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A REVIEW ON HIGH FREQUENCY SOLID STATE TRANSFORMER FOR ELECTRIC LOCOMOTIVE POWER SUPPLY

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ABSTRACT

The future locomotive traction system would be designed to minimize the effects of power quality events (e.g., voltage dips), improve reliability indices and increase performance by reducing losses. Due of their low cost, high reliability, and high performance, normal low frequency in power transformers of traction systems are commonly used. However, the low frequency power transformer has a number of power quality problems, including voltage drop during loading, inability to reduce flicker," exposure to harmonics," environmental concerns about mineral oil etc. The idea of a solid-state transformer (SST) as an alternative approach to the low frequency power transformer essential for locomotive traction power supply (SST). It introduces new functionalities to traction power such as reactive power compensation, limited short-circuit currents and voltage sag compensation as well as new ways to regulate electricity routing. Solid-state transformers, also known as solid-state traction transformers (SSTT) when used in railway traction systems, are a modern type of converter topology that uses a high voltage multi-level rectifier and high-frequency isolation. Many studies on various aspects of this form of converter have been conducted. The topology incorporating high-voltage cascaded inverters and DC to DC converters is the most appealing of the various SSTT topologies. On the basis of previous studies, a new form of electric traction system based on SSTT is proposed in this review paper.

Keywords: Solid-State Transformer (SST), Power Quality, Voltage Sag, HVDC, Electric Traction.

I. INTRODUCTION

With the construction of electrified railways in India, high-power electric locomotives and high-speed trains are applied, which greatly promotes the economic development. The electric traction technology based on power conversion and alternating current (AC) motor speed adjusting is one of the key technologies of electric locomotive and high-speed electric multiple units. So far, most of them have been applied maturely. The research and development of next-generation electric traction system has begun in India to reach higher speed and greater transport capacity, to effectively reduce energy consumption and to realize energy-saving and emission reduction [1].

The main objective of next-generation high-speed train traction system is to scale back the quantity and weight of the system and to enhance efficiency. Within the power-decentralized electric multiple units, the traction systems won't be installed intensively anymore; instead, they're going to be distributed in each compartment of a train. The traction equipment with huge volume will limit the passenger capacity and make structural design of a train more difficult; additionally, the load of traction equipment will directly affect the acceleration and braking performances of a train, thus affecting the safe operation of the train and passenger comfort. In the traction system, the most traction transformer approximately accounts for 1/3 of the whole equipment. Multiple topologies adopting high frequency transformer (HFT) are suggests by scholars to scale back the quantity and weight of main transformer for train traction and to enhance the reliability and adaptability of traction system.

The future locomotive traction system is also being planned to reduce or prevent the effects of power quality incidents (e.g., voltage dips), boost stability indices (e.g., by minimizing the amount and length of interruptions), and maximize performance (e.g., by reducing losses). The normal low frequency in power transformer of traction system is widely used [2]. This is due to their low cost, high reliability, and high efficiency. But as always as there is advantages there is also some disadvantages the low frequency power transformer has few power quality issues like; the voltage drop in loading time, inability to mitigate flicker", sensitivity to harmonics, environmental concerns regarding mineral oil, limited performance under DC-offset load unbalances, and a need for protection of the primary system from problems arising inside or beyond the transformer. It is clear that the Power quality is an extremely important issue especially with utility end users;

this is the fact that makes these problems more serious today than before. The solution was founded, when the concept of a solid-state transformer (SST) was mentioned as an alternative to the low frequency power transformer [3]. At that time the successful demonstration of the concept wasn't so clear, however the advantages of this new concepts were clear. Nowadays with the recent advancements in the field of power electronics and semiconductors, and with the deep understanding of the multilevel converters, the concept became more viable.

II. ELECTRIC TRACTION SYSTEM

The traction system that uses electricity in all stages or some stages of a vehicle movement is referred to as an electric traction system. In an electric traction system the driving power to draw a train is generated by the traction motors. The electric traction system can be broadly divided into two groups: one is self-powered and the other one is third-rail system. The self-powered systems include diesel electric drives and battery electric drives that can generate their own power to pull the train; whereas, the third-rail or overhead-wire systems use the power from an external distribution network or grids, and the examples include tramways, trolley buses and locomotives driven from overhead electric lines. The track electrification refers to the type of source supply system that is used while powering the electric locomotive systems .It can be AC or DC or a composite supply. Selecting the type of electrification depends on several factors like availability of supply, type of an application area, or on the services like urban, suburban and main line services, etc.

The three main types of electric traction systems that exist are as follows [4-5]:

a) Direct Current (DC) electrification system

b) Alternating Current (AC) electrification system

c) Composite system.

a) Direct Current (DC) electrification system

The choice of selecting DC electrification system encompasses many advantages, such as space and weight considerations, rapid acceleration and breaking of DC electric motors, less cost compared to AC systems, less energy consumption and so on. In this system, three-phase conventional power from the power grids is de-escalated to low voltage and converted into DC by the rectifiers and power-electronic converters. This type of DC supply is supplied to the vehicle through two different ways: the first way is through the 3rd rail system (side running and under running electrified track and providing return path through running rails), and the second way is through the overhead line DC system. Now this DC supply is fed back to the traction motor like the DC series or compound motors to drive the locomotive, as shown in the figure 1 below.

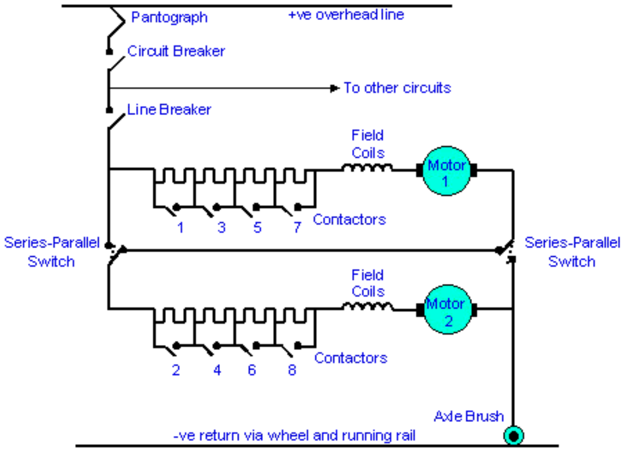

Figure 1: Schematic of simple DC traction power control

DC electrification supply systems range from 500 to 750 V for special systems such as battery systems (600-1200V) for urban railways such as tramways and light metros, to 1500-3000V for suburban and mainline services such as light metros and heavy metro trains. Low voltages (600-1200V) and high currents are used in the 3rd (conductor rail) and 4th rail systems, while high voltages (1500-3000V) and low currents are used in the overhead rail systems.

b) Alternating Current (AC) electrification system

Due to many advantages, such as fast availability and generation of AC that can be easily stepped up or down, easy control of AC motors, smaller substations needed, and the presence of light overhead catenaries that transfer low currents at high voltages, an AC traction system has become very common in recent years, and it is more often used in most traction systems. Single-phase, three-phase, and composite supply systems are available for AC electrification. To allow variable speed to AC commutation motors, single phase systems consist of 11 to 15 KV supply at 16.7Hz and 25Hz. It converts from the high frequency to the low frequency using a step down transformer and frequency converters.

The most common configuration for AC electrification is single phase 25KV at 50Hz. Since it does not need frequency conversion, it is used for heavy haul systems and main line services. The supply is converted to DC to drive DC traction motors in this form of composite system, which is one of the most common.

The locomotive is driven by a three-phase induction motor rated at 3.3.KV and 16.7Hz in a three-phase configuration. Transformers and frequency converters convert the high-voltage distribution system's supply at 50 Hz to this electric motor rating. This system has two overhead lines and a track rail, but it has a lot of issues at crossings and junctions.

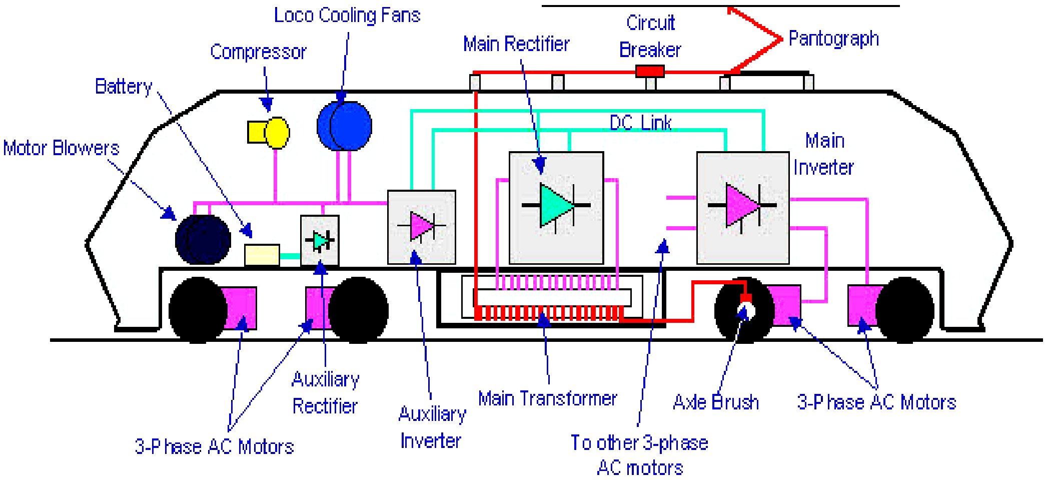

Figure 2: Block Diagram of Modern AC Electromotive

The operation of an AC electric locomotive is represented in Figure 2, where the centenary system is supplied with single-phase power from the overhead system. The transformer boosts the voltage, which is then transformed to DC by a rectifier. A smoothening reactor, also known as a DC connection, filters and smoothens DC to eliminate ripples, and then the DC is converted to AC by an inverter that changes frequency to give the traction motor variable speed (similar to VFD).

c) Composite system

The benefits of both DC and AC systems are combined in this system. There are two major types of these systems: single phase to three phase or Kando systems, and single phase to DC systems A single overhead line carries the single-phase 16KV, 50Hz supply in a Kando system. The transformer and converters in the locomotive move down the high voltage and convert it to a three-phase supply of the same frequency. The locomotive is driven by a three-phase induction motor powered by this three-phase supply. This system is cost-effective because it replaces the three-phase system's two overhead lines with a single overhead line. As we discussed in the AC electrification section, a single-phase to DC system is very common because it is the most cost-effective way of using a single overhead line and has a wide range of DC series motor characteristics. A single-phase 25KV, 50Hz overhead line supply is stepped down by a transformer within the locomotive, and then converted to DC by rectifiers in this configuration. The DC is fed into the DC-drive mechanism, which is used to power the series motor motor and to control its speed and braking systems.

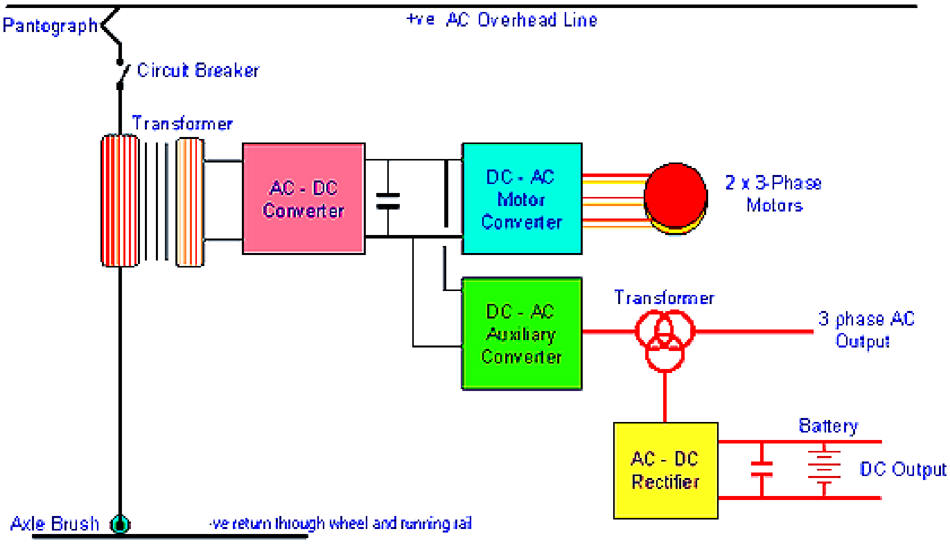

Figure 3: Block Diagram of 25kV traction control system with the 25kV fed into a transformer

III. METHODOLOGY

a) Solid State Transformer basic concept

The basic solid-state transformer topology consists of three main sections: the first is the converter or converters, which is responsible for converting the line low frequency AC into the necessary high frequency AC, the second is the high frequency transformer, and the third section is the converter or converters, which is responsible for producing line frequency AC from the high frequency AC [6]. The high frequency transformer separates the high and low voltage sides of the transformer by providing insulation between its terminals. A solid state transformer's basic structure is shown in Figure 4.

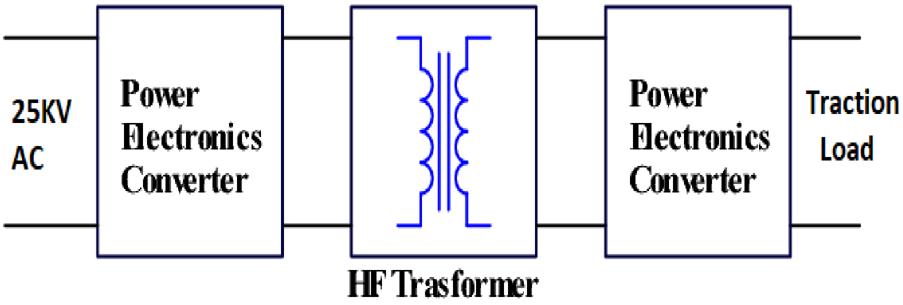

Figure 4: Generalized solid-state transformer circuit.

b) Solid State Transformer configurations

Many solid state transformer power topology equivalents can be found in the literature. They develop a method for classifying SST topologies and selecting the required configuration based on the needs. However, it's exciting to learn that all of those configurations can be categorized into four categories [7].

A. Single-stage with no DC link.

B. Two-stage with low voltage DC link (LVDC).

C. Two-stage with high voltage DC link (HVDC).

D. Three-stage with both high and low voltage DC links.

Figure 5 shows a graphical representation for all the previously stated classes to illustrate them .Insulated Gate Bipolar Transistors (IGBT) and high frequency transformers with high voltage ratings, such as those used in the distribution system, are not readily available at the moment. A modular approach may be one of the solutions to these problems. The ripple of the current would also be reduced using the interleaving technique, resulting in a reduction in the size of the filter used to smooth the current.

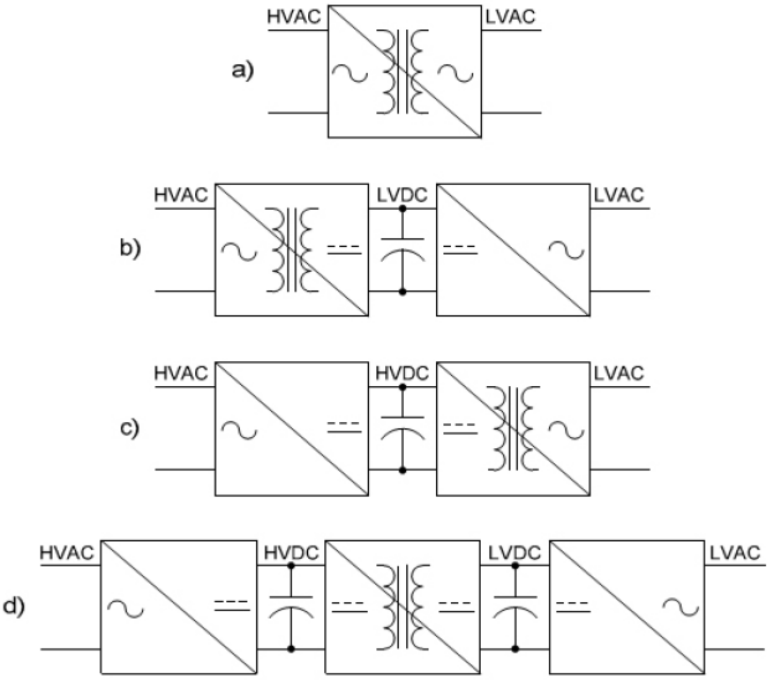

Figure 5: SST configurations: a) single-stage, b) two-stage_with_LVDC_link, c) two-stage with HVDC link_&_d) three-stage.

The three-stage SST architecture can be modeled as seen in Figure 5. It is made up of two semiconducting converter bridges linked by a single transformer in the middle. The first converter is wired to the MV side and transforms three-phase alternating current voltages with frequencies of 50 or 60 hertz to a DC voltage in the MV DC circuit. The MV-converter Bridge's second part then transforms the DC voltage back to AC, but at a faster speed. Because of the higher AC frequency, the magnetic properties of the transformer center are best used, and the transformer may therefore be made considerably smaller while maintaining the same power capacity.

On the LV line, a second converter bridge transforms the high frequency AC voltage to DC and then to the same power frequency, 50 or 60 Hz. SSTs, as shown in Figures 5, use power electronic converters and a high frequency transformer to convert medium or high voltage on the primary side to low voltage on the secondary side. As a result, utilities now have greater grid power while being substantially smaller and lighter. It's worth noting that the same or very similar design can be used to produce a DC secondary-side waveform as well as a high-frequency AC waveform. These alternatives are not investigated in this analysis since neither the configuration nor the architecture depicted in Figure 6 can be substantially altered to accommodate them. This thesis' research is mainly concerned with a three-stage SST for interfacing MV and LV structures.

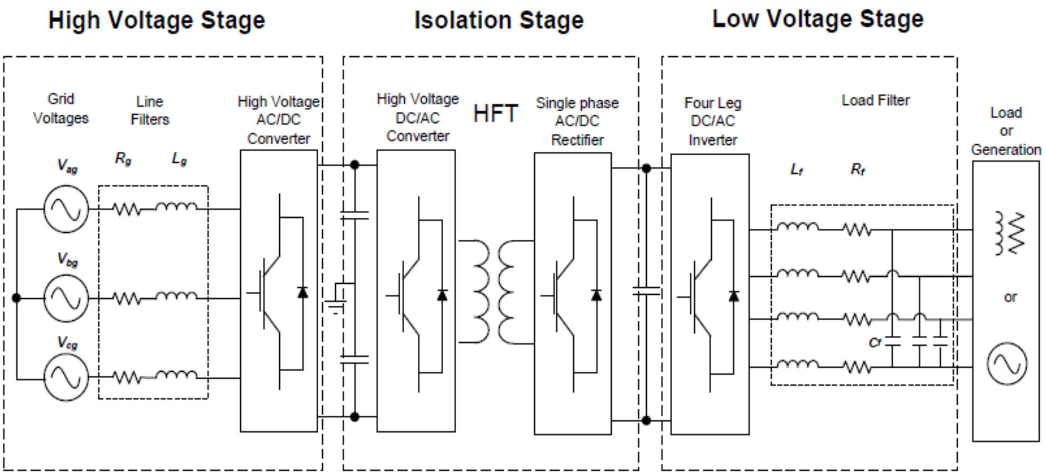

Figure 6: Schematic configuration of a three-stage SST

IV. DESIGN CONSIDERATIONS OF HIGH OR MEDIUM-FREQUENCY TRANSFORMERS

The power converters and transformers for high or medium frequency are central components of an SST topology. In this segment the effect on the transformer will differ based on the topology used to produce an SST. These have to be considered when constructing a transformer (i.e., different current, voltage and leakage inductance requirements). Other transforming architecture requirements should be examined to achieve high performance and power density which are ideal features in an SST and thereby solve the problems of working with high or low frequencies. As a result, the primary goal of this chapter is to present the design which offers a magnet-based core characterization to determine conditions for selection of core materials and examines high-frequency effects on transformer windings [7-8].

a) Magnetic Core Characterization

In a transformer design, the selection of key materials is crucial as it impacts expense, performance and volume. The properties of the magnetic materials are also important to consider. In particular, a core material suitable for a specific application may be characterized with four measures: core failure densities (Pfe), saturation density flux (Bsat), relative permeability (µi), and curie temperature (Tc). Ferrite, silicon steel, amorphous, and nano-cristalline are typical core magnetic materials used for high-frequency transformers.

b) Transformer Core Losses

This section examines the main losses in terms of understanding the characterization of magnetic material. The three main forms of core losses in a magnetic material are loss of hysteresis, reduction of eddy current and loss of waste. The magnetic domain reorientation is associated with the lack of hysteresis.

c) Core Loss Calculation Methods

Several approaches have been proposed in the literature to calculate key losses. The separation of losses is one method for detecting core losses, as stated in the previous section. Other techniques are based on hysteresis modeling, including the models Preisach and Jiles-Atherton. Although the tools are very accurate, there are many estimates and measures needed for a core loss estimate. Analytical estimates on the basis of measured data are most often used to quantify core losses. Particularly, a widely used equation is the Original Steinmetz Equation (OSE):

$$Pv = Kf\alpha Bm\beta$$

where Pv is has the overall average volume transmission losses time, K, α and βare material properties derived from the datasheet of the manufacturer or specified by curve in the sinusoidal excitation course; and Bm is the maximum voltage of flux due to the frequency f excitement voltage.

d) Selection of a Core-Loss Measurement Method

To this end, it is important to note that a number of variables may affect core losses. A few examples are temperature, waveform of excitement, DC conditions and relaxed effects. As a consequence, only numerical equation calculations and measurements can be correctly calculated for core losses. This has led to the suggestion of several key failure approaches to increase the precision of the calculation.

The following are the most desired characteristics of an efficient calculation technique: The analysis of various key loss measures approaches can be concluded [9]:

A. Core-loss measurements can be differentiated from the winding loss

B. Simple implementation and fast measurements

C. Random waveforms applicable

D. Minimum error due to phase discrepancies

V. CONCLUSION

This study reviews the internal structure of the electrical locomotive power supply, from the pantograph to the induction motors, as well as the performance of the rectifier, inverter, and chopper systems as well as the SST. The replacement with the on-board transformer with a high-power converter is one of the most important objectives in railway electrical equipment. Because the transformer runs at line frequency (50 Hz or 16 2/3 Hz), it is a vital component in terms of weight, and it is also characterized by low efficiency. Solid-State Transformers are high-power converters with a medium frequency inductive coupling that are used in this application (SST). SST has become highly significant in the sector of modern electrical power systems as a result of its evolution. This study provides a technological overview of SST's use in electrical systems. The traditional transformer has a number of drawbacks, including core saturation at non-linear loads, poor voltage regulation, and a large bulk. This difficulty can be solved by employing SST, which provides a more efficient output as well as improved power quality. To change the desired impedance, the proposed design methodology utilizes the number of turns in the windings and the isolation distance between the windings as free parameters. These strategies are simple to develop and design implementation using Matlab Simulation

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