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A Comparison between IGBTs and Diode Converters for DC Railway Electrification Systems

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Abstract. This paper describes a comparison between the specific DC railway models with insulated gate bipolar transistors rectifiers and diode rectifiers. As silicon diode was applied to railway electrification system decades ago, the IGBTs rectifiers have not obtained wide application yet. In this research, the performance of these rectifiers is presented and analysed. The power supply to the load, system losses and effects to systems are the main aspects compared in this paper. The analysis presents the possibility that new types of power converters can be adapted in DC railway electrification system. The simulations are carried out with MATLAB and Simulink.

1. Introduction

Modern electric devices in DC railway system are usually fed by diode or thyristors front-ends. Such equipment generates higher harmonic into a grid [1]. Nowadays, with the development of power electronic technology, IGBTs are more and more applied in railway systems. In power supply for DC railway, however, IGBT rectifiers are not applied widely [2].

Combining the thyristor rectifier and IGBT inverter can save the breaking energy from the DC railway system. HESOPTM (Harmonic and Energy Saving Optimizer) system by ALSTOM provide a solution to applying IGBT devices as the power converter in DC railway system.

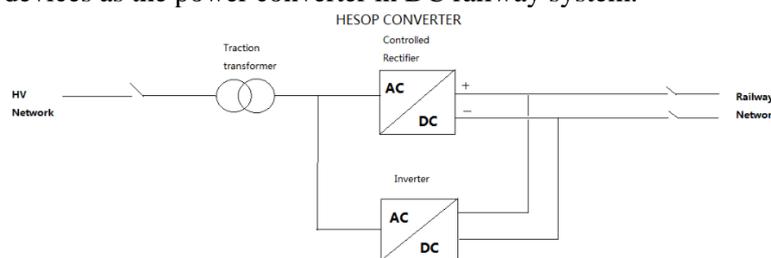


Figure 1. Architecture of the Prototype Power Converter [3]

The previous work and review provided the idea to author to do comparison between the diode rectifier and IGBT rectifier [4]. A numerical study on diode and IGBT rectifiers are also necessary. The Main objective of this thesis is to have a comparison between these two rectifiers, and analyse the reason of low application of IGBT rectifiers. In this thesis, the author tries to assess the possibility of applying the IGBT rectifiers in general DC railway systems. Besides, Study of modelling power system with rectifiers and testing system losses with Simulink is another objective of this research.

In previous works, the research focus on system with fixed load power [5-7]. In this thesis, to explore the difference with different level of train load, the simulations aim to test the performance of the rectifiers in three load levels. The simulation in this thesis can be thought as an extension of the research



in comparison between IGBTs and diode rectifiers in DC railway system. With the extended research, the author tries to find the difference of the systems with these rectifiers in three train load levels. The train model employed in modelling is British Rail Class 508[8]. With the models, we test the system losses, system efficiency, rectifier losses of both two systems. Moreover, the outputs stability is compared to find the difference in power quality.

2. Method

2.1. IGBTs losses

The method of calculation is based on the information provided by the manufacturer [9]. For the conduct losses, let we assume the alternative current is i , a sine wave with amplitude I_p , and duty cycle γ . Then we get the conduct losses:

$$P_{cl} = \frac{1}{2} \left(V_{CE0} I_p \frac{1}{\pi} + r_{ce} \frac{I_p^2}{4} \right) + m \cdot \cos\varphi \left(V_{CE0} \frac{I_p}{8} + \frac{1}{3\pi} r_{ce} I_p^2 \right) \quad (1)$$

Where V_{CE0} is the threshold voltage, r_{ce} is defined as the slope resistance.

In the simulation, the modulation index $m < 1$, which is the linear mode for the PWM. The switching losses are the sum of the turn-on and turn-off energy.

With the datasheet, we need to linear the energy curve, for example the curve in Figure 2[10]. The curve shows the turn-on losses for a IGBT device in the range of operation current. In our simulation, the current is relatively stable, which means the operation period we choose to linear should be short to reduce the difference.

We can describe the linear function as:

$$E_{swl} = E_{on} + E_{off} = (a_{on} + b_{on} \cdot I) + (a_{off} + b_{off} \cdot I) \quad (2)$$

Where E_{swl} is the energy losses per pulse.

Now we get the function of the current and switching frequency f_{sw} :

$$P_{sw} = f_{sw} \left(\frac{a_{on} + a_{off}}{2} + \frac{b_{on} + b_{off}}{\pi} I_p \right) \cdot \frac{V_{DC}}{V_{DCn}} \quad (3)$$

2.2. Diode losses calculations

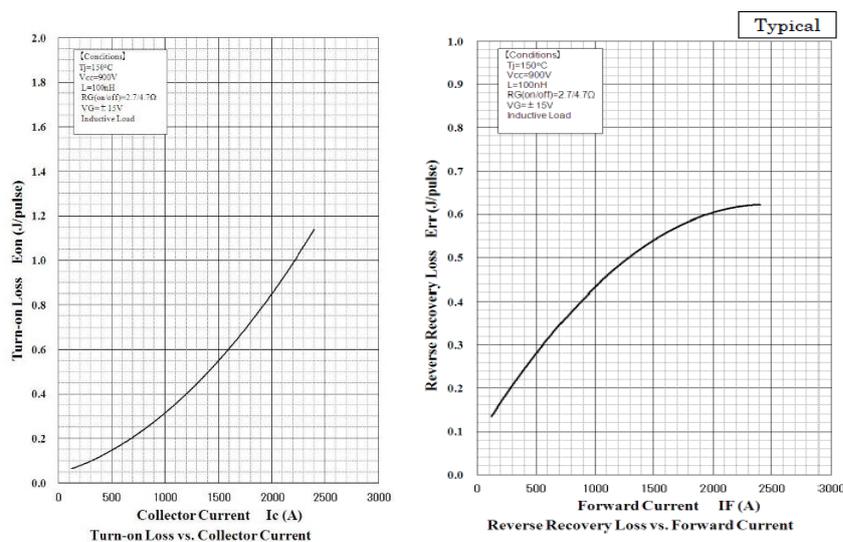


Figure 2 Example curve of specific Diode and IGBT device[10]

Similar to losses calculations of IGBTs, we can describe the conducting and switching losses of diode device as:

$$P_{cD} = \frac{1}{2} \left(V_{D0} I_p \frac{1}{\pi} + r_d \frac{I_p^2}{4} \right) - m \cdot \cos\varphi \left(V_{D0} \frac{I_p}{8} + \frac{1}{3\pi} r_d I_p^2 \right) \quad (4)$$

$$P_{sw} = f_{sw} \left(\frac{a_{rec}}{2} + \frac{b_{rec}}{\pi} I_p \right) \cdot \frac{V_{DC}}{V_{DCn}} \quad (5)$$

2.3. Power losses calculations

As a IGBT module consist of a IGBT and a parallel diode, to calculate the total losses, we should combine the losses of IGBT and diode.

For conducting losses, we get

$$P_{cIGBT-total} = P_{cI} + P_{cD} \quad (6)$$

For switching losses, we get

$$P_{swIGBT-total} = P_{swI} + P_{swD} \quad (7)$$

3. Modelling

3.1. Modelling of loads

To simulate the operating of the train, we need to simulate the variation of the resistance of the lines and tracks. In this research, the data of the train is from the British Rail Class 508, which has a nominal power output 656kw. The operation speed is set to 60km/h.

The models of load for the system with diode rectifier and IGBT rectifier are totally same to accurate the results of the simulation. The basic topology of the system is shown in Figure 3.

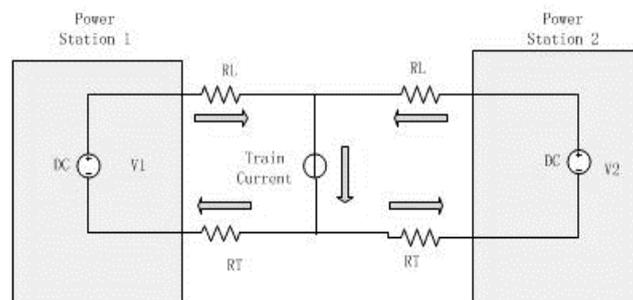


Figure 3 Basic scheme of the system[11]

3.2. Modelling of diode rectifiers

In the simulations of performance of diode rectifiers, the topology is based on a system with 12-pulse rectifier transformer. The input power voltage from the AC grid is set as 33kV. The diode rectifiers used in simulations are composed of a set of diodes instead of the diode rectifier bridge provided in Simulink. With the diode rectifiers, we can also test the single diode power losses, which cannot be realized by using the default model in Simulink. To accurate the simulation results, the resistance of the diode module needs to be calculated. In this simulation, we choose the model 5SDF 20L4521, product from ABB. The characteristics curves is shown in Figure 4.

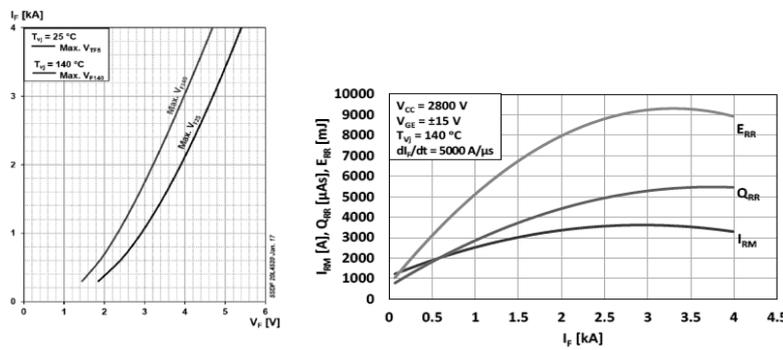


Figure 4 Characteristics curves for diode 5SDF 20L4521

3.3. Modelling of IGBTs rectifiers

Different from the model with diode rectifier, the IGBT rectifier demand controllers to operate the switch of IGBTs. The basic topology for single IGBT power station is shown in Figure 5.

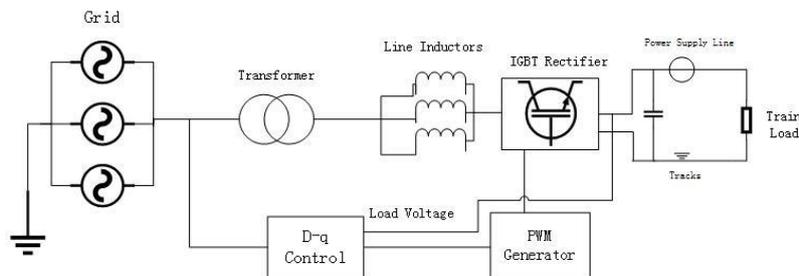


Figure 5 Simplified topology for system with single IGBT rectifier

Both systems need PWM controller. To meet the demand of controlling two power station at the same time, we use two inside current loops and one outside voltage loop when modify the PWM controller. As we use PWM rectifier, the boost inductors are necessary in the system. To reduce the harmonics, filter is adapted in the circuit.

The IGBT rectifier is composed of 6 sets of IGBT module. Each single IGBT module consists of a IGBT and a parallel diode. The PWM control signals from the PWM generator module is divided and linked to each IGBT module to control the gate. Within the IGBT model, the modules to test conducting losses and switching are also included. In our simulation, we choose the model MBN3600E17F produced by HITACHI. The V-I characteristics curves of the devices are shown in Figure 6.

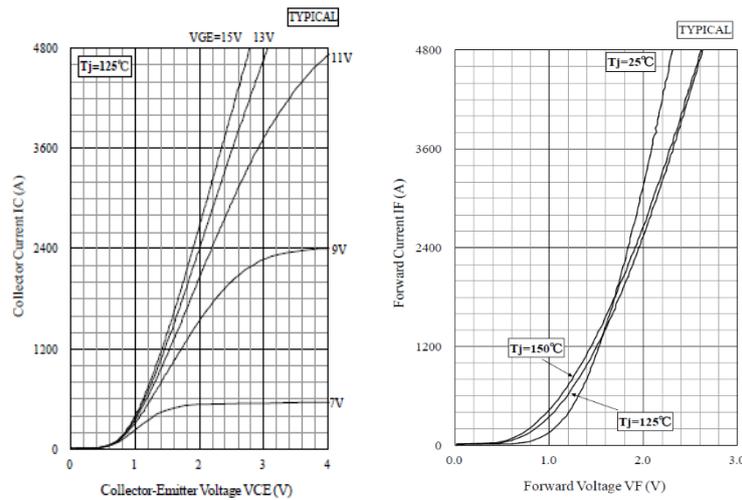


Figure 6 V-I characteristics for IGBT and diode

With given coefficients, we can predict the losses of the modules.

In the models, we need to define the modulation index m and power factor angle in the formulas. In d-q control module, we set a part to check the modulation index and the power factor angle and modulation index. The results are shown below.

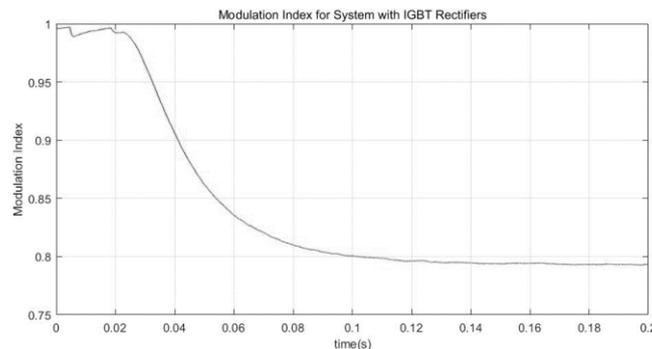


Figure 7 Modulation index

According to Figure 9, in steady-state, the modulation index is above 0.795. Then we set the modulation index m to 0.8

To use the formula to calculate the losses, we set the power factor angle $\varphi = 180^\circ$.

With the equations, we can get the prediction of the conducting losses:

$$P_{CI} = 43.02 \text{ W}, P_{CD} = 225.7 \text{ W}$$

With function 2.29 and 2.34, we can also calculate the steady-state value of the switching losses:

$$P_{SWI} = 1483 \text{ W}, P_{SWD} = 492.1 \text{ W}.$$

The switching frequency f_{sw} is set to 10kHz in our simulation.

With these prediction values, we can use a paralleled resistor to simulate the switching losses in the rectifiers as the IGBT module provided in Simulink is ideal.

4. Results

4.1. Load voltage and circuit current

In this section, the results of the simulations with three trains are shown. As the nominal power of the two power stations is 2MW with three trains load is 1.968kW, these results can show the performance of the systems operating with heavy loads.

The five points, 50m, 500m, 1000m, 1500m, 1950m are chosen to test the performance. The load voltages are shown in Table 1 below,

Table 1 Load voltage

Rectifier type	50m	500m	1000m	1500m	1950m
Diode system (V)	718.3	700.9	694.1	700.9	718.3
IGBT system (V)	747.8	730.2	702.5	730.1	747.7

The circuit currents are shown in Table 2 below,

Table 2 circuit currents

Rectifier type	50m	500m	1000m	1500m	1950m
Diode P1 (A)	2001	1745	1417	1062	739
Diode P2 (A)	739	1062	1417	1745	2000
Diode Total (A)	2740	2807	2835	2805	2739
IGBT P1 (A)	1318	1348	1390	1348	1318
IGBT P2 (A)	1318	1348	1390	1348	1318
IGBT Total (A)	2636	2696	2780	2696	2636

4.2. Efficiency

In the simulations, we also calculate the efficiency of the systems with one train, two trains and three trains in load systems. The comparisons are shown in Figure 8,

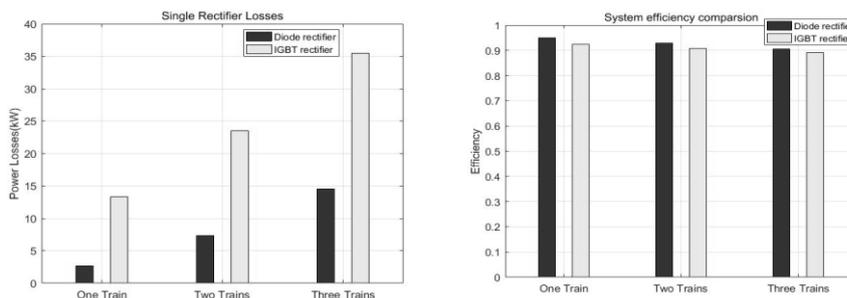


Figure 8 Comparison of single rectifier losses and System efficiency

4.3. Power quality

The power quality is compared according the output voltage of train and power factor.

The power factor of system with diode rectifiers are test in simulation with one train. The power factor is calculated with the active power and reactive power: power factor = $\frac{P}{\sqrt{P^2+Q^2}}$

With the model, we get the power factor of the system with diode rectifiers is 0.968.

The power factor in IGBT system is almost unit. With calculation, the power factor of system with IGBT rectifiers is 0.99. Considering the heavy load in practical applications, the power factor in system with diode rectifiers is worse. However, with PWM controller, the system with IGBT rectifiers will have unity power factor.

In the terms of waveform of output voltage of load, the comparison is shown Figure 9 below,

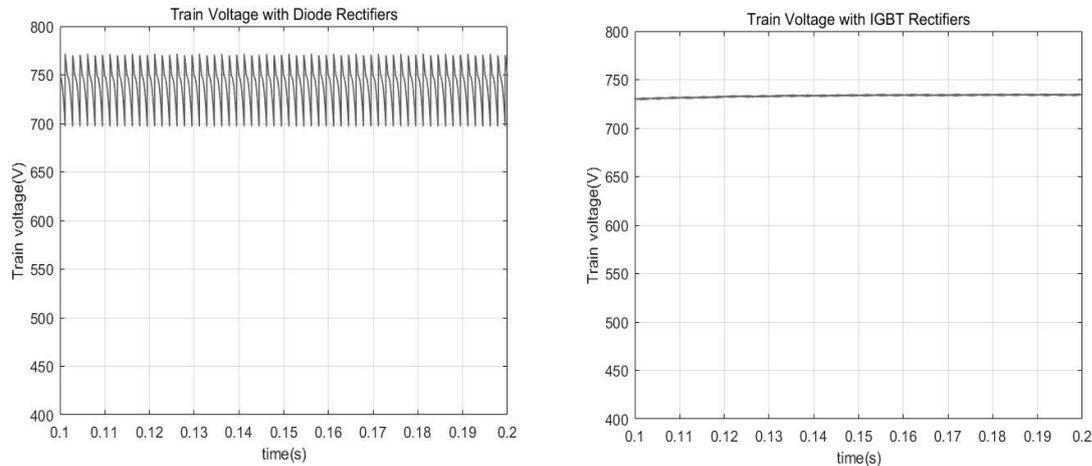


Figure 9 Comparison of output voltage

5. Conclusions

With the results from the simulations, performance of the IGBT rectifier and diode rectifier are shown directly. In aspect of efficiency, the systems with diode rectifiers show better performance, though the difference between these two systems becomes lower with heavier load. The diode rectifier has lower power losses in simulations. Excluding the switching losses, however, the system with IGBT rectifiers consume less power in circuit. The IGBT rectifier also has better performance in voltage regulation when the system operates in heavy load. The advantage in voltage regulation allows the distance between two power stations longer, which contribute to reducing construction cost [12].

Besides, the lower range of current in load circuit reduce the demand of high current tolerance power supply lines. In terms of power quality, system with IGBT rectifiers shows the feature of lower voltage oscillation and less harmonics[13]. Unity power factor with IGBT rectifiers can also improve the power quality. Moreover, the bi-directional feature of IGBT makes the rectifier can cooperate with IGBT inverters to deal with the breaking regenerative energy, which contribute to reducing energy consume and higher power efficiency[14]. On the other hand, the diode rectifier, which can stand high current easily, still fits the DC railway electrification system well. The IGBT rectifiers need complex control system to operate properly. The complexity means more cost and maintenance[15]. As rectifier, the IGBT module can still obtain application in specific DC railway electrification systems which need higher power factor and lower harmonics.

For future works, the research should focus on combine the diode or thyristor rectifiers with the IGBT inverters to improve the efficiency of the systems and reusing the regenerative power of the railway system.

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