).

## 4. Conclusion

The solid state traction transformer, which provides a reduction in weight and volume transported by additional features, is considered a valid solution for the replacement of large size low-frequency transformers. Designing a conversion system of this type is not an easy task, and some of the challenges presented in the literature are presented here in this paper. SSTT offers some advantages over the conventional solution, such as weight and volume reduction, greater efficiency and greater control flexibility against network disturbances. The functional properties of this type of technology have been demonstrated previously by many authors, but more integration work is still needed to reduce costs before a first market implementation is seen. In the meantime, an important milestone was recently commissioned and specially made to successfully commission the world's first electronic power transformer on a regularly operating locomotive.

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