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Impact of High Short-Circuit Current on Air Insulated Station Strain-Bus Design

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SUMMARY

The generalized approximate method, recommended in IEEE STD 605-2008, is widely used for the strain or flexible bus design calculations. With notable increase of short-circuit levels around the globe, the direct application of such approximate method described in the standard shows very high level of forces associated with short-circuit current that would have great economic impact, and in some cases raises difficult constructability concerns as designers cannot find insulator strings that can meet this level of force. On the other hand, the Finite Element Analysis (FEA) method provides more accurate time-domain solution of the problem based on instantaneous values of short-circuit current. The application of FEA based analysis tool that takes into account instantaneous fault current magnitude and structural dynamics of the conductors and insulator strings are considered in this paper. Though it is computationally exhaustive, the result attained by using it is more accurate and mimic, to better extent, the actual forces observed in the field compared to approximate methods recommended in the standards.

This paper presents a comparison between IEEE STD 605-2008 Standard and FEA method as applied for air insulated strain-bus design calculations. It is also demonstrated that the results obtained by following IEC 60865 equations corelate well with FEA method than they do with IEEE 605. The comparison uses the design of a strain bus of new 230kV air insulated substation as a practical case study. In this substation, a three phase flexible bus system is modeled in SAMCEF Field software v16.2 which is an FEA based analysis tool that takes into account instantaneous fault current magnitude and structural dynamics of the conductors. Simulation results were then compared with the IEEE STD 605-2008 simplified analyses. Results showed that forces during short circuit matches very well with the simplified calculations. However, the difference is large for the drop back and pinch effect forces. The difference can be attributed to the generalization of simplified calculation to worse case as opposed to time-domain solution of the problem based on instantaneous values of short-circuit current in FEA. The phase clearances are found to be larger in FEA citing the fact that simplified calculation assumes displacement of middle phase by the same magnitude as the outer phases which is not the case in real life due to simultaneous pull on the middle phase in opposite directions from the outer phases. This phenomenon is apparent from the FEA results.

The research work presented in this paper concluded that to ensure arriving at economic design that meet forces exerted on the strain bus during high short circuit current and to ensure that the design does not face constructability dilemma, there is an imminent need to update the IEEE 605-2008

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standard to completely harmonize with the approach presented in IEC standard 60865. These changes, if approved, can introduce substantial savings as illustrated in the presented case study for the cost associated with the development or up-rating existing air insulated HV station strain-bus design.

KEYWORDS

Strain bus, High Voltage, Substation, Finite Element, Short Circuit force, substation design, bus support, insulator.

1. INTRODUCTION

Traditionally the High Voltage and Extra High Voltage substations built based on strain (or flexible) bus arrangements consist of conductors supported by strain (or string) insulators at the ends and steel gantry structures (commonly referred to as portal type structures [1]). Analysis of short circuit forces in strain bus arrangements unlike rigid bus arrangements is quite complex in nature due to the fact that the short circuit forces occurring in strain bus arrangements are time varying not only because of alternating nature of fault currents but also because of ever changing phase to phase separation distances due to displacement under action of the very forces. To arrive at economical design, it is imperative to estimate as accurately as possible these forces which will enable proper selection of support elements (structure and insulators and other hardware) that are subjected to these forces.

The forces acting on the conductors cause a rapid acceleration of the conductors either towards or away from each other depending upon direction of the instantaneous current flow in each phase. The stresses are transmitted to the supporting elements like insulators and support structures. The available tools at disposal to substation design engineers to calculate such forces are simplified hand calculations laid out in standards such as IEEE 605-2008 [3] and IEC 60865 [4] and advanced computer simulations using finite element analysis. They are helpful for typical design cases and require only general input data. The results of such calculations are generally the maximum values of tensile forces and displacements. The procedure inherently contains safety margins and approximations at several stages of calculations [1, 2].

On the other hand the finite element analysis tools can be applied to any structural configuration but at the same time require detailed modelling information to truly represent the configuration in a model form. The finite-element methods have been demonstrated to produce good match with experimental setups by various investigators [5, 6]. Simplified methods allow calculations by hand with analytical equations and figures. The computation of dynamic and non-linear behaviour of structural elements is accurately captured in finite element analysis leading to accurate estimation of short circuit forces. The results are only limited by the degree of accuracy and detail of input data. Commercially available Finite Element programs such as ADINA [7], ASTER [8], SAMCEF [9] are capable of calculating the electromagnetic forces due to the short circuit currents. For this paper, SAMCEF software is used.

In this paper, a case study is undertaken for a greenfield 230kV AC switchyard employing strain bus design. The short circuit forces are calculated both by simplified method as well as finite element method. Specifically, the analytical equations and figures laid out in IEEE standard 605-2008 [2] constitute the hand calculations and SAMCEF software constitute for finite element analysis. The inputs used for both methods are consistent to have just comparison of the results. The paper concludes with discussion on comparison results and recommendations based on the results.

2. DESCRIPTION OF THE CASE STUDY AND CALCULATED VARIABLES

The bus arrangement studied in this paper is a typical three phase bundled conductor design supported by two portal type structures supported by string insulators on both ends as shown in Figure 1. The geometry, short circuit current information and conductor data are shown in the following tables:

Table 1: General design data

Parameters		Value
Maximum Operating Voltage		230kV
Fault current data	RMS Fault Current	36.0kA (three-phase short-circuit) 42.8kA (single-phase to ground)

	Fault current duration	0.484 seconds
	System Frequency	60 Hz
	X/R ratio	42.1
Ice	Radial ice thickness at any ambient temperature other than -20˚C.	0 mm
	Radial ice thickness at ambient temperature -20˚C.	37.7 mm
Temperature	Ambient temperature for sag calculation in summer	40 ˚C
	Ambient temperature for sag calculation in winter	-20 ˚C & -50˚C

Figure 1: Bus Arrangement

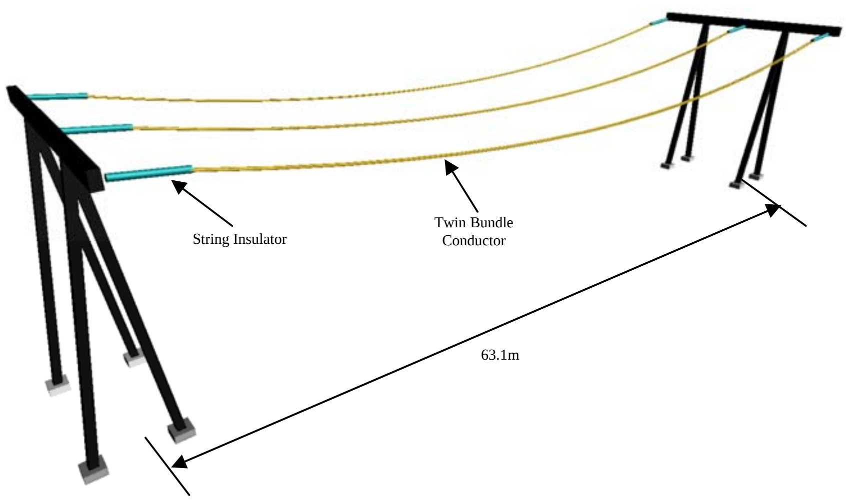

Table 2: Physical design data

Parameters		Value
Bus Conductor Data	Selected phase conductor & outside diameter	2000 MCM AAC Cowslip, 41.4 mm dia.
	Conductor Cross-sectional area (mm^2)	1013
	Linear mass (Kg/m)	2.8
	Conductor Young's modulus (GPa)	68.9
	Conductor coefficient of thermal expansion (1/˚C)	2.31×10^{-5}
	Conductor support point height above ground (m)	18
Span and structure data	Distance between two supports (m)	63.1
	Insulator Length (m)	2.5
	Insulator Diameter (m)	0.075
	Insulator Young's modulus (GPa)	60
	Length of the conductor span carrying current (m)	58

	Distance between spacers (m)	29
	Phase-to-Phase distance (m)	4.57
	Number of sub conductors and distance between sub conductors	Two bundled conductors, spaced 0.33m apart
	Equivalent Support Stiffness (N/m)	Infinite

The quantities of interest in the analysis are:

- Maximum tensile short circuit force during fault current, F_t
- Maximum tensile short circuit force when the conductor drops back, F_f
- Maximum tensile force caused by Pinch effect, F_{pi}
- Maximum phase-to-phase clearance during short circuit

Calculations are performed for three conductor temperatures representing three weather scenarios:

- - 20˚C (with ice)
- - 50˚C (without ice)
- 90˚C (summer)

3. ANALYSIS RESULTS

For hand calculations, step by step procedure laid out in Annex I of IEEE 605-2008 was followed to determine the key parameters. For FEA, a structural dynamic analysis tool named SAMCEF Field v16.2 as used to model the three phase strain bus system. The software takes into account the instantaneous fault current magnitude and structural dynamics of the conductors and the insulator strings. Tables 4 and 5 also include a column presenting results of calculations following IEC 60865-1 technique. Essentially IEEE and IEC standards simplified calculations are identical. For the purpose of this exercise, to have just comparison, the support structure was represented in SAMCEF as a rigid immovable point by setting its stiffness to a very high value. As an initial step the static tensile and sag at resting state was calculated respecting the minimum phase to ground clearance and conductor rated tensile stress. Table 3 below indicates the static tensile forces and corresponding sags. Tables 4 & 5 summarize the short circuit forces and phase displacements during short circuit calculated by the three methods. The pinch effect forces were calculated using Single Phase to Ground fault current as it is higher than three phase bolted fault.

Table 3: Sag and Tension

Sag & Tensions	Temperature	Sag	Tension (N)
Winter Sag	-20˚C	1.59 m	1.59 m
Winter Sag	-50˚C	1.25 m	1.25 m
Summer Sag	90˚C	2.50 m	2.50 m
Summer Tension	90˚C	5450 N	5450 N

Table 4: Tensions applied to insulators during and after short circuit

Short Circuit Forces	Temperature	IEEE 605 (N)	FEA (N)	IEC 60865 (N)
Maximum tensile short circuit force during fault current, F_t (N)	-20˚C	30,846.2	29,000	30,193.4
	-50˚C	38,807.4	40,100	37,612.9
	90˚C	18,753.7	18,125	18,612.9
Maximum tensile short circuit force when conductors drop back, F_f (N)	-20˚C	130,135.1	55,500	90,037.1
	-50˚C	121,057.6	74,375	88,588.1
	90˚C	149,505.1	26,250	95,335.1

Maximum tensile force caused by Pinch effect F_{pi} (N)	-20˚C	101,884.9	-[1]	65,836.6
	-50˚C	107,339.3	-	74,185.1
	90˚C	94,723.8	-	54,621.0

Table 5: Displacement during short circuit

Diplacements	Temperature	IEEE 605 (m)	FEA (m)	IEC 60865 (m)
Maximum horizontal displacement within a span, b_h (m)	-20˚C	1.01	1.3	1.04
	-50˚C	0.815	1.13	0.866
	90˚C	1.542	2.0	1.556
Minimum phase to phase clearance during fault condition, a_{min} (m)	-20˚C	2.552	3.1	2.482
	-50˚C	2.939	3.5	2.838
	90˚C	1.487	2.3	1.459

4. DISCUSSION

It can be observed that the force during short circuit correlate very well in all methods. The difference is large for the drop back forces. The phase clearances are found to be larger in FEA citing the fact that simplified calculation assumes displacement of middle phase by the same magnitude as the outer phase which is not the case in real life due to simultaneous pull on the middle phase in opposite directions from the outer phases. The difference in drop back forces can be attributed to the generalization of simplified calculation to worse case as opposed to time-domain solution of the problem based on instantaneous values of short circuit current in FEA. In other words, simplified calculations assume drop back will occur irrespective of the displacement of conductors whereas FEA may not show conductors actually dropping back depending on the conductor mass and displacement of conductor from its resting position. Following obervations can be made from the results :

1. Despite the fact that IEEE 605 simplified calculation is derived from IEC 60865, except the short circuit tensile pull during short circuit and conductor displacements the drop back and pinch effect forces are quite different when calculated using two standards.

2. FEA results tend to agree more with IEC 60865 results than IEC 605.

3. Designing systems to withstand such higher forces suggested by IEEE approach is not economical and in some cases impractical.

Following main differences between the IEEE and IEC calculations were found that are believed to be the underlying reason for the mismatch between the results:

1. Conductor Flexibility: IEC uses actual Young's modulus which takes into account the actual tensile force acting on the conductor. In other words, the Young's modulus of conductor is not a constant per IEC philosophy. IEEE on the other hand assumes a constant Young's modulus. This results in the difference between the flexibility of conductor and its ability to absorb forces. For lower forces, actual Young's modulus is also lower improving the flexibility in turn improving the force absorption resulting in lower tensile forces acting on the support elements.

[1] Pinch effect force calculations was not numerically possible by FEA due to the fact that bundle conductor spacing becomes zero during short circuit due to mutual attraction resulting in singularity.

2. Support Structure Flexibility[2]: IEEE ignores structural flexibility for portal type structures with horizontal strain insulators, whereas IEC does not. The damping capability of the structure is nil in IEEE approach resulting in extremely large forces.

3. Selection of design force for Support Structure: IEEE recommends using three times the larger of the three forces (F_t, F_f and F_{pi}) for structures supporting three phase bus systems. IEC on the other hand recommends using twice the larger of three forces for two phases plus one times the static tensile force for the third phase. Evidently, the IEC approach results in lower forces applied on support structure.

5. CONCLUSION

This paper attempts to present a comparative analysis of tensile forces and conductor displacement in event of short circuits on commonly used flexible or strain bus systems in High Voltage substations by following three techniques – Simplified hand calculations using IEEE 605 & IEC 60865 and Finite Element Analysis. The comparison uses the design of a strain bus (employing twin bundled conductors) of a 230kV air insulated substation as a practical case study. Results showed that the tensile forces during short circuit and phase displacements are similar when calculated using the three techniques. However, the difference is large for the drop back and bundle pinch effect forces. IEEE 605 tends to overestimate the short circuit forces resulting in an uneconomical design. The underlying reasons found for the mismatch between the results especially between IEEE 605 and IEC 60865 are believed to be the way the two standards treat conductor Young's modulus, support structure rigidity and selection of design forces for support structures. It is imperative to update the IEEE 605-2008 standard to completely harmonize with the approach presented in IEC standard 60865. These changes, if approved, can introduce substantial savings as proven in the presented case study for the cost associated with the development or up-rating existing air insulated HV station strain-bus design.

End of text

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[2] Though this paper did not consider structural flexibility even in IEC calculations, it is worthwhile highlighting the difference here.