Arctic Regions: Icing at Low Temperatures and Modern Semiconductor Systems for De-Icing Overhead Transmission Line Wires

KHRENNIKOV[1] A.YU., KUVSHINOV[2] A.A., ALEKSANDROV[3] N.M.
[1]Scientific & Research Centre of FGC of UES Rosseti, Kashirskoe highway, 22/3, 115201, Moscow, RUSSIA
[2]Togliatti State University, Beloruskaya str., 14, 445050, Togliatti, RUSSIA
[3]SPE Dynamics, Anisimova str., 6, 428000, Cheboksary, RUSSIA

Abstract: - The article shows that when operating overhead transmission lines in a number of regions, there is a serious problem of the glacial deposits of wires during the autumn-winter period. As a passive measure against the glacial deposits, various wires of increased strength can be used. One of the traditional active methods is the melting of glacial deposits on alternating current lines by creating short circuits or direct current using uncontrolled or controlled rectifier blocks. The development of new means to prevent glacial deposits on the overhead transmission lines consists of the use of combined conversion units capable of performing melting of glacial deposits, if necessary, and the rest of the time compensating for reactive power. The most promising one should recognize the melting of glacial deposits with an ultra-low frequency current that combines the advantages of melting with an alternating current of the industrial frequency (on three wires at the same time) and a DC current (limited only by the active resistance, smooth regulation of the melting current).

Key-Words: overhead transmission lines, melting of glacial deposits, direct current, ultra-low frequency current.
Received: April 19, 2021. Revised: April 15, 2022. Accepted: May 11, 2022. Published: July 7, 2022.

1 Introduction

In a number of regions, operation of overhead transmission lines is severely complicated by ice formation of the wires in autumn and winter, due to the fact that average time of eliminating icing-related emergencies exceeds average time of eliminating emergencies caused by other reasons by 10 and more times. Research has shown that ice coating on overhead line wires is formed at the air temperature of approx. -5 C° and wind speed of 5...10 m/s. Permissible thickness of ice coating is from 5 mm to 20 mm for overhead lines with nominal voltage of (3 – 330) kV, located in climatic regions of I to IV ice formation severity [1].

Various high-strength cables/ wires can be used as a passive de-icing method. For examples, ACCC wire (Aluminum Conductor Composite Core wire), which is a number of aluminum wires placed around carbon-fiber and fiberglass epoxy core [2]. ACCC wire core keeps stable dimensions because its thermal expansion coefficient (1.6·10 ºC) is almost ten times less than steel has (11.5·10 ºC). Due to this, ACCC wires can withstand high temperature for a long time, thus preventing ice coating formation.

It is also worth noting Aero-Z® wire, consisting of one or several concentric wires (internal layers) and Z-shaped wires (external layers). Each layer of the wire has lengthwise twist of a definite pitch. Smooth surface reduces wind load by 30-35% and prevents snow and ice buildup. However, Aero-Z® wire has limitation for ice melting time because it cannot withstand temperature increase over 80°C for a long time.

Overall, practical implementation of passive de-icing methods is possible only in cases of designing and commissioning new transmission lines. Modernization of ‘old’ overhead lines would incur significant costs.

Due to these reasons, research for methods of active de-icing of overhead lines is urgent. Among traditional methods, one can note melting ice on overhead line wires with alternative current by artificially inducing short circuits or with direct current by using uncontrollable or controllable rectifiers [3, 4]. However, in the first case, it is possible to damage overhead line wires, and in the second case, the expensive rectifiers are not used for most part of the year. At the same time, modern hardware of power electronics provides additional opportunities and incentives to develop new de-icing methods devoid of the indicated drawbacks.

Issues of ice coating formation and de-icing are topics of a large number of scientific papers. This work sets the task to systemize and perform comparative analysis of existing methods of de-icing, and finding solution to ice coating problem will help choose the most suitable one for particular local conditions from the many technical solutions at hand.

2 Classification of de-icing methods.

The known de-icing devices and methods use the following types of physical impact to remove ice and rime deposits from transmission line wires (Figure 1):

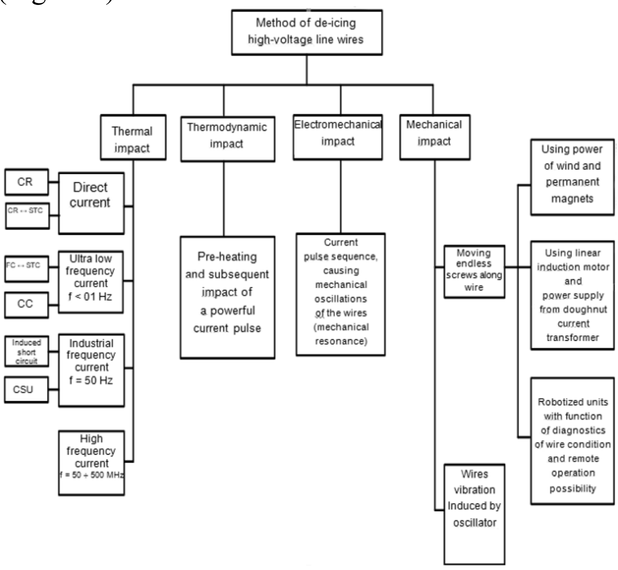

Fig. 1. Classification of known methods of removing ice coating from overhead line wires

In figure 1: CR – controllable rectifier; STC – static thyristor compensator; FC – frequency converter; CC – cycloconverter; SCU – series compensation unit;

- thermal impact by heating the cable to the temperature of (120 - 130) 0C, which melts the ice coating, or by preventive wire heating to (10 - 20) 0C to prevent ice coat formation;
- thermodynamic by preliminary heating until a melt layer is formed between the wire and the ice coating and subsequent "shaking up" of the wires with by Ampere force, arising when a powerful current pulse passes;
- electromechanical impact by creating cyclical current pulses that induce mechanic vibration of the wires cause ice coating destruction. Efficiency of electromechanical impact is enhanced when such current pulses parameters are used that induce mechanical resonance;
- mechanical impact by moving endless screws along the wire, using wind energy, energy of high-voltage line phase current electromagnetic field, permanent magnets, linear induction motor, by inducing wire vibrations with the help of an oscillator (these shall not be further considered because they do not use converter equipment). We shall consider a common drawback of mechanical systems, which is the need for manual mounting on the wire, dismounting from the wire, as well as moving from one wire to another. This requires special technical means (vehicle-mounted aerial work platform) and maintenance personnel, which increases operating expenses and complicates operation in hard-to-reach areas.

3 Thermal impact with alternate current of industrial frequency

Melting ice with alternate current is used only on the lines of voltage lower than 220 kV, with wires cross-section less than 240 mm [3]. Power is supplied, as a rule, by substation buses of voltage of 6 - 10 kV, or by a separate transformer unit. Ice melting circuit should be selected in such a way as to ensure that the current passing through high-voltage lines exceeds permissible continuous current by 1.5 – 2 times. Such excess is justified by the short duration of melting process (~1 h), and by more effective cooling of the wire in wintertime. For standard steel reinforced aluminum Type AC wires with cross-section of (50 ÷ 185) mm, the estimate value of one-hour ice melting current intensity lies in the range of (270 ÷ 600) A, while the intensity of the current preventing wire icing lies in the range of (160 ÷ 375) A.

However, it is impossible to select the necessary value of short circuit current only by selecting ice melting circuit. Exceeding the above-mentioned values of melting current can cause wires burnback and subsequent irreversible loss of strength. At lower values, a single passing of short circuit current may not be sufficient to fully remove the ice coating. Then, short circuits have to be repeatedly induces, which further worsens the consequences.

It is possible to avoid the mentioned negative consequences by using an alternate current thyristor compensator, the scheme of which is shown in Figure 2 [5]. In ice melting mode, switch 7 is OFF, and switch 8 is ON. Possible methods to regulate melting current are pulse-phase method by changing switching angles of power thyristors 1, 2, and 3; or pulse width method, by changing number of voltage supply periods.

In reactive power compensation mode, switch 7 is ON, and switch 8 is OFF. In this case, power thyristors 1, 2, and 3 and reactors 4, 5, and 6 form a thyristor-reactor group connected into a triangle, that is a part of the static thyristor compensator. The authors consider the possibility to use capacitors instead of reactors. In this case, reactive power compensation will be performed with the help of a regulated capacitor bank.

However, whichever regulation method is used, ice melting is done by alternate current of industrial frequency and requires significant power supply (dozens of MVA), because real resistance of overhead line wires is much less than inductive resistance. Total supply power is increased due to large reactive load which is useless for ice melting. It is possible to increase melting efficiency by applying series capacitive compensation of inductive resistance, if capacitors are used as part of the proposed unit. However, the authors did not consider such alternative.

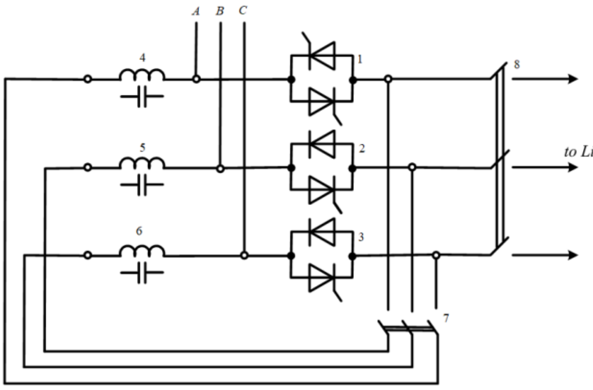

Fig 2. Unit for compensation of reactive power and ice melting

It is also worth considering a combined unit for compensation of reactive power and ice melting, the scheme of which is shown in Figure 3 [6]. In ice melting mode, switch 7 is ON and shunts reactor 6, switch 9 shuts off capacitor bank 8, and switch 10 is ON. This enables simultaneous melting on all wires of overhead line.

In of reactive power compensation mode, switches 7 and 10 are OFF, and switch 9 is ON. The result is a typical static compensator circuit consisting of transistor modules 1, 2 and 3, reactors 5 and 6 on alternate current side, and capacitor bank 8 on direct current side. This structure can work in power generation mode as well as in reactive power consumption mode.

The unit shown in Fig. 3 has a significant drawback, in particular, incomplete use of gating section in melting mode. This can be explained by the fact that the melting current passes only through the ‘lower’ phase switches 1, 2 and 3 of the converter bridge. Converting the bridge circuit into three alternate current switches will require additional switching gear and a substantially more complicated power circuit.

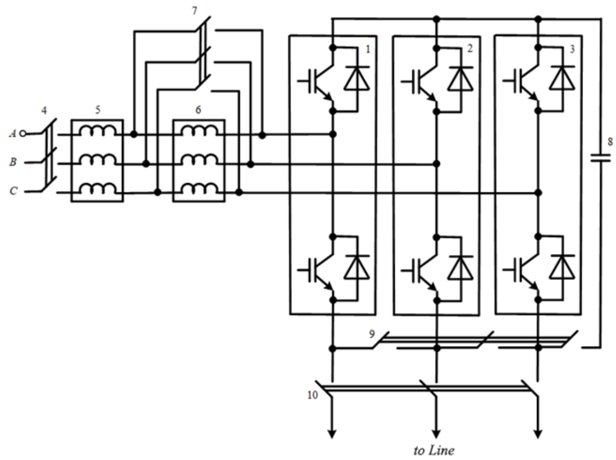

Fig 3. A combined unit for compensation of reactive power and ice melting.

4 Thermal impact of direct current.

For the first time, ice melting with direct current as a prospective method of de-icing high-voltage phase wires was mentioned in [7]. Among the first mass produced units for direct current ice melting were silicon cell ice melting rectifiers VUKN-16800 - 14000, created using Larionov circuit, based on silicone uncontrollable rectifiers VK-200 with rectified voltage of 14 kV, rectified current of 1200 A, and output power of 16800 kW [8]. Schemes of ice melting with rectified current are considered in detail in [4].

Main drawbacks are that high-voltage lines must be shut off, while rectifier is not operated for most part of the year because there is a necessity for ice melting only in winter. It is worth noting the proposal to melt ice by pulsing current without shutting off high-voltage lines [9]. Rectifier is connected to the cut of the heated wire in such a way that direct current does not pass through power transformer and current transformer. Wires are heated with alternate current with alternating-current component that is defined by high-voltage line load, and direct-current component defined by rectified voltage and real resistance of melting circuit. However, this proposal does not increase rate of using rectifiers and will require additional switching gear for practical implementation.

This justifies attempts to extend functional capabilities by combining in one unit an ice melting rectifier and a reactive power compensation unit. This enables all-year operation, which significantly increases economic efficiency.

JSC NIIPT, Scientific & Research Institute of Direct Current (Saint-Petersburg) has developed a container-type converting unit for the combined unit for compensation of reactive power and ice melting (see Fig. 4) [10].

The converting unit (Figure 4) includes transporting container 1, thyristor units 2, and control modules 3, forced air cooling system 4, disconnector 5 with electric power drive 6, anode lead 7, cathode lead 8, phase lead 9 of converter bridge, Control, Regulation, Protection and Automation System (SRPAS) 10, disconnectors 11, and 12, and capacitor tanks 13.1, 13.2, and 13.3.

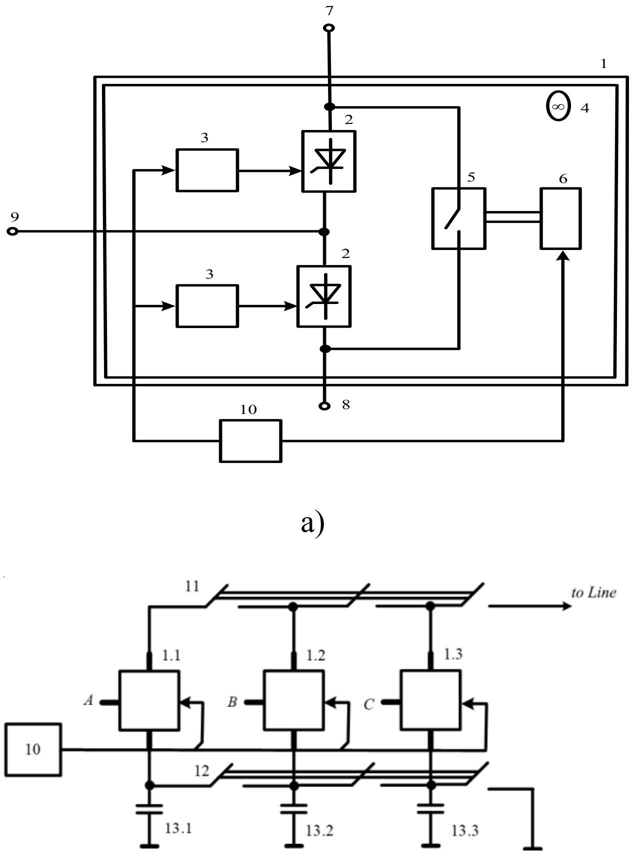

Fig 4. Scheme of container-type converting unit (a) and combined unit (b) for compensation of reactive power and ice melting, disconnectors 11, and 12, and capacitor tanks 13.1, 13.2, and 13.3.

Power equipment is designed for operation in moderate to cold climate zones (design for UHL1 climate zone, acc. to Russian GOST) and placed into a closed steel container set upon a basement in an open part of the substation. Power supplied is delivered from 10 kV coil from a dedicated transformer. The converting units shown in Figure 4a are used to make a combined unit, shown in Figure 4b.

In ice melting mode, disconnectors 11 and 12 are closed (see Figure 4b), disconnectors 5 (see Figure 4a) are open. A circuit of a three-phase bridge rectifier is created that provides nominal rectified voltage of 14 kV, nominal melting current of 1400 A, and capability to regulate melting current in the range of (200...1400) A.

In reactive power compensation mode, disconnectors 11 are 12 open, and disconnectors 5 are closed. This creates a circuit of capacitor tanks13.1, 13.2, and 13.3, which is controlled by thyristor modules aligned in parallel-opposite connection 2. However, compensation mode allows only step control of reactive power.

It is possible to avoid the latter drawback by using a combined unit for ice melting and reactive power compensation, shown in Figure 5 developed by JSC NIIPT, Scientific & Research Institute of Direct Current [11].

The combined unit for compensation of reactive power and ice melting consists of feeding transformer 1, three-phase disconnectors 2, and 16, three-phase reactors 3, and 15, high-voltage bridge converter 4, direct current capacitor tank 5, one-phase disconnectors 6, and 7, control system 8, assemblies 9 ÷ 14 of fully controllable devices with reverse diodes, and resonance transformer 17.

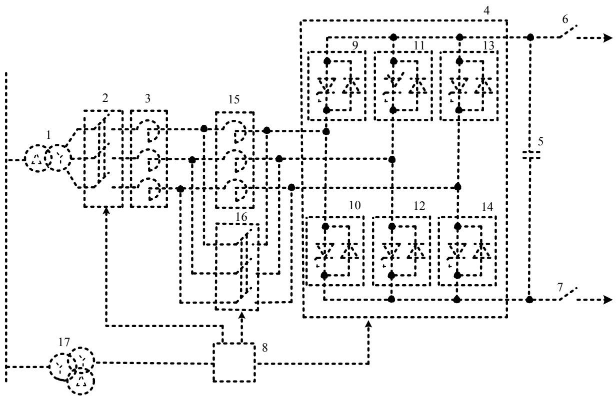

Fig 5. Combined unit for compensation of reactive power and ice melting

In ice melting mode, disconnectors 6, 7 and 16 are ON. Melting is done with direct current. Melting current is regulated by high-voltage pulse width modulation method (PWM). For example, when load current passes through diodes of assemblies 13 and 10, the fully controllable device from assembly

9 or 14 connects in PWM mode. This causes a short-time loop of double-phase short circuit 9 – 10 or 13 – 14. The load is shunted, and melting current is regulated. Speed of short-circuit current buildup is limited by reactor 3. Due to selecting PWM frequency and rate, the thyristor is blocked before short-circuit current increases to a dangerous value. At the same time, conducting interval of thyristor is less than in reactive power compensation mode. In reactive power compensation mode, disconnectors 6, 7 and 16 are OFF. High-voltage bridge converter 4 operates in STATCOM (static compensator) mode.

A number of authors who judge by their own work experience are of opinion that only 7% to 30% of the heated wire length is actually coated in ice during the melting. This is explained by the fact that different areas of high-voltage line happen to be in different climatic conditions due to rotation angle and impossibility to predict wind direction at the moment of ice coating formation. Consequently, significant amount of electric power is wasted. Therefore, a mobile unit is proposed that will enable to go to those areas of high-voltage lines where ice coating on the wires is identified.

Mobile generator for melting ice on overhead transmission lines [12] is installed on vehicle-mounted platform, the three-phase bridge rectifier is powered (0.4 kV) by two diesel ADV320 generators, each generating 320 kW. It is equipped with conductors and terminals to connect to overhead line wires, and with electric buses to connect wires in the span between the towers into ice melting circuit. The proposed technical solution enables ice melting on the length of two spans of overhead line on phase conductions and ground wire.

Common drawback of all devices that use direct current to create thermal impact is the necessity to use ice melting scheme “wire - wire” or “wire - two wires”. Both schemes lead to increase of melting time and, consequently, power costs. To decrease melting time, melting scheme “three wires - earth” should be preferred, but grounding devices of substations, as a rule, are not designed to hold relatively long passing of direct current of strength up to 2000 A.

There are other ways to remove ice deposits from the wires of overhead power lines: thermal impact by ultra-low frequency current [13-18], thermal impact of high-frequency current [14].

4 Conclusion

The dominant trend in development of new methods for de-icing high-voltage line wires is the use of combined converter units that can melt the ice when necessary and compensate reactive power during the rest of time. The most advantageous method is ice melting by ultra-low frequency current that combines advantages of melting by industrial frequency alternate current (on three wires simultaneously) and melting by direct current (limited only by real resistance; melting current can be smoothly regulated). Another advantage of this method is that the unit for ice melting by ultra-low frequency current is easily transformed into a static compensator of reactive power. This lets use the costly converting equipment during the whole year. However, this method has the disadvantage of the necessity to shut off overhead lines for de-icing.

The latter disadvantage can be completely avoided by using technology of flexible alternate power transmission [18] that involves converting equipment theoretically capable, if necessary, to provide regular wire heating that prevents formation of ice coating.

5 ACKNOWLEDGMENT

The authors are grateful to the staff of the research and production company “Energy-T” for useful remarks and practical implementation of the equipment for melting ice with direct current on the wires of overhead lines of electric networks “Ulyanovskenergo” and “Bashkirenergo”.

References:

[1] *Electrotechnical manual*, in 3 volumes. Volume 3. In 2 folios. Folio 1. Generation and distribution of electric power (Edited by MPEI Professors: Orlova, I.N. (Senior Editor) et al.). Version 7, amended and complemented. – Moscow: Energoatomizdat. – 1988. – 880p. (in Russian).

[2] Alekseev, B.A.. Improvement of overhead transmission lines capacity and use of wires of new grades. *// ELEKTRO Journal*. – 2009. – Issue 3. – pp.45-50. (in Russian).

[3] National Standard Guideline Document RD 34.20.511 (34-70-028-82) *Guidelines for ice melting by alternate current. Part 1.* Moscow: Soyuztekhenergo, 1983. (in Russian).

[4] National Standard Guideline Document RD 34.20.511 (34-70-028-82) *Guidelines for ice*

melting by direct current. Part 2. Moscow: Soyuztekhenergo, 1983. (in Russian).

[5] Patent of Russian Federation (RF) № 2505898 МКИ H02G7/16, H02J3,18. Device for compensation of reactive power and ice melting //Yu.P.Stashinov, V.V.Konopelko. – Publ. 27.01.2014.

[6] Patent of RF № 2505903 МКИ H02J3/18, H02G7/16. Combined unit for compensation of reactive power and ice melting // Yu.P.Stashinov, V.V.Konopelko. – Publ. 27.01.2014.

[7] Burgsdorf, V.V. Ice melting by direct current without shutting off the line // *Electrical stations*. – 1945. – Issue 11. (in Russian).

[8] High-voltage rectifying unit of type VUKN-16800-14000 (silicon cell ice melting rectifier). Annotated list of major research and experimental works performed in Mordovia Research Electrotechnical Institute (1965-1968). – Informelektro, 1970. (in Russian).

[9] Genrikh, G.A., Denisenko, G.I., Mishin, V.V., Stryapan, V.N.. *Special modes of powerful static converters of ice melting units on power transmission lines*. Kiev – Publishing union “Vishha shkola”. – 1975. – 242p. (in Russian).

[10] Patent of RF № 2390895 МКИ H02G7/16, H02J3/18. Converting container-type device for combined ice melting and reactive power compensation unit // M.K.Gurevich, M.A.Kozlova, A.V.Lobanov, A.V.Repin, Yu.A.Shershnev. – Publ. 27.05.2010.

[11] Patent of RF № 2376692 МКИ H02G7/16, H02J3/18. Combined unit for ice melting and reactive power compensation // Gurevich, M.K., Repin, A.V., Shershnev, Yu.A.. – Publ. 20.12.2009.

[12] Patent of RF № 2522423 МКИ H02G7|16. Mobile generator for ice melting on overhead transmission lines // A.V.Kozlov, A.N.Chulkov, A.B.Shurupov, A.A.Vinogradov. – Publ. 10.07.2014.

[13] Patent of RF № 2505897 МКИ H02G7/16. Method of controllable alternate current ice melting on overhead transmission lines // Yu.P.Stashinov, V.V.Konopelko. – Publ. 31.05.2012.

[14] Patent of RF № 2356148 МКИ H02G7/16. Method and device for de-icing of power transmission lines // V.I.Kaganov. – Publ. 20.05.2009.

[15] Patent of RF № 2520581 МКИ H02G7/16. Device for removing ice and rime coating from power transmission line wires // Shelkovnikov, N.D., Shelkovnikov, D.N. – Publ. 27.06.2014.

[16] Patent of RF № 2166826 МКИ H02G7/16, B60M1/12. Method of de-icing wires of overhead contact system and powertrain transmission lines // A.V.Efimov, A.G.Galkin. – Publ. 10.05.2001.

[17] Patent of RF № 93184 МКИ H02G7/16 for a useful model. Device for de-icing of power transmission lines // R.R.Sattarov, F.R.Ismagilov, M.A.Almaev. – Publ. 20.04.2010.

[18] V.I.Kochkin. New technologies to improve power transmission lines capacity. Controllable power transmission // *Electrotechnics News*. – 2007. – Issue 4(46). (in Russian).

[19] Peng Li, Na Zhao, Donghua Zhou, Min Cao, Jingjie Li, Xinling Shi. Multivariable Time Series Prediction for the Icing Process on Overhead Power Transmission Line// *Scientific World Journal*, Volume 2014, Article ID 256815, 9 p.

[20] H. Hou, X. Yin, Q. Chen, D. You, G. Tong, D. Shao. Review on the wide area blackout of 500 kV main power grid in some areas of south china in 2008 snow disaster. *Automation of Electric Power Systems*, vol. 32, no. 11, pp. 12–15, 2008.

[21] K. Savadjiev, M. Farzaneh. Analysis and interpretation of icing rate meter and load cell measurements on the Mt.Bélair icing site. In *Proceedings of the 9th International Offshore Polar Engineering Conference*, vol. 2, pp. 607–611, Brest, France, 1999.

[22] X. B. Huang, Q. D. Sun. Mechanical analysis on transmission line conductor icing and application of online monitoring system. *Automation of Electric Power Systems*, vol. 13, no. 14, pp. 98–101, 2007.

[23] L. Yang, Y. Hao, W. Li et al. A mechanical calculation model for on-line icing-monitoring system of overhead transmission lines. *Proceedings of the Chinese Society of Electrical Engineering*, vol. 30, no. 19, pp. 100–105, 2010.

[24] Y. Xu, R. G. Bosisio. Goubau ice sensor transitions for electric power lines. *Sensing and Imaging*, vol. 10, no. 1-2, pp. 31–40, 2009.

[25] I. Y. H. Gu, U. Sistiaga, M. Sonja et al., “Automatic surveillance and analysis of snow and ice coverage on electrical insulators of power transmission lines,” in *Proceedings of the International Conference (ICCVG '08)*, vol. 5337 of Lecture Notes in Computer Science, pp. 368–379, Springer, 2008.

[26] Y. Sakamoto, Snow accretion on overhead wires, *Philosophical Transactions of the Royal*

Society A, vol. 358, no. 1776, pp. 2941–2970, 2000.

[27] M. Farzaneh and K. Savadjiev, Statistical analysis of field data for precipitation icing accretion on overhead power lines, *IEEE Transactions on Power Delivery*, vol. 20, no. 2, pp. 1080–1087, 2005.

[28] L. Makkonen, Modeling power line icing in freezing precipitation, *Atmospheric Research*, vol. 46, no. 1-2, pp. 131–142, 1998.

[29] X. Wu, L. Li, and X. M. Rui, Icing load accretion prognosis for power transmission line with modified hidden semi-Markov model, *IET Generation, Transmission & Distribution*, vol. 8, no. 3, pp. 480–485, 2014.

[30] S. Rajakarunakaran, D. Devaraj, G. S. Venkatratnam, and K. Surja Prakasa Rao, Articial neural network approach for fault detection in LPG transfer system, *Applied Soft Computing*, vol. 8, no. 1, pp. 740–748, 2008.

[31] P. McComber, J. De Lafontaine, and J. Laflamme, A neural system to estimate transmission line icing, in *Proceedings of the 8th International Workshop on Atmospheric Icing on Structures (IWAIS '98)*, pp. 101–106, Reykjavik, Iceland, 1998.

[32] E. Larouche, J. Rouat, and G. Bouchard, Exploration of static and time dependent neural network techniques for the predicion of ice accertion on overhead line conductors, in *Proceedings of the 4th International Workshop on Atmospheric Icing of Structures (IWAIS '00)*, Chester, UK, 2000.

[33] P. Li, N. Li, Q. Li, M. Cao, and H. Chen, Prediction model for power transmission line icing load based on data-driven, *Advanced Materials Research*, vol. 144, pp. 1295–1299, 2011.

[34] P. Li, Q. Li, M. Cao, S. Gao, and H. Huang, Time series prediction for icing process of overhead power transmission line based on BP neural networks, in *Proceedings of the 30th Chinese Control Conference (CCC '11)*, pp. 5315–5318, Yantai, China, July 2011.

[35] Q. Li, P. Li, Q. Zhang, W. Ren, M. Cao, and S. Gao, Icing load prediction for overhead power lines based on SVM, in *Proceedings of the International Conference on Modelling, Identification and Control (ICMIC '11)*, vol. 6, pp. 104–108, June 2011.

[36] L. Makkonen, Models for the growth of rime, glaze, icicles and wet snow on structures, *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 358, no. 1776, pp. 2913–2939, 2000.

[37] L. E. Kollár, M. Farzaneh, and P. van Dyke, Modeling ice shedding propagation on transmission lines with or without interphase spacers, *IEEE Transactions on Power Delivery*, vol. 28, no. 1, pp. 261–267, 2013.