Continuous Monitoring and SCADA Integration of the Sag of Overhead Electricity Transmission Cables Based on the Measurement of their Slope

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***Abstract* - This paper presents a proposed system for the continuous monitoring of conductor sag values in overhead electricity transmission lines through slope angle measurement, by using a mathematical model based on the catenary equation. By measuring the axial angle of the conductor and the slope angle by means of the double axis tilt sensor, the sag value can be calculated in case of cable swings. Using ModBus protocol the value of the tilt sensor can be read by the software application and the calculed sag value is send to SCADA. The results obtained according to the proposed algorithm developed in LabVIEW software environment showed that the system could meet the technical requirements for measuring conductor sag in electricity transmission lines.**

Cuvinte cheie: *săgeata cablului, clinometru, monitorizare, SCADA.*

Keywords: *conductor sag, tilt sensors, monitoring, SCADA.*

I. Introduction

The continuous progress of society requires an increasing demand for energy, and the electricity consumption is growing constantly. The increasing demand for electricity consumption has led to new methods of electricity transmission, while environmental costs and problems have become more and more important. The increase in the capacity of safe transmission through the existing transmission lines is one of the directions approached in the field of electric power supply networks. Such an approach can solve not only the problem of peak loads or short failures during transmission but can also reduce the investments in new transmission lines, the number of new transmission lines with direct implications in achieving economic and social benefits [1-4].

The quality of the cable basically determines the limit of the load capacity in the process of electricity transmission by electric power supply networks. In order to prevent overloading, the design load capacity for the transmission lines is determined as a parameter with a set value, which depends on the worse weather conditions. However, usually such adverse weather conditions rarely occur, so the potential for electricity transmission by cables is not used to the full in most cases [5-9].

Since a close relationship is defined between the transmission line sag and the electrical power transmitted, the measurement of the transmission line sag can reasonably and accurately determine the rating of the electrical power that can be transmitted or, considering otherwise, it can be determined whether and to what extent the thermal stability limit is exceeded, depending on the electrical power with which the line is loaded. In addition, the sag value can vary with the temperature of the transmission line, which causes the distance measured vertically or diagonally between the line, at the peak of the sag and earth to be reduced, and thus the reliability of the network to be affected. Therefore, in the process of electricity transmission, through the continuous and accurate monitoring of the sag values of overhead transmission lines, the energy could be supplied more efficiently by ensuring, at the same time, the safety of the energy system. The sag of overhead transmission lines is in close interdependence to their load carrying ability. Real-time conductor sag monitoring can contribute to the dynamic range control of the line load and to an increase in reliability [10-12].

The technique for conductor sag determination, based on the principle of slope measurement and by using the mathematical model of the catenary curve provides greater accuracy than other techniques used for the same purpose. The test results show that the sag determination system reaches the required parameters for the proposed project.

The paper is organized as follows: Section 2 describes the sag measurement methods. Section 3 presents the proposed sag measurement based on cathenary algorithm and simulation in LabVIEW and Mathscript software development. In Section 4 is presented the hardware and software implementation of the proposed algorithm.

The paper ends with a section of conclusions describing the main aspects of the proposed method for measuring conductor sag in electricity transmission lines, some conclusions will be made and some ideas will be pointed out for continuation of work.

II. Sag Measurement Methods

The basic sag measurement methods include:

- The detection method (a theodolite or similar device is frequently used);

The instruments used to measure the horizontal and vertical angles in geodesy and topography are called theodolites. A theodolite is a device that is used only for the measurement of the angular values of horizontal directions between two or more points in the field, as well as the slope of these directions with high and very high precision. Theodolites are used to carry out works for determining the geodesic triangular networks.

- GPS monitoring;
- Conductor temperature and cable tension measurement for sag determination;
- By using projection techniques for sag determination;
- Line slope measurement for sag determination.

Some features (advantages and disadvantages) of conductor sag determination are shown in table 1.

TABLE I. CONDUCTOR SAG DETERMINATION

Sag measurement method	Features
Detection method	It is simple, it has a high degree of accuracy, the need for on-site operating staff excludes the possibility of real-time monitoring
GPS	It is accurate, it involves complex algorithms which are difficult to implement, it is costly
Temperature and cable tension	It is relatively inexpensive, it involves the measurement of too many parameters, the calculation algorithm is complex, it introduces large errors
Projection technique	It is easy to implement, it requires specialized photographers, the processing of images is difficult, it introduces large errors
Line slope	It is relatively simple, inexpensive, the calculation algorithm is simple, it introduces small errors

Compared to the methods listed above, the method based on slope measurement has several advantages.

The transmission cable is suspended and fixed between two towers. Due to the large distance between the two towers, the rigidity of the cable influences quite a bit the flexibility of the cable section considered. Thus, for the engineering mathematical calculations performed, the rigidity of the cable will be ignored, considering the transmission cable as flexible. The flexible cable is bendable enough, so it is only strain (tensile) resistant, not bending resistant. The tension direction at any point of the overhead cable section is manifested on the axial direction.

In theory, there are two methods of calculating the cable stretch sag: the catenary and the parabolic method.

Generally, in the plain (flat) and hilly regions, the effective length of the overhead line between two suspension towers is approximately 5% higher than the distance between the towers. According to the technical calculations, often the dead weight of the overhead cable which is distributed evenly on the unit of length is manifested only in the direction of the two suspension points, and according to this hypothesis, we can approximate that the curve according to which the suspended conductor is positioned is a parable. In mathematical calculations, the most practical way of modeling the form of overhead cables refers to the situation where the weight of the cables is distributed evenly on their own length and is effectively manifested on their entire length.

Catenaries and related curves are used in architecture and engineering, in the design of bridges and arches, so that forces do not result in bending moments. In the offshore oil and gas industry, "catenary" refers to a steel catenary riser, a pipeline suspended between a production platform and the seabed that adopts an approximate catenary shape.

In the mathematical model the chain (or cord, cable, rope, string, etc.) is idealized by assuming that it is so thin that it can be regarded as a curve and that it is so flexible any force of tension exerted by the chain is parallel to the chain. The analysis of the curve for an optimal arch is similar except that the forces of tension become forces of compression and everything is inverted. An underlying principle is that the chain may be considered a rigid body once it has attained equilibrium. Equations which define the shape of the curve and the tension of the chain at each point may be derived by a careful inspection of the various forces acting on a segment using the fact that these forces must be in balance if the chain is in static equilibrium.

According to this hypothesis, the positioning function of the overhead conductor is the catenary function.

III. THE PROPOSED SAG MEASUREMENT CATHENARY ALGORITHM

For the development and implementation of the conductor sag calculation algorithm, we will start with the catenary equation and we make the following notation:

- Angle – θ_0 [degree]
- Angle – θ_1 [degree]
- Cable rise – h [m]
- Cable run – L [m]
- Cable weight – G [N]
- Weight/length – w [N/m]
- Cable length – l [m]
- Horizontal component of the cable tension – H [N]
- Coordinates of minimum point of the cable (x_s, y_s), where the origin of coordinates system is positioned at the top of the shorter pillar (see Fig. 1).

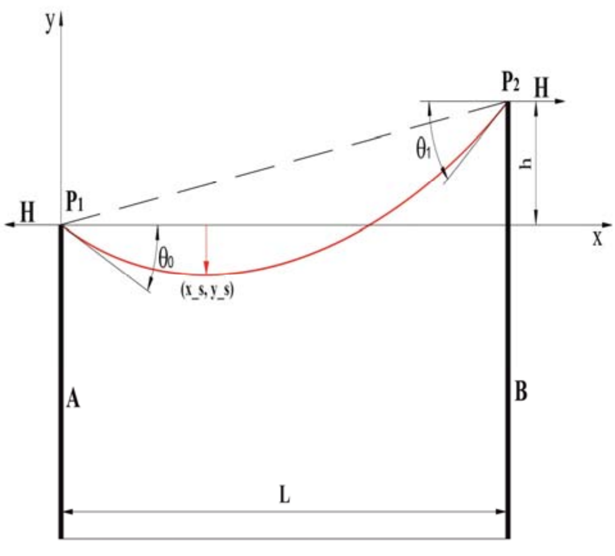

Fig. 1. The conductor sag

The following equation can be formulated [13]:

$$y' = \frac{dy}{dx} = sinh\left(\frac{w}{H} \cdot x + K_1\right) \qquad (1)$$

Of which after integration the following equation is obtained in an implicit form:

$$y = \frac{H}{w} = cosh\left(\frac{w}{H} \cdot x + K_2\right) \qquad (2)$$

Where the integration constants are:

$$K_1 = a\,sinh\left(\frac{w \cdot h}{2 \cdot H \cdot sinh\frac{w \cdot L}{2 \cdot h}}\right) \qquad (3)$$

$$K_2 = -\frac{H}{w} \cdot cosh(K_1)$$

The length of the cable is calculated as follows:

$$l = \int_0^L \sqrt{1 + \left(\frac{dy}{dx}\right)^2}\, dx \qquad (4)$$

and the following implicit equation is obtained:

$$l = \frac{H}{w}\left(sinh\left(\frac{w \cdot L}{H} + K_1\right) - sinh(K_1)\right) \qquad (5)$$

It is solved according to the following notations:

$$T = tan(\theta_0) + tan(\theta_1) \qquad (6)$$

$$M = a\,sinh\left(\frac{h \cdot T}{2 \cdot l \cdot sinh\frac{L \cdot T}{2 \cdot l}}\right) \qquad (7)$$

length l of the cable is determined from the implicit equation below.

$$T - sinh\left(M + \frac{L \cdot T}{2 \cdot l}\right) + sinh\left(M - \frac{L \cdot T}{2 \cdot l}\right) = 0 \qquad (8)$$

For the Matlab simulation, the resolution is done by calling the fsolve function, and for the real-time implementation the bisection method can be used.

While the horizontal mechanical stress at the ends of H-wire and the weight per unit length w are calculated according to the input data by using the following relationships:

$$H = \frac{G}{tan(\theta_0) + tan(\theta_1)} \qquad (9)$$

$$w = \frac{G}{l} \qquad (10)$$

(x_{min} and y_{min} – i.e. sag positioning) is calculated based on the cancellation of the first derivative (for the minimum condition) and the relationships below are obtained.

$$x^* = \frac{-H \cdot K_1}{w} = \frac{-K_1 \cdot l}{T} \qquad (11)$$

$$y^* = \frac{H}{w} cosh\left(\frac{w \cdot x^*}{H} + K_1\right) + K_2 \qquad (12)$$

Observation: The weight of the cable is necessary only to calculate the horizontal mechanical stress H and the weight per unit length w, otherwise it is simplified for each of the other equations (for example, like the calculation of x*, and practically it is not necessary for the calculation of the sag).

For simulation of the proposed algorithm we use LabVIEW and Mathscript software development [14, 15]. The software block diagram is presented in Fig. 2 and Fig. 3.

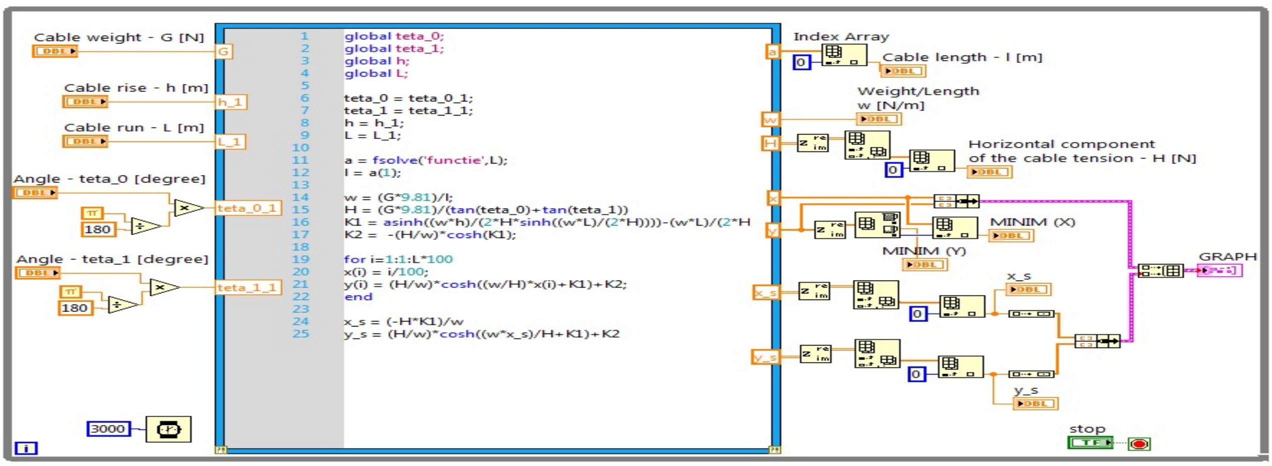

Fig. 2. Software block diagram of the sag measurement catenary algorithm

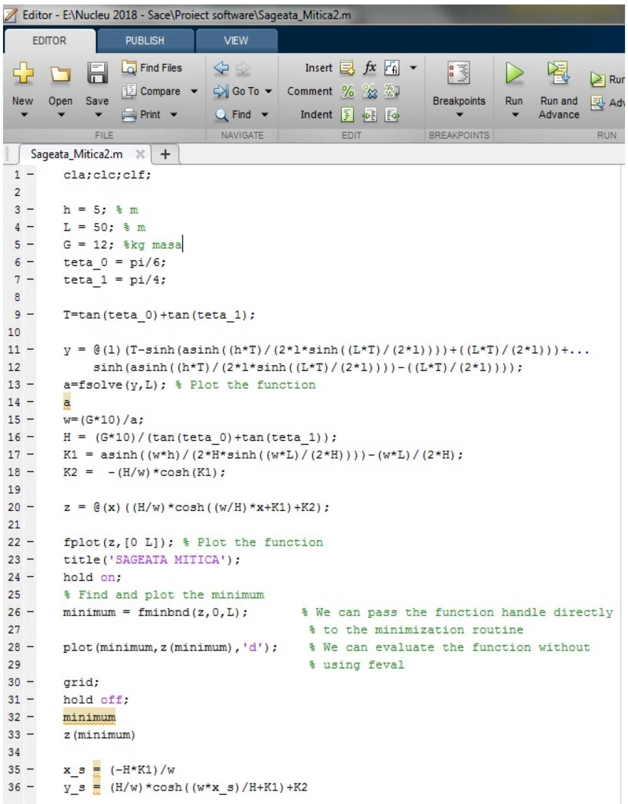

Fig. 3. Mathscript software implementation

Although the LabVIEW language consists of all the necessary elements for writing programs, there is also the possibility of writing source lines in C language through a special structure, the "Formula Node", the node structure. Another special structure, the "MathScript Node" (see Fig. 8), allows the introduction of code lines similar to the MATLAB program. This considerably extends the programming possibilities, allowing the user to write their own code sequences and develop the standard facilities offered by the LabVIEW environment. So it can be said that this is an open environment, which increases its performance.

Modeling is a way to create a virtual representation of a real-world system that includes software and hardware. If the software components of this model are driven by mathematical relations, this virtual representation can be simulated under a wide range of conditions to see how it behaves.

Modeling and simulation are especially valuable for testing conditions that might be difficult to reproduce with hardware prototypes alone, especially in the early phase of the design process when hardware may not be available. Iterating between modeling and simulation can improve the quality of the system design early, thereby reducing the number of errors found later in the design process.

1) Example 1.

Input data: teta_0 = 45 degrees, teta_0 = 45 degrees, Distance between towers L = 37 m, difference in height between towers h = 0 m; Cable weight G = 10 N.

Calculated data:

Specific weight w = 2.38 N/m, cable length l = 41.97 m, Horizontal mechanical stress H = 50 N. Coordinates of the minimum point: x_s = 18.5 m, y_s = -8.6966 m.

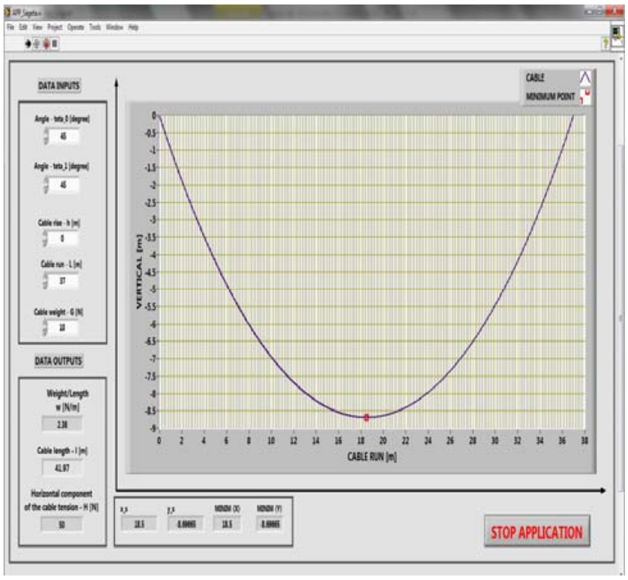

Fig. 4. Software interface for example 1

2) Example 2.

Input data: teta_0 = 30 degrees, teta_0 = 45 degrees, Distance between towers L = 50 m, difference in height between towers h = 5 m; Cable weight G = 12 N.

Calculated data:

Specific weight w = 2.19 N/m, cable length l = 54.67 m, Horizontal mechanical stress H = 76.08 N. Coordinates of the minimum point: x_s = 21.82 m, y_s = -7.0995 m.

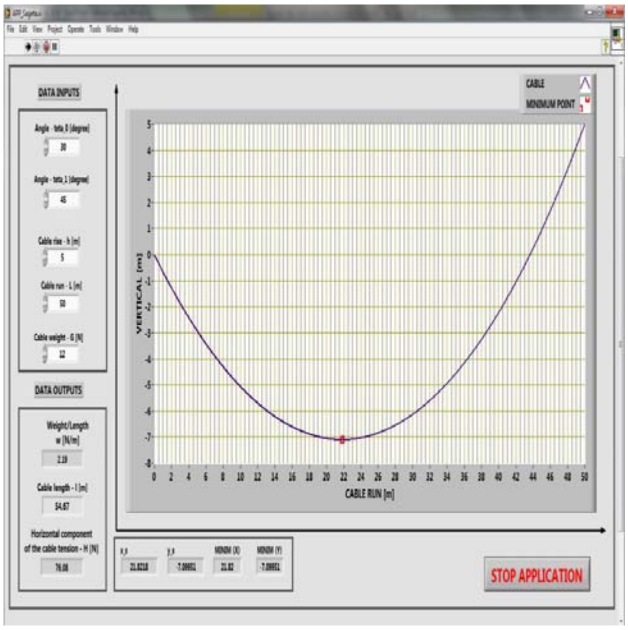

Fig. 5. Software interface for example 2

IV. Hardware and Sotware Implementation

The rapid adoption of the PC in the last 20 years catalyzed a revolution in the instrumentation used for test, measurement, and automation. One major development resulting from the ubiquity of the PC is the concept of virtual instrumentation, which offers several benefits to engineers and scientists who require increased productivity, accuracy, and performance.

A virtual instrument consists of an industry-standard computer or workstation equipped with powerful application software, cost-effective hardware such as plug-in boards, and driver software, which together perform the functions of traditional instruments. Virtual instruments represent a fundamental shift from traditional hardware-centered instrumentation systems to software-centered systems that harness the computing power, productivity, display, and connectivity capabilities of popular desktop computers and workstations. Although the PC and the integrated circuit technology have experienced significant advances in the last two decades, it is software that truly provides the leverage to build on this powerful hardware foundation to create virtual instruments, providing better ways to innovate and significantly reduce costs. By using virtual instruments, engineers and scientists build measurement and automation systems that suit their needs exactly (user-defined) instead of being limited by traditional fixed-function instruments (vendor-defined).

A. Hardware description

By combining information on the design values of the overhead cable with the data provided by the sag online monitoring system based on the slope angle measurement, the sag value for the lowest point of the cable, as well as the peak value of the sag can be obtained, and by using a double axis tilt sensor, the angle of the cable slope relative to the ground level and the oscillation angle can be measured simultaneously.

The diagram of the sag monitoring system is shown in Fig. 6; the tilt measurement sensor is coaxial-mounted with the overhead conductors and the tilt sensor transmits wireless data to the monitoring center.

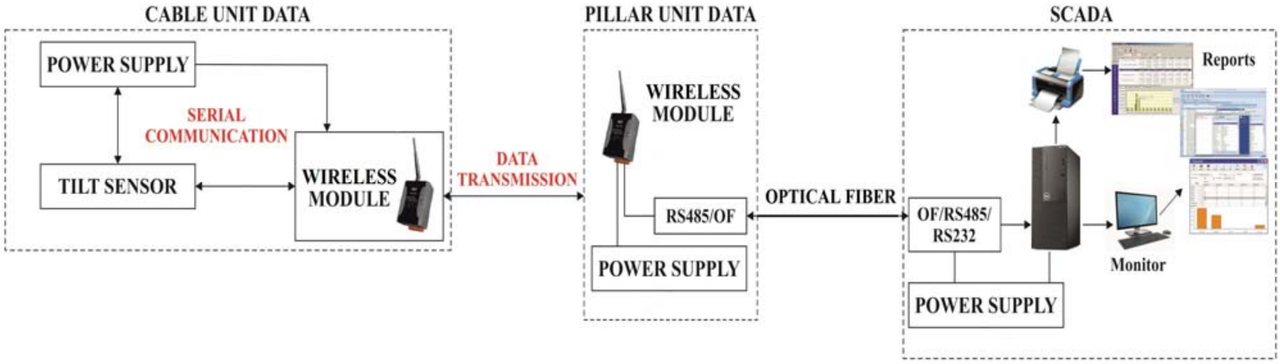

Fig. 6. Block diagram of the cable slope monitoring and sag calculation system

The SOLAR-2 inclinometers are range of high performance low cost dual axis tilt sensors for measurement of angles in both the pitch and roll axes. Through a flexible configuration and calibration program we can supply this device with any measurement range from ±5° to ±45°. It can also be supplied compensated for a specific operating temperature range. The housing is a small, low profile Aluminium housing, hermetically sealed to IP67. The cable is a shielded black PUR cable and is suitable for continuous outdoor use. These sensors utilise a very high performance MEMS (Microelectronic and Microelectromechanical Systems) sensor which exhibits low long term drift compared with many competitive devices.

Fig. 7. The local unit with the tilt sensor

It has an RS232 and RS485 interface option with our standard communication protocol as well as a version with RS485 multi drop ModBus communication protocol. The default configuration is with the baud rate set to 38.4kbps, with 8 data bits, 1 stop bit and no parity. All commands are lower case and 7 bytes long. The time between each character of the command must be less than 100ms otherwise the device will discard the command. The settings are all stored in non-volatile memory.

GT-531 is an intelligent Modbus SMS/GSM Gateway for industry M2M applications. It is convenient for users to apply in M2M applications with the host like PC, PLC, HMI and PAC via Modbus RTU communication. It supports UNICODE format for users to send SMS messages to the specific mobile phones by Modbus RTU protocol with various language. Moreover, the GT-531 also supports the sound alarm application with the pre-defined voice files. It can be used to inform the operator about the urgent event immediately. To manage more GT-53x series remotely, ICP DAS provides SMS DBS software for users to apply in the system. Therefore, the GT-531 can be a powerful tool allowing you to use your mobile phone to monitor and control your business from any location.

The output data of the tilt measurement sensor is transmitted to a signal processing circuit, and then it is transmitted for SCADA (Supervisory Control and Data Acquisition) integration via the GPRS wireless network. The data collected in the monitoring center, which represent the cable slope are accompanied by characteristics of the cable and are used for the calculation of the sag and its location, while being analysed and stored at the same time.

When the determined sag value exceeds the permissible limit, instructions are sent to the units in the field for calls on intensive data acquisition and an alarm signal will be generated.

B. *Software description*

LabVIEW integrates the creation of user interfaces (termed front panels) into the development cycle. LabVIEW programs-subroutines are termed virtual instruments (VIs). Each VI has three components: a block diagram, a front panel, and a connector panel. The latter is used to represent the VI in the block diagrams of other, calling VIs. The front panel is built using controls and indicators. Controls are inputs: they allow a user to supply information to the VI. Indicators are outputs: they indicate, or display, the results based on the inputs given to the VI. The back panel, which is a block diagram, contains the graphical source code. The Fig. 8 shows the software block diagram for the implementation of the sag measurement catenary algorithm in real time.

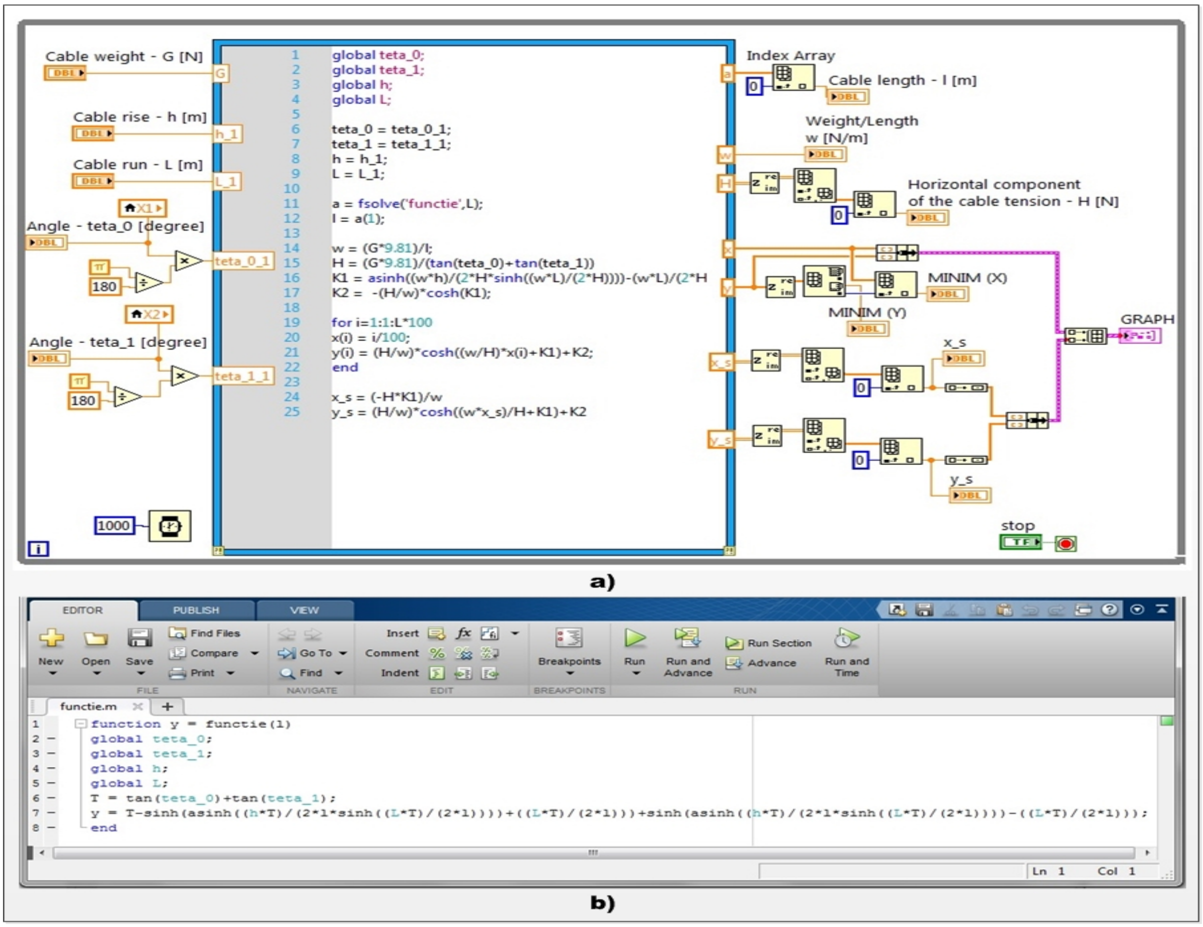

Fig. 8. The software block diagram for implementation of the sag measurement catenary algorithm in real time

NI-VISA (Virtual Instrument Software Architecture) is a software API that greatly reduces the development time of test and measurement systems. It gives developers the ability to easily create codes to communicate with any instrument, over any bus, on most operating systems in use today. It also allows the generation of code that can be moved from one platform to another or from one bus type to another with little or even without changes. This opens the door for creating hybrid systems that make the best and most cost effective use of multiple bus types all used in one test system.

NI-VISA is also kept up to date with new technologies as they are being released (like Ethernet and fire-wire) so any test system developed using the NI-VISA will be able to make use of the latest and greatest bus technologies available, while still leveraging previous technologies to provide a complete communication protocol for today's test and measurement system. Fig. 9 shows the software block diagram of the VISA implementation for the tilt sensors over RS232 communication.

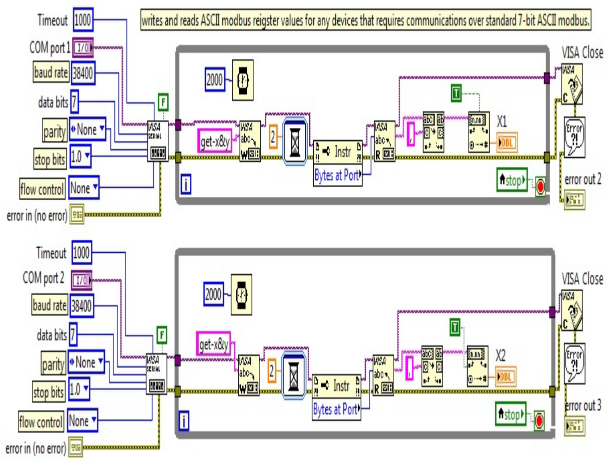

Fig. 9. Software block diagram for VISA implementation for the tilt sensors

The Modbus I/O servers included in LabVIEW provide a middle ground between the easy-to-use range of OPC servers and the powerful low-level libraries that give full control over the protocol. Like an OPC server, I/O servers allow a simple, configuration-based interface for communicating with a Modbus device. Like an OPC server, I/O servers are typically used in applications where supervisory control is important, while distributed microcontrollers are responsible for the high-speed control in the system.

Read and write access to the SOLAR-2 is done using ModBus Function Code 3 (read holding registers) and ModBus Function Code 6 (write single register) commands. These two function codes provide the basic functionality needed by most users of the SOLAR-2. A user defined ModBus function code 110 is provided for less commonly used, off-line functions such as setting serial port parameters and changing the device address.

ModBus device address must be in the range 1 to 247. All devices are shipped with a default address of 100 (decimal). Address 0 is the ModBus broadcast address. With this address all devices will perform the action of the function code. The maximum number of these devices that can be connected on a single network is 128.

All ModBus commands and responses have a 16-bit CRC for error detection. ModBus RTU data is in binary format rather than ASCII, so it cannot be viewed properly on a text terminal. The SOLAR-2 has a built in programmable 120 ohm terminating resistor which can be switched in or out of the circuit using the ModBus address detailed below.

Below is a list of the register locations for reading and writing:

TABLE II. MODBUS REGISTERS

Parameter	Address	ModBus Register Address	Description
X Axis Angle	0x00	40001	Address 0x00 returns the lower 16 bits of the sensor X axis angle. This combines with address 0x01 to form a 32 bit signed integer value equal to the measured angle x 1000.
	0x01	40002	
Y Axis Angle	0x02	40002	Address 0x02 returns the lower 16 bits of the sensor Y axis angle. This combines with address 0x03 to form a 32 bit signed integer value equal to the measured angle x 1000.
	0x03	40003	
Sensor Temperature	0x06	40007	Returns a 16 bit signed integer value equal to the temperature of the sensor in degrees Celsius x 100

Fig. 10 and 11 present the Modbus server implementation.

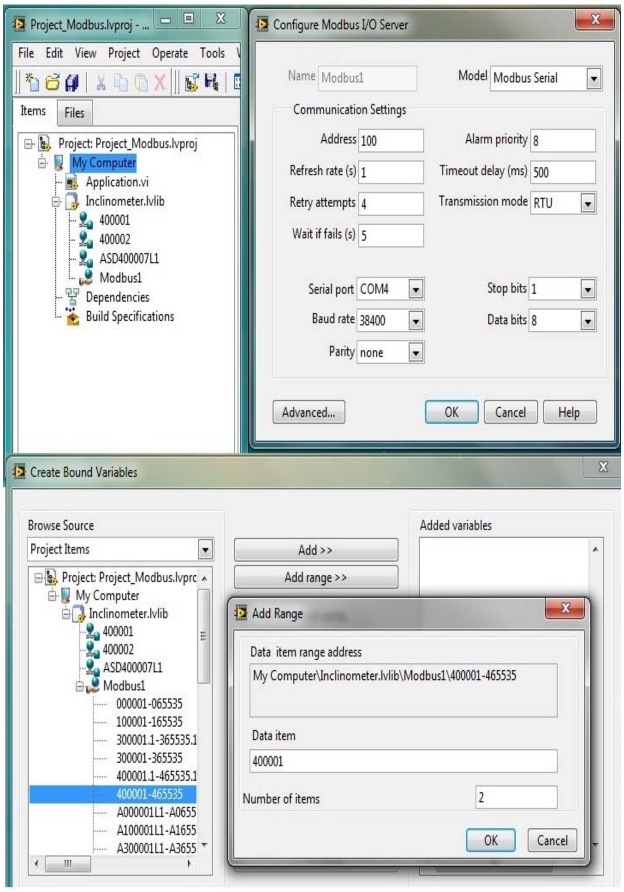

Fig. 10. Modbus Server configuration

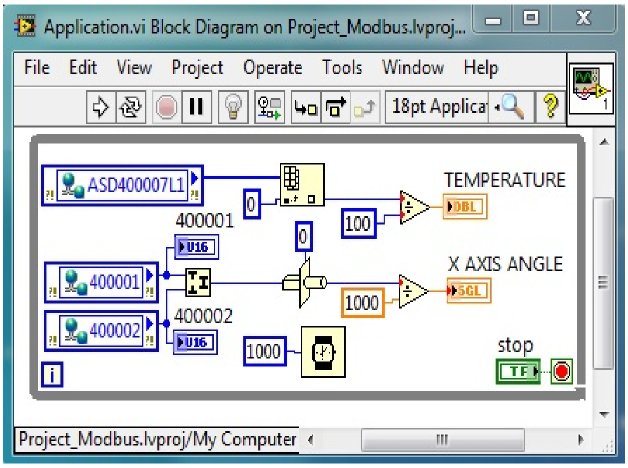

Fig. 11. The software block diagram for the acquisition of the data from the tilt sensor by using Modbus Server

To transmit the information taken from the tilt sensors through the Shared Variable, a simplified programming interface for sharing data was introduced in LabVIEW. Using the network-published Shared Variable, data can easily be transmitted within a system and between the systems.

Once a Shared Variable has been created using the Network-Published, all data written to the variable is available to all systems networked with the host computer. Shared Variables are configured through dialogs accessible from the Project Explorer window.

The interface of the software application is presented in Fig. 12.

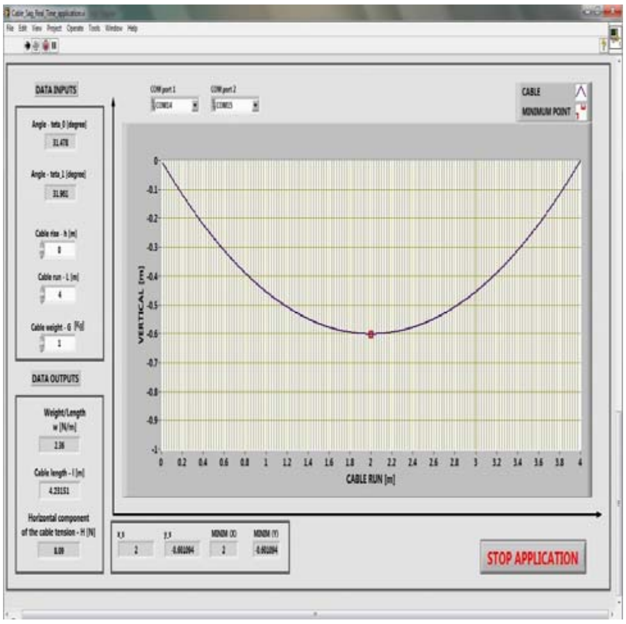

Fig. 12. The interface of the software application

V. Conclusions

The paper presents a proposed system for the continuous monitoring of conductor sag values in overhead electricity transmission lines through slope angle measurement, by using a mathematical model based on the catenary equation.

By measuring the axial angle of the conductor and the slope angle by means of the double axis tilt sensor, the sag value can be calculated in case of cable swings.

The results obtained according to the proposed algorithm showed that the system could meet the technical requirements for measuring conductor sag in electricity transmission lines.

Future work will focus on testing the system for monitoring the conductor sag in an electrical line section.

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First coauthor – 30%

Second coauthor – 20%

Third coauthor – 10%

Fourth coauthor – 10%

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