Corrosion Evaluation with Atmospheric Corrosion Monitoring Sensors and Corrosion Rate Map Development

Teruhisa TATSUOKA¹, Masanori OSADA², Tomohito HIDA³, Yoichi TSUCHIDA⁴, Akio KAWAHARA⁵, Hiroshi OHTA⁶

¹TEPCO Holdings, Inc. TEPCO Research Institute, Yokohama, Japan, tatsuoka.teruhisa@tepco.co.jp
²TEPCO Holdings, Inc. TEPCO Research Institute, Yokohama, Japan, osada.masanori@tepco.co.jp
³TEPCO Power Grid, Inc. Transmission Dept., Tokyo, Japan, hida.tomohito@tepco.co.jp
⁴TEPCO Power Grid, Inc. Transmission Dept., Tokyo, Japan, tsuchida.yoichi@tepco.co.jp
⁵TEPCO Power Grid, Inc. Transmission Dept., Tokyo, Japan, Kawahara.A@tepco.co.jp
⁶TEPCO Power Grid, Inc. Transmission Dept., Tokyo, Japan, ohta.h@tepco.co.jp

Abstract:
Electric power facilities such as steel towers, poles, transmission and distribution lines, substation and power plant facilities have been exposed in various atmospheric environments. These steel structures have been corroded by thin water films on them formed by high humid weather conditions such as acid rain, dew, fog snow. Atmospheric corrosion is accelerated by the range and quantity of deposition on them. Therefore it is important to evaluate the corrosivity of atmospheric environment and corrosion rates of metals and alloys for the application of corrosion control and protection methods and the decision of appropriate maintenance interval against the corrosion of facilities.

Atmospheric Corrosion Monitor type sensors (ACM sensors) have been developed to evaluate the corrosivity of atmospheric environments and corrosion rates of metals and alloys. ACM sensor outputs galvanic current between silver (Ag) and carbon steel (Fe) related to corrosion rates of metals and alloys to be used as a measure of corrosion. The current depends upon relative humidity, RH, and time of wetness, TOW, such as the presence of thin water film from rain, fog, dew or snow, and the quantity of depositions such as adhered sea salt and the other contaminants, which correspond to the severity of atmospheric corrosion.

In this study, Fe/Ag-pair type ACM (Fe-ACM) and Zn/Ag-pair type ACM (Zn-ACM) sensors had been installed on around 150 transmission steel towers at various site for around several years to get corrosion rates and evaluate the atmospheric corrosivity. Moreover, the corrosion rate maps of carbon steel and zinc in various atmospheric environments in Japan were developed using these corrosion data and statistical methods. Multiple regression analysis method was applied to evaluate the relationship between corrosion rates and topographic or meteorological factors.

Keywords:
atmospheric corrosion, corrosion rate map, time of wetness, deposition, sea salt
Introduction

Tsujikawa, Shinohara, Motoda, et al. [1, 2] have developed the Atmospheric Corrosion Monitor type sensors (ACM sensors) and established the ACM sensor diagnosis technology which are expected to evaluate the atmospheric corrosivity with relatively short time monitoring, typically a year. Shinohara, Motoda and Oshikawa, et al. [1, 3 - 5] have applied the ACM sensors to mainly marine environments. Fujita, and Takemura, et al. [6, 7] have investigated the atmospheric corrosivity for a road bridge and a residential steel house with the ACM sensors.

The diagnosis technique for the atmospheric corrosion with ACM sensors has been developed to evaluate the corrosivity of atmospheric environment and carbon steel corrosion rate by Fe/Ag-pair type ACM (Fe-ACM) sensor [1 - 11], zinc corrosion rate by Zn/Ag-pair type ACM (Zn-ACM) sensor [4, 8, 9] and aluminium corrosion rate by Al/Ag-pair type ACM (Al-ACM) sensor [12 - 16].

In this study, Fe-ACM and Zn-ACM sensors have been installed on around 150 transmission steel towers at various sites to obtain corrosion rates of carbon steel and zinc and evaluate the atmospheric corrosivity. Moreover, corrosion rate maps of carbon steel and zinc in large areas of more than 200 km diameter which contained several prefectures and whole Japan were developed using these corrosion data and statistical methods. Multiple regression analysis method was applied to evaluate the relationship between corrosion rates and around 100 topographic and meteorological factors.

Experimental procedure

ACM sensors, hygrometers and thermometers

Figure 1 shows factors on acceleration of atmospheric corrosion. The corrosivity of atmospheric environment is very sensitive to thickness of water film and range and quantity of depositions on metals and alloys. High humid environment produced by dew, fog, mist, rain and snow makes thin water film on metals and alloys. Depositions such as sea salt, SOx, dust, snow melting, etc. agent change thin water film in thin and high concentration electrolyte film. Some salts deliquesce even though in low humid environment. Figure 2 shows relationship between thin water layer and atmospheric corrosion rate [27]. Corrosion rate is strongly influenced by the thickness of water film and electrolyte concentration.

![Figure 1. Factors on acceleration of atmospheric corrosion.](image1)

![Figure 2. Relationship between thin water layer and atmospheric corrosion rate[27].](image2)
Figure 3 shows a schematic diagram of Fe-ACM sensor in dry and wet environments. ACM sensor is a galvanic type corrosion monitor sensor and it consists of three layers, anodic metal layer and insulating layer and cathodic metal layer. In the case of Fe-ACM sensor, insulator and silver paste are printed on carbon steel substrate and baked. In this study, carbon steel and zinc (Z27) were applied as anodic metal substrates and named Fe-ACM and Zn-ACM sensors, respectively. Fe-ACM and Zn-ACM sensors sold by JSCE (Japan Society of Corrosion Engineering) have been widely used in not only Japan [1-16] but also some regions of Asia [17 - 20]. We have developed high purity aluminum alloy anodic metal substrates ACM sensor, Al/Ag-pair type ACM (Al-ACM) sensor, and investigated the capability to obtain aluminum corrosion rate.

Figure 4 shows a schematic diagram of the corrosion reaction and the galvanic current flow of Fe-ACM sensor measured by non-resistant ammeter. When it is high humid circumstances such as dew, fog, rain and snow thin water film is formed on the ACM sensor. At the same time the ACM sensor surface has depositions come from airborne particulate and thin water film becomes thin electrolyte film. Thin electrolyte film makes carbon steel substrate corrode producing galvanic current output. The corrosion of carbon steel substrate yields a galvanic current. The ACM sensor output current depends upon the nature and concentration of dissolved contaminants such as adhered sea salt, solution gas, and ions, relative humidity, RH, and time of wetness relates the thickness of the electrolyte film on the ACM sensor. Total amount of electric quantity and daily average electric quantity are evaluated to understand the corrosivity of the atmospheric environments.

ACM sensor can also estimate the weight of deposited sea salt, Ws, on it at marine and other environments by referring to the experimentally determined “Calibration curve of ACM sensor output current - RH” [1, 3, and 4]. The ion chromatography analysis for the deposition on the ACM sensors after exposure suggests that the sea salt accelerated the corrosion mainly at seacoast region.
Atmospheric corrosion monitoring procedure on transmission steel towers

Fe-ACM and Zn-ACM sensors, thermometers and hygrometers were installed with atmospheric corrosion test specimens for corrosion monitoring on the outer surface of around 150 transmission steel towers in Kanto region and Yamanashi, Shizuoka, Fukushima and Niigata prefectures. Figure 5 shows ACM sensor, thermometers, hygrometers and monitoring system installed on transmission steel tower. Fe-ACM and Zn-ACM sensors were installed on steel towers at 1 - 100 meters high above the ground at each site. ACM sensor output current was measured by non-resistant ammeter and recorded with data logger every 10 minutes. Thermometers and hygrometers were also installed on steel towers and those of output were measured by voltmeter and recorded as well as ACM sensors.

These measurements with ACM sensors at each site had been conducted for around 1 year between 2000 and 2013. ACM sensors were periodically renewed. Amount of deposition on the Fe-ACM sensors was evaluated with ion chromatograph after exposure and the data were used for the corrosion behaviour analysis.

Atmospheric exposure corrosion tests had been conducted for up to several years. These test specimens were made from carbon steel (SS400), galvanized carbon steel (Z27). The carbon steel and zinc test pieces were exposed with ACM sensors at the same site to get the relationships between these corrosion rates and ACM sensor output currents. The calibration curve of carbon steel corrosion rate and daily average electric quantity was delivered by the relationship atmospheric corrosion test specimens of carbon steel and Fe-ACM sensors exposed at the same site and the same time. The calibration curve of zinc corrosion rate and daily average electric quantity was delivered by atmospheric corrosion test specimens of zinc and Zn-ACM sensors exposed at the same site and the same time. The carbon steel corrosion rates and zinc corrosion rates were used to predict appropriate maintenance intervals for transmission steel towers and other steel structures of electric power facilities.

It is expense and tough work to install the data logger monitoring systems to hundreds of transmission steel towers. Ammeter connected to ACM sensors, voltimeters connected to thermometers and hygrometers and data logger connected to these measuring devices were installed to only around 40 of transmission steel towers. Therefore, at other sites, only ACM sensors had been installed on around 110 of transmission steel towers and these ACM sensors removed after exposure were analyzed indirectly at the laboratory of TEPCO Research Institute to evaluate the carbon steel corrosion rates and the zinc corrosion rates of each sites [6]. The accuracy of around 100 corrosion rates estimated by Fe-ACM and Zn-ACM sensors were validated by the data of around 100 corrosion rates measured by atmospheric corrosion test specimens of carbon steel (SS400) and galvanized carbon steel (Z27) and expected by maintenance data of transmission steel towers.
Time of wetness and time of wetness map

Relative humidity and temperature measured by meteorological office in Japan are used for the development of time of wetness map [29]. ISO Time of Wetness, ISO TOW, has been used to evaluate corrosion, therefore it has been very tough work to expect corrosion rate from it precisely. ISO TOW is defined as RH is more than 80 % and temperature is more than 0 °C referred by ISO 9223-92 [11]. Corrosion rate is strongly influenced by the combination of thickness of water film and electrolyte concentration. Therefore only ISO TOW is not enough information as a corrosion factor. In this study, 24 hypothetical times of wetness are defined and their correlate corrosion rate. Time of wetness in wide range area was expected by the drawing of contour lines from relative humidity distribution measured at transmission steel towers and the interpolation of the value of random sampling point. The polynomial interpolation technique was applied to draw time of wetness map with 1 and 5 km mesh [22, 24, 28, 29].

Corrosion rate maps of carbon steel and zinc

Statistical methods were applied to develop corrosion rate maps of zinc and carbon steel in large area of more than 200 km diameter which contained several prefectures and in whole Japan. Multiple regression analysis method was applied to evaluate the relationship between the corrosion rates of carbon steel and zinc evaluated by around 150 of ACM sensor output current, topographic factors and meteorological factors [21 - 26].

Around 100 geographic and meteorological factors in Japan were applied for the statistical evaluation. The multiple regression analysis chose several geographic and meteorological factors suitable for corrosion rate expectation. The techniques and around 150 of corrosion data delivered the corrosion rate equation at each area of 1 and 5 km mesh size and corrosion rate maps of carbon steel and zinc in Japan were developed. These mesh size are enough to recognize the corrosion rate of each transmission steel towers [21, 23, 24].

Results and discussion

Fe-ACM and Zn-ACM sensors output current

Figure 6 shows changes in the Fe-ACM sensor output current, I, relative humidity, RH, and temperature, T, against time at 20 m high above ground at 90 km from coastline of foggy mountainous area site KA in summer in 2007. (From 2007/9/3 to 2007/9/8). The Fe-ACM sensor output current increased as increasing of relative humidity. The Fe-ACM sensor output current showed a peak value, when relative humidity became 100 % due to rain, dew or fog. The currents at the time of rain were larger than those of dew and snowfall. The Fe-ACM sensor output currents in the daytime of 2007/9/6 kept high value as the same as those in rain and dew at night, because at those time the transmission steel tower was covered with fog and was in high humid environments. The Fe-ACM sensor output currents in the sunny daytime were about two order of magnitude lower than those in rain, dew or fog. The disparity comes in the thickness of electrolyte film on the sensors. The mean value of the Fe-ACM sensor output currents at mountainous area like site KA were about two order of magnitude lower than those at seaside area. The disparity comes in the amount of sea salt deposition on the sensor surface at each area with different distance from coastline. At foggy mountainous site KA, Fe-ACM and Zn-ACM sensor output currents in summer were larger than those in winter because the site in summer was much foggier than that in winter.
Figure 7 shows the relationship between Fe-ACM sensor output current and relative humidity at 20 m high above ground at around 90 km from coastline of foggy mountainous site KA in winter 2008 (From 2008/1/1 to 2008/1/15) plotted for Fe-ACM sensors with respect to calibration data under different amount of pre-deposited sea salt. The white circle, square and diamond symbols represent the Fe-ACM sensor output current depending on the pre-determined amount of pre-deposited sea salt measured at laboratory under various RH by Tsujikawa, et al. [1, 2, and 4]. Moreover, significant ACM output currents were observed under 100 % of RH which were judged either rain or snowfall condition while the high RH maintained. These large currents produced by rain or snowfall were eliminated when the corrosivity was evaluated at each site. It is hard to distinguish fog and rain from ACM output currents.

The gradient and distribution of the ACM output currents of site KA was close to those of the $10^{-1}$ g m$^{-1}$ and $10^{-2}$ g m$^{-1}$ pre-deposited sea salt as the open circle and square symbols in Figure 7. The site KA was expected the mild corrosivity environment which had around $10^{-1}$ g m$^{-1}$ and $10^{-2}$ g m$^{-1}$ deposited sea salts. The 50 % cumulative probability of ACM sensor output currents at each site at 70 % RH within a band of plus or minus 2.5 % RH were arranged in descending order. The order was as follows,

Seacoast area = Mountainous area with high RH = Industrial area > City area > Rural area > Mountainous area with low RH.
**Time of wetness and time of wetness map**

Figure 8 shows the frequency of ISO time of wetness, ISO TOW, and some hypothetical time of wetness at 90 km from coastline of foggy mountainous site KA and 55 km from coastline of mountainous site MI. ISO TOW of site KA was higher follows.

ISO time of wetness of site KA defined RH was more than 80 % and temperature was more than 0 °C was 20 % larger than that of site MI. The hypothetical time of wetness of site KA defined RH was more than 80 % was 61 % larger than that of site MI. The difference was expected that the wet condition continues for a long time at site KA because of fog in summer and snow in winter. On the other hand, the wet condition kept for only summer at site MI.

Figure 9 shows the frequencies of annual mean calculated in units of 5 % relative humidity at site KA and site MI. Although both sites were mountainous area, the ratio of 100 % RH at site KA was quite higher than that at site MI. The difference was expected that site KA was foggy throughout the year.

The mean value of chloride ion on the ACM sensors at site KA in winter, in summer was 1.3 and 16.7 times larger than that at site MI, respectively. The corrosivity of atmospheric environment at site KA was severer than that at site MI, because it was strongly influenced by the water film in high humid environments and the amount of depositions.

Figure 10 shows the maps of ISO time of wetness and hypothetical time of wetness weighted by corrosion in Japan. The hypothetical time of wetness weighted at each RH from 20 to 100 % was applied to make time of wetness map, because the correlation coefficient between 150 of corrosion rates and the distribution of the hypothetical time of wetness was the highest in those of ISO TOW and other 24 hypothetical times of wetness.
Evaluation of corrosion rate

Figure 11 shows the relationship between the corrosion rates of carbon steel and daily average electric quantity, \( Q_{\text{day, dew}} \), measured by Fe-ACM sensors at various exposure site [31]. The corrosion rates were delivered by 1 year exposure atmospheric corrosion test specimens of carbon steel exposed at each site. The experimental data of the open triangle symbols delivered by expose at various site agreed rather well with the break line proposed by Motoda, et al. [4] in an equation (1) under the conditions in outdoor exposure sheltered from rain as shown in Figure 7.

\[
\log \text{CR}_{\text{Fe}} (\text{mm year}^{-1}) = 0.379 \log Q_{\text{day, dew}} (\text{C day}^{-1}) - 0.723 \quad \text{Eq. (1)}
\]

They pointed that the corrosion rates of carbon steel exposed under conditions sheltered from rain, \( \text{CR}_{\text{Fe}} \), were well estimated from daily average electric quantity, \( Q_{\text{day, dew}} \), measured by Fe-ACM sensors in the same shelter [4, 8, and 9].

The result in this study revealed that the corrosion rates of carbon steel \( \text{CR}_{\text{Fe}} \), not only in the shelter but also outside of the shelter at various atmospheric environments were well estimated from daily average electric quantity, \( Q_{\text{day, dew}} \), measured by Fe-ACM sensors in the same atmospheric environments.
Corrosion rate maps of carbon steel and zinc

Figure 12 shows corrosion rate map of zinc in Kanto region and Yamanashi, Shizuoka, Fukushima and Niigata prefectures with 1 km mesh size and in Japan with 5 km mesh size [30, 31]. The techniques of corrosion rate evaluation and map drawing for various atmospheric environments of each region were developed using statistical methods. Multiple regression analysis method was applied to evaluate the relationship between corrosion rates evaluated by Fe-ACM and Zn-ACM sensor output currents, topographic factors and meteorological factors, deposition and time of wetness maps.

The corrosion rates of each galvanized transmission steel towers were delivered by these corrosion rate map of zinc and carbon steel. The corrosion rate map has been used as one of the maintenance tool to improve maintenance quality and reduce the repairs and maintenance expenses.

The corrosion rates delivered from the maps were compared with those from atmospheric exposure corrosion test specimens to validate the accuracy of the corrosion rate map. It follows that the good relationship between the corrosion rate map and corrosion test data was revealed.

Results and discussion

(1) The corrosivity of atmospheric environment was evaluated by the Fe-ACM and Zn-ACM sensors and hygrometers and thermometers measured on transmission steel towers at 150 site.
(2) The techniques of corrosion rate evaluation and corrosion rate map drawing for various atmospheric environments were developed using multiple regression analysis methods.
(3) The good relationship between corrosion rate maps and atmospheric corrosion test data revealed that around 150 of corrosion rate data was appropriate to draw precise corrosion rate map for large area which contained several prefectures and whole Japan.
(4) The Corrosion rate maps delivered corrosion rate of each transmission steel tower and contributed to the decision of appropriate maintenance against corrosion such as corrosion inspection interval, paint inspection interval, finding of suitable paint system, the decision of first paint time just before loss of galvanizing layer and the decision of repaint time.
(5) The hypothetical time of wetness map which the time was weighted at each RH from 20 to 100 % improved the accuracy of corrosion rate maps.
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