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RESEARCH ARTICLE

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Reconsidering insulation coordination and simulation under the effect of pollution due to climate change

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Summary

Climate change and air pollution have a direct impact on the performance and lifetime of insulating materials. In recent years, Mazandaran and Golestan provinces in Iran have witnessed a climate change and an increase in air pollution. This problem increases outages and losses in transmission and overhead distribution network. Moreover, traditional and empirical methods have been used for insulation coordination in past decades. As a result, research is needed on the regional power line isolation, revision of insulated surface design, and the number of insulators used. In this paper, a specialized software was used for checking existing lines in Mazandaran and Golestan Regional Power. Insulation computations and isolation studies using MATLAB software were used to present solutions for transmission and overhead distribution networks. This specialized software has the ability to calculate the required minimum air gap and the minimum creepage distance and the number of insulators with due attention to regional pollution, overvoltage due to switching and lightning, and power frequency.

KEYWORDS

insulation coordination, overvoltages, pollution, protection

LIST OF SYMBOLS AND ABBREVIATIONS: General symbols: V, voltage; L, transmission line; HV, high voltage; S, Section; Smax, Number of section transmission line; Lmax, Number of transmission line; A, Altitude above sea level. **Lightening symbols:** BFR, Back Flashover Rate/The desirable number of interruptions per 100-km line; Kwf, The correction factor for wave figure; Kpf, Voltage correction factor of power line frequency; C, coupling coefficient between line guard and conductor phase; Zt, Equivalent surge impedance of tower; NI, The number of insulators; MLCIM, Minimum length of chain insulators for the middle phase; MLCIE, Minimum length of chain insulators for the external phase; Sl, The minimum air gap to achieve optimal BFR. **Switching symbols:** CFO, Critical flashover; SSFOR, switching surge flashover rate; S(s), The minimum allowed air gap to get to optimal SSFOR.

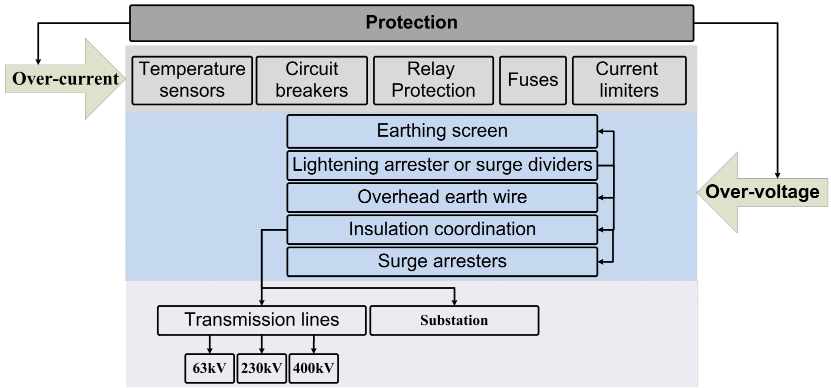


FIGURE 1 Different solutions for protecting against over-current and over-voltage

1 | INTRODUCTION

Transmission lines are always exposed to overcurrent and overvoltage incidents leading to casualties, destroyed equipment, reduced quality assurance, power outages, and insufficient power provision. Protection of power system and its large and small devices against these events is one of the most important tasks that should be performed well to ensure the stability and the permanent activity of power system. This issue is particularly important in power transmission and distribution systems.[1-3] Therefore, various solutions had been used in the electrical industry to prevent these events as shown in Figure 1. Protection against overvoltage requires designing a good insulation coordination in the network. Insulation coordination consists of 2 parts: transmission lines and high-voltage (HV) stations.[4,5] In this paper, insulation coordination review and design has been conducted for 63, 230, and 400 KV transmission and overhead distribution lines. Power transmission and overhead distribution lines need 2 components: cables, which conduct electricity; and electrical insulators that keep cables away from steel towers or pylons.[6-8] Insulators have been used since the appearance of electricity transmission lines. They are equipment used in the transmission and overhead distribution networks for holding voltage carrying electrical conductors and isolation of electrical networks (both mechanical and electrical functions).[9,10] Increased reliability, system safety, and continuous electricity flow are directly dependent upon the proper functioning of insulators. In electrical terms, insulators should withstand both load line voltages and temporary or transient overvoltages in the line.[11-14] The shape and appearance of insulators should be designed in a way that can create the longest path for the electrical arc.[15]

Climate change and pollution have a direct impact on the performance and the lifetime of the insulation. Insulators of transmission lines crossing specific areas can be subject to pollution. The type of pollution and duration of exposure to it are among other factors affecting the system insulation.[16-23] Pollution of the external surface of insulators including industrial and coastal insulators is the major cause of electrical discharge of insulators in common power systems. Electrical discharge of insulators in transmission and overhead distribution lines can cause disruption and power outages imposing high costs on power companies and their customers.[11,24,25]

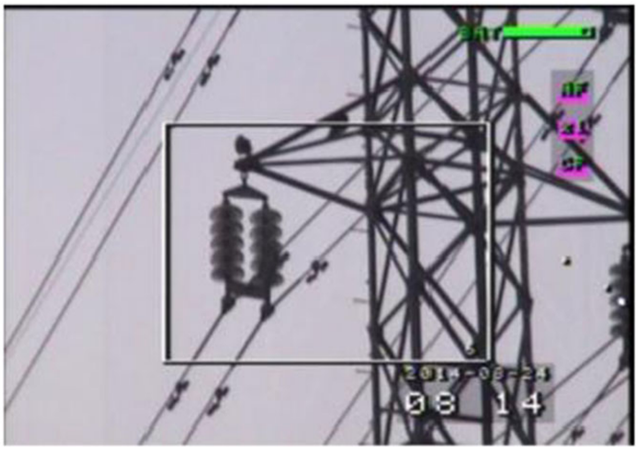
In this article, existing lines in Mazandaran and Golestan provinces were studied. Insulation computations and isolation studies using MATLAB software were used to present solutions for improving reliability of transmission and overhead distribution networks in the area. The designed software has a simple and a user-friendly graphical user interface. First, environmental conditions and weather stations in the area were studied. Then, insulation calculations are performed according to those conditions. Results include determination of required insulation and creepage distances, which are obtained on the basis of standards and technical limitations and are ultimately used to determine the number of insulators.

2 | STATEMENT OF THE PROBLEM

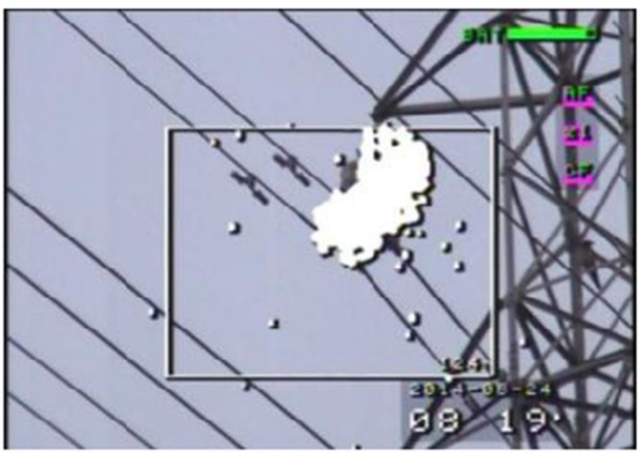
According to International Electrotechnical Commission (IEC) standard, the number of outages in transmission and overhead distribution lines in Mazandaran and Golestan Regional Power per 100-km line within a year is not to be out of the range of 1.5 to 2 times. Therefore, in accordance with the standard, the total number of network outages in a year is not to exceed 120 outages per year given the current kilometers of lines. Unfortunately, the number of outages in 2015 was more than 407 times according to Mazandaran Regional Electric Company (MREC). Outages due to the lack of insulation and poor insulators composed 47% of all network outages according to MREC. In recent years, the Middle East has been experiencing heavy pollution so that the life of insulators has reduced because of the presence of fine dusts, regional pollution, and environmental issues. Nowadays, heavy and super heavy pollutions including salt pollutions in coastal areas in the northern and southern regions of Iran have led to an increase in the number of outages. As a result, the network has frequently experienced unstable voltage, examples of which are stated below.

The problem of pollution on insulators in 400-kV lines, especially Esfarayen-Aliabad transmission line in Northern Iran, has frequently led to outages.[26,27] At the beginning, insulators made by Manet, an Iranian company, were used. After short-term and long-term exposure to pollution, both short-term and long-term outages were experienced, respectively. As a result, an alternative decision was made to use Japanese NGK insulators. However, within less than 8 years, the insulators again suffered heavy pollution. Therefore, frequent short-term and long-term outages started to occur leading to changing the NGK insulators. Given the special heavy environmental pollution in the course of Esfarayen-Aliabad transmission lines, more creepage distance is required in accordance with the pollution level. Figure 2B shows the 63-kV transmission line in Mazandaran and Golestan transmission networks in nonenergized mode. This line has 5 insulators. Figure 2A shows the same line in energized mode, indicating the incidence of corona phenomenon. The line has inappropriate creepage and insulation distance.

According to available information, approximately 47% of errors in HV transmission lines are due to improper insulation. One major consequence of pollutants in such areas is the reduction of insulation or losing the insulation in transmission lines and stations. In such areas, an identification of an effective insulation in pollution scenarios is not only



(A) non-energized



(B) energized modes

FIGURE 2 The 63-kV power line

important for designing and selecting the appropriate type of insulation but also for adopting a proper maintenance plan of insulation devices.[1,12,28-33] According to the literature, field visits, laboratory tests on insulators, computer simulation, and experience, there is a need for reconsidering insulation coordination in Mazandaran and Golestan power network. An inappropriate creepage distance and the number of quality, shape, and type of insulators; length of insulator chains; and operation method have led to frequent outages in the transmission and overhead distribution networks of Mazandaran and Golestan. Furthermore, it is worth mentioning that other challenging problems regarding Mazandaran and Golestan power networks are investigated in other studies.[34-36]

3 | INSULATION COORDINATION AND CLIMATE CHANGE

The main goal of this paper is to consider appropriate insulation coordination against different overvoltages in various environmental conditions; consequently, it is absolutely pivotal to consider these conditions, for instance, pollution, altitude above sea level, and Isokeraunic level, precisely. Furthermore, in addition to humidity, there were pollution as well as emergence of the new phenomena of dust in these provinces contributing to a decrease in creepage distance for insulators, mainly glass and ceramic ones. According to synoptic stations located in the provinces of Mazandaran and Golestan, pollution rates are increased 1° (among low, medium, and heavy) so that it influences creepage distance immensely. In addition, the other indices such as ambient temperature, wind blowing, Isokeraunic level, humidity, and altitude have changed that they considered in revisiting insulation coordination (Algorithm 1 and Figures 3 and 4). Bringing detailed information, as to changes in these indices, is out of the passion of this paper. Moreover, while the number of insulators for voltages of 63 and 230 KV before revisiting were 5 to 6 and 15 to 12, respectively, those of study after revisiting are 5 to 9 and 10 to 20, respectively, depended on the kind of insulators.

Algorithm 1 The algorithm for solving the insulation coordination in MREC network

```
Require: V= V0: V0= 63KV and next voltages are 230KV and 400KV
Require: S= S0 (S0: first section)
Require: l= l0 (l0: first line)
  while V ≤ Vn do
    while S ≤ Sn do
      while L ≤ Ln do
        if Pollution standard is based on IEC 60071-2 then
          input: pollution level is IEC 60071-2
        else
          input: pollution level of Swedish State Power Board(SSPB)
        end if
        do calculation minimum creepage distance followed from pollution
        input: altitude
        do calculation minimum air gap resulted from power frequency
        input: switching surge flash over rate, switching over voltage, critical flash over, standard deviation
        do calculation minimum air gap resulted from switching
        input: Isokerounic level, backflash rate, line grad info
        do calculation air gap followed from lightening
        find the highest amount of accepted air gap and creepage distance
        output: kind and number of insulator, creepage distance, insulator distance
        if minimum creepage distance is dominant then
          insulator is antifog
        else
          insulator is not antifog
        end if
        L= L+1; next line
        S= S+1; next section
        V= V+1; next voltage
      end while
    end while
  end while
  Return optimal power set-points
```

4 | SOLUTIONS

The sparks caused by pollution are usually frequent, and there are reports of failure of insulation and unsuccessful reconnection of switches in HV power lines due to pollution in the region.[26] When sparks occur in tandem, within a short time interval, it is necessary to de-energize the power transmission line.[37] In addition to studies on overvoltage induced by power frequency, lightning and switching as one of the central issues in designing power transmission lines, investigating

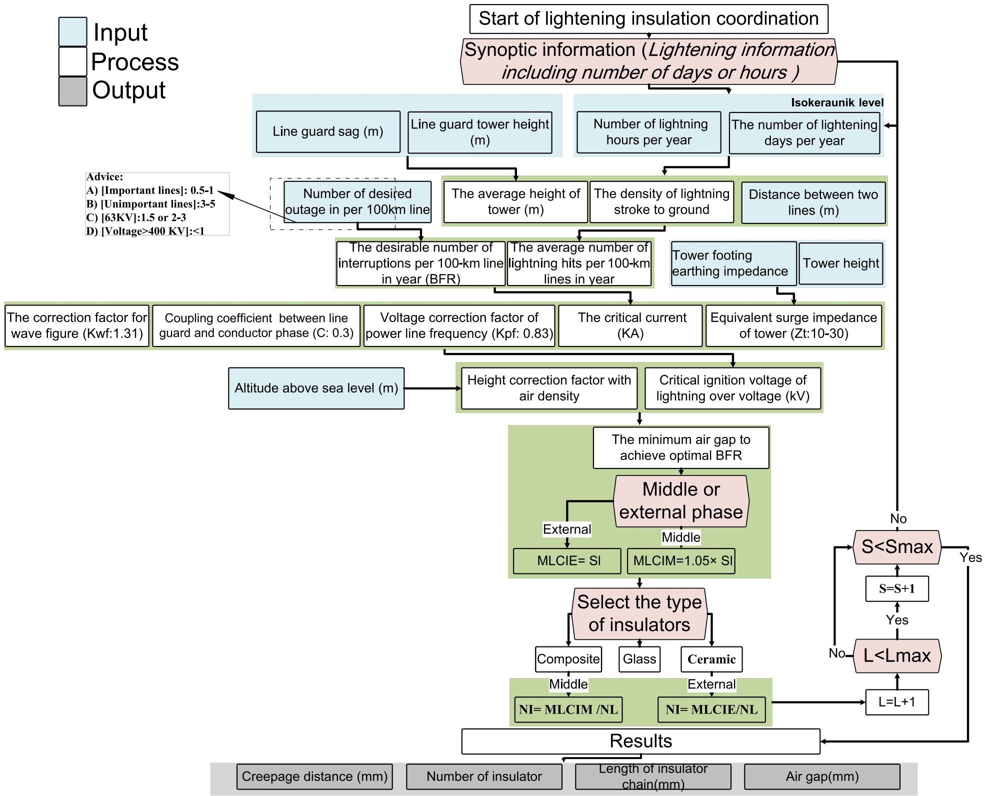


FIGURE 3 Flowchart for calculating the minimum insulation distance required for protection against overvoltage caused by lightning

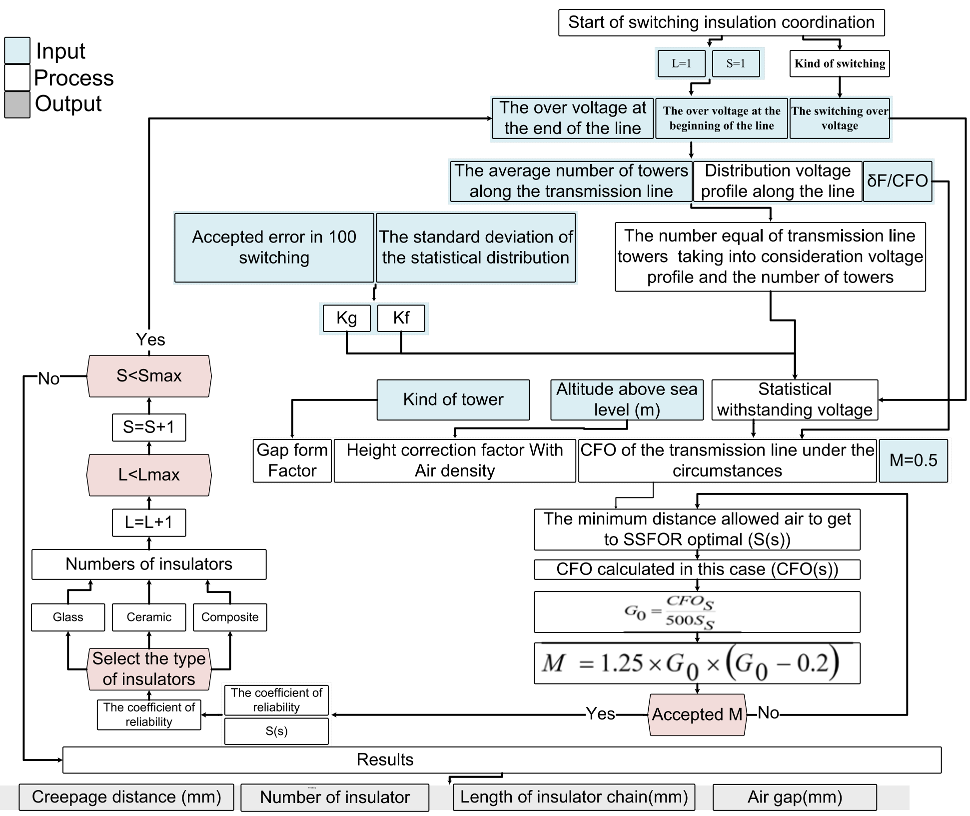


FIGURE 4 Flowchart for calculating the minimum distance of insulation needed to protect against overvoltage due to switching

problems caused by pollution is also necessary.[38,39] Given the problems caused by pollution, including many reported cases of power failure and the complexity of related issues, there is a great potential for a closer investigation.

Algorithm 1 shows the mathematical code for insulation coordination calculations. The algorithm accounts for pollution conditions when determining the creepage distance. Moreover, air gap estimation is based on calculations of power frequency voltage, lightning, and the switching conditions in the area. In general, insulation calculations included 4 phases of calculating pollution, lightning overvoltage, switching overvoltage, and frequency of power overvoltage.[30,40,41] The calculations are summed up in the 2 measures of insulator chain distance and the required air gap.

In a condition of single phase to ground connection, normal phase voltage experiences a temporary increase against what the line isolation must withstand. Such an overvoltage does not have a decisive role in determining the number of insulators compared with the overvoltage caused by lightning or switching. However, these calculations should be used to determine the minimum air gap between conductor and the tower body at the maximum variations in insulator chain.[42,43] Determining the class and degree of pollution in the region where transmission lines are located is of paramount importance, because the pollution class plays a direct role not only in choosing the type and number of insulators but also in determining conductors used in lines (to prevent corrosion of wires). In desert and littoral areas in particular, a combination of sand, salt, and dust is carried by the periodic and daily wind sticks to the surface of objects because of the dew created by temperature difference between day and night. This phenomenon is more acute in overhead insulators and wires. Determining pollution levels and calculating the resulting isolation based on IEC 60071 standard levels for alternating current lines are provided in previous studies.[42] Determination of pollution levels and calculation of isolation based on Swedish State Power Board standard levels in Iran are provided in other studies.[26,42]

The air gap required to protect overhead transmission lines against lightning is determined according to lightning voltage and various factors. If lightning hits the tower, the resulting overvoltage may discharge into conductors through tower arm and insulator chains, leading to an interruption in the transmission line.[42,44] To reduce the risk of sparks, the air gap should not be less than a certain amount. The relevant calculations were performed using the flowchart in the Figure 3. This figure shows the process for calculating the minimum insulation distance required to protect against overvoltage caused by lightning.

Switching overvoltage occurs as a result of power switching and the performance of resources at the beginning and the end of the line. Since such overvoltages can increase the line voltage by several times than that of the nominal voltage and cause a serious damage to transmission line equipment. Therefore, insulation calculations related to switching voltage should be conducted and the air gap should be determined.

Four factors of voltage level, altitude, Isokeraunic level, and pollution level have a decisive role in the calculation of line isolation. Meteorological stations should be used to obtain this information. Network of weather stations in Iran are classified into terrestrial stations, coastal and marine stations, and upper atmosphere stations. Information obtained from synoptic stations, which have 2 subgroups of terrestrial and coastal stations, is used for line design calculations. Terrestrial stations include pluviometry and data logger stations, climatology stations, synoptic stations, complementary synoptic stations, airport stations, agricultural research stations, mountainous area synoptic stations, and automated stations. Coastal and marine stations include synoptic coastal stations, marine stations, and automatic marine buoys. Upper atmosphere stations include upper atmosphere stations, radar stations, meteorological aircrafts, and weather satellites. For better calculations, only information from synoptic stations was used.

This article provides a solution for the problem of outages in power lines of Mazandaran and Golestan Regional Power. First, a review of some of the case studies on the transmission and overhead distribution in provinces of Mazandaran and Golestan is provided along with the type and number of insulators used in them and a summary of the current status of the lines. Then, the cities of Mazandaran and Golestan and their associated synoptic stations are described. Given the types of available standard and antifog insulators and the creepage and insulation distances in each area, the number of insulators required for any city in the provinces of Mazandaran and Golestan for voltage levels of 63, 230, and 400 KV is determined. Then, according to the calculations, the number of insulators required for solving the problem of outages in the lines of Mazandaran and Golestan Regional Power network is provided taking into account the available types of standard and antifog insulators.

5 | THE DESIGNED SOFTWARE

To facilitate working with programs developed for the insulation coordination, all of these programs were placed behind a user-friendly graphical user interface using the graphic part of MATLAB, so that a simple and applied software was

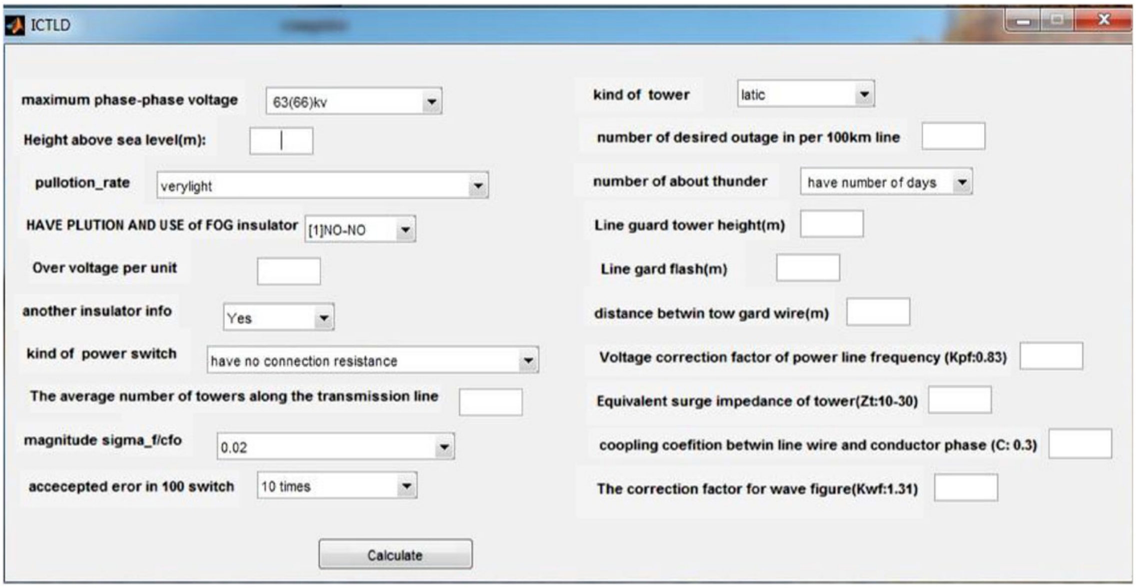


FIGURE 5 Simulation environment for insulation coordination

developed for insulation coordination in various transmission and distribution networks. To ensure the accuracy of the software, the solution results for a number of standard transmission and distribution networks were compared with the reported results. The software was designed using MATLAB. In its first page, there are 20 options for entering the information required for insulation coordination, including the general voltage level information for insulation coordination, the altitude, the pollution level, the selection of antifog insulator, and information needed for insulation coordination in case of overvoltage caused by switching including the overvoltage due to switching, information about the insulators, the type of switch used, the average number of towers along the transmission line, the σF/CFO value, the number of acceptable errors in 100 switching; and information needed for insulation coordination in case of lightning, including the tower type, the number of desired output per 100 switching, the number of lightning per day or hour, the height of line's guard tower, the line's flash guard, the distance between the 2 guard wires, voltage correction factor of power frequency, the tower's surge impedance, coupling coefficient between the guard wire and the conductor phase, and the waveform correction factor. In this program, the information needed to calculate the minimum insulation and creepage distance based on the lightning and switching overvoltage and the amount of pollution in the region should be entered. The insulation coordination is done at the phase voltage levels of 63, 132, 230, 400 and 765 KV. There are 5 pollution levels according to the IEC standard, ie, too light, light, medium, heavy, and very heavy. The program includes a series of default insulators, which can be used for the insulation coordination calculations. If we want to use insulators other than those in the program, the option "Yes" is selected for entering information for new insulators and a new page (Figure 5) opens. After entering the desired information for insulation coordination and hitting the calculation option, a table opens (Figure 5) showing the results of the program including the minimum creepage distance, air gap, and the number of insulators required for each of the effective voltages.

Insulation studies and calculations related to weather conditions were conducted in Mazandaran and Golestan. Therefore, first, environmental conditions and weather stations in the area were investigated. Then, insulation calculations including calculation of overvoltage caused by lightning, switching and power frequency, and calculations to determine the creepage distance according to existing conditions were conducted. The results included the required insulation and creepage distances, which were obtained on the basis of standards and technical limitations and will ultimately be used for determining the number of insulators.

6 | CASE STUDIES ON THE TRANSMISSION NETWORK IN THE PROVINCES OF MAZANDARAN AND GOLESTAN

The list of some of the lines in Mazandaran and Golestan Regional Power with outages due to insulation coordination in recent years is provided in Table 1. The table also provides lines details including the voltage level, the number of bundles and circuits, the type and number of insulators, and the number of outages recorded per year. According to various studies

TABLE 1 Some of the lines with outage problems due to insulation coordination and the related details

	Mazandaran regional Electric Company Line			Insulator Characteristics Before New Planning		Interruptions		
Voltage	**Name**	**Circuit**	**Bundle**	**Number**	**Kind: seramici**	**Number of happening**	**Place**	**Previous solutions**
63 kV	Chehshaid- amol 1-amol 4	1 & 2	1 & 2	5	255 ×146× 320			
	Sade shahid rajaee-zirab	2	1	5	255 ×146× 320			
	Kaghazsazi-sade shahid rajaee	2	1	5	255 ×146× 320			
	Chehlshahid- amol 3- amol 4	2	2	5	255 ×146× 320	2		Replacing existing insulators with fog insulator NGK
	Ghaemshahr- ghaemshahr 2	2	2	5	255 ×146× 320	2		Replacing existing insulators with fog insulator NGK
	Daryasar â babol 2	2	1	5	255 ×146× 320			
	Ali abad- ataabad	2	1	6	255 ×146× 320			
	Danial- tonekabon	2	2	5	255 ×146× 320			
	Nor- mahmood abad	2	2	5	255 ×146× 320			
	Royn- mahmod abad	2	1	5	255 ×146× 320	6	Near royan station	Replacing some insulators with NGK and glass Sediver
	Alamde- chamestan	1 & 2	1	5 and 6	255 ×146× 320			
	Hasankif- kajor	1, 2, & 4	1	6 and 6	255 ×146× 320	2	Most of the towers	Replacing damaged insulators with insulator NGK and sediver
	Rroyan- chamestan					2 in a year	Towers with 5 ceramic insulators made by Mane company	Replacing damaged insulators with NGK ones
230 kV	Neka- dahak	2	1 & 2	16	255 ×146× 320	First 5-6 mo in year 2015	Towers 18, 19, and 20	Replacing insulators of towers 1-16 and 35 to dahak station with fog insulator NGK
	Neka- folade Iranian	2	2	16	255 ×146× 320			
	Neka- zaghmarz	2	2	16	255 ×146× 320			
	Narivaran- daryasar	1 & 2	1	15	255 ×146× 320	3	Towers with string insulators	Replacing existing insulators with composite ones
	Kaghazsazi- babol	2	2	16	255 ×146× 320			
	Ghaemshahr- babol	2	2	16	255 ×146× 320	11	Towers 45, 46, 7, 29, 4, and 26	Replacing insulators of towers 45-56 with fog insulators of NGK and glass ones of "pars insulator company"

(Continues)

TABLE 1 (Continued)

Voltage	Mazandaran Regional Electric Company Line			Insulator Characteristics Before New Planning		Interruptions		Previous solutions
	Name	**Circuit**	**Bundle**	**Number**	**Kind: seramici**	**Number of happening**	**Place**	
	Savadkoh- pardis	1	1	15	255 ×146× 320			
	Chehlshahid- narivaran	1, 2, & 4	1	15	255 ×146× 320	4 times in 2 wk	Towers 36, 37, 53, and 54, which most of them had string insulators	Replacing existing insulators with NGK ones
	Ali abad- gorgan	1 & 2	2	13	255 ×146× 320	3 times in year 2013 and 2 times in year 2014		Replacing 3 insulators with NGK ones
	Minodasht- aliabad	2	2	15 and 16	255 ×146× 320			
	Royan- hasankif	2	2	15 and 16	255 ×146× 320	6	In section of 4 circuit lines	Replacing some insulators with NGK ones

TABLE 2 Types and names of weather stations in the provinces of Mazandaran and Golestan and the recorded data

Station Name	Kind of Sinoptic Station	Pollution Level	Altitude, m	Isokeraunic Level, day in y
		Mazandaran		
SARI	Main sinoptic	Heavy	100-150	15-20
BABOLSAR	Main sinoptic	Heavy	−50 : 0	5-10
KIASAR	Main sinoptic	Low 1378	10-15	
SIAHBISHE	Main sinoptic	Medium	10-15	
GALOGAH	Main sinoptic	Low 0-50	0-5	
BALADEH	Main sinoptic	Medium	2014	5-10
KAJOR	Main sinoptic	Medium	−50 : 0	25-30
RAMSAR	Sinoptic	Heavy	−50 : 0	20-25
NOSHAHR	Sinoptic	Heavy	−50 : 0	10-15
DASHT-E NAZE SARI	Sinoptic	Heavy	0-50	25-30
ALASHT	Sinoptic	Low	1493	20-25
POLSEFID	Sinoptic	Low	560 0-5	
BANDARE AMIRABAD	Sinoptic	Heavy	−50 : 0	15-20
SHAHI	Sinoptic	Heavy	50-100	5-10
AMOL	Sinoptic	Heavy	50-100	0-5
		Golestan		
MARAVE-TAPE	Main sinoptic	Medium		5-10
GORGAN	Airport sinoptic	Heavy	150-200	20-25
KALALE	Airport sinoptic	Medium	150-200	10-15
ALIABAD	Supplementary sinoptic	Low	100-150	0-5
GONBAD-E KAVOS	Supplementary sinoptic	Medium	50-100	5-10
BANDARE TORKAMAN	Sea sinoptic	Heavy		
BANDARE GAZ	Supplementary sinoptic			

about the lines with isolation problems, insulators of the transmission lines (which were often short insulators with a length of 146 mm) were replaced in some cases with NGK and Sediver insulators. To investigate the causes of outages, first, insulation calculations conducted in the next section was used to determine the number of insulators for each city. Then, the number of insulators needed to fix outage problems in the existing lines is provided. Information from synoptic stations is needed for insulation coordination calculations. A list of the type and the name of weather stations in 2 provinces, Mazandaran and Golestan, and the data collected are presented in Table 1. According to Table 1, climatic conditions were collected from the synoptic station and the isokeraunic map of the area. In cities that had no station, information from the nearest station in the vicinity was used. Profiles of cities of Mazandaran and Golestan and the relevant synoptic stations are shown in Table 2.

Given the pollution levels in the provinces of Mazandaran and Golestan, the lines in the area pass through heavy, medium, and light pollution. Creepage distances required to pass through each of these areas were calculated on the basis of guidelines to determine the creepage distance. Results of calculating creepage distance per voltage level of the lines are shown in Figure 6. The IEC standard was used in these calculations.

Using the overvoltage caused by lightning as well as other factors such as the average height of a guard wire from the ground and the altitude correction factor, the minimum air gap for lightning overvoltage was obtained. Naturally, the number of lightning hitting the transmission lines is a function of the Isokeraunic level (IKL) of the area that describes lightning activity based on the number of days per year when a thunder can be heard. In general, the probability of a lightning striking the transmission lines or the risk of IKL area.

According to Figure 7, IKL values of all weather stations in the region are approximately between 0 and 28. In this study, for the ease and the comprehensive coverage, calculations of Isokeraunic were performed from 5 to 30 days per year, with intervals of 5. Given the diversity of the height of the area through which the transmission and overhead distribution network passes in Mazandaran and Golestan, calculations in this study were performed according to the altitude range, from 0 to 2000 meters with intervals of 500 m. Calculations were carried out for each voltage level of 63, 230, and 400 KV. The value given to each interval was the highest air gap applicable for the values in that interval. Maintaining lightning air gap is necessary for protecting the lines against lightning that strikes them. It is notable that this gap specifies the minimum air gap between 2 arrester horns, and the length of the insulated section of insulator chain should proportionally

TABLE 3 Details of cities of Mazandaran and Golestan and the relevant synoptic stations

City	Pollution Rate	Siptonic Station	Altitude, m	Isokeraunic Level
AMOL	Heavy	Amol	24	10
BABOL	Heavy	Gharakheil	−2	13
BABOLSAR	Heavy	Babolsar	−21	10
ALASHT	Low	Alasht	190	21
CHALOS	Medium	Noshahr	0	15
KELARDASHT	Low	Ramsar, Noshahr, and Siah Bishe	1107	17
RAMSAR	Heavy	Ramsar	−20	22
SARI	Heavy	Sari and Dasht-e Naz	23	24
SAVADKUH	Low	Polsefid	610	4
TONEKABON	Heavy	Ramsar	−20	22
FREIDONKENAR	Heavy	Babolsar	−13	8
SHAHI	Heavy	Gharakheil	14	13
KAJOR	Low	Kajor	1550	20
GALOGAH	Low	Galogah	25	4
MAHMODABAD	Heavy	Babolsar and Amol	−20	8
NEKA	Heavy	Dasht-e Naz	45	22
NOSHAHR	Heavy	Noshahr	−20	15
NOR	Heavy	Balade	−21	11
KIASAR	Low	Kiasar	1295	15
SIAHBISHI	Heavy	Siahbishe	1855	14
BANDARE AMIRABAD	Heavy	Bandare Amirabad	20	17
GORGAN	Heavy	Gorgan and Hashem Abad	0	17
GONBAD-E KAVOS	Medium	Gonbad-e Kavos	38	8
KALALE	Medium	Kalale	129	15
ALIABAD	Low	Aliabad	184	9
BANDARE TORKAMAN	Heavy	Bandare Torkaman	−20	11
MINODASHT	Medium	Kalale, Gonbad-e Kavos	900	10
KURDKUY	Heavy	Bandare Torkaman	50	15
MARAVE-TAPE	Medium	Marave-Tape	460	11

increase with respect to the length of horn(s), the type, and the structure of insulators. Figure 7 shows the minimum insulation distance for various voltage levels at different altitude above sea level and IKLs by overvoltage followed from lightning.

Figure 8 shows minimum insulation distance for various voltage levels at different altitudes, and IKLs of overvoltage due to power frequency and switching, and the final air gap required.

Summary of results for insulation calculations based on switching over-voltage is shown in Figure 8 with the symbol s. Also, given the variation in two parameters of altitudes and voltage level in the lines of the area, the results are presented for all voltage levels and altitudes.

The minimum air gap required from the body of the tower was obtained using the critical ignition voltage curve versus air gap. The minimum air gap corresponding to the power frequency overvoltage was calculated for various voltage levels and altitudes as shown in Figure 9 with the symbol PF.

The required air gap was obtained from maximum values of overvoltage due to power frequency, switching, and lightning. In Mazandaran Regional Power, at 230 and 400 KV voltage levels, switching overvoltage had the highest value, while at 63 KV, the highest value belonged to lightning overvoltage. Regarding lightning overvoltage, according to statistics of the number of lightning in the area, the air gap for the entire Regional Power was set at IKL 10 (Figure 7) to account for the worst case scenario and yet obtain results closer to reality. Here, C shows the ultimate air gap required.

According to insulation calculations and studies of synoptic stations, the air gap and creepage distance required for the lines of 63, 230, and 400 KV located in the provinces of Mazandaran and Golestan are presented in Figures 9 and 10, respectively.

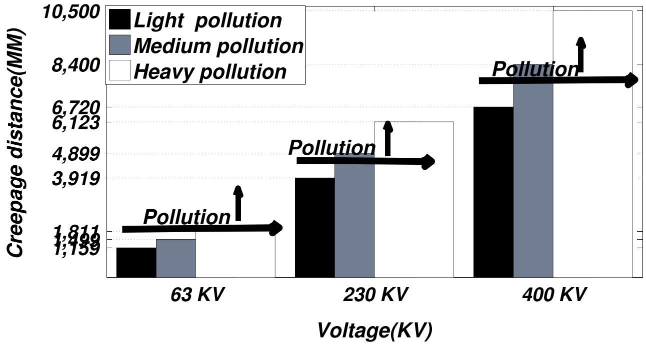


FIGURE 6 Minimum creepage distance per different voltage levels at different pollution levels

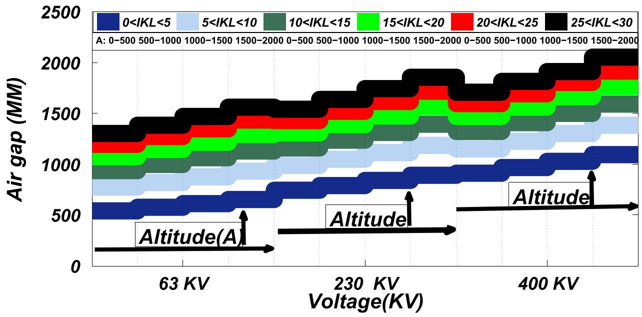


FIGURE 7 Minimum insulation distance of various voltage levels at different altitudes and Isokeraunic levels (IKL) by lightning voltage

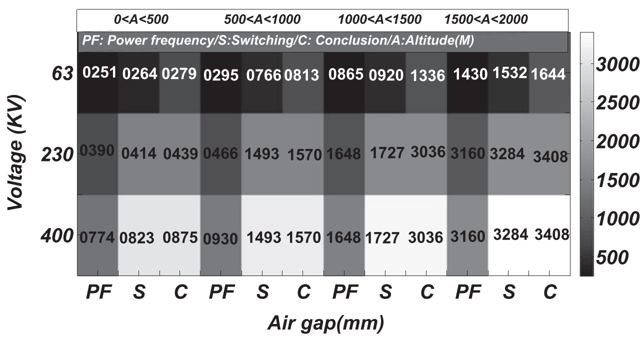


FIGURE 8 Minimum insulation distance of various voltage levels at different altitudes and Isokeraunic levels by overvoltage due to power frequency and switching and the final air gap required

The most common types of insulators used in transmission lines especially those in Iran are ceramic and glass insulators. These insulators, which are known as disk insulators, have different types based on their mechanical strength and dimensions. Conductor weight and type determine the insulator's mechanical strength, and the creepage distances and insulation distance determine its dimensions. Insulators used at 63, 230, and 400 KV voltage levels are presented in Figure 11 and Figure 12. It is worth mentioning that based on experience and given the difficulty in replacing insulators in tension strings at the operation phase of transmission lines, 1 insulator is added to each strain string corresponding to the suspension string.

Standard ceramic and glass insulators with 320 ×146× 255 (Weight [KN] × insulator length [mm] × creepage distance[mm]) and composite insulators are recommended for 63 KV lines. It is worth mentioning that since air gap values exceed creepage distance values in transmission lines with voltage level of 63 KV in Mazandaran and Golestan, using ceramic and glass antifog insulators is not recommended. For 230 KV lines, standard insulators with dimensions of 320 ×146× 255 or 370 ×170× 255 mm, antifog ceramic and glass insulators with dimensions of 440 × 146 × 255 or 525 ×170× 330 mm, and composite insulators are recommended. For the voltage level of 400 KV, standard ceramic and glass insulators with dimensions of 380 ×170× 280, antifog ceramic and glass insulators with dimensions of

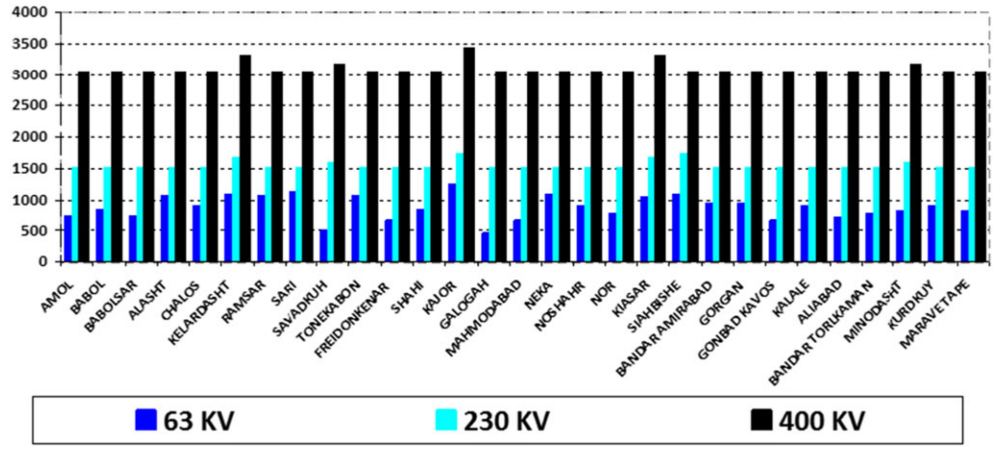


FIGURE 9 The air gap (mm) required for the lines of 63, 230, and 400 KV in the cities of Mazandaran and Golestan

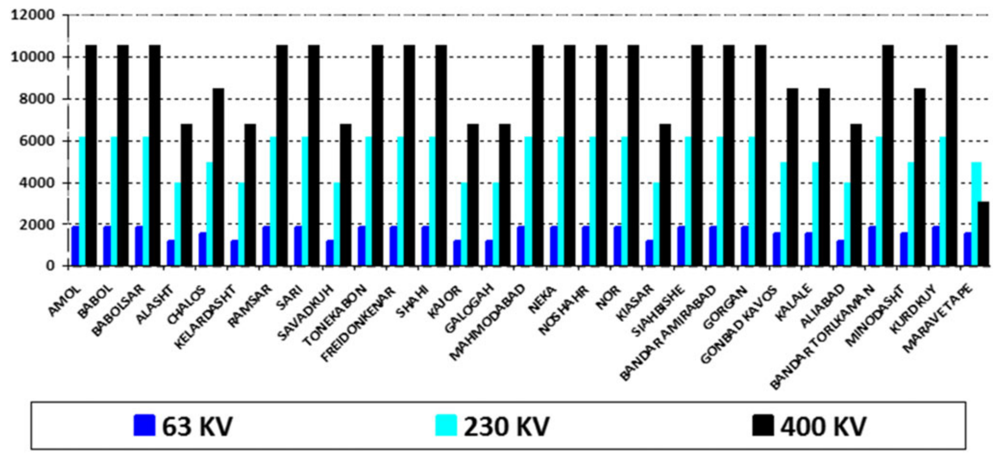


FIGURE 10 The creepage distance (mm) required for the lines of 63, 230, and 400 KV in the cities of Mazandaran and Golestan

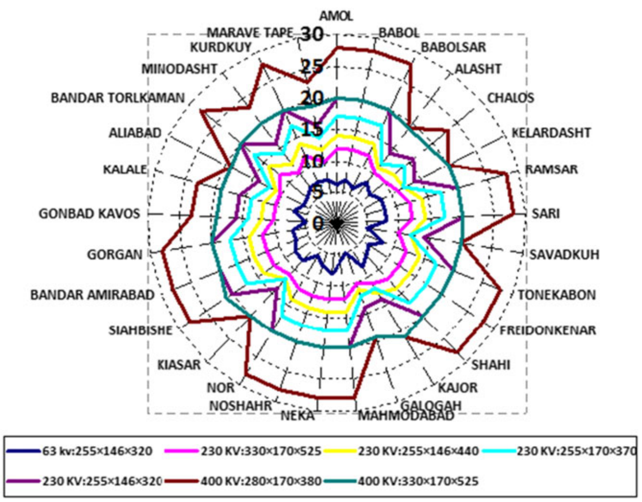


FIGURE 11 Number and type of insulators required for voltage levels 63KV, 230KV, and 400KV in cities of Mazandaran and Golestan

525 × 170 × 330, and composite insulators are suggested. In short, with the progress in technology, technical defects of composite insulators have been fixed and their production costs have witnessed a decline, so that today, they are more economical than plate insulators (in lines with higher voltage). This, along with low weight and ease of transport, installation and replacement have led to the spread of composite insulators in transmission lines.

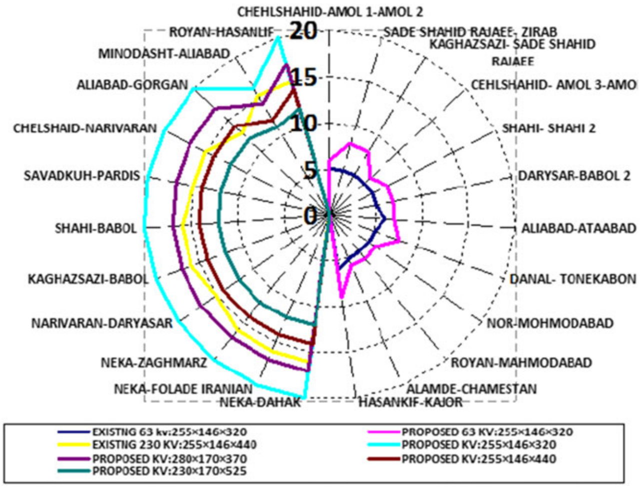


FIGURE 12 Solutions for outage problems in overhead distribution and lines of transmission networks of Mazandaran and Golestan)

The number and type of insulators needed for different voltage levels of network lines in the cities of Mazandaran and Golestan are shown in Figure 11. This figure shows results for the required antifog insulators. At a voltage level of 63 KV, the insulators needed for Savadkooh and Galougah are 4 and 5 for suspension and strain strings, respectively. However, because of the possibility of an increased number of days with a lightning in the year and increased levels of pollution and in turn creepage distance required in the coming years, minimum numbers of 5 and 6 insulators are suggested for suspension and strain strings, respectively. At a voltage level of 63 KV, calculations to determine the air gap required to withstand the lightning overvoltage were performed given the desirable rate of a maximum 1 line output per 100 km/year. It should be noted that the insulation calculations for lightning overvoltage in 63 KV lines of Mazandaran is dominant. In addition, Alasht, Kiasar Kalardasht, Ramsar, Sari, Tonkabon, Kojour, Neka, and Siah Bishe have the high number of days with lightning per year; consequently, we can decrease an insulator if the amount of the desired output at 100 km/year is increased to 1.5.

At a voltage level of 230 KV in Alasht, Kalardasht, Savadkooh, Kojour, Galougah, Kiasar, and Aliabad, the number of required insulators were 13 and 14 for suspension and strain strings, respectively. However, because of the possibility of increased levels of pollution and in turn creepage distance required in the coming years, minimum numbers of 14 and 15 insulators are suggested for suspension and strain strings, respectively.

According to the calculations, solutions for the problem of outage in the studied lines are presented in Figure 12. As mentioned, to choose the number and type of insulators required for each of the transmission lines, first the required creepage and insulation distances were calculated taking into account the geographical and climatic conditions of the area. Then, the number of each insulator type was calculated. Figures 11 and 12 show the lines with isolation problems in Mazandaran and Golestan Regional Power along with the type and number of insulators proposed to overcome the outage problems in these lines. As it is clear, the number of insulators used in these lines is less than required, which has led to sparks and outage in the lines. Therefore, by replacing the type and number of insulators recommended and providing the required creepage and insulation distances, the outage problems in the lines will be resolved.

7 | CONCLUSION

Insulation coordination in Mazandaran and Golestan was improved based on the field information, experiments, and simulations. Modifications in the insulation coordination of the network has reduced the outage frequency and time, and the amount of lost energy, and improved the profile of transient voltage and, in turn, the network reliability. After revising the insulation coordination in some lines, the outage time declined by 80%, and the number of outages reduced to a rate of 130 times. Also, the lost energy reduced by 200 MWh. It is recommended that the revision of coordination insulation be generalized to all existing lines.

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