Real Time Monitoring Of High Voltage Transmission Line Conductor Sag: The State- of-The-Art

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Abstract— there have been developments in real time monitoring of a power transmission line system for the past and in recent years. This paper characterizes and evaluates various methods developed to measure conductor sag in real time. Some of the methods are still at initial stage of simulation and have not yet been applied in industry, while others are currently used by the power utility companies around the world. The optimum use of existing high voltage transmission lines requires a real time condition monitoring. In South Africa, detecting such critical infrastructure proactively in real time is still a challenge. We synthesis these methods and review the current power line carrier used by ESKOM South Africa. We conclude by drawing attention to the accuracy and strength of possible methods which could be applicable in future.

Keywords—Power quality, Reliability and Sag

I. INTRODUCTION

Long distance high voltage power lines are very important in electricity power delivery because power stations are normally built far away from power loads. During the transmission process, balance must be constantly maintained to match the power supply and demand. World climatic changes have an impact on our existing electrical transmission line performance. The electric current flowing in the lines should be measured to avoid overloads, phase unbalance and fluctuation. Line positions should be monitored to keep track of the sagging and galloping situations. Sagging can lower the conductor to a usage height above the earth. The oscillations can cause serious transmission problems, such as flashover due to infringed line to line clearance, risk of mechanical failure of transmission tower, and excessive loading stress [3], [7]. Conductors between two transmission towers often suffer sagging and galloping phenomenon. According to IEEE Standard 1159-1995 Recommended Practice for Monitoring Electric Power Quality, sag is a decrease in RMS voltage at the power frequency for durations from 0.5cycles to 1 minute, reported as the remaining voltage [16]. Sagging can lower the conductor to an unsafe height above the earth. It can be caused by oscillations which can result into serious transmission problems, such as flashover due to infringed line-to-line clearance, risk of mechanical failure of transmission tower, and excessive loading stress. Efforts have been made to understand this phenomenon better and develop means of protecting the transmission line against this problem. The low frequency, high amplitude induces vibration on this transmission line conductors as a result, causes serious galloping which result to more sagging.

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It is valid to interpret galloping as an oscillation of either a single or bundled conductor due to wind force or wind-induced vibration on an iced or wet snow accretion on the conductors.

It is also caused by steady crosswind acting upon asymmetrically iced conductor surface. Large amplitude is normally observed on a vertical position depending on the line construction and the oscillation mode excited.

The cost associated with galloping can be due to damaged components which require inspection and repair. It damages the conductor strands which result in to a conductor breakage or sagging and dynamic overload. In the event of this situation, patrolling need to be performed to detect any damage. This requires a helicopter or some sort of physical view, which increase costs and results unplanned maintenance.

The problem of sagging has the impact on system reliability and power quality of service. There may be a losing of customers who are very sensitive to power quality. There can also be a swinging of the suspension points longitudinally to the power line which is likely caused by the variation in tension; that could accompany galloping and act to couple the galloping motions in adjacent spans, resulting to a sagging phenomenon [15].

II. A MATHEMATICAL APPROACH

A. Review of sag Catenary

The shape of the catenary changes with conductor temperature, ice and wind loading, and time. To ensure adequate vertical and horizontal clearance under all weather and electrical loadings, and to ensure that the breaking strength of the conductor is not exceed, the behavior of the conductor catenary under all conditions must be known before the line is designed. The future behavior of the conductor is determined through calculations commonly referred to as sag-tension. Sag tension calculations predict the behavior of conductor based on recommended tension limits under varying loading conditions. These tension limits specify certain percentages of the conductors rated breaking strength that is not to be exceeded upon installation or during the life of the line. These conditions, along with the elastic and permanent elongation properties of the conductor, provide the basis for determining the amount of resulting sag during installation and long-term operation of the line. Accurately determined initial sag limits are essential in the line design process. Final sags and tensions depend on initial installed sags and tensions and on proper handling during installation. The final sag shape of conductors is used to select support point heights and span lengths so that the minimum clearances will be maintained over the life of the line. If the conductor is damaged or the initial sags are incorrect, the line clearance may be violated or the conductor may break during heavy ice or wind loading [11], [17].

The shape of a catenary is a function of the conductor weight per unit length, w, the horizontal component of tension, H, span length, S, and the maximum sag of the conductor, D. Conductor sag and span length are illustrated in Fig.1 for a level span. The exact catenary equation uses hyperbolic functions. Relative to the low point of the catenary curve shown in Fig.1, the height of the conductor, $y(x)$, above this low point is given by the following equation [14]:

$$y(x) = \frac{H}{w}\cosh\left(\left(\frac{w}{H}x\right)-1\right) = \frac{w(x^2)}{2H} \qquad (1)$$

For a level span, the low point is in the center, and the sag, D, is found by

$$D = \frac{H}{w}\left(\cosh\left(\frac{wS}{2H}\right)-1\right) = \frac{w(S^2)}{8H} \qquad (2)$$

At the end of the level span, the conductor tension, T, is equal to the horizontal component plus the conductor weight per unit length, w, multiplied by the sag, D as shown in the equation below:

$$T = H + wD \qquad (3)$$

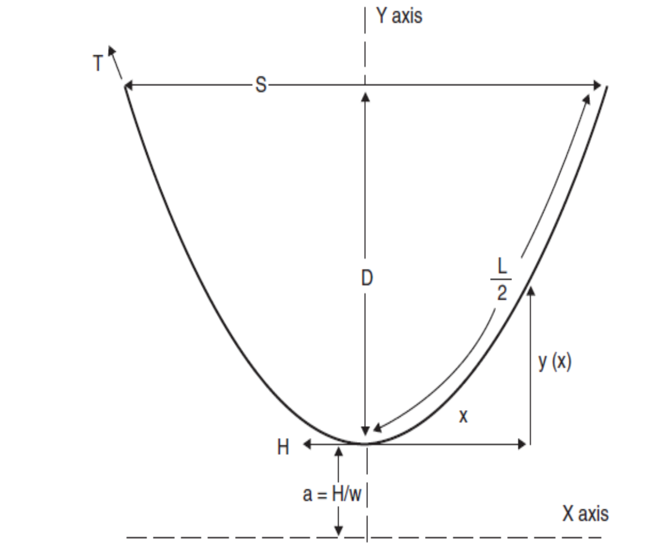

Fig.1 The catenary curve for level spans

Considering the conductor length from the low point of the catenary from either direction of the sag can be obtained as follows:

$$L(x) = \left(\frac{H}{w}SINH\left(\frac{Sw}{2H}\right)\right) = S\left(1 + \frac{x^2(w)^2}{6H^2}\right) \qquad (4)$$

For a level span, the conductor length corresponding to $x = S/2$ is the half of the total conductor length and the total length, L, is:

$$L = \left(\frac{2H}{w}\right)SINH\left(\frac{Sw}{2H}\right) = S\left(1 + \frac{x^2(w^2)}{24H^2}\right) \qquad (5)$$

The parabolic equation for conductor length can also be expressed as a function of sag, D, by substitution of the sag parabolic equation, giving:

$$L = S + \frac{8D^2}{3S} \qquad (6)$$

Conductor Slack is the difference between the conductor length, L, and the span length, S. The parabolic equations for slack may be found by combining the preceding parabolic equations for conductor length, L, and sag, D.

$$L - S = S^3\left(\frac{w^2}{24H^2}\right) = D^2\left(\frac{8}{3S}\right) \qquad (7)$$

The slack of the conductor in a span can contribute to the changes in conductor sag, such that:

$$D = \sqrt{\frac{3S(L-S)}{8}} \qquad (8)$$

For inclined spans: they may be analyzed using essentially the same equations that are used for level spans. The catenary equation for the conductor height above the low point in the span is the same. However the span is considered to consist of two separate sections, on to the right of the low point and the other to the left of the low point. The shape of the catenary relative to the low point is unaffected by the difference in suspension point elevation. In each direction from the low point, the conductor elevation, relative to the low point is

$$y(x) = \frac{H}{w}cosh\left(\left(\frac{w}{H}x\right)-1\right) = \frac{wx^2}{2H} \qquad (9)$$

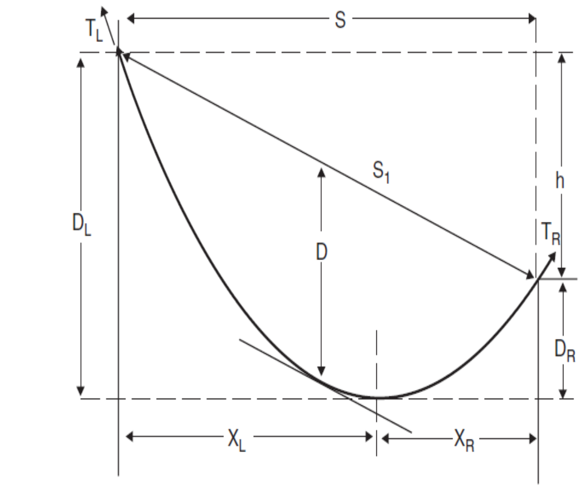

Fig.2, shows the inclined catenary

The horizontal distance XL from the left support point to the low point in the catenary is

$$XL = \frac{S}{2}\left(1 + \frac{h}{4D}\right) \qquad (10)$$

The horizontal distance, XR, from the right support point to the low point of the catenary is:

$$Xr = \frac{S}{2}\left(1 - \frac{h}{4D}\right) \qquad (11)$$

From the inclined catenary span $S1$ is the straight-line distance between support points, S, horizontal distance between supports, h, vertical distance between support points, D, the sag measured vertically from a line through the points of conductor support to a line tangent to the conductor.

The midpoint sag D is approximately equal to the sag in a horizontal span equal to the length to the inclined span, knowing the horizontal distance from the low point to the support in each direction, the preceding equations for $y(x), L, D$ and T can be applied to each side of the inclined span, S1. Knowing the horizontal distance from the low point to the support point in each direction, the preceding equations for $y(x), L, D,$ and T can be applied to each side of the inclined span. The total length in the inclined span is equal to the sum of the lengths in XR and XL sub-span sections:

$$L = S + (X_R^3 + X_L^3)\left(\frac{w^2}{6H^2}\right) \qquad (12)$$

B. A view of a position vector for conductor

When we review the position of a stretched conductor, such that the position vector $X(l,t) = (X(l,t), Y(l,t))$ with corresponding tension vector $T(l,t) = T(l,t)\,(cos\psi, sin\psi)$, where ψ is the positively oriented angle between the cable tangent and the horizontal. The tension vector is tangent to the cable because of the assumed negligible bending stiffness. The conductor element stretched under tension is represented as follows:

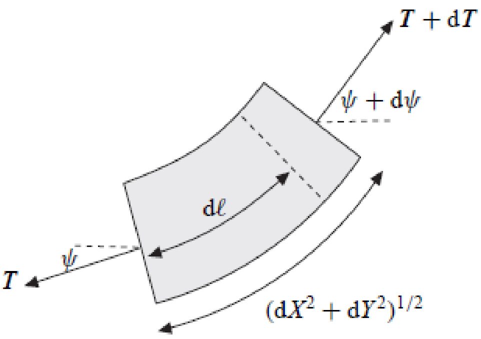

Fig. 3, conductor element under tension stretch

Now considering a small cable element, dl. Due to gravity, cable tension, and inertial forces, this element is stretched however the mass remain the same. A conductor element is elongated in proportion to tension, according to Hooke's law, such that:

$$\left(dX^2 + dY^2\right)^{1/2} = \left(1 + \frac{T}{EA}\right)d\ell. \qquad (13)$$

According to a Newton's law, the internal tension and the external gravity forces are in equilibrium with the inertial forces, such that; $dT = \left(g e_y + \frac{d^2y}{dx^2}\right) m\, dl$

$$\frac{\partial X}{\partial \ell} = \left(1 + \frac{T}{EA}\right)\cos\psi, \quad \frac{\partial Y}{\partial \ell} = \left(1 + \frac{T}{EA}\right)\sin\psi, \qquad (14)$$

The equation result in the limit $dl \xrightarrow{yields} 0$ are given by

$$\frac{\partial}{\partial \ell}\left(\frac{T}{1 + T/EA}\frac{\partial X}{\partial \ell}\right) = m\frac{\partial^2 X}{\partial t^2}, \qquad (15)$$

$$\frac{\partial}{\partial \ell}\left(\frac{T}{1 + T/EA}\frac{\partial Y}{\partial \ell}\right) = m\frac{\partial^2 Y}{\partial t^2} + mg, \qquad (16)$$

$$\left(\frac{\partial X}{\partial \ell}\right)^2 + \left(\frac{\partial Y}{\partial \ell}\right)^2 = \left(1 + \frac{T}{EA}\right)^2. \qquad (17)$$

For the boundary and coupling conditions in the figure 4, below

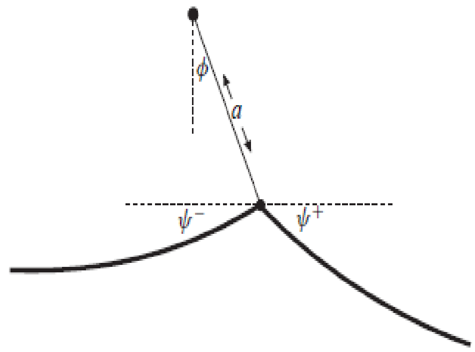

Fig. 4, boundary and coupling conditions

$L = 0$ and $L = NL$ For a fixed support

$$X = 0, \quad Y = 0 \quad (\ell = 0), \qquad (18)$$

$$X = NS,\ Y = 0 \quad (\ell = NL), \qquad (19)$$

At suspension string:

$$\left[X\right]_{\ell = nL-}^{\ell = nL+} = 0, \qquad (20)$$

$$(X - nS)^2 + (Y - a)^2 = a^2, \qquad (21)$$

$$\left[T\cos(\phi - \psi)\right]_{\ell = nL-}^{\ell = nL+} = 0. \qquad (22)$$

Where ϕ is the angle of the supension string

The mathematical approach help us to understand the problem of sag more clearly and the behavior of the transmission line under galloping conditions. Hence it only help us to reduce various problem parameters in to a single clear problem.

III. CURRENT TRANSFORMERS

They are typically used for current measurement. However, they are expensive and limited by their magnetic core characteristic and narrow bandwidth [1]. The CTs performance under distorted conditions is usually characterized by means of the frequency response test. The method uses an excitation waveform (primary current) that consists of one harmonic current, with adjustable amplitude and phase shift, superimposed on the fundamental current. The measurement of harmonic current phasor is characterized by two basic errors:

1. The *h-order* harmonic ration error:

$$\%e_h = \frac{KIsh - Iph}{Iph}.100 \qquad (23)$$

Where: $K = Ns/Np$ is the nominal transformer ratio (Ns and Np are the secondary and primary number of turns, respectively); Ish and Iph are the (RMS) values of the secondary and primary number of turns respectively); Ish and Iph are the (RMS) values of the secondary and primary h-order harmonic currents, respectively;

2. The *h-order* harmonic phase angle error:

$$\varepsilon_h = \alpha_{sh} - \alpha_{ph} \quad (24)$$

Where: α_{sh} and α_{ph} are the secondary and primary harmonic current phase angles, respectively. These indexes were used to characterize two current transformers excited by a non-sinusoidal current. Basically Current transformers measures the flow of current in a conductor not the position of the conductor, therefore cannot detect sag. There are some existing devices that can directly or indirectly measure sag of transmission lines.

IV. POWER LINE CARRIER METHOD

It determines average overhead conductor height variations by correlating sag with measured variations in the amplitude of signals propagating between PLC stations [8], [9]. The PLC-SAG technique, determines average overhead conductor height variations by correlating sag with measured variations in the amplitude of signals propagating between PLC stations. It is fundamentally based on the theory of natural modes supported by multi-conductor transmission lines. PLC system Provide a highly reliable infrastructure for the transmission and reception of data, speech and protection signals between stations.

A. PLC Attenuation Sensitivity and Height Variation

Attenuation of the PLC signal is due to two major contributions: that is attenuation due to the transmission line, including the effect of ground resistivity; which is complex and requires the rigorous theoretical analysis of modal propagation on multi-conductor transmission lines and attenuation due to the coupling system, is simple to compute. With outer-to-outer phase coupling, the signal level is sensitive to variations in line height. The PLC-SAG technique makes use of this phenomenon to remotely monitor the average height movement of the OHTL [9].

B. PLC based on the Modal theory

The voltage propagation is referred at the product of impedance and admittance matrices given by

$$P = ZY \quad (25)$$

The voltage propagation matrix is determined in terms of its eigenvalue matrix λ and eigenvectors E_v such that

$$P = E_v \; E_v^{-1} \lambda \quad (26)$$

The eigenvectors are determined by the fixed, physical geometry of the transmission line. The eigenvalues describe the variable or dynamic characteristics of the solution. The modal of the system is constructed from the eigenvector columns, and is fixed by the transmission lines physical geometry. For a horizontal transmission line, the columns of the Clarke matrix give a good approximation of the natural modes.

$$\begin{bmatrix} \frac{1}{2} & 1 & 1 \\ -1 & 0 & 1 \\ \frac{1}{2} & -1 & 1 \end{bmatrix} = M \quad (27)$$

Mode 1 is defined by the first column and is the mode with the lowest attenuation. Mode 2, the differential mode, is defined by column 2 and it propagates with a lower phase velocity and higher attenuation than mode 1. It makes a significant contribution to the total received signal. Mode 3 is the common mode and is heavily attenuated due to ground losses and can be neglected. Relative amplitudes of the modes, which are excited on transmission line, are determined by the voltage excitation vector applied to the line by PLC coupling configuration.
Eigenvalues of the propagation Matrix describe the dynamic characteristics of the different natural modes of the system. Thus the attenuation and phase retardation of modes are associated with the eigenvalues.
The horizontal transmission line can be determined in terms of the voltage on phase NV_{pN} as

$$\begin{bmatrix} e^{-\gamma 1x} & 0 & 0 \\ 0 & e^{-\gamma 2x} & 0 \\ 0 & 0 & e^{-\gamma 3x} \end{bmatrix} E_v \; E_v^{-1} \begin{bmatrix} V_{p1} \\ V_{p2} \\ V_{p3} \end{bmatrix} = V_x \quad (28)$$

Where $e^{-\gamma 3x}$ is the scalar factor, E_v is the sending end voltage
This is not accurate as conductors swing differently in different conditions more specifically when we consider the wind induced vibrations. Although this method is currently used by ESKOM South Africa, it is clear that advancements are needed in order to obtain measurements in real time. This method can only obtain the sag through average calculation of signal amplitudes.

V. POWER DONUT

A. Considering the Fourier's law of heat conduction

According to Fourier's law of heat conduction, local heat flow in x direction is such that $q_x = -k\frac{dT}{dx}$ where k is the thermal conductivity (W/m C). Q is the vector quantity and can have x, y and z components. Therefore the heat transfer in a power transmission line conductor cannot determine the vertical movement of the conductor in real time. However it can help in the dynamic design of the line rating at initial stage.
It is installed on live conductor wires [2], [3]. However, this device measures the conductor surface temperature rather than the core temperature for calculating sag.
Giving the standard heat flow as
$Local\ Heat\ flow\ (Q) = -k\nabla T$
Where k is the material conductivity and ∇T is the temperature gradient. It is not always true that K should be treated as the constant. The thermal conductivity of a material varies with temperature; the variation can be small over a significant range of temperatures for some common materials. In anisotropic material, the thermal conductivity typically varies with orientation; where k is represented by a second-order tensor. In no uniform material, k varies with spatial location.
It is an instrument platform for remote monitoring of overhead transmission lines, powered directly from the conductor electric field. This instrument performs measurements of voltage, current, conductor temperature and the angle of inclination

Fig.5, Power donut temperature sensor

This is installed on live conductor wires [2]. However, this device measures the conductor surface temperature rather than the core temperature for calculating sag. In addition, this platform is very expensive and its installation requires working with live wires is more risky.

VI. GLOBAL POSITIONING SYSTEM

Based on a constellation of 24 satellites, which uses the Navigation satellite Timing and Ranging (NAVSTAR) developed, launched, and maintained by the United States government [4] , [5].

It is a worldwide navigation and positioning resource for both military (i.e., precise positioning service) and civilian (i.e., standard positioning service) applications. This method relies on accurate time-pulsed radio signals in the order of nanoseconds from high altitude Earth orbiting satellites of about 11 000 nautical miles, with the satellites acting as precise reference points. These signals are transmitted on two carrier frequencies known as the L1 and L2 frequencies. The L1 carrier is 1.5754GHz and carries a pseudo-random code (PRC) and the status message of the satellites. There exist two pseudorandom codes: the coarse acquisition (C/A) and the precise (P) codes. The L2 carrier is 1.2276GHz and is used for the more precise military PRC. The signals from four or more satellites are received by a specially designed GPS receiver, and the following simultaneous equations are solved:

$$(X_{sk} - X_{rj})2 + (Y_{sk} - Y_{rj})^2 + (Z_{sk} - Z_{rj})^2 = (R_k - dT) \quad (29)$$

$$K = 1, 2 \ldots \mathrm{N}$$

$$k = 1, 2, \ldots, n \quad n \geq 4$$

Where $(X_{sk}, Y_{sk}, \text{and } Z_{sk})$ represents the kth satellite position $(X_{rj}\ Y_{rj}, Z_{rj})$ denotes the unknown jth receiver position, R_k denotes the range to kth satellite, and dT is the unknown receiver clock bias converted to distance. This gives the longitude and latitude of the receiver (i.e., defectively x and y), the altitude of the receiver (effectively z), and the time that the measurement was made t. interestingly, the GPS transmission is made at low power level (the signal strength at the point of reception is about -90 to -120dBm). At this power level, the SNR is very low at the surface of the Earth. The attenuation of the noise is accomplished by averaging the received signal. The noise is averaged and a distinctively coded signal appears as an output. The averaging processes, as well as the solution of (1) are the main time limiting processes that determine how often a GPS measurement can be made.

There is a potential in this technology, although there are some errors contributing to estimates. The differential GPS is generally used in order to decrease the selective availability errors. This mode consists of the base and the rover. The main disadvantage of the DGPS is the requirements of a second GPS receiver and corresponding communication equipment between the base and rover instruments.

The accuracy of the direct instrumentation of o overhead power line conductor sag measurement is about 19.6 cm range and 70% of the time. In the implementation of this technology, the phenomenon of the corona discharge in a transmission line conductor is a challenge in that it creates potentially intolerable conditions for radio reception in the 930MHz and 1.5 GHz frequency bands.

This method relies on accurate time-pulsed radio signals in the order of nanoseconds from high altitude Earth orbiting satellites of about 11 000 nautical miles, with the satellites acting as precise reference points. This technique is promising; however the challenge such as electromagnetic interference (EMI) from the phase conductors is questionable.

VII. IMAGE PROCESSING

In image processing an edge is the boundary between an object and its background appearance. This represents the frontier for single objects. If the edges of image objects are identified with precision all objects can be located and their properties such as area, perimeter and shape can be calculated. Edge detection is an essential tool for image processing technology.

There are two advanced and optimized edge detector in image processing, namely canny edge detectors and infinite symmetric exponential filter. These detectors follow different algorithms such that for canny edge detection, it is represented as follows [12], [13]:

1. Read the image I.
2. Convolve a 1D Gaussian mask with I.
3. Create a 1D mask for the first derivative of the Gaussian in the x and y directions.
4. Convolve I with G along the rows to obtain Ix, and down the columns to obtain Iy.
5. Convolve Ix with Gx to have Ix', and Iy with Gy to have Iy'.
6. Find the magnitude of the result at each pixel

$$M(x, y) = \sqrt{I_x'(x, y)^2 + I_y'(x, y)^2} \quad (30)$$

The Infinite Symmetric Exponential Filter uses another optimization function to find the edge in an image this function can be written as:

$$C_N^2 = \frac{4\int_0^\infty f^2(x)dx \cdot \int_0^\infty f'^2(x)dx}{f^4(0)} \quad (31)$$

The function C_N is minimizing with an optimal smoothing filter for an edge detector, which result into an infinite symmetric exponential filter, as follows;

$$f(x) = \frac{p}{2} e^{-p|x|} \quad f(x,y) = a \cdot e^{-p(|x|+|y|)}$$

1D 2D (32)

The filter in the infinite symmetric exponential filter edge detector is presented as one dimensional recursive filter. By presuming the 2D-filter function real and continuous, it is given by;

$$f[i,j] = \frac{(1-b)b^{|x|+|y|}}{1+b} \quad (33)$$

In some instances, image processing technique, uses automatic image analysis technique for extracting information from the line insulators. This concerns the detection of snow overage on insulators on the line and the detection of swing angles of insulators with respect to the vertical position. It must be clear that no real-time detection of the actual transmission line is made by this technique; hence it cannot be translated or be linked to real time dynamic rating of the line. It is also a costly technique and its installation requires contact with phase conductors for placing the targets

VIII. ELECTROMAGNETIC COUPLING METHOD

It is based on the magnetic field surrounding the conductor [7], [8], [11]. For different line configurations, the grounded wire position and the sag calculation need to be modified. Also, Electro Magnetic Interference from nearby transmission lines cannot be neglected. It calculates the current flow and line positions from the magnetic field emanated from the phase conductors.

IX. MAGNETO RESISTEVE SENSORS

Provided the sensitivity of the magnetic sensors is sufficient, the electric and spatial information of the overhead line can be found by inverse calculation from the magnetic field measured at the ground level [6]. These sensors are still in early design, although experiments results are promising. The accuracy of this technique is questionable. Factors such as multiple power conductors, bundle conductors and image current due to a conducting ground have to be taken in to consideration.

X. AUTONOMOUS ROBOT TECHNIQUE

This technique uses electromagnetic energy from the line and run along the conductor while making the inspection [10]. The stability and reliability of this technique is questionable as the magnetic field emanated from the conductors always vary and the storage of such.

XI. CONCLUSION

The current power system is ideally exposed to different factors such as galloping phenomenon which result in to sagging problem. The methods discussed in this paper mostly do the determination of sag by means of either devices/sensors which require electric field energy to operate. These devices are mounted on the live conductor or the line insulator. Although the PLC method is expensive and does the measurement by comparing average variation of amplitude signals, it is more safe and easy to operate in terms of data processing and monitoring. However the challenge still remains to develop a technique for real-time detection of the conductor itself. GPS could be more valuable in future if the EMI challenge is overcome. The advancement in research for other technologies based on electro-magnetic field theory is needed to address these limitations. Other methods are more dependent on the line electric field for the power supply and it is very difficult to store such for a longer period.

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