Optimised design consideration of suspension choppers in Maglev train using SiC MOSFET modules

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Abstract: Electromagnetic suspension (EMS) Maglev trains attracted to suspend above a track is a green type of track transportation. The suspension control box adopting a closed-loop feedback controller outputs a levitation current that flows into the electromagnets producing a desired magnetic force to levitate the train. Without contact frictions, such a promising type of transportation saves considerable electricity for propulsion. Minimising the volume and weight of Maglev trains attracts great research interests and continuous engineering effort as that is closely correlated with levitation power consumption and, more importantly, the construction cost. This paper mainly discusses volume and weight optimisation of suspension control box that contains a suspension chopper in EMS Maglev trains using the state-of-the-art SiC MOSFET modules. By analysing the mission profile of a typical suspension chopper, SiC MOSFET is found to be perfectly suitable for suspension chopper optimisation because of its low power losses. An optimised heatsink design of suspension chopper is given, whose volume is only 21% of the previous design. By utilising a RC snubber, the new SiC MOSFET suspension chopper prototype is built without showing serious voltage ringing. This provides a promising prospect for further optimisation of suspension control systems.

1 Introduction

Maglev trains are an environmental-friendly type of track transportation. It has great advantages including low traction energy consumption (free of mechanical friction), low noise, and ride comfort. Electromagnetic suspension (EMS) is an important type of Maglev train systems. Most commercial Maglev lines in the world adopted EMS Maglev train type including high-speed German Transrapid series, medium/low-speed Japanese HSST series, Korean UTM series, and Chinese CME series [1–4]. Initially, high speed (up to 450 km/h or even higher) is the target of EMS Maglev train. High-speed EMS Maglev trains, adopting high-efficiency linear synchronous motor for propulsion, normally have integrated levitation and propulsion machinery magnets as shown in Fig. 1a. The high-speed Maglev type also needs extra guidance and brake magnets as well as their corresponding control systems, which is very similar to that of suspension control systems. Therefore, such a high-speed type is very expensive and sophisticated. Utilising linear induction motors for propulsion, the medium/low-speed Maglev trains (up to 110 km/h) are composed of separated levitation and propulsion systems as shown in Fig. 1b. The magnet together with the F-shaped rail is responsible for producing the levitation force as well as the guidance force that is automatically generated if a misalignment is placed between the F rail and magnet. This system is much simpler and much less costly. This medium-/low-speed Maglev technique has a broad application prospect with its own advantages of lower construction cost, lower maintenance expenses, smaller turning radius, and better climbing ability compared with conventional railway transportation at comparable speeds [1, 2]. Recently, continuous effort is made by Korean and Chinese Maglev engineers to develop a medium-speed Maglev train that could run up to 200 km/h [4, 5].

The general suspension control principle of all EMS Maglev types is shown in Fig. 2a. The difference between the actual air gap fed back by air gap sensors and a reference is sent into a control DSP where the required duty cycle is calculated. The acceleration sensor is used to provide an extra feedback loop for stability consideration. An extra current feedback loop can also be used to increase the system response [1]. The system is a classical multi-loop feedback proportional-derivative (PD) controller. Then, suspension choppers produce levitation currents that flow into the electromagnets producing desired magnetic force to levitate the train stably whenever the train is moving or still. The suspension chopper is normally a quarter I/IV chopper structure [1]. Although the propulsion energy consumption is considerably reduced for such a suspended vehicle, the levitation power consumption is still significant. Resembling the aircraft requirement, the weight, and volume of Maglev train requires to be minimised so that its loading capability can be enhanced and the levitation energy consumption can be minimised as well. For massive production and easy maintenance, the suspension control box is expected to be as compact and integrated with magnets as possible. Therefore, optimising suspension choppers is of great necessity. Here, based on the Changsha Maglev Express (CME) Maglev train, the suspension chopper design optimisation is discussed, which enlightens the future optimisation of the overall suspension control box.

2 Power loss comparison

In the suspension chopper of CME Maglev train, the 1200 V/300 A FF300R12KT3 Silicon IGBT module is used. The typical levitation

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Fig. 1 EMS Maglev train principle based a side view
(a) High speed, (b) Middle/low speed [1]
current waveform of a CME Maglev train suspension chopper is shown in Fig. 3. The DC-link voltage is 330 V. There are several considerations for such an over rating voltage/current selection. First, the stray inductances in the loop are all still comparatively large due to the internal layout of our CME suspension system; Second, there might be a serious current overshoot at the start of levitation; Third, the rail plate is hard to be perfectly flat, which could also bring a large levitation overshoot occasionally during movement. The levitation current sometimes might go over 100 A as shown in Fig. 3. As a result, the voltage and current overshoot during switching is severe.

Therefore, in our design, we choose an over rating voltage (redundancy) of IGBT to ensure SOA operation at this stage, which is a typical engineering approach. A large margin is considered. Our current rating is also large, which also springs from a similar consideration. Another consideration is from reliability. Such a choice is also related to the lengthened lifetime design. According to reference [6, 7], the rating can be used to improve the lifetime of IGBTs by lowering the thermal stress of each chip inside the module. The similar choice is also adopted by Maglev engineers in Germany, Japan, and Korea.

With the development of SiC MOSFET modules [8–12], it is believed that SiC MOSFET is superior to Silicon IGBT in switching frequency, switching loss, and high-temperature application. The loss table of SiC MOSFET Module CAS120M12BM2 and Silicon IGBT Module FF300R12KT3 has been plotted using the online simulation software provided by the manufacturers [13, 14]. SiC MOSFET Module CAS120M12BM2 is used because this is so far one of the highest current rating modules that are available in the market. The gate resistor is set to be 10 Ω (the internal gate resistor is not considered) as it has been chosen in the CME design. Both the switching and conduction losses are included in Fig. 4. The switching frequency is 5 kHz.

It can be seen that SiC MOSFET module is advantageous to Silicon IGBT module. The switching losses for SiC MOSFET module is only around 10% of those for IGBT module over a large current and temperature range. For conduction losses, the SiC module has less losses in the lower current range. With the increase of operation current, the SiC module will have larger conduction losses compared with Silicon IGBT module. However, the typical levitation current for suspension chopper is around 30 A (at no load). The typical range for the levitation current is in [25 A, 60 A], which can be reflected in Fig. 3. According to the study in [5], the designed junction temperature at the toughest environment temperature 50°C (the heated rail surface) is about 80°C. We can further look at Fig. 5 that at 80°C SiC MOSFET module is also very advantageous in conduction losses as well within the typical levitation current range that is mentioned previously. The cross-
over point where the SiC MOSFET module has larger conduction loss is around 60 A.

3 Heatsink optimisation

As it has been presented in the previous section, SiC MOSFET module will have much smaller power losses under the typical suspension chopper operation condition compared with Silicon IGBT modules. This would be very helpful to reduce the requirement on the heavy and bulky heat sink.

Each carriage of CME Maglev trains contains five bogies. Each bogie is made of two suspension magnetic modules located on both sides of the track. Each magnet module contains four coils, every two of which are controlled by one suspension control box. A suspension control box is composed of mainly six parts, including a suspension chopper, DC power supply, contactors voltage/current measurement devices, control PCBs, and inductors to absorb current spikes. A real view of a suspension control box is shown in Fig. 6a. The dimension is presented and the total weight is about 34 kg. A Maglev carriage is supported by 10 suspension control boxes. Due to the usage of a mechanical bogie, the mutual mechanical interaction between magnetic modules under a carriage is decoupled. Each suspension control box operates individually. All the suspension control boxes share a similar operation condition, expect for the front and end suspension control box that has to consider the eddy current effect [1]. The main circuit of one suspension chopper is shown in Fig. 2b. The power part is constituted by two Infineon FF300R12KT3 IGBT modules. The suspension chopper provides a unidirectional current for the load electromagnet. (Fig. 7)

The previous suspension chopper is the largest and heaviest component inside the CME suspension box as shown in Figs. 6b and c. It includes two IGBT modules, snubber capacitances, gate drivers, a DC-link capacitance, a heatsink, and a fan. The heatsink and DC-link capacitance occupied most volume of the suspension chopper. The proportion that each component occupied is estimated in Fig. 6b. It can be seen that the suspension chopper takes around one quarter of the whole weight. For the volume, the suspension chopper is around one-seventh. It is also important to note that there are over 60% of the whole volume which is not well used. However, it can also be noted that due to the fact that there is so much free space the iron case wrapping around the suspension.

![Fig. 5 Conduction loss comparison at 80°C](image)

![Fig. 6 CME Suspension control box](image)

(a) The real view and its dimension, (b) The volume percentage, (c) The weight percentage

![Fig. 7 Ansys simulation of CME suspension chopper](image)

(a) Fan is used at a harsh environment temperature of 50°C, (b) No fan is used at a harsh environment temperature of 50°C

J. Eng., 2019, Vol. 2019 Iss. 17, pp. 4050-4054

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chopper take over 40% of the total weight. Clearly, there is tremendous potential for reduction in weight and volume for the suspension control box. The suspension chopper stands as the core part of the whole box. Therefore, it is of great importance to minimise the suspension chopper, which will be the focus of this paper.

To reduce the weight and volume, the heatsink of CME suspension chopper is taken to carry out thermal simulation. At the normal operation condition, the IGBT junction temperature of the CME design is shown to be 80°C when the typical current is 35 A. This is under the toughest environment temperature, 50°C (the rail surface temperature in Changsha's summer). If the fan is broken, the junction temperature rises to 121°C, which means that there is still around only 29°C margin for reliability consideration. The maximal junction temperature for the IGBT module used is 150°C. By adopting SiC MOSFET modules, the total power losses could be reduced. Therefore, the thermal simulation by icepak is carried out to minimise the heat sink. For SiC MOSFET module, there are three chips in parallel unlike that in the previous CME design where only two chips are paralleled. If we still take 35 A as the typical or average operation current condition, the heatsink can be reduced to 21% of its previous design in weight and 15% in volume. The junction temperature of SiC MOSFET chips without a fan is 120°C as has been shown very reliable in the current design using Silicon IGBTs [5]. If the fan is used (the rotating speed is identical to that in the CME design), it can be seen that the normal junction temperature is also 80°C for each chip in Fig. 8b.

4 Discussion and future work

In section 2, the switching losses of both SiC MOSFET and Silicon IGBT modules are obtained from online simulation provided by the manufacturer. However, the influence of stray inductance in the circuit cannot be considered. As a result, there might be some differences between the actual switching losses and those obtained by the online simulation software. Using a double pulse test experimental platform, the turn-on and turn-off waveforms of SiC MOSFET modules can be plotted in Figs. 9a and b. Fig. 9a shows at turn-off a ringing on \( V_{ds} \) is observed. The voltage overshoot is beyond 600 V. The \( dv/dt \) is very large. The ringing of \( I_d \) at turn-on is even more severe, which can be seen in Fig. 9b. In both cases, the power losses can be calculated by using the measured voltage and current waveforms. The losses are higher than those predicted in the look-up table in Fig. 4. More importantly, the ringing will cause severe EMI source so EMI filters must be installed at the 330 V DC side to avoid pollution to the power supply. Adopting advanced gate drivers might also be considered in the future design to suppress EMI [15, 16]. However, in whatever cases, the switching losses must be obtained from experiments to achieve more accurate estimation of the device junction temperature for heatsink design. By using a RC snubber following a similar design method in [17, 18], a SiC MOSFET suspension prototype is built showing that the voltage ringing is much suppressed as shown in Fig. 10. A very low sampling frequency LEM current sensor is used to obtain the voltage waveform which represents an average levitation current of around 26 A. A disturbance suppression circuit might be added to get rid of the noises as shown.

Once the heatsink of suspension chopper is optimised, the layout of the suspension chopper box must be re-designed. As the switching losses are closely related with the stray inductances shown in Fig. 9, a further optimisation must be made to minimise all the stray inductances. Except for that, from Figs. 6b and c, another issue that must be considered is to further minimise the volume of the whole suspension control box. This would be very helpful to reduce the area of iron case which would be of great importance to reduce the whole weight of suspension control box.

It is an interesting try-out in such a Maglev train application for SiC MOSFET as most main stream investigations are made on how to use the high switching frequency of SiC MOSFETs to achieve higher power density. Here, in the suspension chopper design, experience has shown that 5 kHz is enough to achieve very stable
and reliable levitation whenever in the movement or still. As the conduction losses and switching losses are both small during the given levitation current range, the SiC MOSFET provides a very interesting solution to achieve a light, compact, and integrated design of the suspension control box.

5 Conclusion

This paper mainly discussed volume and weight optimisation of the key component in Maglev train, i.e. suspension chopper, using the state-of-the-art SiC MOSFET modules. By analysing the mission profile of suspension choppers, SiC MOSFET is shown to be perfectly fit for light, integrated, and compact suspension chopper design. Compared with silicon IGBT modules with a similar rating SiC MOSFET modules have much smaller switching power losses and conduction power losses within the typical operation range of levitation current. For the optimised design, the overall volume of heatsink in a single control suspension chopper can be reduced by as much as 79%, weight by 85%, which would give much space and potential for further optimisation of the whole suspension control box. A SiC MOSFET suspension chopper prototype has also been built where the RC snubbers are very useful to suppress the voltage ringing.

6 Acknowledgments

The authors would like to thank the support by the National Natural Science Foundation of China under grant no. 51607182, the 13th five-year national key R&D program of China under grant no. 2016YFB1200601-B11, and the Maglev Technology Research Centre of Hunan Province, China (Project: research on self-diagnostics and maintenance for middle-speed Maglev controller).

7 References

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