Damage Detection Strategies in Structural Health Monitoring of Overhead Power Transmission System

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DAMAGE DETECTION STRATEGIES IN STRUCTURAL HEALTH MONITORING OF OVERHEAD POWER TRANSMISSION SYSTEM

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ABSTRACT

Overhead power transmission lines, their supporting towers, insulators and other elements create a highly distributed system that is vulnerable to damage. Typical damage scenarios cover cracking of foundation, breakage of insulators, loosening of rivets, as well as cracking and breakage of lines. Such scenarios may result from various factors: groundings, lightning strikes, floods, earthquakes, aeolian vibrations, conductors galloping, icing, and also include sabotage or terrorist attacks. It is impossible to monitor every kilometre of power lines, especially when they pass through inaccessible areas like mountains or swamps. This implies that many of the damage scenarios mentioned remain unnoticed or are detected too late. In most cases damage of the power system leads to instantaneous blackouts of small regions, but huge blackouts are also possible. Every power outage causes a great financial loss, threats to hospital patients, public transport or even national security. The paper presents a brief introduction to the field of damage detection in transmission towers, emphasising indexes calculated by simple processing and using artificial neural networks. Problem of line sag monitoring is also mentioned. The paper ends with a short report on possible financial impacts of an SHM system for electric energy transmission and distribution system.

KEYWORDS : *Transmission tower, power line, energy transmission, modal analysis, damage detection*

1. INTRODUCTION

The main task of electric energy Transmission and Distribution (T&D) System is to deliver energy from the generator to the consumers. "Transmission" literally describes the high voltage part of T&D System that goes from the power plant to substations near demand points. "Distribution" refers to the low voltage part of T&D System that connects substations and consumers' switchgear boxes. Both of them consists of transmission towers (e.g. suspension or crossing), power lines (overhead or underground), insulators, vibration dampers (e.g. Stockbridge type), switchgears and transformers. Due to the type of a line, alternating current (AC) or direct current (DC), other electrical equipment (like AC/DC and DC/AC converters) is met. T&D System in Poland operates on 19 electric power plants and is made of 245 HV lines that gives a total of 13 053 km of HV lines distributed on the area of 312 679 km^2. In details, there are: 1 line of 750 kV on a distance of 114 km, 77 lines of 400 kV on a total distance of 5383 km and 167 lines of 220 kV on a total distance of 7948 km. There is also underwater 1500 kV DC connection with Sweden by a line 245 km long. Whole T&D System lines are coupled with 101 HV transmission stations and outnumbered LV substations. The total transient power transmitted by the lines in Poland is about 23 GW (3rd March 2014) [1].

One of the nowadays world greatest problems are unpredicted power outages. "Blackout" is defined as a short- or long-term loss of the electric power to an area. There are various reasons for such situations. One them are weather related blackouts that state about 70% of total power outages:

lightnings, cloudbursts, blizzards, icing, gales, local floodings, storms. A human factor is also a well-known cause of blackouts: incorrect fitting of the element, terrorist attacks, sabotages, wrong decisions on power capability of lines. Among all of the causes one escapes the attentions - this being ageing. Due to age of many T&D System elements, consequences of severe weather conditions are much more serious. An example could be a mechanical loading capability decrease of a power line due to erosion caused by aeolian vibrations [2]. It is worth mentioning, that in Poland most of transmission towers were built in the 70s. HV transmission towers were built as steel lattice constructions, but LV towers are made of wood or steel reinforced concrete.

This paper considers damage detection of steel latticed towers. It is a complex structure made of simple elements - beams. Their task is to carry mechanical loading of power lines. There are different types of towers, which depends on the line supporting way: tangent suspension, angle suspension, tangent strain, angle strain, tangent dead-end, angle dead-end. Angle structures are used when a line must change its direction. Tangent structures are used otherwise. Typical loading consist of power lines, e.g. single AFL-8 525 overhead line weights 1933 kg/km, where usually two or more lines are used per one phase. This states that a suspension tower M52 has to carry 6 such lines. Typical equipment met on power lines are insulators and Stockbridge dampers. Typical insulators are ceramic, glass or made of glass fibre reinforced polymer, what additionally increase the loading of a tower. Damage of a span should be divided into 2 categories: damage of a tower and damage of a line. The former can be classified as fatigue cracking, crossarm cutting, foundation cracking, rotation of a tower (due to miry terrain), rivets loosening, etc. Typical line damage includes breaking, shirt-cutting, insulator cracking, rust occurrence, fatigue, cracking, etc. Many of them are caused by ageing, vibrations (conductors galloping, aeolian vibrations) and human factors.

Figure 1 : Suspension tower type M52.

Nowadays solutions for damage detection focus on regular inspections using various technologies. Mainly, an inspector has to observe possible damage during visual inspection, but recent achievements in Unmanned Aerial Vehicle technologies allow to send a copter with a mounted camera to take necessary photographs of neuralgic places. However, this type of remote inspection is extremely expensive, either to send an inspector to a distant remote terrain or to purchase a UAV. Moreover, photos taken by UAV have to be analysed by a trained person in order to find possible damage. Both these methods seems to have unacceptable disadvantages. This states that damage detection and structural health monitoring of transmission towers and lines makes a great field for research with promising applications in the nearest future [2].

2. Transmission tower monitoring

A lattice type of power transmission tower is a construction of simple beams connected together to create a complex structure capable to carry load of power lines. Usually, even their severe damage does not lead to blackout immediately, but a combination of strong wind or icing with damage is a common scenario for a beginning of power outage. This is the main reason for studies over SHM for T&D System. Almost all of work already done in this area concentrates on modal analysis of tower [3].

Among damage detection strategies, two methods seems to be the most popular - analysis of a frequency shift and artificial neural network processing [4–8]. The first one is based on the comparison of actual natural frequencies of a transmission tower and their reference values. The reference values can be calculated using the Finite Element Method or measured if the tower is newly erected. Both of these approaches have advantages and disadvantages. First of all, numerical simulations represent the physical phenomena and are vitiated by an error of many simplifications. However, cost-savings often overcome this problem as measurements of natural frequencies requires availability of equipment and qualified staff. Moreover, damage to the structure can be done during tower erection, e.g. improper fitting, human errors, while the second approach will assume damaged state as a reference what is not acceptable [9]. In this paper, FEM is applied to calculate the reference and damaged state values of natural frequencies.

Tower type M52 will be investigated (fig. 1). This is a suspension tower for 220 kV applications very common in Polish environment. The investigated example is $39.5m$ high, first arms are on $26.5m$ height, second on $32.7m$, third on $38.1m$ length of the first arms is $19m$, the second arms is $14.4m$ and third is $9.2m$. The tower carries 6 lines of AFL-8 525 and two optical power ground wire (OPGW) for safety and communication purposes (fig. 1). The unit weight of live lines is $1933kg/m$ and for OPGW is $550kg/m$. Simulations were conducted using ANSYS software, an environment for simulating mechanical, electrical, fluid-flow, thermal and many other phenomena. Each element of a tower was modelled as a two node beam element. Damage was simulated as a complete destruction of a crossarm i. e. the given element was removed from the model. The authors chose to model damage for each crossarm separately, so there is only one damaged element present in the method. Although, this could be taken as a unnatural case, this approach gives valuable information on the sensitivity of a given method. The healthy modes were obtained for the tower without loading and different loading modes that can be met during exploitation - change in wires type, missing line, etc. Missing wire could be threaten as a damage scenario, but the authors considers only planned maintenance so a damage detection (in tower) system should work accurately during power line maintenance.

The first proposed damage indicator is a simple index based on following formula:

$$DI_1 = \sum_{n=1}^{10} (D_n - R_n)^2 \tag{1}$$

where D is a vector of natural frequencies of the structure with damage, R is a vector of reference values of the structure. Despite simplicity of this index it gives satisfactory results in almost every case, what is presented in Fig. 2.

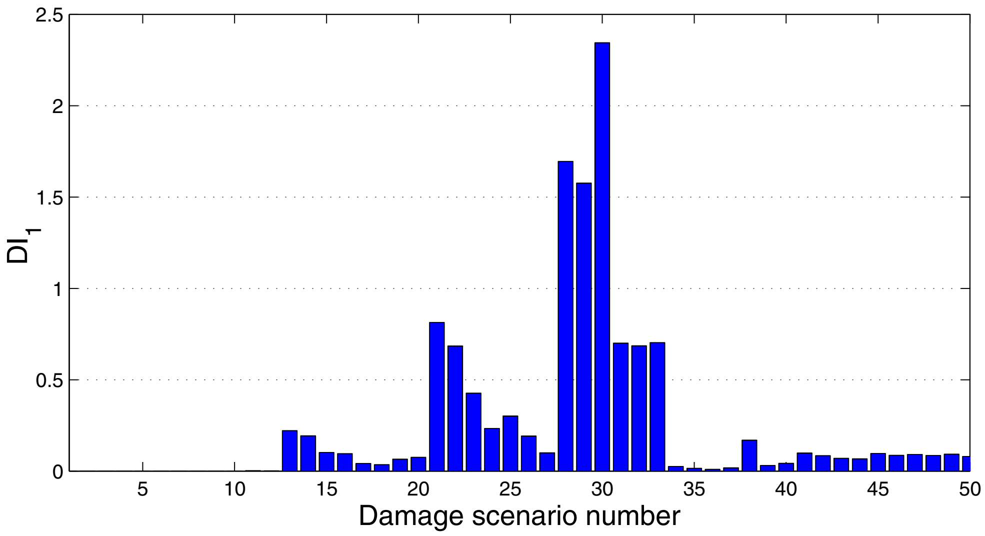

Figure 2 : Values of DI_1 for various damage scenarios.

If damage is present in the lower parts of the tower, its index value is relatively close to the healthy state, so one can tell that this damage index is not well-suited for the particular damage type. If we introduce a weighted damage index with a weight matrix W the mentioned problem can be overcomed. Fig. 3 presents only damage scenarios that consider damage near the lower part of the tower using DI2 algorithm. Some of the scenarios, mainly 1 and 3, produce still low DI_1 relatively to other scenarios, although they simulate serious damage of a cutted leg. This implied that other methods, maybe based on local tension values should be proposed.

$$DI_2 = (D_n - R_n)^T W (D_n - R_n) \tag{2}$$

Another technique that is commonly used for damage detection is pattern recognition by artificial neural networks (ANN). ANN belongs to the class of artificial intelligence methods for solving complex problems based on functions of neurons of the brain. ANN is divided into layers. Input layers applies the gives signals to the rest of the network, especially to the hidden layers that compute value for the output layer. The hidden layers are functions that multiply their inputs by weights and use a given transfer function to obtain the layer output. The knowledge of how to calculate the output is stored as weights values. Algorithms for calculating these values are called learning methods. There is a great variety of such methods and their choice is crucial for many applications. In the investigated problem of damage detection, the authors created 3-layered ANN (one input, one hidden and one output layers) with a sigmoidal tangent function as a transfer function. The number of neurons in the hidden layer was varying according to the experiment. In the output layer, there was only one neuron that classified the inputs into 2 categories: damaged or undamaged structure. As a learning function the authors used a scaled conjugate gradient backpropagation algorithm. This is a method for supervised learning - ANN is shown the input and the desired output. ANN changes its weights and supervisor tells if the fit is satisfactory or not. This method allows the neural network for generalisation and it is hardly overtrained as it is easily possible using e. g. Levenberg-Marquardt algorithm. ANN created in MATLAB environment is presented in Fig. 4.

The first ten natural frequencies were the input for ANN then it has to classify them into 2 groups. Among all damage scenarios, 30% were used for training, 35% for validation (checking the ability for generalization) and rest 35% for testing (provides ANN performance tests after training). The

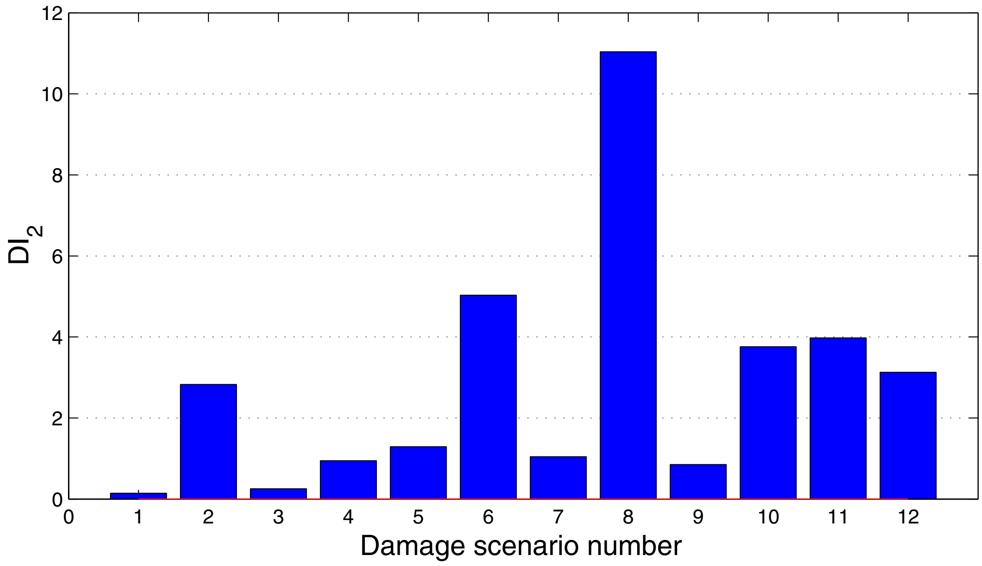

Figure 3 : Values of DI_2 for chosen damage scenarios.

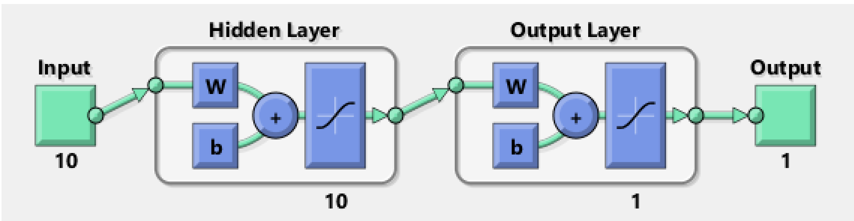

Figure 4 : Neural network created for damage detection purposes.

separation of scenarios into these groups was made randomly. At the end, the artificial network was not able to classify perfectly the natural frequencies into two separate groups. In Fig. 5 confusion matrix for 10 neurons in hidden layer is presented.

Table 1 presents the number of wrongly classified damage scenarios as a function of hidden layer neurons number. What can be easily seen, even a great number of neurons in the hidden layer cannot overcome the problem of perfect classification. A probable explanation of this phenomenon is that some of the frequencies in damaged case are very close to the frequencies of undamaged case. The ANN algorithm tries to create a hyperplane that will separate these data into two groups. Due to proximity of these two group, the algorithm is unable to perform perfectly, so it tries to minimize the error leaving the space for "false alarms". Similar results were obtained for other learning algorithms.

3. Transmission line monitoring

One of the greatest problems of electric power lines monitoring is the sag estimation. Sag is probably the most critical parameter of the line. No grounded object can be present closer to the live line than the safe separation distance due to high probability of an arc discharge. Moreover, a live line has to be on a proper distance from human and animal living areas to prevent negative influence of the electromagnetic field generated by the line. These are the reasons why the amount of sag should be continuously monitored. Nowadays, lines are placed on towers at heights that are sufficient for mentioned purposes. This implies that the costs of towers are greater than an optimal value. Sag is a resultant of four components - strain due to the line weight, mechanical loading, ambient temperature

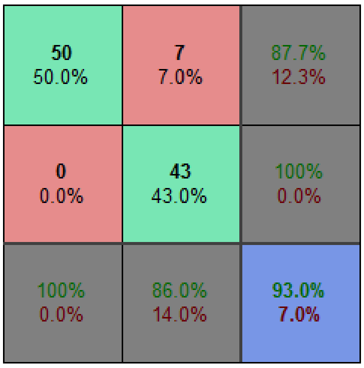

Figure 5 : Confusion matrix produced for checking ANN performance.

Table 1 : List of badly classified damage as a function of neurons quantity

Number of neurons	No. of badly classified scenarios
2	34
3	25
4	11
5	17
6	4
7	3
8	5
9	7
10	7
50	3

and electric current. Due to slenderness of the line, the first one is obvious. The second one reflects loading due to abnormal situations, e.g. icing, but also placing specialized electric devices (which fortunately can be neglected). Ambient temperature may increase sag during summer season as line elongates with temperature increase. The opposite situation is present during winter. The last one, current heating is an effect of Joule's heat that is proportional to the squared current value. Sag can be controlled by increasing or decreasing the power (current) transmitted. This implies dynamic line loading possibility through sag estimation or measurement. However, no method for a direct measure of sag exists. Nowadays, sag estimation is performed as follows. Temperature and various other weather parameters of the power line area are measured using conventional weather stations. The desired parameters are often delivered by a government part responsible for weather forecasting. Next, line temperature and current are being measured. All these values are input parameters for a thermodynamic model of a power line that calculates actual sag. More detailed information is delivered by IEEE Standard 738-1993 [10].

The most natural possibility of measuring strain is application of resistive strain gauges fails in this application. Sensors should be placed directly on the live line, so the electromagnetic field will make readings useless. Moreover, this is an example of passive sensors, hence additional power cables are needed. In high electromagnetic fields, such cables will act as antennas, therefore they could destroy gauges. The application of fibre Bragg gratings sensors (FBGs) or Brillouin sensors could overcome all mentioned constraints. Considering a following example one can obtain interesting results. The span is long for 1200 m, terrain is flat, so there is no slope between both ends of line. The line is AFL-8 525, aluminum and steel Young modulus - 60 MPa and 207 MPa, thermal expansion coefficient for both materials - $23 \cdot 10^{-6}\ 1/K$ and $11.5 \cdot 10^{-6}\ 1/K$. The line length in this case is equal 1207.963 m and sag is $60,0\ m$. If temperature drops down for $-15\ K$ and icing for area type I is applied then line elongates only by 0.89 m ($736,8\ \mu\varepsilon$), but sag increases for 3.21 m (5.35%). This is to show that even during winter sag can increase due to mechanical rather than electrical loading. Strain of the line has relatively high value, so it could be easily measured using Brillouin scattering sensors. Despite readings from the sensors system provide information about strain only and sag is not measured directly, this technology allows for calculation based on more reliable variables than spatial temperature distribution. Moreover, such a system can be coupled with a dynamic line loading system providing an optimal lines use. To the day of submission the authors did not perform the experiment and it is their plan for the nearest future.

4. Anticipation of economical impact of SHM of T&D system

Electric power delivery is one of the parameters of national safety and its disruption can even destabilise a country. Unfortunately, many of power outages happen due to severe weather condition causing multimillion losses for electric companies. The power undelivered to consumers is money that was not earned that is why companies are talking about their financial loss. Due to icing, long lasting rain and miry terrain one of the towers near Szczecin in Poland fell in 2008 [11]. This caused a cascade of falling towers as they were heavily loaded by ice. It caused a blackout for over milion people. Generators in power plants had to be stopped as their loading dramatically decreased what could result in their destruction. Many facilities had to stop their production and so they suffered a great loss of income. What was more tragic, few hospitals had to cancel 1702 surgical operations.

The described case clearly shows that a blackout could have been avoided if only a system for early warning of destruction possibility had existed. Such a system could detect extraordinary loading due to icing on towers and lines and inform the energy operator. Cities could be supplied with energy from different lines as there are always at least two different lines that supplies a city. Table 2 presents the financial loss due to blackout near Szczecin in 2008 with description. The cost of one FBG sensor is lower than 100 EUR, few of them should be placed on one tower with a line. Based on rough calculation one can say that a measuring circuit for one span should cost less than 2000 EUR. This is only a case of fibre optics technology application and nothing stops from introduction any other, cheaper, technology that also would be well suited for purposes. Working out such technology will make a company an undisputed leader in SHM for electric power grid.

Table 2 : List of costs and losses of blackout in Szczecin (Poland) in 2008 [11]

Cost type	**Amount of money**
Rescue action	829 728 PLN (197 555 EUR)
Local goernment interventions (e.g. water supplying)	979 463 PLN (233 205 EUR)
Compensations costs	3 250 000 PLN (773 810 EUR)
Loss and direct costs	28 486 295 PLN (6 782 451 EUR)
Unsaled energy	7 923 024 PLN (1 886 434 EUR)
Total of companies losses & costs	43 698 410 PLN (10 404 383 EUR)
Railway costs	887 568 PLN (211 325 EUR)
Hospitals costs	537 537 PLN (127 985 EUR)

Conclusion

Structural Health Monitoring of electric power Transmission and Distribution system is an alarming problem of the nowadays world. Towers and lines are being often exploited much longer than their design lifetime and it is not a problem of developing countries only. Tackling this problem requires serious cooperation of mechanical and electrical engineers as the T&D system is a complex composition of transformers, lines, towers, insulators and many others. The presented paper shows a brief introduction to the field. It also gives some information about damage indexes for a transmission tower damage assessment based on natural frequencies calculations. It is shown that simple processing of the frequency shift may give better results than the application of the artificial neural network. However, further studies in this area are needed, mainly in damage detection for different types of damage, damage localisation and identification. These ideas are extremely urgent because of the lost income of electric companies.

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