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6-10 kV Overhead Power Lines Efficiency Research under the Influence of Wind and Ice Loads

[1]Vladimir Y. Kabashov, [2]Lyudmila P. Andrianova, [3]Ildar I. Gabitov, [4]Rustam S. Aipov, [4]Andrey V. Linenko, [4]Marat F. Tuktarov, [5]Rustam R. Galiullin, [4]Rinat B. Yarullin and [4]Ural R. Yarmukhametov
[1]Department of Vital Functions Safety and Technological Equipment,
[2]Department of Electricity and Electrical Energy Use in Agriculture,
[3]Department of Automobiles and Machine-Tractor Complexes,
[4]Department of Electric Machines and Equipment Departments,
[5]Department of Electricity Supply and Application of Electric Energy in Agriculture,
Federal State Budgetary Educational Establishment of Higher Education,
Bashkir State Agrarian University, 50-Lletia Octyabrya Str., 34, Ufa, Russia

Abstract: The study shows that the majority of emergency shut-offs of 6-10 kV overhead power lines under the influence of wind and ice are due to dangerous rapprochement, clashing and wire breaks. Clashing and dangerous rapprochement of wires that cause emergency shut-offs of lines often occur in spans with disadjustment sag of the wires from 20-60%. The conducted experimental studies have shown that the distances between the wires with their pendulum oscillations decrease with increasing of disadjustment sag of the wires, wind speed and also with a decrease in the span length. At wind speeds in the range of 17.5-18.6 m/sec, the distance between the wires at the maximum rapprochement in 50 m span is 1.28-1.36 times less than in a of 100 m span. It is shown that the minimum distances between wires are observed at wind directions to the axis of the span within 40-90°. It has been experimentally established that the ice coating on the wires lead to a reduction in the distances between the wires by 26-34%. A new design of the spacer is proposed which prevents dangerous wires rapprochement during swaying under the influence of wind and low-frequency oscillations such as “Galloping”.

Key words: Overhead power line, emergency shut-off, span, sag of wire, rapprochement and clashing of wires, wind, ice

INTRODUCTION

In Russia, 30% of the population lives in agricultural areas and about 30% of the gross product falls to agriculture. The further development of agricultural areas and the standard of living of their population largely depend on the reliability and quality of electricity supply to consumers. Thus, ensuring an effective and reliable electricity supply to agricultural areas is an important national political and economic task.

Reliability of the power supply system for consumers in rural areas and urban-type settlements depends to a large extent on the operation of a 6-10 kV electrical network. 6-10 kV overhead power lines (6-10 kV overhead lines) accounts for a significant share (44.9%) in the content of 0.38-220 kV power lines located on the on the books of Rosset (Khlopova, 2018) being the most widely used in countryside.

Such overhead lines of such a network characterized by a large length and branching are often exposed to emergency shutdowns (Forssen *et al*., 2017). It should be noted that 70-80% of all breakdown periods in agricultural enterprises power supply of agro-industrial complex occur due to damage in 6-10 kV networks while 90% of emergency shutdowns occur in overhead lines (Belikov and Fomin, 2018). Due to the high percentage of electrical networks wear in particular network equipment (up to 80%) as well as the degradation in the operation quality, the duration of facilities the interruption of electric power supply is 75 h/year and the energy losses reach 20-30% (Podobedov *et al*., 2016).

Damage of overhead power lines structural elements (electricity pylons interphase connecting rods insulators, wires, wire attachments points) in case of emergency shutdowns lead to significant material and labor costs in repairing and restoring lines for normal operation of the

Corresponding Author: Vladimir Y. Kabashov, Department of Vital Functions Safety and Technological Equipment, Federal State Budgetary Educational Establishment of Higher Education, Bashkir State Agrarian University, 50-Letia Octyabrya Str., 34, Ufa, Russia

network and interruptions in the electric supply power lead to production downtime, economic downfall and deterioration of produced agricultural products (Savadjiev and Farzaneh, 2003; Ershov *et al*., 2017).

Emergency shutdowns of overhead power lines occur under the influence of wind, ice and ice-wind loads which causes massive power shut-offs to consumers (Usmanov *et al*., 1980; Klinger *et al*., 2011). So, for example in April 2018 in the territory of 6 subjects of the Central Federal District of the Russian Federation, due to the impact of strong wind (with gusts up to 20-25 m/sec), massive shutdowns occurred in electrical networks of 35-500 kV and massive emergency shutoffs in 6-10 kV distribution networks. In the Tver region, 155 overhead power lines of 6-10 kV and 2195 substations (6-10 kV transformer substations) were disconnected in the Smolensk region -38 overhead power lines of 6-10 kV and 342 substations, in the Moscow region 48 overhead power lines of 6-10 kV and 791 substation, in the Vladimir region -18 overhead power lines of 6-10 kV and 197 substations, in the Tula region -41 overhead power lines of 6-10 kV and 513 substations in the Ryazan region -26 overhead power lines of 6-10 kV and 354 substations. In total there were 115,550 people without electricity.

The 6-10 kV overhead power lines have relatively short spans, small internal wire attenuations, wire sags, wire distances which in the course of operation leads to a significant disadjustment sag of the wires in a span, causing dangerous rapprochements and clashing under the impact of wind. Small cross-sections of wires, their torsional stiffness, contribute to the formation of unilateral ice coating with an aerodynamically unstable profile, often causing low-frequency oscillations (galloping) of the wires under the influence of wind. These structural features of the span elements of 6-10 kV overhead power lines explain their higher damageability under the influence of wind and ice loads in comparison with overhead power lines of 35 kV and more (Golebiowska *et al*., 2017; Kabashov, 2017).

The swinging of wires under the influence of an unsteady wind flow in a span as well as the galloping of the wires lead to their mutual movements towards each other, causing their dangerous rapprochements, touching, flashover and short circuits (Shklyarchuk *et al*., 2007; Zhou and Liu, 2016). Wire touching that cause emergency shutdowns of overhead power lines are usually accompanied by successful operation of automatic reclose or manual actuation. However, multiple short-circuits lead to serious damage of the wires that require immediate repair or their breakage due to the burnout of a significant number of wires.

Clashing and dangerous rapprochements of wires causing emergency shutdowns of 6-10 kV overhead power lines are observed relatively often and occur as a rule with their asynchronous swayings when in the span wires are stretched with different sags. At the same time, according to the data of the electric grid enterprises of the Bashkir energy system, the disadjustement of wire sags was form 20-60%. The main reason of disadjustement is the wire stretching-out in one of the adjacent spans due to weakening or damaging the wire binding of the wire to the pin insulator during operation under the influence of uneven ice and wind loads (Kabashov, 2011; Glybina *et al*., 2017; Zakaryukin *et al*., 2017).

Purpose of the study: Conducting an experimental evaluation of the mutual movement of wires during their rapprochements in the span of overhead power lines of 6-10 kV, depending on the amount of disadjustment sags of the wires, wind speed, wind direction to the span axis, span length, mass and size of ice coating being formed on wires.

MATERIALS AND METHODS

A special complex of 10 kV lines was constructed for the Belebeevsky electrical networks of the Bashkir power system for carrying out experimental studies of mutual movements of wires during their rapprochements under the influence of wind. The complex is located in a zone classified by climatic conditions to a special area by ice and III by wind.

To measure the minimum distances between the wires with their pendulum swaying and rapprochements under the influence of wind, the complex is equipped with a test plot comprising four spans of 50 m each and three 10 kV overhead power lines anchor spans of different lengths (50, 75 and 100 m) to study the effect of the span length on possible rapprochements of the wires (Kabashov, 2011). Spans are parallel to each other for a small distance between each other. The intephase connecting rods are equipped with tensioning devices for changing the tension and the size of wire sags of in the spans. To measure the distances between the wires during their mutual approach under the influence of wind, the developed device was used which was installed in the middle of the span at the height of the wire suspension. Distance measurements between the wires and adjustment of the device were carried out directly at an altitude of 1.0-1.5 m without lifting personnel to the height of the wire suspension.

RESULTS AND DISCUSSION

To perform the research, let's imagine the disajustment coefficient of the two-wire sags (f_1, f_2) ($f_2>f_1$ in the span of overhead power line in the following way:

$$\delta_f = \frac{f_2 - f_1}{f_1} \quad (1)$$

In this case:

$$f_2 = f_1(1+\delta_f) \quad (2)$$

Disajustment of wire sags in the span is most often occurs due to the low strength of the wire to the insulator which leads to slippage of the wire through the fastener and its elongation in one of the adjacent spans.

The research shows that with an insignificant extension of the wire in the span, the voltage and sags of the wires change sharply (Andrievskiy *et al*., 1976). The total change in the length of the wire in the span due to its elongation is described by the expression:

$$\Delta L = \frac{8}{3.1}\left(f_2^2 - f_1^2\right) - \frac{1^3.\gamma_1}{8.E}\left(\frac{1}{f_2} - \frac{1}{f_1}\right) \quad (3)$$

Where:
1 = Span length where wire sags are measured (m)
γ_1 = Reduced wire weight (N/m•mm^2)
E = Modulus of wire elongation (N/mm^2)

Substituting the Eq. 2 into the expression Eq. 3, we obtain:

$$\Delta L = \frac{8}{3.1}.f_1^2.\left(\delta_f^2 + 2.\delta_f\right) + \frac{1^3.\gamma_1.\delta_f}{8.E.f_1.(1+\delta_f)} \quad (4)$$

Performing algebraic transformations, we obtain the Eq. 5:

$$\delta_f^3 + \alpha.\delta_f^2 + b.\delta_f + c = 0 \quad (5)$$

where, a = 3:

$$b = 2 + \frac{3.1^4.\gamma_1}{64.E.f_1^3} - \frac{3.1.\Delta L}{8.f_1^2}; \ c = -\frac{3.1.\Delta L}{8.f_1^2}$$

After substituting the expression δ_f = y-1 the cubic Eq. 5 reduces to the form:

$$y^3 + p.y + q = 0 \quad (6)$$

Where:

$$p = b-3 = \frac{3.1^4.\gamma_1}{64.E.f_1^3} - \frac{3.1.\Delta L}{8.f_1^2} - 1; q = 2-b+c = -\frac{3.1^4.\gamma_1}{64.E.f_1^3}$$

The discriminant of Eq. 6 is defined by the expression:

$$Q = \left(\frac{p}{3}\right)^3 + \left(\frac{p}{2}\right)^2 \quad (7)$$

When solving Eq. 6, the real radicals are defined as follows; Under Q>0:

$$y = \sqrt[3]{-\frac{q}{2} + \sqrt{Q}} + \sqrt[3]{-\frac{q}{2} - \sqrt{Q}} \quad (8)$$

Under Q<0:

$$y = 2.\sqrt{-\frac{p}{3}}.\cos\frac{\alpha}{3} \quad (9)$$

Where:

$$\cos\alpha = -\frac{q}{2.\sqrt{-\left(\frac{p}{3}\right)^3}}$$

Calculations made for the aluminum-steel 50/8.0 wire of 6-10 kV overhead power line in the IV wind and III ice regions showed that at ΔL = 0.02 m the coefficient of the wire disadjustment sags in the span of 60 m in length is 5.2 times larger, than in the span of 100 m.

In the formulation of experimental studies of wires rapprochements in the spans of the 10 kV complexes under the influence of wind, it was taken into account that this process is of a random nature, therefore, experimental observations continued for 10 years with the aim of accumulating a sufficient amount of data. The measurements were carried out 3-5 times for 20-25 m, followed by averaging the experimental data.

To measure the speed and the direction of wind, we used MS-13, M 61 anemometers and a specially, made manual weather vane. The experiments were carried out in a span of 50 m long, the distance between the aluminium-steel -50/8.0 wires horizontally was1.2 m, sag of the wires was 0.7 m at wind speeds from 7-20 m/sec and different disadjustment coefficients of wire sags: 0.1, 0.2, 0.3, 0.4.

The results of the measurements showed that the distances between the wires at their maximum rapprochements decrease with increasing wind speed while an extensive scatter of the experimental data is observed because of the non-stationary nature of the effect on the wires of the wind flow. The results obtained should be presented in the form of a limited range of values of the minimum distances between the wires D_{min}, depending on the wind speed V. Therefore, the area of the experimental data is limited by two curves representing its upper and lower boundaries which are described by the corresponding regression equations:

Table 1: The minimum distance between wires at different wind speeds and disadjustment coefficient of wire sags

Disadjustment coefficient of wire sags δ_f	The minimum distance between wires (m) at wind speed (m/sec)					
	8.5	10.2	12.0	13.8	16.2	18.5
0.1	1.11	1.07	1.04	0.99	0.95	0.89
0.2	1.06	1.00	0.96	0.88	0.81	0.74
0.3	1.01	0.95	0.88	0.79	0.69	0.61
0.4	0.95	0.87	0.80	0.67	0.56	0.46

$$4.10^{-4}.V^2\text{-}0.033V+1.282 \leq D_{min} \leq 8.10^{-5}.V^2\text{-}0.013V$$

Under δ_f = 0.1 and:

$$\text{-}2.10^{-5}.V^2 0.042.V+1.322 \leq D_{min} \leq 2.10^{-4}.V^2\text{-}0.028V+1$$

Under δ_f = 0.2. The obtained data are presented in Table 1 in order to assess the impact on the distances between the wires at their maximum rapprochement of wire sags disadjustment coefficient.

The analysis of the experimental data presented in Table 1 shows that the minimum distances between the wires for their asynchronous swaying under the influence of the wind decrease with an increase in the disadjustment coefficient of the wire sags. An increase in the coefficient by 0.1 causes a decrease in the distance to 0.14-0.15 m.

In order to assess the impact of the wind direction speed on the amount of the wire rapprochement during the processing of experimental data, a separate analysis of the initial material was carried out, grouping it into different ranges of angles between the axis of the span of the line and the direction of wind speed: 20-40°, 40-60°, 60-80°, 80-100°. The results of the processed data showed that the orientation of the line relative to the direction of the wind speed does not practically affect the amount of wire rapprochements in the angles range of 40-90°. However, it should be noted that at such wind directions, the maximum values of the wire rapprochements were observed. At angles <40° there is a significant reduction in the magnitude of the wire rapprochements which eliminates the possibility of flashover, short circuits and emergency line shut-off.

In order to assess the impact of the span length on the minimum distances between the wires for their asynchronous pendulum swaying and mutual approaches, experimental studies were carried out in spans of different lengths (50, 75 and 100 m) at a wind speed from 7.0-18.6 m/sec at an angle of 60-90° to the axis of the span. During the experiments in the spans, a disadjustment of wire sag with a coefficient of 0.2 was established. Experimental data are presented in Table 2.

Table 2: Minimum possible distances between wires of different length

Wind speed (m/sec)	Minimum distances between wires (m) in span length (m)		
	50	75	100
7.0	1.05	1.06	1.07
8.2	1.03	1.04	1.06
9.0	1.01	1.03	1.04
10.2	0.97	1.00	1.03
11.0	0.95	0.97	1.01
12.4	0.90	0.94	0.98
14.2	0.82	0.88	0.94
15.0	0.79	0.84	0.92
16.2	0.73	0.83	0.90
17.5	0.68	0.77	0.87
18.0	0.64	0.73	0.85
18.6	0.61	0.73	0.83

The analysis of the data presented in Table 2 indicates a decrease in the distance between the wires with a decrease in the span length. Thus, at the maximum rapprochement of wires, the distances between them in a 50 m span at wind speed of 17.5-18.6 m/sec are from 1.28-1.36 times lower than in a span of 100 m. It should be noted, that the impact of the span length increases with increasing wind speed.

On the basis of the research results presented in the research Kabashov in spans with disadjustment of wire sags the eccentric ice coating on the wires differ in mass and size (Kabashov *et al*., 2013). In the research Kabashov and the impact of the mass and size of eccentric ice coating on the frequency of pendulum oscillations of the wires caused by wind influence was established (Kabashov and Nafikov, 2015). Therefore, disadjustment of wire sags in the span with not identical ice coating on wires enhance their asynchronous oscillations and increase the amount of mutual approach.

To confirm this conclusion, the distances between ice-coated and glaze-ice and rime depositions wires in a span of 50 m in length at a wind speed from 8-16 m/sec at an angle from 65-90° to the axis of the span were experimentally determined. The experiments were carried out at disadjustment sags of wires with coefficients of 0.2, 0.3. The results of the measurements were compared with the database of experimental studies on the distances between the wires without ice coating on wires at the same speeds and wind directions.

A comparative analysis of the obtained data showed that the distances between the wires decrease on the wires with ice and glaze-ice and rime depositions. Thus, at a wind speed of 12 m/sec, the distance between wires with glaze-ice and rime depositions with the size of 62×43 mm decrease by 26% and with the size of 82×56 mm decrease by 34%.

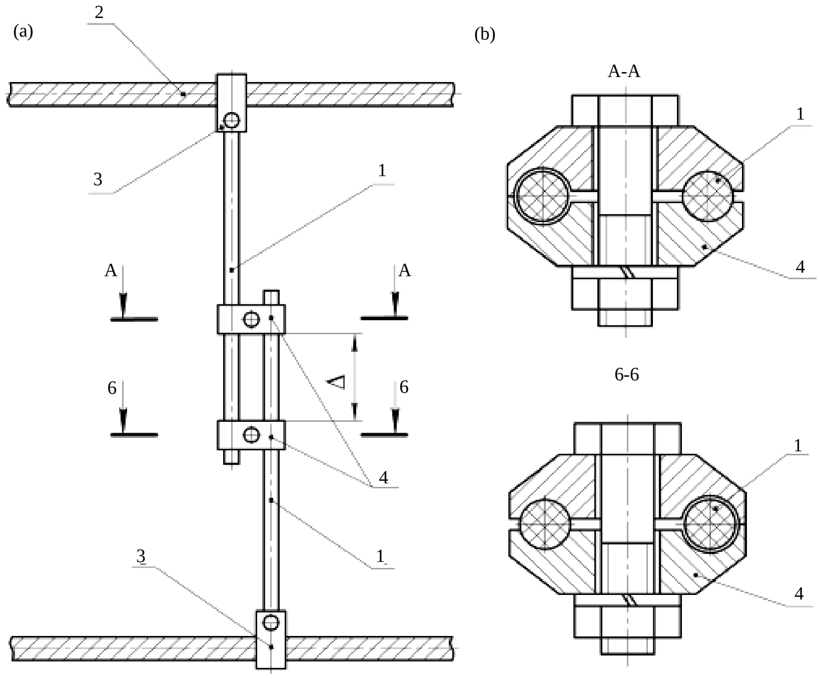

Fig. 1: Interphase insulating spacer

The most effective way to increase the operational reliability of 6-10 kV overhead power lines is to install interphase insulating spacers between wires in the span of the line (Bekmet'ev *et al*., 1979; Kong *et al*., 2014; Liu *et al*., 2016). Spacers are successfully used in Japan, China, USA, Central Europe and other countries.

Interphase insulating spacers are installed mostly to prevent the clashing and galloping of wires caused by wind on the wire covered with unilateral ice-coating.

Nowadays interphase insulating spacers have been developed and are being applied on the basis of plastic-glass rods with various coatings.

Interphase insulating spacers do not eliminate the galloping of wires and often lead to synchronous oscillations of all wires connected by them as a single oscillatory system (Bekmet'ev *et al*., 1979). In this case, there are significant dynamic loads in the structural elements of the span, causing their damage. Therefore, the design of an interphase insulating spacer was developed which ensures damping of oscillations at the beginning of the wires galloping development.

Interphase insulating spacer for 6-10 kV overhead power lines (Fig. 1) consists of two rods 1, made of plastic-glass rods which are fixed to the wires 2 by means of clamps 3. The mutual longitudinal movement of the rods 1 relative to each other with a restriction is provided by means of the groove clamps 4, each of which is rigidly fixed to the rods 1 and one of the holes of the clamp 4 being formed with an inner diameter larger than the outer diameter of the rods 1.

When galloping wires with small amplitudes, the groove clamps, moving together with the rods do not reach the extreme positions which reduces the transfer of oscillatory energy between the wires due to the absence of a rigid connection between the rods. During the galloping of wires with large amplitudes, the rods move before the clamps collide against each other while the energy loss during the collision helps to reduce the amplitude of the galloping in the initial period of its development or leads to its suppression.

The amount of looseness **Δ** between the spacer groove clamps which provides effective dampening of the wires galloping is 0.79. A_m (A_m-Amplitude of oscillations). This amount is chosen from the condition for providing oscillation suppression with the most probable amplitude.

Some observations for the behavior of wires equipped with rigid and developed damping spacers during five ice-and-wind seasons were made on the complex of 10 kV experimental lines. Besides in one span rigid spacers were installed and damping in the other one. Two spacers were installed in each span: the first one was in the 1/4 zone of the span length between the upper and one of the lower wires, the second one was in the 3/4 zone of the span length between the upper and the other lower wire.

In the spans with rigid spacers, 13 cases of wire galloping were recorded in the case of unilateral ice-coating wires with dimensions of 10-15×8-10 mm and wind speeds of 8-15 m/sec. In six cases, galloping of one of the wires with four half-waves with an amplitude of 0.15 m and a frequency of 1.8-2.2 Hz was observed. Four cases of simultaneous galloping of two wires with four half-waves with their swaying in the horizontal plane were recorded with the amplitude being 0.10-0.15 m and the frequency of 3-5 Hz. In three cases, two-half-wave galloping of two wires with amplitude of 0.25-0.30 m and a frequency of 1.2-1.6 Hz was observed. Moreover in the span with installed damping spacers a small four-half-wave galloping of the lower wire with a peak (double amplitude) of 10 m and a frequency of 2 Hz was recorded.

Thus, the test results of the developed interphase spacer showed its effectiveness in the damping of the wire galloping.

The analysis of electricity supply state to agricultural consumers shows that the level of its reliability does not meet the established requirements and norms. Undersupply of energy, long periods of intermittent electrical power lead to significant losses, downfall in agricultural production, decline of living conditions of the rural population. The overwhelming majority of overhead power lines emergency shutdowns occur due to wire damage caused by wind and ice. Wire breaks occur mainly due to burns during their clashing or dangerous rapprochement followed by flashover in the spans with maladjustment of their wire sags. The least reliable in this respect are overhead lines with a voltage of 6-10 kV.

For the first time the measurements were carried out in the full-size spans of 10 kV overhead power lines between the wires at their maximum rapprochement under the influence of wind and also an impact assessment was made. We assessed the impact on their degree amount of disadjustment of the wire sags, wind flow speed, wind direction to the span axis, span length, mass and sizes of ice coatings on wires. It is established that the distances between the wires in their mutual approaches decrease with increasing wind speed, the disadjustment coefficient of wire sags and the decrease in the span length. The established impact of the length of the span on dangerous approaches and the clashing of the wires is confirmed by the results of an analysis of emergency shutdowns of the high voltage overhead power lines of 10 kV of a number of electric grid enterprises on the territory of Northern Kazakhstan, made by Mayzel and Venediktov (1974) and presented in their research. It is shown that the number of shutdowns due to the clashing of the wires or their dangerous approaches with the subsequent flashover in terms of 100 km of lines per year in spans of up to 60 m in length are 4 times larger than in spans of 90-100 m in length.

The line orientation relative to the direction of the wind speed has practically no effect on the wires rapprochement amount at the angular range of 40-90°. At angles <40° there is a significant decrease in the wires rapprochement distance which excludes the possibility of flashover, short circuits and line emergency shut-offs as evidenced by the results of studies performed by Dusebaev and Abdimuratov as applied to overhead power lines in Kazakhstan (Dusebaev and Abdimuratov, 2017).

Experimental studies have shown that the ice and glaze-ice and rime depositions on wires leads to a decrease in the distances between the wires at their maximum rapprochement under the influence of wind. At wind speeds of 12 m/sec or more, these distances are reduced by 26-34%.

Practical application and results: The accounting of the research results obtained in the design of 10 kV overhead power line will allow us to make more reasonable choice of the distances between the wires in those cases when it is determined by the wind conditions of the operation of the wires in the span.

To improve the efficiency of the 10 kV overhead power line under wind and ice conditions an interphase insulating spacer has been developed and tested which prevents dangerous rapprochement of wires during oscillations under the influence of wind and reduces the intensity of low-frequency oscillations such as "Galloping" of wires.

Damping spacers are introduced in Sibayskie, Belebeyevsky, Central ishimbay, Neftekamsk, Northeast, Kumertau power grid enterprises of the Bashkir energy system and also on Aktobe RU "Zapkazenergo, RU Alma-Ataenergo" (a City of Alma-Ata).

CONCLUSION

In order to reduce the damageability of overhead power lines, the duration of power supply interruptions for agricultural consumers, it became necessary to conduct experimental studies of the causes, nature and magnitude of their mutual rapprochements in the span under the influence of wind. No similar research of 6-10 kV overhead power lines have been conducted.

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