Analysis of overvoltage impact on shell-type on-board traction transformer by multi-physics field simulation

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Abstract. With the rapid development and increasing demands for the high-speed railway in China, it is of great significance to examine the defects of the high-speed train and ensure the safety of the operating railway. In the actual operation of the high-speed train, there is a split-phase section to transit the train to the next substation power supply arm. In this particular stage, operational overvoltage would occur as the VCB and the pantograph switch on and off, which threatens the safety of the operation of high-speed trains and contributes to the breakdown of transformer windings, which is indispensable in transformer operation. In this work, a finite element model of shell type on board traction transformer is constructed and multi-physics field simulation results, including electromagnetic field, temperature field, and flow velocity field, are analyzed to investigate the potential risky spots in the practical operation of high-speed train under overvoltage impulse, which could be supportive in maintaining the devices and detecting the winding defects.

Keywords: traction transformer, overvoltage, finite element model, muti-physics field.

1. Introduction

Enhancing the operational velocity and loading capacity of high-speed trains is the consistent pursuit of the high-speed railway system, whose increasing requirement in traction power capacity would contribute to technical problems in the traction power supply system, which might consequently diminish the performance of the railway system. Nowadays, single-phase alternating current (AC) power supply mode is applied to most of the traction power systems, where high-speed trains receive traction power from substations through the catenary. Vehicle-mounted pantograph achieves dynamically supplying the traction power by the electrical contact with the catenary. In this power supply system, the power supply arms, which provide the traction power along the catenary, are separated and divided into different sections based on the location of the terrestrial substations, also known as section-divided split-phase power supply mode. Separated about 20km from each other, the adjacent power supply arms are insulated by a phase-split section, as shown in Fig. 1. Before passing the split-phase section, the high-speed train should be unloaded, and the vehicle-mounted vacuum circuit breaker should be switched off in advance to prevent malfunction of vehicle-mounted devices caused by phase difference and potential difference. The VCB is switched on shortly after the train passes the split-phase section to recover the power supply. High-frequency operating overvoltage occurs as the contacts of VCB switch on and off when passing through the split-phase section [1-2].

During the frequent split-phase operation of the high-speed train, the induced over-voltage impulse and inrush current in the on-board traction transformer (OBTT) would threaten the safety of both OBTT and terrestrial substations. Specifically, the operating over-voltage, which approaches approximately 2-3 times the nominal voltage of the traction transformer, could lead to damage to the transformer insulation layer and its lifespan. As for the inrush current, where the current rises to 6-8 times the nominal current, its enlarged current would contribute to partial discharge and partial overheating, which could further result in the damage of the insulation layer and break-down windings of the traction transformer as shown in Fig. 2.

Therefore, it is of great importance to construct a finite element model so that the performance of the transformer in terms of electromagnetic field, temperature field, and flow velocity field can be analyzed. In this paper, the performances of multi-physics field simulations are examined for CRH380 shell-type on-board traction transformers. Based on the simulation results, local hotspots are detected and suggested for maintaining devices and locating defects in the transformer.

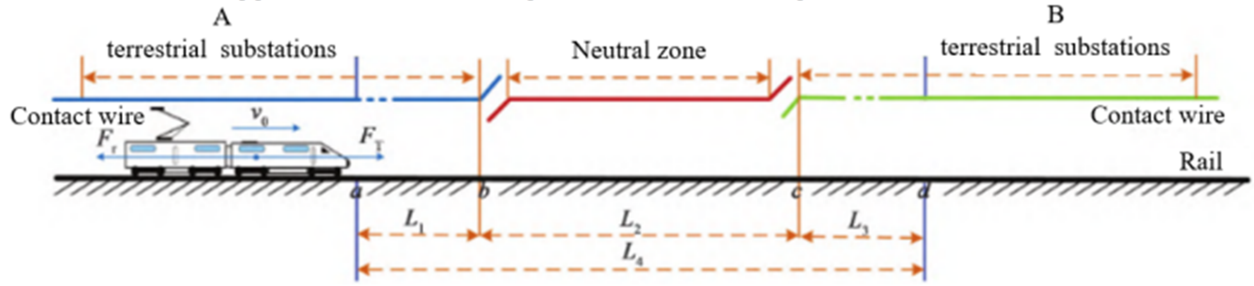

Fig 1. Split-phase operation of the high-speed train.

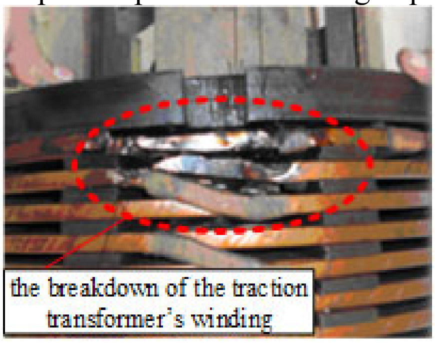

Fig 2. Break-down of the traction transformer's winding

2. Generation Mechanism of Operational Overvoltage in On-board Traction Transformer

Operational overvoltage occurs when the high-speed train passes through the split-phase section, where adjacent power supply arms are insulated and connected. Switching the vehicle-mounted VCB off before passing the split-phase section would avoid malfunction of the short circuit, while the VCB is then switched on once passed the neutral zone to recover the traction power supply. The high-speed train slides through the split-phase section by its inertia. Apart from the vehicle-mounted VCB, the pantograph disconnects the catenary in advance avoiding electrical contact, and reconnects after passing the split-phase. Operating VCB and pantograph would lead to the occurrence of overvoltage and inrush current. As the VCB switches on and off, an oscillation circuit is formed by the resonant inductors and capacitors of the traction system. Moreover, the abrupt change in current and voltage would contribute to a greater induced voltage of the inductance, which directly results in operational overvoltage.[3-4] Continuously passing the phase-split section would make the traction transformer suffer from high-frequency overvoltage impulses. The measured induced high-frequency overvoltage peaked at 62.51 kV and had a frequency of 205.57 kHz as shown in the figure below.

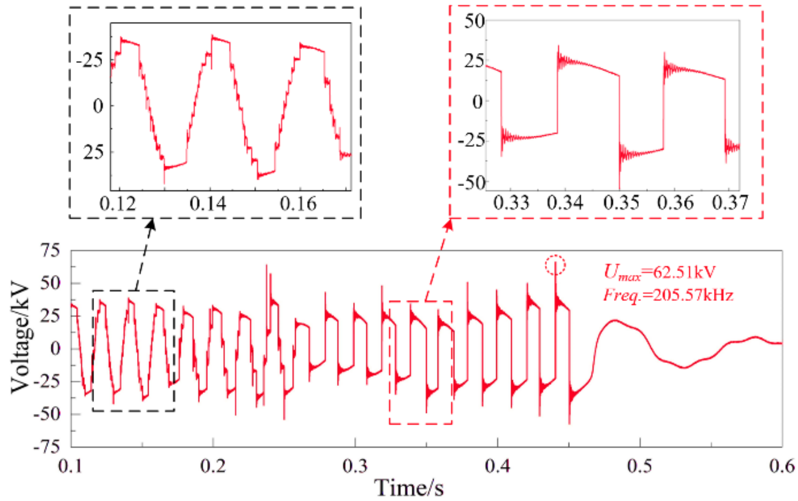

Fig 3. Examined overvoltage waveform when passing the split-phase section.

3. Finite Element Model Construction

3.1 Calculating the Parameters of the Traction Transformer

Certain parameters of the shell-type traction transformer, where the iron core surrounds the windings as shown in Fig. 4, should be determined before constructing a COMSOL finite element model. Specifically, the parameters mainly include the detailed structure of the iron core and the windings, such as the window size of the iron core or the number of windings turns. With the length, width, and height of both the iron core and the windings provided in the datasheet, including the primary, secondary, and tertiary windings, it is the winding turns and the spacing of the different windings that are to be determined. More importantly, the order of the windings for the traction transformer should be confirmed as well since it determines the geometric structure of the transformer.

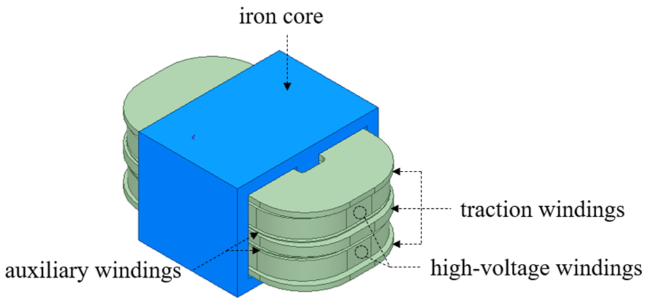

Fig 4. Shell-type on-board traction transformer.

The winding arrangement of the shell-type transformer windings should be vertically symmetric. The traction windings are located at the top and middle, while the high-voltage windings are set beneath the traction windings. Moreover, the auxiliary winding surrounds both the top and beneath the middle traction winding.

Since the layer numbers are given, the winding turns are calculated through the ratio of transformation and voltage values of the windings as in the equation:

$$\frac{N_{pri}}{N_{sec}} = \frac{V_{pri}}{V_{sec}} \tag{1}$$

Where N_{pri} and N_{sec} suggests the number of turns in primary and secondary windings, while V_{pri} and V_{sec} are the voltages applied to the windings.

Additionally, the spacing of the different windings could be arranged and designed based on the window height of the iron core of the transformer and the given height of different windings as shown in Table II. For instance, the high-voltage winding, whose height is 112mm, has 20 layers as provided in the datasheet. Hence, the spacing between adjacent layers and the thickness of the layers could be determined accordingly.

The resultant electrical parameters of the transformer are shown in Table I.

Table I Transformer Electrical Parameters

Parameters	Windings		
	Primary winding	Secondary winding	Tertiary winding
Capacity/kVA	3855	1667.5×2	520
Nominal voltage	25000	1658	400
Frequency/Hz	50	50	50
Number of turns	88	30	14
Number of layers	20	4×2	2

Table II Transformer Size Parameters

Parameters	Windings		
	Primary winding	Secondary winding	Tertiary winding
Length/mm	1280	1315	1315
Width/mm	720	730	730
Height/mm	112	60	54

3.2 Establishing the Finite Element Model of the Traction Transformer

Since the parameters of transformers are determined, 2 possible finite element models should be considered. The first option is the traction transformer in front view as shown in Fig. 5, where the specific turns for different windings are constructed and arranged compactly. Although the front-view model with a non-closed iron core on the left would be effective in electromagnetic field simulation, it can still be badly performed in flow velocity simulation since the right side of the iron core in the 2D axial symmetry model is considered to be an enclosed space, where the transformer oil is not expected to flow correctly. The result of meshing is shown in Fig. 6, where 56822 triangles and 16144 quadrangles are constructed. The windings are constructed and divided into various sizes of quadrangles based on the winding types. For instance, a single turn of the top traction winding is made of 2×2 quadrangles, whereas that of high-voltage winding consists of 2×4 quadrangles. The Iron core and the spacing are constructed by triangles.

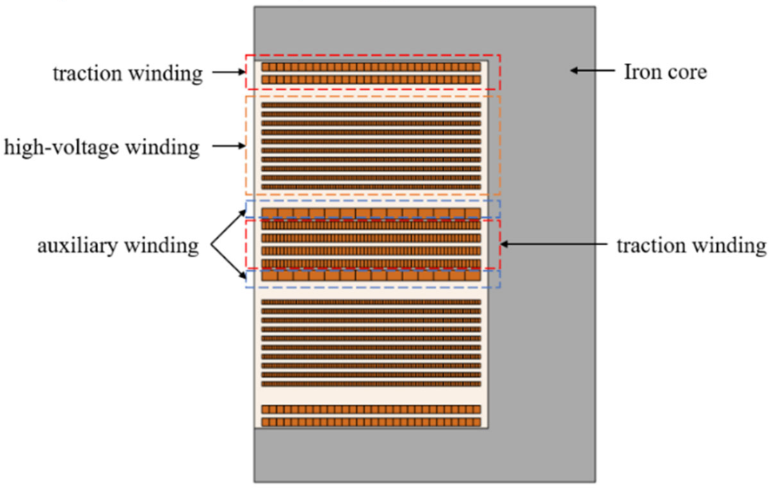

Fig 5. FEM of shell type on board traction transformer (front-view).

Illustrated in Fig. 7, the second option for model construction is a side-view transformer, where the turns of the windings could be simplified. In this case, the side view model is suitable for both electromagnetic and flow velocity simulation as the iron core does not restrain the flow of transformer oil compared to the front-view design. The entrance and exit of the oil tank are constructed as well. Therefore, comparing the two approaches, the side view of transformer oil is selected to perform the multi-physics field simulation. The meshing result for the FEM of the side view transformer is shown in Fig. 8, where 8800 triangles and 2400 quadrangles are constructed. Similar to the previous meshing scheme of front-view FEM, the windings in the side view are constructed in quadrangles and the remaining part, which includes the iron core and oil tank are meshed in triangles.

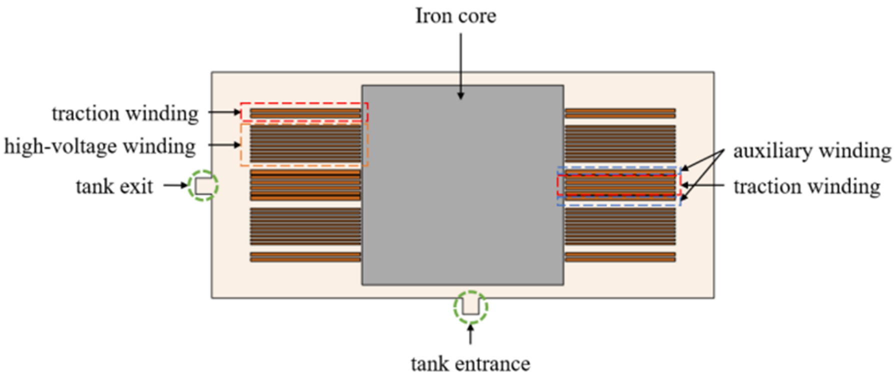

Fig 7. FEM of shell-type onboard traction transformer with the entrance and exit of the oil tank (side-view).

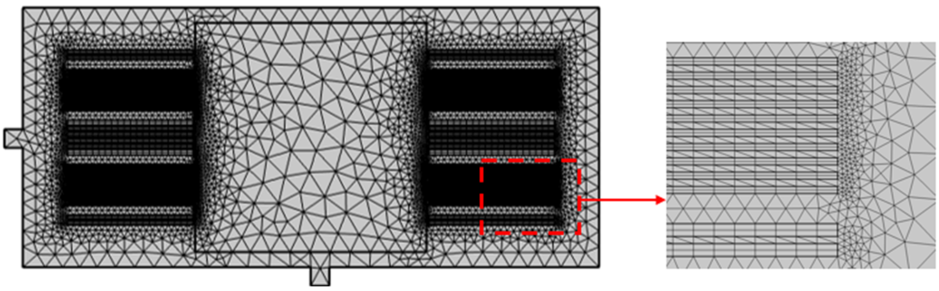

Fig 8. Meshing result of FEM (side-view).

4. Mult-field Analysis

The influence of the operational overvoltage on OBTT could be investigated by the performance of the multi-physics field simulation, including electromagnetic field simulation, temperature field simulation, and flux velocity field simulation., which would provide sufficient information for the performance of the transformer under operational overvoltage. Therefore, multi-physics field simulations should be calculated and analyzed. Specifically, the electromagnetic field simulation would present the distribution of magnetic flux density when certain operating conditions are applied and the influence of the overvoltage impulse could be determined. The temperature field and flow velocity field should be considered together as the flow of cooling transformer oil will directly lead to the variation of the temperature field. The integrated analysis would examine the effect of operational overvoltage for OBTT and would, to some extent, provide the foundation for maintaining and inspecting the potential risk spot of the shell-type traction transformer.

In terms of electromagnetic field simulation, one effective way to illustrate the distribution of magnetic flux density in COMSOL is by applying the frequency domain steady-state solver, where the distribution of the magnetic flux density is presented at the steady state of the system. Two stimulation approaches, current stimulation, and voltage stimulation, are proposed in COMSOL. As for electromagnetic field simulation, voltage stimulation should be applied since high voltage is applied to the primary windings which would induce current in other parts of the windings. In this case, a source voltage of 62.51 kV for high-voltage winding (primary winding) under operational voltage impulse conditions, as proposed before, should be the source of stimulation of the finite element model. The simulation results in terms of the electromagnetic field are shown in Fig. 9.

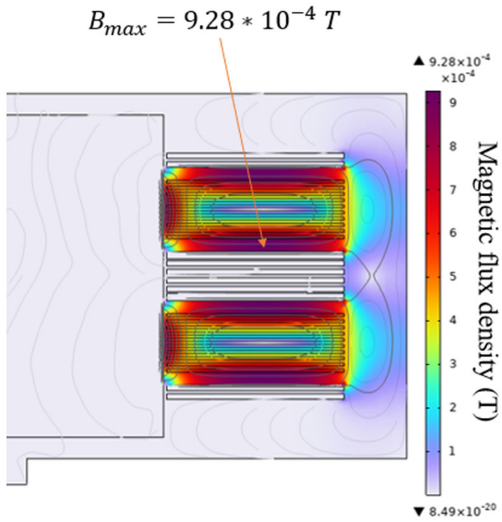

Fig 9. Magnetic flux density distribution of OBTT applying 62.51 kV under 205.57 kHz.

Illustrated by Fig. 9, the most magnetic flux density is concentrated surrounding the high-voltage windings, with a relatively high value labeled in the figure. It is indicated that the higher magnetic flux is located at the top and bottom part of the high-voltage winding, which could result in partial discharge and risky electromagnetic interference.

As for the temperature field, the main contributor to the temperature rise is the electromagnetic heating effect caused by the voltage applied to the high-voltage windings and the induced current at other windings. To cool down the windings, transformer oil is applied to immerse the windings and transfer the heat to the oil, which would protect the windings from overheating and breakdown. In terms of setting the simulation, the entrance and the exit are settled to direct the flow of transformer oil, and the average flow speed of oil is set to be 0.45 m/s. Using the frequency domain transit state solver, the temperature and flow velocity field simulations from 0 s to 100 s are calculated as shown in Fig. 10.

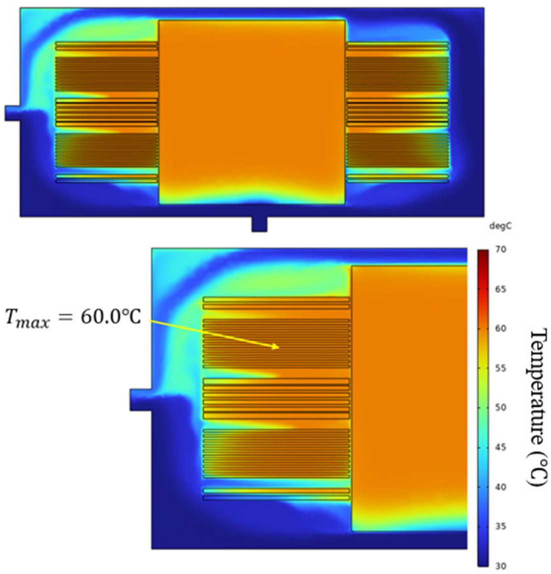

Fig 10. Temperature distribution of OBTT with transformer oil.

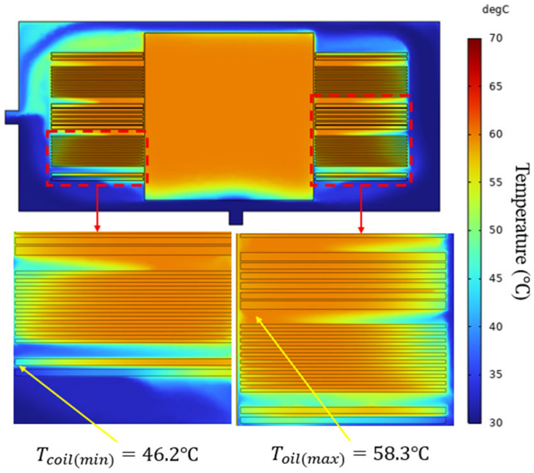

Fig 11. Temperature distribution of OBTT with transformer oil (partial cooling effect and oil maximum temperature).

As shown in Fig. 10, before the transformer oil flows in, the initial temperature of the transformer and the transformer oil are respectively set to 60℃ and 30℃. As shown in Fig. 11, the temperature of the partial windings is dropped as the transformer oil flows in, especially at the edges of the windings, where a minimum coil temperature of 46.2℃ is obtained. The transformer oil carries the heat of the windings, and its temperature rises as well, finally reaching a maximum value of 58.3℃. Although the temperature of the iron core and the windings are greater than other parts of the FEM, it is discovered that the maximum temperature point of FEM, which is approximately 60.0℃, locates at the edges of the auxiliary windings and the high-voltage windings as the maximum temperature point is continuously shifting along the windings, which would contribute to the thermal aging process. Therefore, the maximum temperature spot in simulation could be supportive in overheating point detection and further maintaining the devices.

In terms of the flow velocity field of transformer oil, as shown in Fig. 12, with a maximum value of 0.65 m/s, the oil flow velocity is highest at the oil tank entrance and exit compared to the other regions. The value of flow velocity also tends to be higher at the edges of the iron core and the windings.

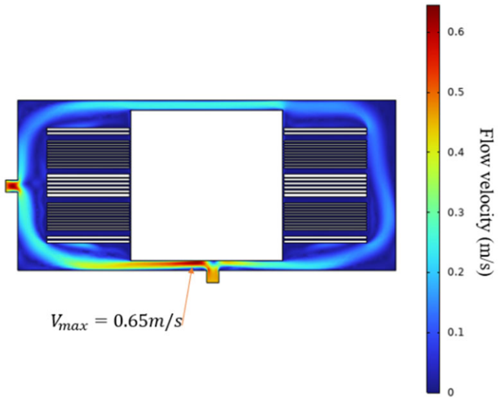

Fig 12. Flow velocity distribution of transformer oil in OBTT.

5. Conclusion

The continuous and increasing demand for operational speed and loading capacity of the high-speed train would challenge the safety and reliability of the high-speed railway system, especially the vehicle-mounted devices, such as VCB, train body, and traction transformer. In the frequent passing split-phase operation, the overvoltage tends to invade the OBTT, which would result in short-circuit and the breakdown of the windings. In that case, the influence of the overvoltage impulses should be determined in the electromagnetic field, temperature field, and flow velocity field. FEM of the traction transformer of different views are constructed and simulated. Applying a 205.57kHz and 62.51 kV voltage to the primary winding, the simulated maximum magnetic flux density is found at the edge of the high-voltage windings and auxiliary windings, which is the same as the results for temperature field simulation, where the maximum temperature of 60.0°C is also found at the edges. The high magnetic flux could lead to partial discharge and electromagnetic interference, while high temperature would accelerate the thermal aging process. Therefore, a prediction of risky spots in the windings is located as the maximum magnetic flux and the maximum temperature spot show consistency, which could be supportive in maintaining the OBTT and detecting the flaws.

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