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AC LINE – SIDE POWER CONVERTERS FOR ELECTRIC LOCOMOTIVES

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Abstract: The electric locomotives use, more and more, AC motors (induction motors, synchronous motors) robust and height, but with sophisticated power electronic converters. The exigency of the providers of electric energy stimulates the research for new valuable line-side converters. The paper analyses an evolution of this kind of power electronic converters.

Key – words: electric traction, power converters (rectifiers – inverters), regenerative braking.

1. INTRODUCTION

For the electrical traction, various supplying systems are today in use: DC (3kV; 4,5kV, etc.) – Systems, AC (15kV – 16 2/3 Hz; 25kV – 50Hz) – Systems and others. The system of AC – 25kV – 50Hz is today in development due to its advantages: simple connection with the (national) power system using relative simple equipment, a smaller diameter of the contact wire (overhead conductor) at higher voltage, simple catenary systems. That is because the authors focus their attention on this system.

The general structure of a AC – locomotive is given in figure 1.1. and comprises:

- the main transformer MT, with (usually) more secondary windings (700 – 3000V),
- the Line – Side Converter LSC (input in AC, output in DC);
- the Link – Circuit LC, a dedicate low – pass filter;
- the Motor – Side Converter (MSC) and
- the Traction Motors TM.

The traction – motor type is decisive for the main features and the structure of the power electronic circuits.

The Line – Side Converter (LSC) in the general case provide for:

a) the proper intermediate electrical energy (voltage, current, wave shape): this energy, finally, feeds the traction motors; the energy flow is from AC – Line to motors;

b) the back transfer of the electrical energy from the motors (driven by the inertial forces) to the line (to achieve the regenerative braking).

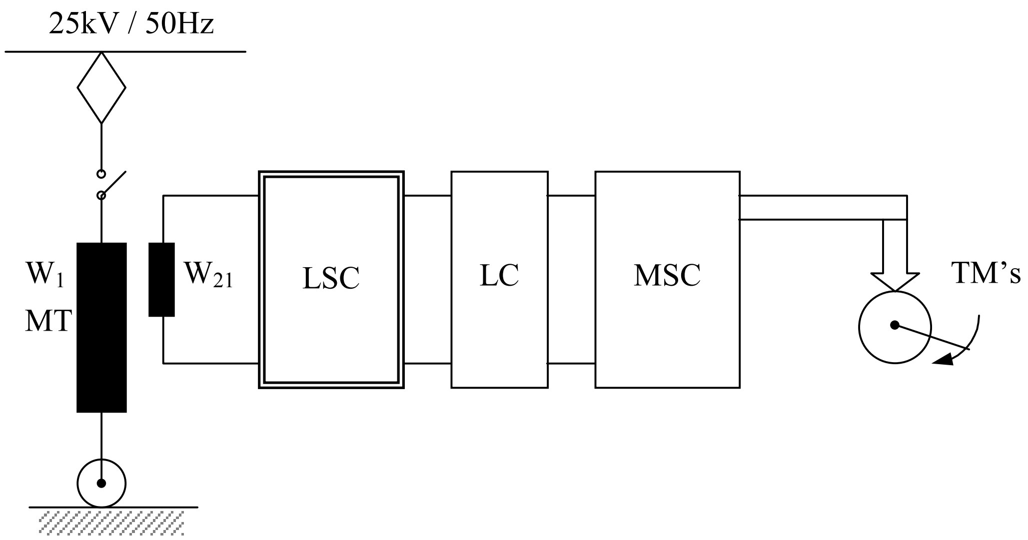


Figure 1.1. The general structure of a AC locomotive

2. LSC FOR DC TRACTION MOTORS

The DC traction motor is an older technical solution, with a simple way to control but with numerous drawbacks: a small (W/kg) ratio, need for expensive maintenance.

The Motor Side Converter is not necessary (reduced power electronics).

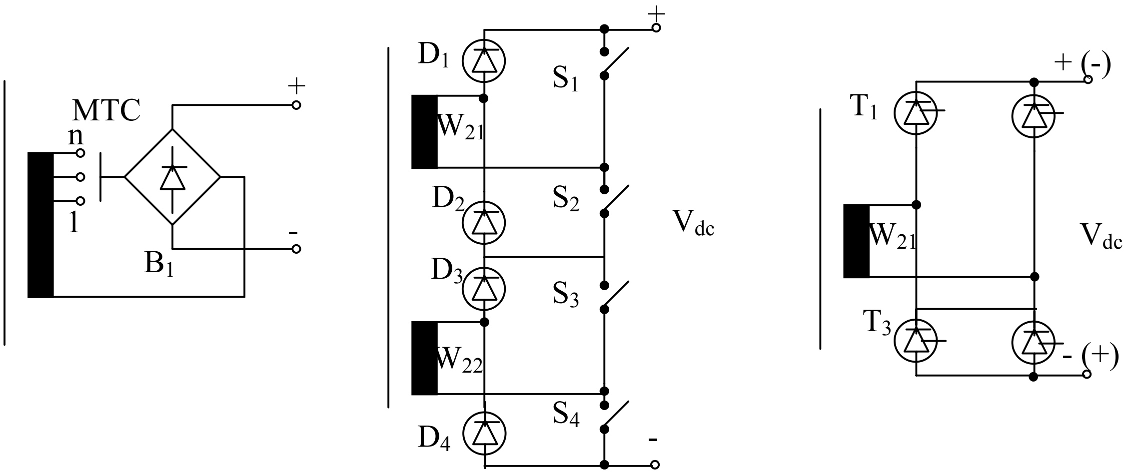


Figure 2.1. Converters for DC – traction motors

a) Mechanical Tape Changer and uncontrolled rectifiers
b) "Step" – rectifiers
c) Bridge Controlled Rectifier

For the Line – Side – Converters, a simple solution, still in use, is based on the mechanical tap changer (MTC) and an uncontrolled bridge, figure 2.1.a, in order to generate a desired DC- voltage (V_{dc}) in a certain range. The converter generates high – order harmonics in power line and do not enable the regenerative braking.

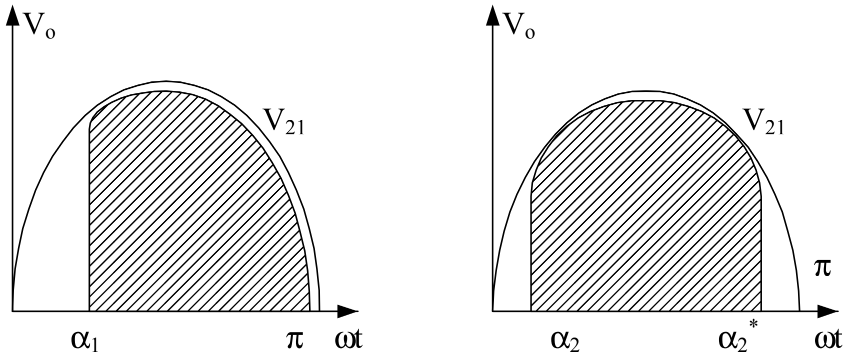


Figure 2.2. Voltage waves for controlled rectifier with
a) delaying phase – angle
b) symmetrical phase angle

A complete static version comprises a bridge with four (equivalent) thyristors with phase – control. The problem of the harmonics and the necessity of filters are more stringent. If the control strategy is based on delaying phase angle (figure 2.2.a), additional reactive power is asked from the power line. This reactive power produces a supplementary voltage drop on the overhead contact wire.

If the thyristor are replaced with GTO's, the forced commutation enables the ON – phase – angle (α_2) and the OFF – phase – angle (α_2^*), so that the reactive power may be reduced to zero or can be negative (capacitive).

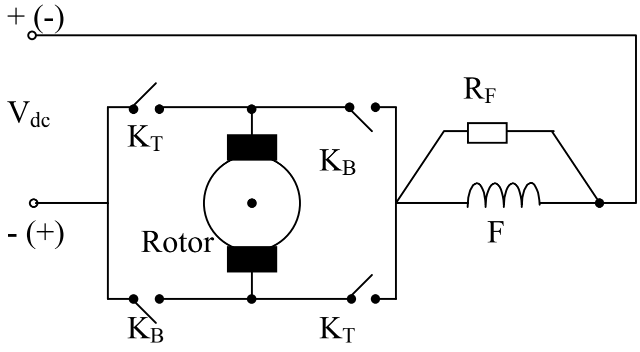
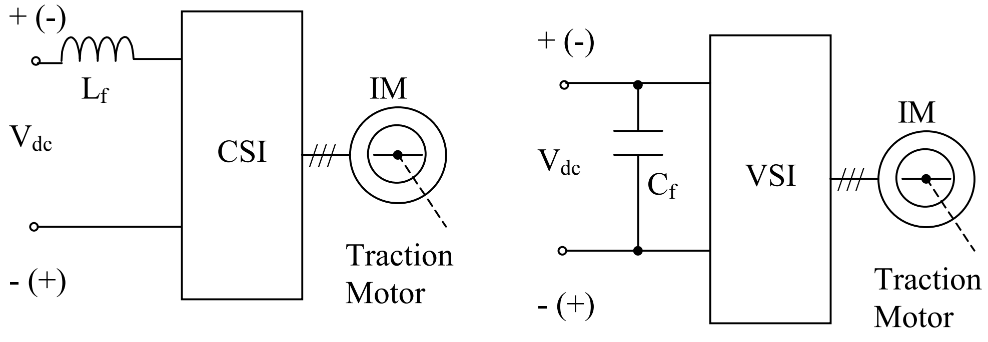


Figure 2.3. About the regenerative braking

Now, using electromagnetic contactors (K_T for Traction, K_B for Brake) connected to the rotor, in order to achieve the **regenerative braking**, the contactor is switched to the state K_B (K_B closed, K_T open). The rotor voltage "changes" the sign and the line side controlled rectifier operates with an adequate firing angle, as inverter. The instantaneous regenerated power is controlled with the firing angle α_1 (usually $\alpha_1>\pi/2$). The regenerated current wave shape is quite different from a sinus function, hence the harmonic content is a pregnant disturbing factor of the power line.

3. LSC FOR AC – TRACTION MOTORS

The AC – traction motor (specially induction motor) is the ideal solution for the heavy conditions of operation in railway traction but the control electronics is sophisticated and expensive.



a) b)

Figure 3.1. Induction motor (IM) modes of operation
a) with CSI b) with VSI

The MSC may be:

- a **current – source inverter** (CSI) by which the power supply is a DC – current source (impressed **current** with an important inductor as DC – link filter)
- a **voltage – source inverter** (VSI) where there exists a large capacitor as DC – link filter: the power supply is a DC – voltage source (impressed voltage)

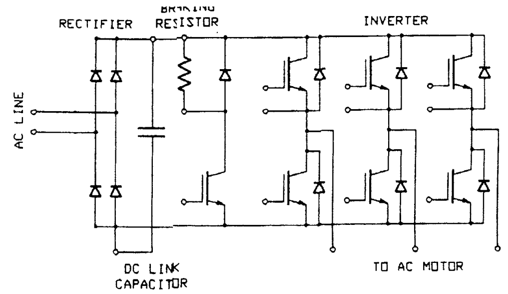
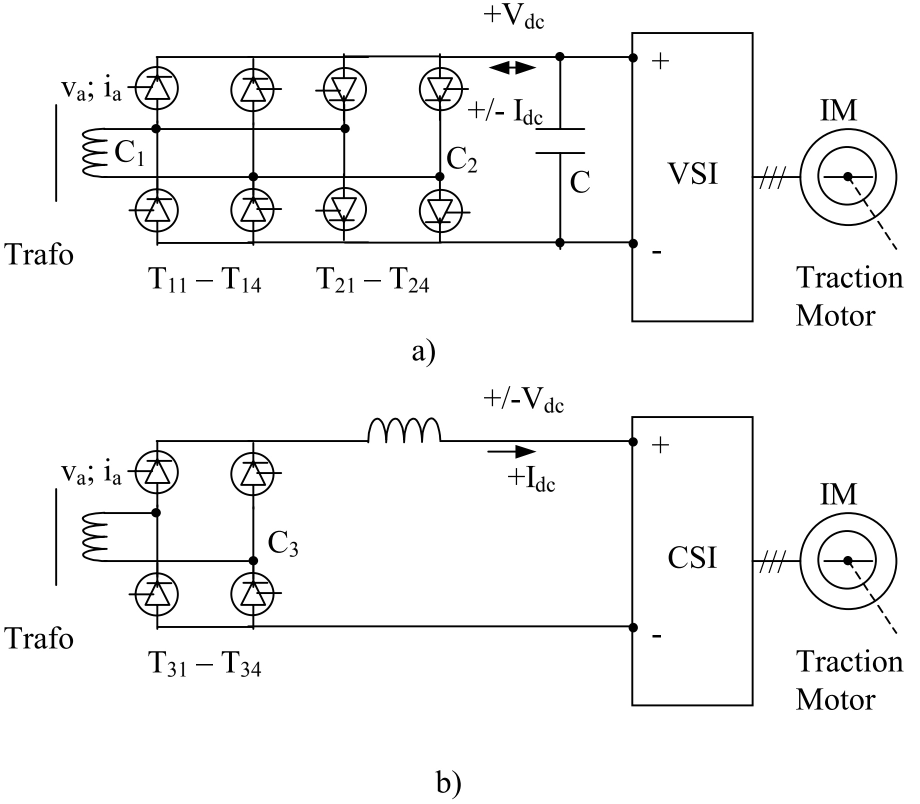


Figure 3.2. Four quadrant motor converter

If the traction motor (TM) is in **motor** mode, both (V_{dc}) and (I_{dc}) are positive (power flow: AC line → AC motor). In a **generator** mode (braking operation), a (CSI) changes the sign of the (V_{dc}) keeping (I_{dc}) positive while a (VSI) reverses the link – current, keeping (V_{dc}) positive.

In order to have simple electrical equipment, many locomotives enable only the resistive (electrical) braking, figure 3.2, where the IGBT based inverter is a (VSI) version. By braking, the DC – capacitor voltage rises. The voltage can be kept constant using a braking resistor. The converter enables a four-quadrant operation of the traction motor:

- motor: in direct (“direct” phase sequence) or in reverse (“reverse” phase sequence)
- generator (with braking IGBT and resistor) in “direct” or in “reverse”.



a)

b)

Figure 3.3. Silicon Controlled Rectifiers with
a) VSI b) CSI

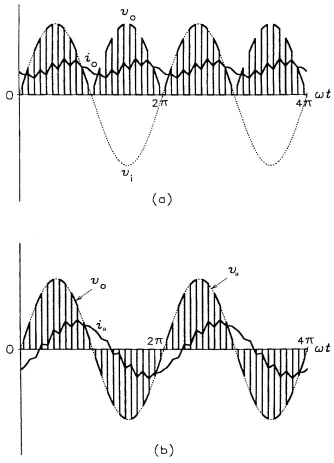


Figure 3.4. Voltage and current waves for a PWM generic rectifier

In order to recover the braking energy and return it to the AC supply line, a controlled rectifier is required. Silicon Controlled Line Commutated Rectifiers (SCR's) are commonly used in practice, figure 3.3, but they require large line filters to improve the current drawn from the line.

Because the SCR is a "one - direction – current" semiconductor, by (VSI) are necessary two converters: C_1 – rectifier, C_2 – inverter, while the (CSI) needs only one connecter.

A PWM rectifier is an

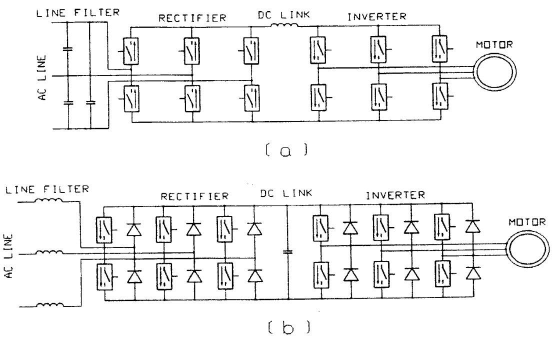


Figure 3.5. PWM converters: a) VSR and CSI; b) CSR and VSI

elegant and modern solution for LSC's. The principle of PWM rectifiers with lines – side variables (v_a, I_a) and DC- link – side variables (v_o, i_o) is presented in figure 3.4.

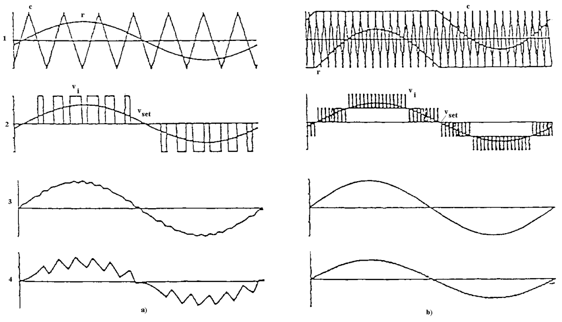


Figure 3.6. Methods for current control:
1. Carrier signal (c) and reference signal (r);
2. Rectifier input voltage (v_i) and voltage set – value (v_{set}); 3. Primary current of the transformer; 4. Rectifier input current

With the PWM strategy, a four-quadrant operation of the traction motor is possible if the rectifier is an "inverse copy" of the inverter, figure 3.5. The Voltage Source Rectifier (VSR), identical with a (CSI), operate with (CSI), and vice versa.

The current source – rectifier operates in a step up ("boost") manner. With a proper control strategy, the current from the AC – line may be (with some approximation) sinusoidal. The evolution of the voltage and current of the line – side converter with GTO's (carrier frequency 420 Hz, figure 3.6 a) or with IGBT (carrier frequency 1,5kHz, figure 3.6.b) is possible with zero reactive power.

4. CONCLUSIONS

An ideal electric power converter would be characterized by:

a) small switching loses by higher frequency;
b) zero reactive power;
c) low – harmonics content;
d) reduced sensitivity to parasitic parameters.

With the progress of the power semiconductor devices (IGBT's, GTO's, MCT's), new and fast step are made toward an "ideal converter". But, a very important factor, which determines the performance, is the control circuit. For the line – side rectifiers, for instance, substitution of the PWM – strategy (applied to fast and powerful devices) is the key of the new valuable results.

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