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Power Electronics advancement in Electric Traction Drives-An Overview

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Abstract— This paper presents the power electronics advancement in electric traction drives. In this paper the power electronics traction transformer and multilevel converter are used to improve the performance of electric traction dives. In this paper power electronics devices are used with the traction drives so that the harmonics developed after inversion operation can be reduced using multilevel converter. The main advantage of multilevel converter kind of topology is that it can generate almost perfect current or voltage waveforms, because it is modulated by amplitude instead of pulse-width.In this paper introduction to power supply used in electric traction and medium frequency transformers using cycloconverters are used to reduce the frequency of the AC supply used in electric traction. 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. This paper also discussed the power quality improvement in electric traction drives using power electronics devices. In this paper there is a discussion of the replacement of conventional pantographs by using unconventional current collection from a contact line for electric traction vehicles.

Key words: Electric traction, Multilevel converter, Power electronics traction transformer, power supply in electric traction drives, Unconventional current collection from a contact line

I. INTRODUCTION

A. General

Presently we are using power electronics in railways as a converter and inverter function. From the first ignitron, to the present IGBT's, five decades of research have led to such a progress in terms of power, quality of the wave and in convergence to one of the power factor. IGBT's have allowed managing power in three phase asynchron motors which was difficult and costly to be made with GTO's. On board of a traction unit, need of variable speed, very small room, absence of three phase network made it difficult to use and drive three phase motors with conventional electro techniques. To solve this, power electronics was especially well adapted.

B. Multilevel converter

Power Electronics technologies contribute with important part in the development of electric vehicles. On the other hand, the PWM techniques used today to control modern static converters for electric traction, do not give perfect waveforms, which strongly depend on switching frequency of the power semiconductors. Normally, voltage (or current in dual devices) moves to discrete values, forcing the design of machines with good isolation, and sometimes loads with inductances in excess of the required value. In other words, neither voltage nor current are as expected. This also means harmonic contamination, additional power losses, torque ripple, and high frequency noise that can affect the controllers.

C. Power Electronics Traction Transformer(PETT)

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).

D. Unconventional current collection from a contact line

The electric energy is collected from a contact line through a gliding electric contact realized between the catenary and the pantograph. The main request for such a system is to provide a constant pressure into the contact point in order to have an optimum energy transfer from the wire to the pantograph and to the vehicle.

The real time response of the pantograph's movement is an important criterion for the estimation of the current collecting quality.

II. MULTILEVEL CONVERTER

A. Basic Principle

The circuit of fig.1 shows the basic topology of one converter used for the implementation of multistage converters. It is based on the simple, four switches converter, used for single phase inverters or for dual converters. These converters are able to produce three levels of voltage in the load: +Vdc, -Vdc, and Zero.

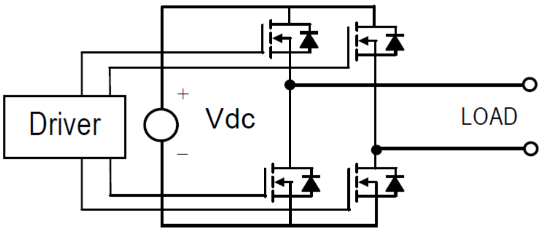

Fig. 1: Three-level module for building multi-stage converters

B. Multistage Connection

The multi-stage connection can be implemented with two, three, or any number of three-level modules. The figure 2 displays the main components of a four-stage converter, which is being analysed in this work. The figure only shows one of the three phases of the complete system. As can be seen, the dc power supplies of the four modules are isolated, and the dc supplies are scaled with levels of voltage in power of three. The scaling of voltages in power of three allows having, with only four converters, 81 (3^4) different levels of voltage: 40 levels of positive values, 40 levels of negative values, and zero. The converter located at the bottom of the figure has the bigger voltage, and will be called Master. The rest of the modules will be the Slaves. The Master works at the lower switching frequency, which is an additional advantage of this topology.

With 81 levels of voltage, a four-stage converter can follow a sinusoidal waveform in a very precise way, as shown in figure 3. It can control the load voltage as an AM device (Amplitude Modulation). The figure 3 shows different levels of amplitude, which are obtained through the control of the gates of the power transistors in each one of the four converters.

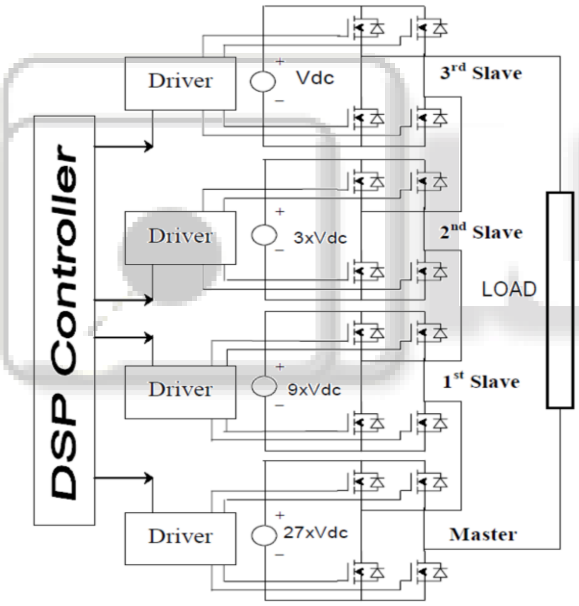

Fig. 2: Main components of the four-stage multiconverter.

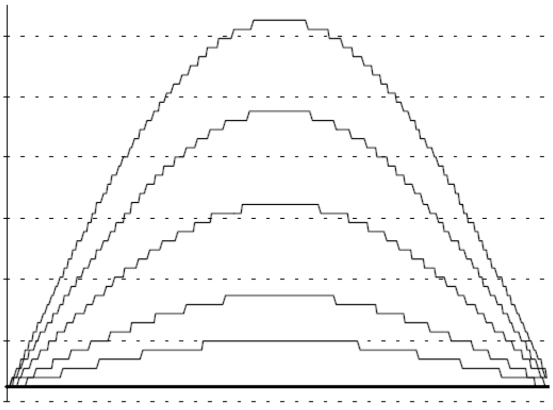

Fig. 3: Voltage AM using a four-stage converter

C. Power Distribution

One of the good advantages of the strategy described here for multiconverters is that most of the power delivered comes from the Master. A little more than 80% of the real power is delivered by the Master converter, and only 20% for the Slaves. Even more, the second and third slave only deliver 5% of the total power. That means, the dc power sources needed by the Slaves are small.

III. POWER ELECTRONIC TRACTION TRANSFORMER

A. PETT Architecture

Various architectures/topologies have been considered for the realization of a PETT for tractions applications. Early works considered the use of thyristor based solutions as illustrated in Fig.4. The primary side of the MFT(Medium frequency transformer) 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.

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.The cycloconverter from Fig.4 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.

A PET prototype based on the topology from Fig.5 has been used , 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.

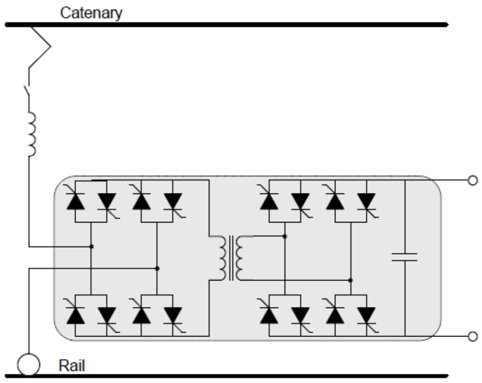

Fig. 4: PET topology with source commutated primary converter

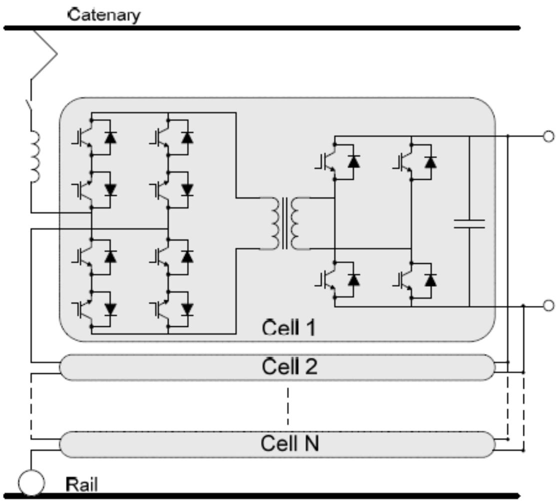

Fig. 5: PET topology with cascaded source commutated primary converters.

B. *Medium Frequency Transformer(MFT)*

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:

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

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 thewaveform 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.

IV. UNCONVENTIONAL CURRENT COLLECTION FROM A CONTACT LINE

The contact line has an important variation of its elasticity, with significant differences between the suspension pillars and the middle of the span. This elasticity is defined as a ratio between the over-high *h* (the difference between the static and dynamic level) and the force *f* of the pantograph over the wire:

$$e = {}^{h}\!/_{f} \qquad (1)$$

An important characteristic of the wire is the uniformity of the elasticity given by the relation:

$$u = \frac{e_{max} - e_{min}}{e_{max} + e_{min}} \cdot 100 \quad [\%] \qquad (2)$$

where: *e*max and *e*min are the maximum and minimum elasticity. These variations on elasticity will also influence the movement of the pantograph, resulting acceleration, a deceleration and a change in the direction of its movement, which is a permanent transient regime. The pressure force of the pantograph *Fpf* acting over the wire is a result between the force *Flift* given by mechanical lifting system of the pantograph.

A. *Unconventional Power collecting Possibilities*

The elimination of the physical contact between the wire and the pantograph and the use of the controlled electric arcs could assure an energy transfer on the medium and high speed vehicles.

Thus, for low speeds, the power collecting could be realized by mechanical contact (area 1, Fig. 6) and for medium and high speeds the power collecting could be realized by the control of the electric arcs (area 2, Fig. 6), avoiding the interruption area 3. Figure 6 is a particular case, but in reality the areas of the mechanical contact, the electric arcs, the power interruption and the power reconnection could be very different.

Using the electric arcs as an unconventional electric vehicle power supply. where the studies shows the possibilities of a good power supply for speed of 250 km/h even for a gap of about 6 mm between the contact line and the pantograph’s shoe. For higher speed it seems to be necessary an aero-dynamical protection of the electric arcs or a magnetically controlled field to maintain the arcs. The magnetic control is very difficult even for uniform magnetic field.

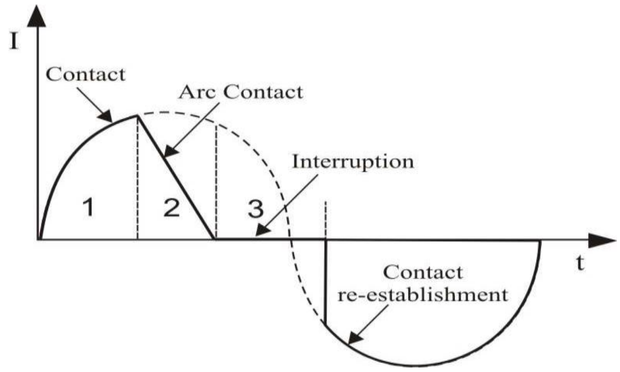

Fig. 6: The mechanical contact, the electric arcs, the power Interruption and the power reconnection.

Another solution is the power collecting by induction, which can be realized in two ways:

(1) Power collecting without a magnetic circuit and at high frequency (about 5 kHz);
(2) Power collecting with an open magnetic circuit.

The first solution was tested for the first time on a mine locomotive supplied from a contact line realized with two isolated contact lines, CL1 and CL2, placed above the rails and criss-cross to limit the inductive voltages over the near metals. On the locomotive there is an electric receiver Rv produced from wires with or without iron core. The electromotive force was rectified and supplied a D.C. series traction motor. The system has the advantages to eliminate the sparks due to the classical power collecting but has disadvantages because of a low efficiency, the necessity of a higher frequency and because of the double contact line.

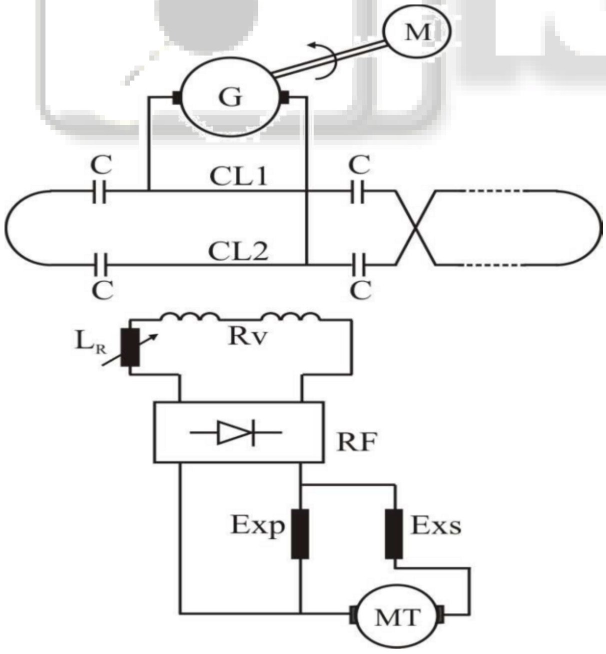

Fig. 7: Power collecting without a magnetic circuit.

V. TRACTION POWER SUPPLY

Traction power supply has some important constraints: structurally, it is a system with one active conductor wire and rails for return current. Electrically, with the requirements coming from power suppliers, there is a necessity to reduce strongly any disturbance in terms of quality of the electrical wave: harmonics, phase unbalance, flicker: a perfect consumer is wished! On the other hand, trains are moving and the impedances seen upstream by a traction unit change at any moment. Also, harmonics generated by traction units will also flow through variable impedances creating a risk of instability of the network with over voltages as a consequence. As a matter of fact, any fixed system working with power electronics will have to be assessed towards EMC, particularly against track circuits for signalling purposes.

With all these requirements, it is always possible to fulfil them by implementing classical electro technique solutions such as increasing the short circuit power by building new HV transmission lines, new sub stations. But often, such hard and costly installation would be oversized with the effective need and therefore power electronics will offer an adjusted solution. This participates to a reduction of the impact on the environment if it avoids new construction of HV lines and substations.

VI. CONCLUSION

By using the different techniques discussed above the power loss due to the conventional switches will reduced upto a certain extent by using power electronics switches.

Multilevel converter can reduce the power losses due to slaves because most of the active power generated by master slave of the converter (about 80% of the active power).

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.

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