Contacts Impact Phenomena in a 126 kV Vacuum Circuit Breaker

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Abstract- **The contacts closing impact phenomenon of vacuum interrupter is a basic event in a vacuum circuit breaker, which reveals lots of information including impact force, bouncing duration, stress distribution and so on. The objective of this paper is to investigate the contacts impact phenomenon in a 126 kV vacuum circuit breakers. PVDF (polyvinyldene fluoride) piezoelectric sensors were used to measure impact force of a 126 kV vacuum circuit breaker at a closing velocity of 1.5 m/s. In addition, a finite element analysis simulation model of contacts impact in a 126 kV vacuum interrupters was set up by using ANSYS / LS-DYNA software. The experimental results showed that the maximum contacts impact force of a 126 kV vacuum circuit breaker was about 10^5 N at 1.5 m/s closing velocity, which is are in good agreement with the simulation results. And the simulation results also showed that the maximum impact force, durations of contact bounce and the maximum stresses of contact were related with some parameters of vacuum interrupter, such as contact shape, elastic modulus of contact material, impact velocity and contact spring force.**

I.   INTRODUCTION

A closing operation of a vacuum circuit breaker is invariably accompanied by impact phenomena. The impulse force when two butt-type electrodes collide with a closing speed is significantly higher than the contact force [1-4]. Thus, it is an ordeal for the mechanism performance of the vacuum interrupter and even the whole vacuum circuit breaker. Some parts of vacuum circuit breaker may be destroyed under an excessive impact force. Therefore, the impact, as a basic phenomenon, should be well considered before designing vacuum circuit breakers.

Many researchers have investigated the impact behavior of electrical contacts. Barkan [5] developed a mathematic model of the dynamic impact. And he also measured the dynamic force by using a strain gage during closing a pair of no-current contacts. Mcbride [4] investigated the electrical contacts impact phenomena passing current of vacuum interrupters. All the mentioned researches were in a field of low and medium voltage circuit breakers. As the development of high voltage vacuum switchgears became more and more important, and the operating energy increased in the high voltage vacuum circuit breaker [6]. However, the impact data of a 126 kV vacuum circuit breaker is vacancy.

The objective of this paper is to investigate the impact phenomena of a 126 kV vacuum circuit breakers, which reveals lots of information including impact force, bouncing duration, stress distribution and so on. The conclusion can be taken the reference for the mechanical design in a 126 kV vacuum circuit breaker.

II.   EXPERIMENTAL SETUP

Fig. 1 shows the contact impact measurement system of a 126 kV vacuum interrupter. It is difficult to measure an impact force of contacts directly in a vacuum circuit breaker because the contacts are sealed in a vacuum interrupter with a glass or ceramic envelope and stainless steel shield. However, we use a 126 kV vacuum interrupter without an envelope and shield, and put a PVDF sensor on a fixed contact to record the impact force during impact. The fixed rod was fixed vertically on the ground. The movable contact was moving towards the fixed contact via a free falling. The drop height of the contact gap was about 120 mm and the estimate impact velocity (average velocity during 2 ms before contacts impact) was approaching to 1.5 m/s. And a displacement sensor was used to record a velocity characteristic of the movable contact which was connected on the top of the movable contact.
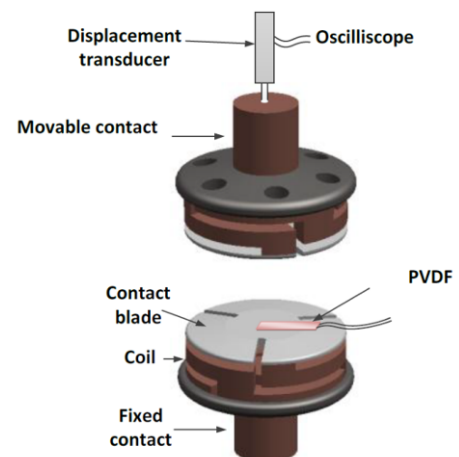

Fig. 1. Contact impact measurement system of a 126 kV vacuum interrupter.

The detail structure of test vacuum interrupter was shown in Fig. 2. The test vacuum interrupter had a 2/3 coil-type AMF contact structure [7]. There were a double "T" beam made of stainless steel inside the coils and three steel nail supports across the coil in order to increase its structure strength. A fixed contact connected with a 390 mm in length copper cylinder rod which a steel rod was inside. And a movable contact connected

with a 500 mm in length steel cylinder rod in which a copper rod was in side. And the mass of movable part in the test is about 9.6 kg.
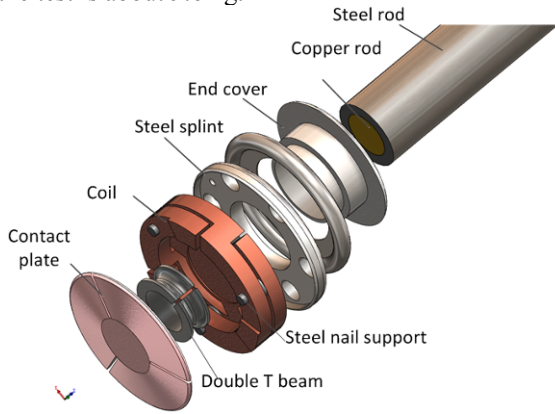

Fig. 2. Contact structure of test vacuum interrupter

In addition, we used PVDF (Polyvinylidene Fluoride) piezoelectric sensors to measure the impact force between two contacts. The measurement circuit of one PVDF piezoelectric sensor was shown in Fig. 3. The PVDF piezoelectric sensor will produce a certain electrical charge as applying a corresponding pressure. The charge passes through a 510 Ω non-inductive resistor during impact time and an oscilloscope was used to monitor the voltage of the resistor. The charge of the PVDF piezoelectric sensor in one impact test is the voltage across the resistor V(t), and the total charge accumulated is

$$Q(t) = \int_0^t \frac{V(t)}{R} dt \tag{1}$$

The PVDF sensor has its intrinsic dynamic sensitivity coefficient (K) which is defined to show the relationship between the pressure and the charge of per unit area, and the impact pressure measured by PVDF sensor is:

$$F = \sigma \cdot A = K \cdot Q \cdot A \tag{2}$$

Where K the coefficient, Q the corresponding charge, A contact area, and σ is the stress of the PVDF piezoelectric sensor.
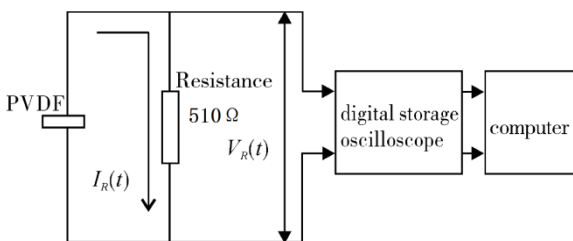

Fig. 3. Measurement circuit of PVDF sensor.

Thus, the coefficient of sensor (K) needs to be calibrated before testing. The calibration is tested in a standard split Hopkinson compressive bar as shown in Fig. 4. We compared the results of the measurements between strain gages and the PVDF piezoelectric sensor in the Hopkinson link. In a same impact test, the stress was measured by the strain gauges on the input and output bars. And the total charge of PVDF sensor can be obtained by the voltage measurement of resistance.

According to change the input velocity of bullet, the stress of strain gauges is linear increased as the total charges of PVDF sensor with a dynamic sensitivity coefficient (K) of 5.0721 (100MPa/ μ C/cm^2), as shown in Fig. 5.
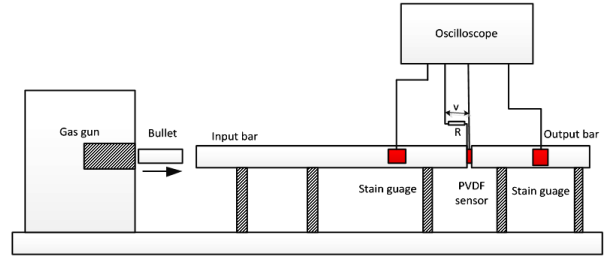

Fig. 4. Calibration test bench of PVDF sensor.
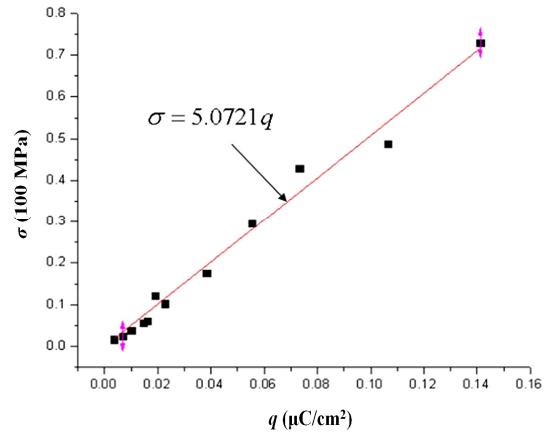

Fig. 5. The relationship between stress and charges measured by PVDF piezoelectric sensor.

III. RESULTS

The displacement of the movable contact and the voltage across the resistor measured by PVDF piezoelectric sensor were shown in Fig. 6. The average velocity during 1ms before impact is 1.5 m/s. Through the voltage data from Fig. 6, the impact force can be calculated by (1) (2), where K is 5.0721 (100 MPa/μC/cm^2),

The relationship between impact force and time is shown in Fig. 7. The peak value of impact force is 98116N at the impact velocity of 1.5 m/s, and the duration of first impact phenomena is 0.431ms.
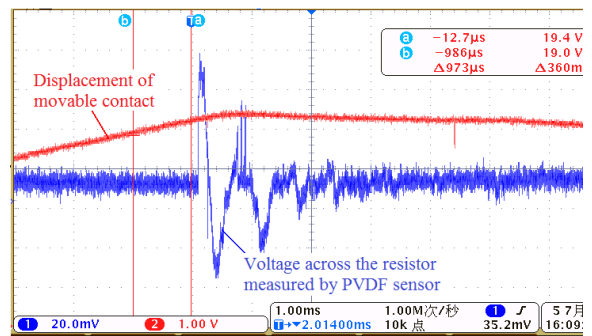

Fig. 6. A displacement curve of movable contact and the voltage curve across the resistor measured by PVDF piezoelectric sensor.
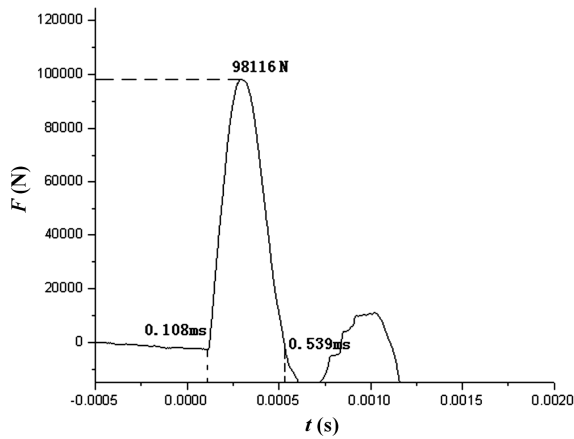
Fig. 7. The calculated impact force curve.

IV. DISCUSSION

A. Simulation setup and result

In order to analysis the impact phenomena of the 126 kV vacuum interrupter in detail, a finite element analysis simulation model was set up based on the 126kV vacuum interrupter (as shown in Fig. 2) and it was analyzed by using ANSYS/LS-DYNA software. The element analysis software is used for analyzing a static and dynamic response of structures deformation.

We also applied a contact force to the movable contact from the point of a contact spring during an overtravel. And the force was a function of the displacement of movable contact (d) as follow:

$$F_{\text{contact}} = F_0 + 50d \qquad (3)$$

Where F_0 the initial press of contact spring, 5150N, and d is the displacement of movable rod which is a function of time.

The impact velocity is 1.5 m/s. And the contact material is CuCr50 (50% wt. Cr), which has a density of 8000 kg/m³, a modulus of elasticity of 10^{11} Pa, a Poisson's rate of 0.32, a yield stress of 2.5×10^8 Pa, and a shear modulus of 10^8 Pa. And the material of copper rod and coil is copper. The material of the double T beam, steel nail, steel splint, end cove and steel rod is stainless steel. The fixed rod is fixed with ground and all mass of the movable part is 9.6 kg.

A simulation result of impact force in one closing operation was shown in Fig. 8. It was shown that there were a number of contact impacts during one closing process. The first contact impact force had a peak value of 108247 N and the duration is 0.345 ms. The peak values of contact impact forces decrease with the numbers of contact impacts because of energy dissipation.

Compared with the measurement and the simulation data the peak value of impact force by the measurement is 98116N at a velocity of 1.5 m/s. Adding the contact force of 5150 N at the beginning of contact impact, the date of impact force should be 103266 N, which is very close to 108247N by simulation. The error was less than 5%.
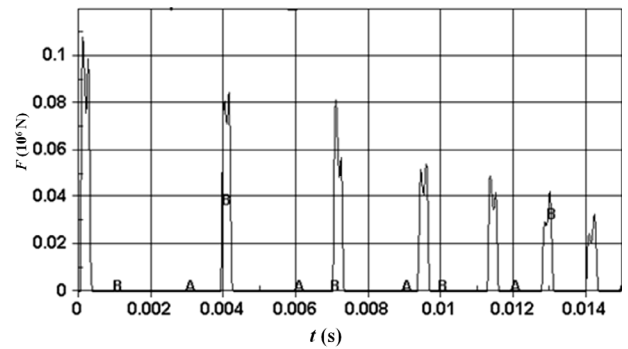

Fig. 8. The simulation impact force curve at an impact velocity of 1.5m/s.

The displacement of movable contact was shown in Fig. 9. The total bounce duration (T) is 12.5ms when closing velocity was 1.5m/s. And the parameters of each contact bounce were measured include the bounce displacement "Z_i", the contacts separation time "T_i", and the separation velocity "u_i".

The coefficient of restitution "e" can be defined as a dissipation ratio of separation velocities [2]. This is based on an assumption that e is independent of impact velocity. And e is calculated as following:

$$e_i = \frac{u_1}{v} = \frac{u_2}{u_1} = \cdots etc. \qquad (4)$$

It is shown that the coefficient of restitution "e" is about 0.75 in Table I. This restitution coefficient can be very useful for predicting the status of the following contact impact and bounce phenomena based on the first one.
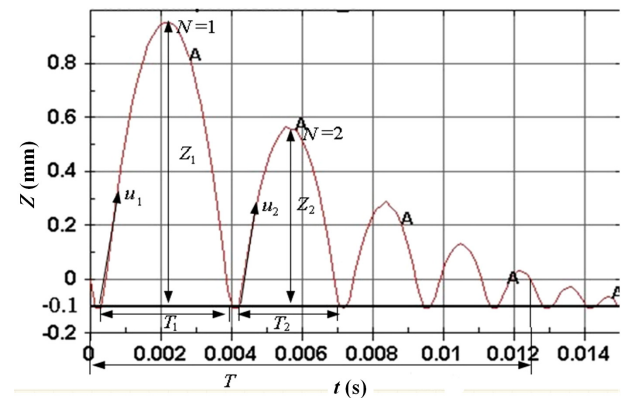

Fig. 9. The contact displacement for contact bounce.

Table I. THE PARAMETERS OF BOUNCE CHARACTERISTIC

i	1	2	3	4	5
Z_i(mm)	1.0604	0.6692	0.3933	0.2380	0.1326
T_i(ms)	3.75	2.85	2.25	1.80	1.35
u_i(m/s)	1.1310	0.9392	0.6992	0.5288	0.3928
e_i		0.7540	0.8304	0.7445	0.7563	0.7428

B. The influence of impact velocity and contact force on the impact phenomena.

It is convenient to adjust design parameters in a simulation model such as impact velocity and contact

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spring force to analyze its influence of impact phenomenon. A relationship between a peak value of the first-impact force (F_1) and an impact velocity (V) in a range from 1.0 m/s to 2.0 m/s and contact force (F_0) in a range from 2000N to 10000N is shown as follows:

$$F_1 = 55621.0 F_0^{0.02} V + F_0 \qquad (5)$$

And the separation gap (Z_1) and the duration (T_1) of the first bounce had a relationship with the impact velocity (V) and contact force (F_0) as followed, respectively:

$$Z_1 = \frac{2440.0}{F_0} V^2 \qquad (6)$$

$$T_1 = \frac{13433.0 \times V}{F_0} \qquad (7)$$

By using these equations, we can predict the impact phenomenon including the peak value of impact force, the separation gap and contact bouncing duration in a 126 kV vacuum circuit breaker.

C. Stress distribution on the impact load

We also investigated a stress distribution of contact components including contact plate, coil, steel nail support and double T beam support under the impact load. The stress distribution was shown in Fig. 10 and a comparison between the peaks stress and the allowable stresses of materials of each component was shown in Table II. It is found that the entire peak stresses of contact plate, steel nail support and double T beam exceed the allowable stresses of each materials under the impact load. And the peak stress of coil is lower by 11% than the allowable stress. The structure of contact plate and supports might be destroyed under such large dynamic load.

(a) Contact plate (b) coil

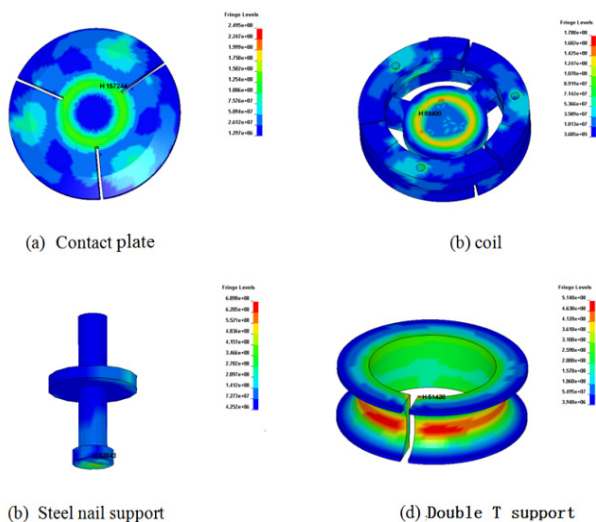(b) Steel nail support (d) Double T support

Fig. 10. The stress distribution of four components of contact at an impact velocity of 1.5 m/s.

D. Future work

The measurement of impact force mentioned above is an approximation of the no load closing operation in a 126 kV vacuum circuit breaker. However, it is certainly true that once the contacts closed on load, the impact behaviors will differ from the no-load situation. Therefore, further work should be done to obtain a more precise value of impact force. However, our measurement can provide a start point for understanding an impact force of a 126 kV vacuum circuit breaker.

TABLE II THE STRENGHTH CHECK OF FOUR
COMPONENTS UNDER THE IMPACT LOAD

	Contact blate	Coil	Steel nail support	"I" beam support
Contact materials	CuCr50	Cu	Steel	Steel
Allowable stresses (Mpa)	125	200	345	345
Peak stresses (Mpa)	250	178	689	514
Percentage of overload	100%	-11%	99.7%	49%

V. CONCLUSION

A finite element analysis simulation model of contact impact in vacuum interrupters was set up for a 126 kV VCB by using ANSYS/LS-DYNA software. The dynamic characteristic of contact impact including impact force, bouncing duration and stresses were obtained from the simulations. The maximum impact force of the 126 kV vacuum interrupter was experimentally validated by PVDF piezoelectric sensors at a closing velocity of 1.5 m/s. Both the simulation and experimental results supported that the maximum impact force of the 126 kV VCB was about 10^5N.

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