High Corrosion Resistance Conductor for Overhead Transmission Lines

Masato WATABE*, Hideto ITO, Koji NAGANO, Toshinobu TSUJI, Nobuaki SUGA
and Yasuhiro AKASOFU

The deterioration of overhead transmission lines in Japan has been continuing and transmission failures caused by corroded aluminum conductor steel reinforced (ACSR) conductors have increased year by year. From the viewpoints of securing reliable power supply and prolonging the life of ACSR conductors, Sumitomo Electric Industries, Ltd. has developed a high-corrosion-resistance ACSR conductor jointly with the Kansai Electric Power Co., Inc. (KEPCO). The conductor is highly resistant to sea salt because of the high corrosion resistance offered by aluminum-manganese alloy clad steel wires used in the steel core part. The corrosion resistance of the conductor is about 1.6-2 times higher than that of the conventional ACSR/AC conductor. Using conventional materials for the aluminum wires, this product offers high economic efficiency with a minimal cost increase. Since 2012, the conductor has been installed into many transmission lines in KEPCO's area and other regions in Japan.

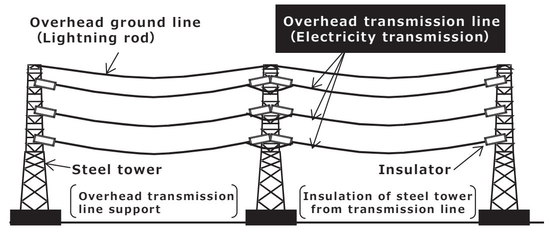
Keywords: overhead transmission line, corrosion, sea salt, galvanic corrosion, aluminum alloy

1. Introduction

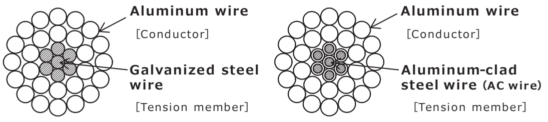
In Japan, overhead transmission lines were constructed extensively from the 1960s to the 1980s, and many conductors in these transmission lines have been operating for more than 40 years. Since Japan is surrounded by the sea, many transmission lines were constructed along the coast and many aluminum conductor steel reinforced (ACSR)*1 conductors (Fig. 1) and other aluminum-based conductors have been exposed to a harsh natural environment for many years. Transmission failures caused by corrosion of conductors occur occasionally. The corrosion of conductors is progressing year by year and transmission failures caused by the breakage of conductors has also begun to occur in recent years, and therefore immediate implementation of transmission line failure prevention measures is required.

From the viewpoints of securing reliable power supply and prolonging the life of ACSR conductors, Sumitomo Electric Industries, Ltd. and the Kansai Electric Power Co., Inc. (KEPCO) have jointly developed a new alloy-applied transmission conductor that has superior corrosion resistance to sea salt, and put the new conductor into practical use in actual transmission lines.

This paper describes and discusses the corrosion progress behavior of overhead transmission conductors, the method for improving their corrosion resistance, the manufacturability of aluminum alloy materials, and the corrosion resistance of the newly developed ACSR conductor.



(a) Overhead transmission facility



(b) Conductor construction (ACSR*1)

(c) Conductor construction (ACSR/AC*2)

Fig. 1. Overhead transmission facility and examples of the construction of overhead transmission line conductor

2. Basic Study for the Development of High Corrosion Resistance Conductor

2-1 Actual state of conductor corrosion in Japan and development goal

The actual state of the corrosion of overhead transmission conductors in Japan(1) is shown in Fig. 2. This figure was made by analyzing the conductor corrosion data of all electric power companies in Japan according to environment/cause. According to this figure, corroded conductors caused by only sea salt account for 74% of all corroded conductors. When the corroded conductors installed in

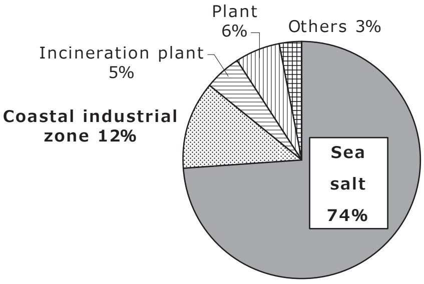


Fig. 2. Actual state of the corrosion of overhead transmission conductors in Japan(1)

coastal industrial zones is included, the sea salt-corroded conductors account for 86% of all.

An example of a sea salt-corroded ACSR conductor used in an actual transmission line(1) is shown in Photo 1. One of the notable characteristics of sea salt corrosion of a conductor is that its surface rarely deteriorates but the aluminum wires inside the conductor suffer accelerated corrosion in many cases. It is difficult to detect the inner corrosion by visually inspecting surface conditions of conductors, leaving the corrosion of transmission conductors as an unseen problem.

Thus, the inner corrosion of conductors by sea salt is a serious problem to be solved urgently and we established a sea salt corrosion prevention technique as the goal of our development activity.

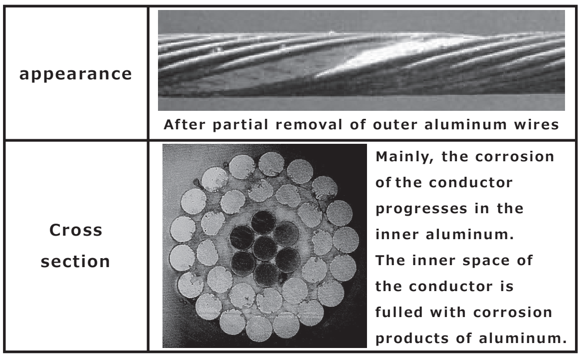


Photo 1. Example of sea salt-corroded ACSR conductor from actually used transmission line(1)

2-2 Progress of sea salt corrosion and approach to corrosion resistance improvement

At Sumitomo Electric, we made accelerated corrosion test equipment (Fig. 3) that can simulate the actual use conditions of a transmission line in order to evaluate the progress of corrosion of the conductors. This test equipment sprays a corrosive water solution intermittently on the test conductor while heating it with an electric current. Thus, the equipment moisten and dry the test conductor repetitively to accelerate its corrosion.

Using this equipment, we evaluated the sea salt corrosion progress with time in ACSR conductors and clarified the following corrosion mechanism:(2)-(4)

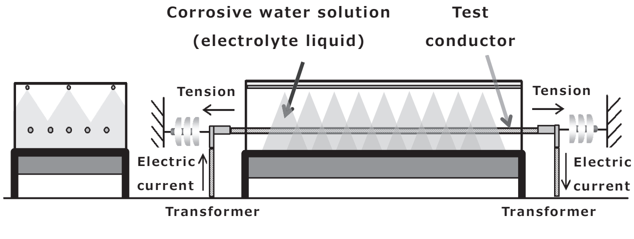


Fig. 3. Accelerated corrosion test equipment

① In the initial stage of corrosion, water containing sea salt penetrates into the conductor. The sea salt increases gradually inside the conductor and promotes the corrosion of both the aluminum wires and the zinc layer of the steel core wires inside the conductor.

② After the zinc layer is eroded due to corrosion, the steel surface of each core wire is exposed. When the exposed steel surface contacts the inner aluminum wires, a galvanic corrosion*3 occurs between the aluminum and steel materials. As a result, the aluminum wires progress corrosion vigorously as shown in Photo 2 and Fig. 4.

③ In contrast, ACSR/AC*2 conductors delay the exposure of steel surfaces and therefore they are superior to ACSR conductors in terms of sea salt corrosion resistance.

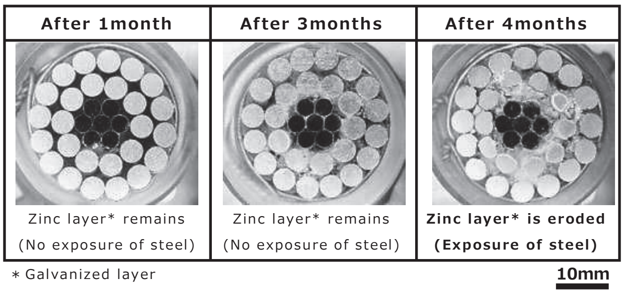


Photo 2. Progress of sea salt corrosion of ACSR conductor (Cross section of conductor)(2)

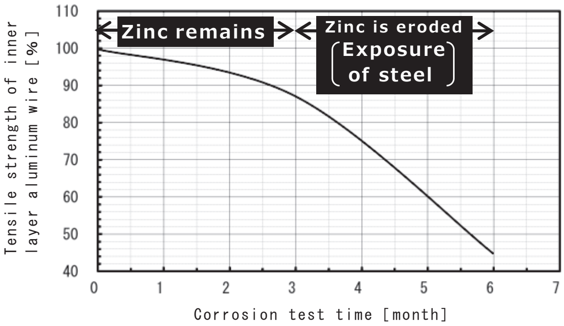
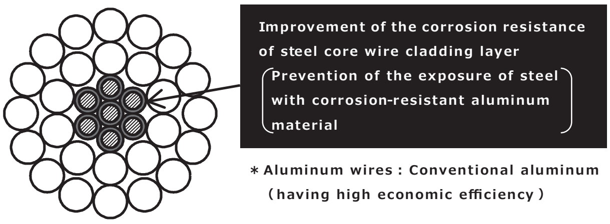


Fig. 4. Progress of sea salt corrosion of ACSR conductor (Tensile strength of Aluminum wire)(3)

As discussed above, it was confirmed from the corrosion test results that the sea salt corrosion resistance of ACSR conductors depends largely on the exposure of the steel core wires' surfaces and their subsequent galvanic corrosion effects on the aluminum wires.

Based on the above finding, we developed a steel core wire clad with high-corrosion-resistance aluminum to prevent the galvanic corrosion action of the core wire and thereby protecting the conductor from sea salt corrosion (Fig. 5).



Improvement of the corrosion resistance of steel core wire cladding layer (Prevention of the exposure of steel with corrosion-resistant aluminum material)

＊Aluminum wires : Conventional aluminum (having high economic efficiency)

Fig. 5. Cross section of corrosion-resistant ACSR conductor (Sea salt corrosion preventive measure)

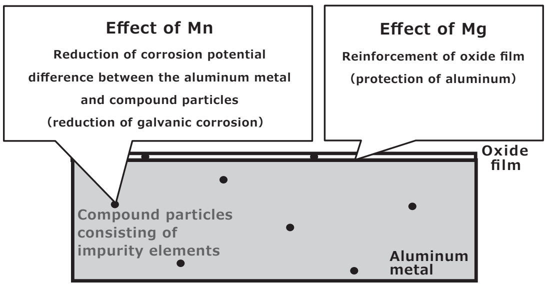


Fig. 6. Improvement of aluminum's corrosion resistance by adding Mn and Mg (schematic illustration)

2-3 Criteria for selecting corrosion-resistant aluminum material suitable for cladding steel core wire

The corrosion resistance of aluminum depends mainly on its contain elements (type, concentration, state of existence) and oxide film (formed state) on the surface. Electric aluminum ingot contains minute quantities of iron (Fe), silicone (Si), and other elements as unavoidable impurity elements (Table 1). Since the solid solubility limit*4 of Fe in aluminum is extremely low,(5) Fe tends to exist in aluminum in the form of compounds such as Al-Fe and Al-Fe-Si particles.

It is already known that these compound particles in aluminum affect the corrosion resistance for the following reasons:

① Galvanic corrosion effect caused by corrosion potential difference between the aluminum metal and compound particles.

② Reduction in denseness of oxide film on aluminum surface and the accompanying lowering of the substrate protection property.

When considering these adverse effects of compound particles, it sounds effective for improving the corrosion resistance to reduce the content of these impurity elements. However, high purity aluminum will increase its cost.

Table 1. Standards for chemical content of electric aluminum ingot and actual example of content (wt.%)(5)*

	Al	Si	Fe	Cu	Mn	Ti+V
standard	≥ 99.65	≤ 0.1	≤ 0.25	≤ 0.005	≤ 0.005	≤ 0.005
Actual example	99.79	0.05	0.16	0.001	0.002	0.00015

＊JIS H 2110

Finally, we decided to test the usefulness of aluminum alloys with manganese (Mn), magnesium (Mg) added as cost-effective corrosion-resistant aluminum materials. The objective of use of an Al-Mn alloy was to reduce the corrosion potential difference between the aluminum metal and compound particles consisting of Fe, Si, and other impurity elements, and thus to minimize the galvanic corrosive action between these materials. On the other hand, the objective of use of an Al-Mg alloy was to reinforce the oxide film formed on the surface of the aluminum metal and thus to enhance the protection property of the oxide film (Fig. 6).

3. Narrowing of the Content of Aluminum Alloy Elements

Using a small-size melting/molding device consisting of a graphite crucible and water-cooled mold, we made two types of aluminum alloy specimens each with different quantities of Mn or Mg added and evaluated their processability and corrosion resistance.

To check the processability of these alloys, we cold-forged and cold-drew 30 mm-diameter cast alloys until their diameter to 4.5 mm while annealing them as needed. During this process, we observed some defect on the surface of the drawn specimens. Flaws or cracks occurred on the surface of both the Al-Mn and Al-Mg alloy specimens when the Mn- and Mg-addition quantities exceeded certain limits. From this result, it was known that Mn- and Mg-addition deteriorate the processability.

To check the corrosion resistance of these alloys, we carried out an accelerated wet-dry cycle corrosion test using sodium chloride as the principal corrosive component. After the test, we observed the cross-section of each test specimen and measured the corrosion depth. The measurement results clarified that both alloy specimens demonstrated a tendency of reduced corrosion depth with increasing their Mn- and Mg-content. From this result, it was known that Mn- and Mg-addition enhance the corrosion resistance.

The evaluation results for the above two types of alloys are shown in Table 2. To develop a high corrosion-resistant conductor, it is indispensable to select an alloy composition that can provide high processability and corrosion resistance. After due consideration of the cost of alloys, the effects of alloys on conductor properties, the processability of alloys having similar compositions we experienced in the past and other factors, we narrowed down the Mn-content of the Al-Mn alloy to the range of 0.2 to 1.0 wt.% and the Mg-content of the Al-Mg alloy to the range of 0.5 to 1.5 wt.%.

Table 2. Evaluation results for test specimens made by small-size melting/molding device

Mn and Mg concentrations	Low ⇔ High
Manufacturability	High ⇔ Low
Corrosion resistance	Low ⇔ High

4. Manufacturability Evaluation Using Mass Production Facility

Using mass production facilities, we made six types of aluminum alloy materials for aluminum-cladding applications and evaluated the processability. The composition of six types of alloy materials are shown in Table 3. Then we manufactured aluminum-alloy-clad steel wires with the promising five types of alloy materials and finally we manufactured ACSR conductor with promising three types of alloy materials.

Table 3. Aluminum alloy compositions for manufacturability evaluation

No.	Test specimen name	Alloy composition
1	0.2%Mn	Al-0.2 wt.%Mn
2	0.5%Mn	Al-0.5 wt.%Mn
3	1.0%Mn	Al-1.0 wt.%Mn
4	0.5%Mg	Al-0.5 wt.%Mg
5	1.0%Mg	Al-1.0 wt.%Mg
6	1.5%Mg	Al-1.5 wt.%Mg

4-1 Aluminum alloy materials for cladding application

Using the continuous casting and rolling machine installed at Sumitomo Electric Toyama Co., Ltd, we made 9.5-mm-diameter aluminum alloy wire rods to make the aluminum-alloy-clad steel wires that are discussed in Subsection 4-2. The surface quality of two types of Al-Mn alloy specimens (0.2% Mn and 0.5% Mn) and three types of Al-Mg alloy specimens was comparable to that of conventional electric aluminum wire rods. In contrast, the aluminum alloy specimen added with 1.0% Mn was slightly inferior to the other five types of specimens in terms of manufacturability, and therefore it was excluded from the group of promising aluminum alloy claddings.

4-2 Aluminum alloy-clad steel wire

Using J-Power Systems Corp.'s mass production line, we made steel wires clad with the five types of alloys discussed in Subsection 4-1 and evaluated the surface quality of each aluminum-alloy-clad steel wires. As a result, alloy specimens added with 0.2% Mn and 0.5% Mn permitted stable production of aluminum-alloy-clad steel wires having high surface quality, while alloy specimen added with 0.5% Mg was slightly inferior to the above Al-Mn alloy specimens in manufacturability. In contrast to these three types of aluminum alloy specimens, alloy specimens added with 1.0% Mg and 1.5% Mg were unsuitable for stable cladding steel wires, and therefore they were excluded from the group of promising cladding materials.

4-3 Conductors

The steel wires clad with aluminum alloys with 0.2% Mn, 0.5% Mn, and 0.5% Mg described in Subsection 4-2 were cold-drawn until their diameter to 2.6 mm. Then each types of aluminum-alloy-clad steel wires were stranded together with aluminum conductive wires to trial manufacture ACSR conductors having an aluminum cross-sectional area of 160 mm^2. In the drawing and stranding process, no flaw, crack or separation was observed on the surface of cladding layer for all three types of alloys. The surface quality of the trial manufactured conductors was comparable to that of conventional conductors, as shown in Photo 3.

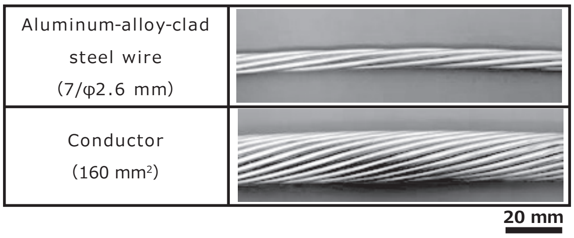


Photo 3. Typical appearances of trial manufactured aluminum alloy-clad steel wire and conductor (Aluminum alloy with 0.5% Mn)

4-4 Comprehensive evaluation

The results of manufacturability evaluation using the mass production facilities are summarized in Table 4. Based on the evaluation results, three types of aluminum alloys with 0.2 wt.% Mn, 0.5 wt.% Mn, and 0.5 wt.% Mg were selected as materials suitable for the new high corrosion-resistant conductor.

Table 4. Results of manufacturability evaluation

No.	Specimen name	Aluminum alloy wire rod*1	Aluminum alloy-clad steel wire*1	Conductor*1	Comprehensive evaluation*2
1	**0.2%Mn**	○	○	○	◎
2	**0.5%Mn**	○	○	○	◎
3	1.0%Mn	△	—	—	※
4	**0.5%Mg**	○	△	○	◎
5	1.0%Mg	○	×	—	※
6	1.5%Mg	○	×	—	※

*1 ○ : Good △ : Unsuitable × : Difficult to use − : Excluded from evaluation
*2 ◎ : Promising ※ : Excluded from promising alloy group

5. Property of Corrosion-Resistant Alloy Conductor and Its Practical Use in Transmission Lines

5-1 Property

(1) Corrosion resistance property

To compare the corrosion resistance of the three types of alloy-applied conductors (described in Subsection 4-3) with that of a conventional conductor (ACSR/AC: for comparison), accelerated wet-dry cycle corrosion tests were carried out.

(a) Appearance

The typical appearance(6) of the aluminum alloy-clad steel wires after accelerated corrosion test are shown in Photo 4. The test specimens with 0.2% Mn and 0.5% Mn lost their original metallic gloss, but they did not exhibit any conspicuous corrosion defects. In contrast to the above two specimens, the specimen with 0.5% Mg exhibited definite corrosion defects. Corrosion defects were also detected on the conventional aluminum-clad steel wire that was used for comparison, and the severity level of these defects was higher than those detected on the specimen with 0.5% Mg.

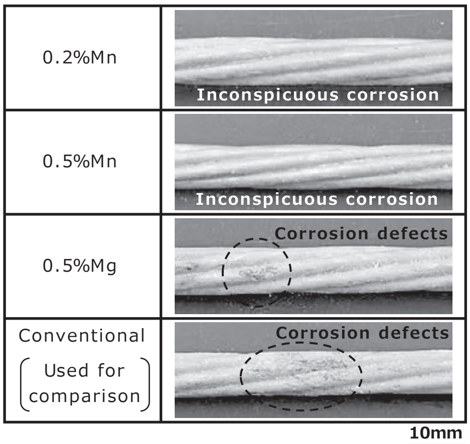


Photo 4. Appearances of aluminum-alloy-clad steel wires after accelerated corrosion test (7/ø2.6 mm)(6)

(b) Cross section

Typical cross sections of the aluminum-alloy-clad steel wires after accelerated corrosion test(6),(7) are shown in Photo 5. The cross-section of each test specimen was evaluated at about 20 positions. As a result, corrosion of the test specimens with 0.2% Mn and 0.5% Mn was not sufficiently heavy to expose the surface of their base materials (steel). In contrast, the test specimen with 0.5% Mg exposed the steel surface in a few places. The conventional aluminum clad steel wire specimen also exposed the steel surface more extensively than the test specimen with 0.5% Mg.

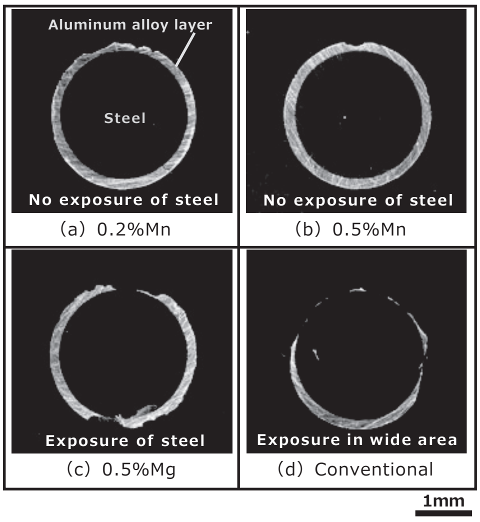


Photo 5. Cross sections of aluminum alloy-clad steel wires after accelerated corrosion test (ø2.6 mm)(6),(7)

(c) Corrosion depth

The progress of corrosion depth in each aluminum-alloy-clad steel wire(6),(7) with time is shown in Fig. 7. The corrosion depths in the test specimens with 0.2% Mn, 0.5% Mn, and 0.5% Mg were less than that in the conventional aluminum-clad steel wire specimen.These results verify that the addition of Mn or Mg enhances the corrosion resistance of aluminum. Among these three types of alloy specimens, the specimen with 0.5% Mn had the highest corrosion resistance and its value was 1.6 times of the conventional specimen. From this fact, we can say that the exposure of the steel surface of aluminum-alloy-clad steel wire with 0.5% Mn starts 1.6 times later than conventional aluminum clad steel wire. That means 160 mm^2 ACSR conductor comprised of aluminum-alloy-clad steel wire with 0.5% Mn has 1.6 times longer life before starting to corrode heavily than conventional 160 mm^2 ACSR/AC.

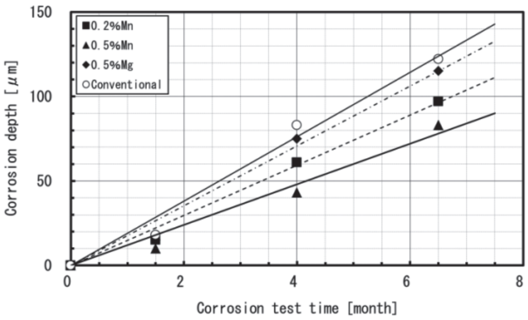


Fig. 7. Corrosion depth in each aluminum alloy-clad steel wire (ø2.6 mm)(6),(7)

Based on the above evaluation results, we selected an aluminum alloy containing 0.5 wt.% of Mn as the material most suitable for cladding the core steel wires of the new conductor.

We have been evaluating other sizes of conductors. For example, a conductor having an aluminum cross sectional area of 410 mm^2 has been found to have a corrosion resistance about two times higher than that of conventional conductors.

(2) Mechanical and electrical properties

The mechanical and electrical properties of the new aluminum-alloy-applied conductor and its aluminum-alloy-clad steel wires were measured. The results showed that the mechanical property of both the new conductor and its aluminum-alloy-clad steel wire is equivalent to that of ACSR/AC conductors and will not raise any problem in practical use. The electric resistance of the new conductor was slightly higher than that of an ACSR/AC conductor, but lower than that of an ACSR conductor.

5-2 Use of newly developed conductor for actual transmission lines

The new alloy-applied corrosion-resistant conductor (Al-0.5 wt.% Mn) was first installed in the KEPCO's 275-kV transmission line in 2012. Since then, the new conductor has been installed into many transmission lines not only in the KEPCO's area but also other electric power companies in Japan. As of April 2016, the total installed length of the new conductor was 1,062 km.

6. Conclusion

From the viewpoints of securing reliable power supply and prolonging the life of ACSR conductors, Sumitomo Electric and KEPCO have jointly developed an aluminum-alloy-applied conductor with a high resistance to sea salt corrosion.

Composed of a corrosion-resistant aluminum-alloy (Al-0.5 wt.% Mn)-clad steel wire as the tension member, the newly developed conductor has a corrosion resistance 1.6 to 2 times higher than that of a conventional ACSR/AC conductor. The new alloy-applied corrosion-resistant conductor was first installed in KEPCO’s 275-kV transmission line in 2012. Since then, KEPCO and other electric power companies in Japan have been expanding the use of the high-corrosion-resistance conductor.

We will continue our efforts to develop and expand the application of new conductors such as heat-resistant aluminum conductors, high-strength aluminum conductors, overhead ground wires and other conductors. We will work to enhance the reliability of the transmission line and prolong the life of conductors.

7. Acknowledgements

We are sincerely grateful for the cooperation of KEPCO’s staff members in the development of the new conductor and its installation in actual transmission lines.

Technical Terms

∗1 Aluminum conductor steel reinforced (ACSR): An overhead transmission conductor that uses a galvanized steel wire as the tension member and aluminum wires as the conducting material.

∗2 Aluminum conductor steel reinforced/aluminum clad (ACSR/AC): An overhead transmission conductor that uses aluminum-clad steel wires as the tension member and aluminum wires as the conducting material.

∗3 Galvanic corrosion: A phenomenon the base metal suffers accelerated corrosion and the noble metal delays corrosion when different metals are in electrical contact in a corrosive environment.

∗4 Solid solubility limit: The maximum concentration at which the other atomic state element can dissolve in the matrix phase metal.

References

(1) The Institute of Electrical Engineers of Japan, “The conductor corrosion phenomena of overhead transmission lines,” the technical roport No.968, pp.5-6 (June 2004)

(2) Y. Takagi, O. Oguri, M. Sakata, H. Ito, M. Watabe et al., “Research of the Corrosion Behavior of Conductor for Overhead Transmission Lines (No.2),” Conference paper JIEE conf. of Div.B, no.19, pp.21-22 (September 2006)

(3) Y. Takagi, O. Oguri, M. Sakata, H. Ito, M. Watabe et al., “Research of the Corrosion Behavior of Conductor for Overhead Transmission Lines (No.3),” Conference paper JIEE conf. of Div.B, no.19, pp.23-24 (September 2006)

(4) Y. Takagi, O. Oguri, M. Sakata, H. Ito, M. Watabe et al., “Research of the Corrosion Behavior of Conductor for Overhead Transmission Lines (No.4),” Conference paper JIEE conf. of Div.B, no.19, pp.25-26 (September 2006)

(5) Y. Murakami et al., “Foundations and industrial technology of aluminum materials,” Japan Aluminum Association, pp.342-344 (2010)

(6) N. Shimizu, T. Omote, H. Ito, M. Watabe, “Development of Estimating Method for Conductor corrosion and High Corrosion resistant Conductor for overhead transmission lines,” CIGRE Session Paris 2016, No.B2-303, pp.1-6, Paris, France (August 2016)

(7) S. Ikoma, S. Doi, H. Ito, M. Watabe et al., “Development of Anti-Corrosion for Conductor,” Conference paper JIEE conf. of national convention, no.7, pp.188-189 (March 2010)

Contributors

The lead author is indicated by an asterisk (∗).

M. WATABE*
- Assistant Manager, Technology Development Department

H. ITO
- Senior Assistant General Manager, Overhead Transmission Line Division

K. NAGANO
- Group Manager, Technology Development Department

T. TSUJI
- Group Manager, Overhead Transmission Line Division

N. SUGA
- Manager, Overhead Transmission Line Department, J-Power Systems Corp.

Y. AKASOFU
- Assistant Manager, Engineering Department, Sumitomo Electric Toyama Co., Ltd.