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An Analysis of Mechanical Effects of Short Circuit on Strain Bus using Finite Element Approach and Validation by Modelling an Actual Strain Bus subjected to Short Circuit Tests by Comparing Computed Results with Experimental Data

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SUMMARY
Strain bus consisting of flexible bare conductors suspended from supporting steel structures with insulators and hardware is widely used in air insulated substations. Strain bus conductors bear sag and tension caclculated to operating requirements. During system transients, strain bus conductors are subjected to strong electromagnetic forces due to short circuit currents, causing them to be displaced from their rest positions and resulting in increase of tensile forces. Phase conductors drop down after circuit breaker interrupts fault causing conductors to start swinging and resulting in further increase in forces.

The increased dynamic forces can compromise the integrity of conductor hardware, insulators and bus supporting structures. An unsuccessful breaker reclosing before damping of conductor swing out may increase risk of flashover between phases.

Two strain bus spans with variant configuration along with supporting steel structures were modelled using finite element analysis program and simulated for non-linear analysis for three phase 63 kA fault. Dynamic conductor tensile forces, displacements and swing angles were computed. A third model was developed matching the design of an experimental test span which was subjected to real short circuit tests. The model was simulated for non-linear analysis using short circuit curent and configuration which were used in experiment. The simulation results matched the experimental data recorded during the experiment.

The validation of results of finite element non-linear analysis of strain bus experimental test span model validated the results of non-linear analysis performed on the other two strain bus models.

KEYWORDS
Strain – Bus - Conductor – Sag - Swing - Static – Force – Tension - Dynamic - Relative – Displacement – Structure – Stiffness – Substation - Short Circuit.

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1. Introduction

Strain bus system because of its cost effective and environment friendly design, is widely used in transmission stations of high voltage and extra high voltage classes of outdoor air insulated design. The strain bus system comprises of flexible bare conductors, conductor hardware, strain insulators and steel supporting structures. The insulators designed to basic insulation level (BIL) specific to voltage class isolate phase conductors from ground potential. Bare strain bus conductors suspended from steel supporting structures sag because of their own dead weight, weight of insulators and hardware; and therefore supporting steel structures of considerable height are used in order for providing sufficient clearance to equipment installed underneath and safety to maintenance personnel against the risk of flashover to ground due to air insulation breakdown governed by equivalent standard rod gap spacing.

The phase conductors are designed to calculated static sag and are spaced adequately apart to allow displacement under transient conditions for meeting minimum striking distances selected on the basis of standard basic insulation levels. This requires the employment of tall, wide and strong steel supporting structures at both ends of strain bus spans. The most common type of supporting steel structures used for strain bus application are lattice steel type with some exceptions of tubular or hollow structural section (HSS) design.

Strain bus system strung overhead with static conductor sag and tension is further exposed to additional stresses because of its air insulated design when it is subjected to electromagnetic forces due to system short circuits and wind loads. When short circuit occurs, strong electromagnetic forces are generated between phase conductors; intensity of which increases as square of magnitude of short circuit current. Due to strong electromagnetic forces, strain bus conductors are displaced from their static or rest positions attaining elevated positions until the time fault is interrupted by circuit breakers commanded by protection relays deployed. During this time, conductors attain significant potential energy which once released by removal of short circuit; drop down and start swinging about their rest positions. The higher the magnitude of short circuit, the stronger are the electromagnetic forces, as well as the swing out of strain bus conductors.

The displacement of strain bus during short circuit; then drop down and swinging after removal of short circuit induces strong dynamic tensile forces in conductors which are much higher in comparison with their initial static tensions. Electromagnetic forces act on strain buses for a short duration of short circuit depending on circuit breaker trip time and protection relays response time to fault and trip signal relayed to circuit breaker (s) which with modern high speed circuit breakers and IEDs is in the order of 5 cycles and 12 cycles for 60 cycles per second power system frequency for cases of successful circuit breaker tripping and breaker failure condition respectively. The other condition which strain bus system can experience is breaker unsuccessful reclosing when breaker opens to clear an initial fault but recloses after predetermined time delay and opens again due to the persistent fault condition which causes the bus to see the fault twice in a short duration of time before the conductors come to rest because of initial short circuit.

Although, fault durations are short; however, the impact of faults on strain bus system resulting in dynamic forces is very significant and lasts longer than fault durations. Therefore, the strain bus systems must be designed for their normal operating as well as power system transient operating conditions. In addition to dynamic forces caused by conductor swing out, another phenomenon called bundle collapse or pinch effect also becomes important when phase conductors consist of more than one conductor per phase. The bundle collapse phenomenon is an even more stringent condition for bundled strain bus; however, is not the subject of this paper and will not be discussed further.

The present infrastructures of majority of power utilities was placed in service several decades ago when power systems were much smaller in terms of generation and transmission capacities. Eventually system short circuits were also smaller in magnitudes than in present day's exponentially grown up power systems which result in very high short circuits. In the perspective of large growth of short circuit currents; it has become imperative both for new infrastructure to be designed and aged infrastructure to be evaluated and assessed against risk of failure under transient conditions. The impact on both types of infrastructure could be drastic in terms of either constraint on their operation or implementation of new design concepts culminating into huge capital investments. In order to assess the capabilities of existing infrastructures and to develop strategy of planning and engineering of new infrastructures; a thorough and comprehensive analysis is warranted.

During the past two decades, many utilities have commenced efforts to this end and have evolved different tools and strategies for addressing the challenge. Efforts have also been made for using new approaches for analysing the problem including finite element analysis but not to the extent of being validated by appropriate methods. In this paper, the challenge of dynamic forces induced into strain bus system due to short circuits will be analysed in a detailed and comprehensive manner using a commercial finite element program capable of conducting non-linear analysis. This will be done by modelling two strain bus designs which are typically used in transmission system. Finite element analysis results will be compared with simplified calculation method. Finite element analysis methodology adopted will further be validated by third model built to match an experimental strain bus span which was subjected to real short circuit tests.

2. Methodology

2.1 Simplified Calculations Approach

Generally simplified calculations approach is employed in the industry for calculating mechanical effects of short circuits on strain bus for obtaining an optimum design for meeting set of parameters specific to each case. The simplified methods are available as general guidelines provided in industry standards such as IEC 60865-1 [1], IEC TR 60865-2 [2] and IEEE std. 605-2008 [3]. In general, IEEE std. 605-2008 uses a method similar to that given in IEC std. 60865-1-2011. Both of these industry standards provide method for the calculation of mechanical effect of short circuit on strain bus for phase conductors in horizontal configuration which is the most severe configuration in comparison with vertical configuration used in transmission stations. Annex G of IEEE std. 605-2008 provides simplified calculations for the example of section 4.2.4 of CIGRE brochure WG 02 of SC23, 1987 [4] using a method similar to the one given in IEC std. 60865-1 and example given in Annex I of IEEE std. 605-2008. This simplified method will be used for comparing results of finite element analysis.

2.2 Finite Element Analysis Approach

Simplified calculation methods are generally conservative. The reason for conservatism lies in the fact that simplified methods overestimate several parameters. Another major factor is the stiffness of supporting steel structures; in addition to stiffness that of strain bus conductor, insulators and conductor hardware. In simplified method, the stiffness is mostly based on equivalent stiffness of conductors and insulators, whereas the stiffness of supporting steel structures is generally not accounted for. As opposed to the simplified method, in finite element method conductor, insulators, conductor hardware and most importantly supporting steel structures can be modelled at the same time in precise manner in terms of their geometries and physical properties due to which the stiffness of each of the component can be taken into account.

The finite element method provides several advantages over the simplified method. This includes three degrees of freedom at each boundary between conductor, hardware, insulators and supporting structures. In this manner, a more realistic approach towards stiffness of all elements including supporting structures can be incorporated into the model for simulations for each phase contrary to simplified method which uses the parameter on generic basis for single phase only. Finite element method also permits simulating short circuit in all three phases based on characteristics of each phase paving way for more accurate estimate of electromagnetic forces against the simplified method. Furthermore, simulation results obtained from finite element method provides history of computed quantities over the duration of simulation, whereas in simplified method discrete quantities are estimated in linear terms.

2.3 Strategy Employed for Finite Element Analysis

In this paper, an analysis of two strain bus spans is being presented. The design of both bus span models is based on a design typically used in transmission stations at 230 kV voltage level. The model of bus span 1 consists of twin bundle conductors per phase with span length of 29.7 m; whereas the model of bus span 2 consists of single conductor per phase with span length of 53.3 m. Strain buses in both spans are attached to lattice steel structures consisting of two towers supporting a girder at each end of bus spans with bus attachment height of 15.6 m. Buses are attached to structures using single insulator chains; each chain consisting of 14 suspension insulators. Spacing between phase conductors is 4.6 m. Physical properties of materials of bus components used in finite element models were based on properties of actual components.

Additionally, in order to validate finite element simulation results of two bus span models, a third model was simulated. This model used the same design philosophy as that of the other two models and represented a strain bus span consisting of single conductor per phase of same size and material as was used for other two bus span models. The bus span was also supported on similar lattice steel structures. As an exception, this span had a reduced spacing between phases of 1.52 m. Bus was attached to supporting structures at height of 10.3 m. The insulators and conductor hardware used on this span was also of similar design. Actual short circuit tests were conducted on this strain bus span installed in outdoor yard of a third-party test laboratory during the year 2010. The experimental data recorded during tests and physical dimensions of test span were used to match and calibrate the model to experimental test span and to validate the model to measured data.

2.4 Short Circuit and Wind Loads

A maximum three phase short circuit current of 63 kA rms symmetrical was used for simulation of model of twin conductor bus span 1 for a maximum duration of 15 cycles i.e. 0.25s for system frequency of 60 cycles per second for representing breaker failure condition as the worst condition of short circuit stress. For the case of model of bus span 2 consisting of single conductor per phase, an initial short circuit of 63 kA rms symmetrical was applied for a duration of 5 cycles i.e. 0.083s followed by 45 kA after 1.0 second reclosing delay for representing an unsuccessful circuit breaker reclosing for the same fault duration.

A time constant of 0.08s and phase angle of 88° corresponding to system X/R ratio of 30 was used for taking into account DC component of short circuit current into the simulation of finite element models. The phase angle corresponded to the angle by which current lags the voltage at the instant when the short circuit occurs. A winter temperature of -10°C and an ice load of 13 mm thickness on strain bus conductors was used for simulating winter condition. In order to make realistic comparison of results of finite element simulations with simplified method, no wind load was used in simulations except for a nominal wind of 0.225 Pa corresponding 0.6 m/s was used in simulations of both models which IEEE std. 605-2008 Annex I used for sizing the conductor ampacity.

2.5 Short Circuit Force Equations

Simplified method given IEEE std. 605 derived from IEC std. 60865-1 uses equation 22 given here below for estimating linear electromagnetic force (N/m) on strain conductor in three phase system on the outer conductors:

$$F' = \frac{\mu_o}{2\pi}\,0.75\,\frac{I_{k3}^2}{a}\,\frac{l_c}{l} \tag{1}$$

The finite element program used for simulations uses Biot-Savart law to compute electromagnetic forces. The force (N) induced by element j on element i is computed by the equation:

$$\vec{F}_{ij} = \frac{\mu_o}{4\pi}\int_{e_i}\int_{e_j}\frac{i_i\,(t)i_j(t)}{r^3}\left(\vec{r}\wedge d\vec{s}_j\right)\,\wedge d\vec{s}_i \tag{2}$$

The total force (N) on element i is given by the sum over j:

$$F_i = \sum F_{ij} \tag{3}$$

Three phase short circuit is defined in finite element program by equations given here below:

$$i_1 = I_M\,[\sin(\omega t - \varphi) + \sin\varphi\,.\,e^{-Rt/L}] \tag{4}$$
$$i_2 = I_M\,[\sin(\omega t - \varphi + 120) + \sin(\varphi + 120)\,.\,e^{-Rt/L}] \tag{5}$$
$$i_3 = I_M\,[\sin(\omega t - \varphi + 240) + \sin(\varphi + 240)\,.\,e^{-Rt/L}] \tag{6}$$

3. Analysis of Simulations of Strain Bus Spans 1 and 2

3.1 Strain Bus Span 1

Bus span 1 along with supporting steel structures was simulated for 63 kA rms symmetrical three phase short circuit current using finite element program for simulating breaker failure condition. Calculations were also performed for the bus span using the simplified method. The simulation results of both methods are given in table I with plan view of bus span arrangement shown in figure 1.

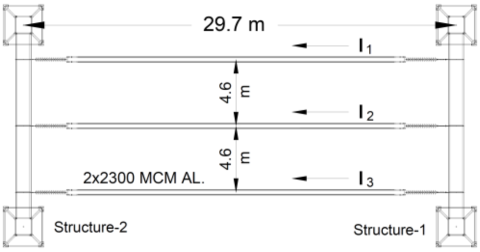

Figure 1 – Strain Bus Span 1

Table I – Results for Strain Bus Span 1

	Finite Element Method	Simplified Method
Static (Initial) Tensile Force (kN)	8.44	8.4
Static (Initial) Conductor Sag (m)	1.2	1.2
Max. Tensile Force during Short Circuit (kN)	19.1	14.2
Max. Tensile Force after Short Circuit (kN)	30.6	147.3
Max. Dynamic Sag (m)	1.52	N/A
Max. Conductor Horizontal Displacement (m)	0.99	1.09
Min. Clearance (m)	3.6	2.38
Max. Swing Angle (deg.)	33	57.3

The results show that the simplified method provides conservative estimate of all quantities. The tensile force after short circuit estimated by simplified method is overly conservative except for the tensile force during short circuit which is lower than that computed by finite element method. This concludes that tensile force after short circuit is 10 times of tensile force during short circuit which is not as expected because energy of strain bus system cannot jump to such a high level after conductor drop down as the actual source of energy i.e. short circuit is already removed.

On the other hand; the tensile force after short circuit computed by finite element method is about 50% higher than tensile force during short circuit which is indicative of the fact that finite element computations are realistic because a 50% increase in force after short circuit is also rationalized by the conductors drop down from approximately half the swing out computed by finite element method in comparison with swing angle estimated by simplified method.

Looking from the perspective of static tensile force, the tensile forces during and after short circuit computed by simplified method do not show a realistic relation with static tensile force as well as because the tensile forces during and after short circuit are approximately 1.7 and 17.5 times respectively of the static tensile force. Moreover, the tensile force after short circuit computed by simplified method is almost 5 times higher than the corresponding force computed by finite element method when the static tensile forces computed by both methods are the same. The tensile forces computed by finite element method show a more realistic trend in terms of static tensile force. A similar analysis is applicable about the minimum clearance between phase conductors and conductor swing angle.

3.2 Strain Bus Span 2

Bus span 2 along with supporting steel structures was simulated for an initial short circuit of 63 kA followed by a second short circuit of 45 kA three phase rms symmetrical using finite element method for a duration of 5 cycles i.e. 0.083s for each short circuit to simulate unsuccessful circuit breaker reclosing with reclosing delay of 1.0 second. The simplified method referenced in section 2.5 does not permit application of second short circuit and therefore, cannot simulate unsuccessful circuit breaker reclosing. Consequently, calculations using simplified method were performed for initial short circuit only. Results of both methods are given in table II with plan view of bus span arrangement shown in figure 2.

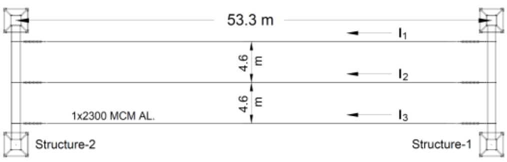

Figure 2 – Strain Bus Span 2

Table II – Results for Strain Bus Span 2

	Finite Element Method	Simplified Method (Initial S.C. only)
Static (Initial) Tensile Force (kN)	8.4	8.1
Static (Initial) Sag (m)	2.0	2.0
Max. Tensile Force during Initial Short Circuit (kN)	13.2	10.2
Max. Tensile Force after Initial Short Circuit (kN)	18.6	77.2
Max. Tensile Force during Second Short Circuit (kN)	25.2	N/A
Max. Tensile Force after Second Short Circuit (kN)	33.4	N/A
Max. Dynamic Sag (m)	2.47	N/A
Max. Conductor Horizontal Displacement (m)	1.78	1.62
Min. Clearance (m)	3.63	1.33
Max. Swing Angle (degrees)	36	41.4

Due to limitation of the simplified method, the results for bus span 2 can only be compared with finite element method for the initial short circuit. Maximum tensile forces during and after initial short circuit calculated by simplified method for bus span 2 show the same trend as was observed for bus span 1 which again indicates that simplified method produces conservative results in comparison with finite element method.

The simulation results of finite element method related to initial short circuit for bus span 2 also show the same trend as was noted in case of bus span 1 which is indicative of finite element method’s consistency and accuracy in analysing the problems.

The simulation results for tensile forces during and after second short circuit show an increase in forces from the level as a result of initial short circuit which is reasonable and was expected. The reason of the increase is because the bus conductors dropped down after initial short circuit and started swinging under dynamic forces. Then, before the conductors could completely be damped out; a second short circuit although of a lower magnitude was applied immediately after 1.0 second of time delay. Since, the conductors still contained energy from previous shot of short circuit and a second shot caused the conductors to gain additional energy by moving them apart due to electromagnetic forces and drop down again; therefore, the bus conductors responded with additional energy in terms of enhanced dynamic movement resulting in increased tensile forces.

4. Experimental Test Strain Bus Span

A model of strain bus span was built using finite element program to match exactly with an actual experimental test span along with supporting steel structures which was simulated for same short circuit current which was used during the experiment [5].

The static tensile force and static sag of the finite element model were calibrated exactly to match with those during experiment. A short circuit current of 50.35 kA rms symmetrical was injected into the centre phase conductor from the end at structure 1 in finite element model; while the same current was permitted to return through the outside phase conductors divided into equal halves using shorting jumpers between phases at the end of structure 2. This was done to simulate the current injection and electrical circuit configuration to match exactly to the conditions which were used when the tests were conducted during experiment. During the experiment, static tensile force, static sag, tensile force after short circuit were recorded by the instrumentation in the test set up.

The results of finite element simulations along with corresponding data recorded during experiment are given in table III. A plan view of experimental test span, showing short circuit current injection scheme and 3D view of finite element model are shown in figures 3 and 4.

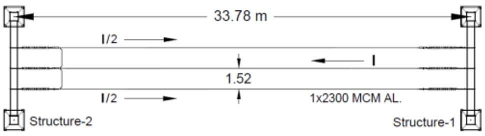

Figure 3 – Experimental Test Span

Table III – Results for Experimental Test Span

	Finite Element Method	Experimental Data
Static Tensile Force (kN)	13.5	13.5
Static Sag (m)	0.4	0.4
Max. Tensile Force during Short Circuit (kN)	24.2	N/A
Max. Tensile Force after Short Circuit (kN)	25.6	24.1

From the simulation results, it is noted that static tensile force and static sag computed by the finite element method exactly match with the coresponding data of experimental test span. This permitted the finite element model to calibrate to the same intial conditions which were used during experiment. Similarly, by using same current injection method which was used during experiment further made the model and simulations an exact replica of experimental test span.

The comparison of tensile force after short circuit computed by finite element method with the coresponding tensile force recorded during experiment shows a close and very reasonable agreement by 6% differential between simulation and experiment. Tensile force during short circuit was not available from experimental data.

The finite element simulation results of experimental test span for tensile force during and after short circuit show a narrow margin among them which is slightly different than what was observed during analysis of bus spans 1 and 2. Although the force after short circuit is higher than the force during short circuit which is the same trend as in other bus spans; however, the reason for a smaller margin is the static sag of experimental test span which is much smaller than static sags of bus spans 1 and 2. Due to smaller sag, the conductor drop down after short short circuit will not result in significant increase in tensile force. Another

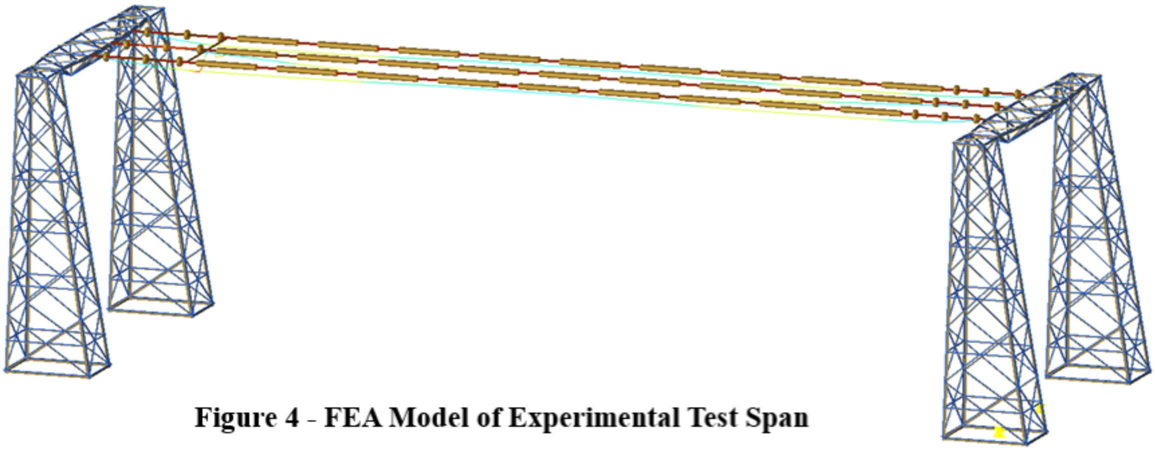

Figure 4 - FEA Model of Experimental Test Span

reason is the short circuit current injection scheme used in experimental test span in which outside conductors carried half the magnitude of current injected in centre phase which is not the same in case of bus spans 1 and 2.

5. Conclusion

The analysis of strain bus spans 1 and 2 conducted in previous sections has convinced that the simplified method tends to overestimate tensile forces, minimum clearance between phase conductors and conductor swing angles due to short circuit. At the same time, the tensile force during short circuit was underestimated by the simplified method for bus spans 1 and 2 which implies that simplified method is inconsistent in estimating the gravity of the impact of short circuit on strain bus and therefore, cannot be trusted specially when the short circuit are higher and wind load also needed to be simulated.

The reason for such inconsistency in simplified method lies in the fact that the simplified method makes estimates of complex parameters such as static tensile force, tensile forces during and after short circuit, and conductor swing based on simplified equations. The effect of DC component of short circuit current is not taken into account precisely. The effect of electomagnetic force is estimated generically using a single value of short circuit current applied to all three phases and in linear terms. The dynamic response of bus conductors after conductors drop down upon removal of short circuit by opening of circuit breaker is also estimated based on factors used by simplified equations which result in overestimation.

Another reason of overestimating force after short circuit and to an extent underestimating force during short circuit by the simplified method also leads to the fact that simplified method depends on equivalent stiffness of the bus conductor and insulator chain system only and do not take into account actual response of supporting steel structures which does not only depends on material properties but also depends on geometrical configuration of structures themselves.

The significance of stiffness of supporting steel structures which in fact are an integral part of strain bus system together with conductor and insulators is significantly important in determing static and dynamic response of strain bus before, during, and after short circuit. Supporting steel structures thmselves having flexible behaviour, and by virtue of which they absorb part of the energy during short circuit and dissipate the energy during conductor swing by thier vibrational displacement ; exhibiting response coresponding to its own frequency of vibration which directly affects calculations of the aforementioned quantities. The displacement of supporting steel structure due to short circuit forces was verified during short circuit experimental tests conducted on strain bus in 2010.

The simplified method take into consideration thermal expansion of bus conductors due to short circuit current; however the effect is most likely overestimated which results in overestimating horizontal displacement of conductors and minimum clearances between phase conductors. Moreover, simplified method has additional limitations such as it cannot simulate strain bus operating condition of circuit breaker reclosing.

Finite element method can take into account all of the above constraints those simplified method has, can perform simulations on actual geometrical configurations of strain bus components including supporting steel structures, and can simulate operating conditions as required. Due to the these advantages finite element method has over simplified method, it provides accurate, precise, consistent and detailed results. Finite element method can provide history of computed parameters which helps in performing in depth analysis of the problem. This also permits detailed analysis of supporting steel structures in case warranted.

As a result of the work presented in this paper with respect to finite element method versus simplified method for analysing strain bus system for assessing the response of strain bus system under the influence of short circuits; it is concluded that the finite element analysis method can be trusted for analysis involving complexity based on verification by finite element analysis of the experimental test span in which the simulations were found in agreement with the results recorded during the experiment.

In concluding the comprehensions from the preceding sections; conducting finite element analysis of strain bus systems is recommended for existing transmission infrastructure for their condition assessment, system planning and engineering of strain bus systems for new infrastructure which will result in accurate, and cost effective solutions and can help in determining strategies for ensuring reliable transmission system operation along with enhanced safety for operating personnel.

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