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A Finite Element Analysis Approach for Calculating Forces Acting on Station Post Insulators, 'A' Frame Assemblies, and Corners of Rigid Bus Due to High Short Circuit Currents and Extreme Wind

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SUMMARY

For the design of bus in bulk supply transmission stations, rigid bus is the option of choice because of to its ability to sustain stresses caused by high short circuit currents and wind loads. Rigid bus consists of hollow tubular conductor supported on porcelain station post insulators. Generally large stations layout requires main, diameter and jitney buses to turn at angles and crossing over adjacent bays. This is achieved by installing rigid bus at different elevations using 'A' Frame assemblies.

Calculations of mechanical effects of electromagnetic forces due to short circuit current and wind acting on straight parallel runs of buses and their supporting insulators is performed using classical simplified methods. However, the simplified method does not provide guidelines for cases when buses change direction. Due to change of bus direction, the current also changes direction which affects electromagnetic field. As a result, electromagnetic forces do not remain uniform in the vicinity of direction change. Due to this reason, design engineers make engineering judgement in such cases based on simplified method applicable to straight runs by providing additional design margins resulting in over investments yet without having design confidence.

The inability of simplified method to assess stresses at direction change and increase in short circuit currents resulting from tremendous growth of power systems have necessitated for employing more accurate approach for estimating dynamic effects of short circuits on rigid bus changing direction. In this paper, finite element analysis approach will be used for analyzing dynamic forces acting at corners of rigid bus changing direction, 'A' frame and other elements. This will be done by modeling rigid bus configurations typically used in 230 kV stations using commercial finite element program and the findings will be presented.

KEYWORDS

Rigid – Bus - Conductor – 'A' Frame- Station Post Insulator – Cantilever Rating - Force – Dynamic - Structure – Stiffness – Short Circuit.

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1. Introduction

In transmission stations, two types of buses are used for permitting the flow of bulk power through various elements like autotransformers and transmission line bays. The two types are strain and rigid bus. Although cost effective, however, strain bus has limitations at high short circuit currents because of its tendency to swing out resulting in high tensile forces and reduction of clearances between phases during short circuit.

Consequently, rigid bus is the choice in case of high short circuit currents. Displacement of rigid bus from its rest positions due to short circuit forces and wind is unnoticeable. Moreover, its construction permits placing phases at shorter distances apart in comparison with strain bus. As a result, rigid bus design results in comparably smaller station footprint and cost savings in terms of real state. Low profile associated with rigid bus is an added advantage which eliminates concerns with respect to aesthetics permitting its use in urban areas. Rigid bus consists of hollow tubular bus conductors supported on station post insulators using different types of bus supports and low-profile supporting steel structures of hollow structural section (HSS) construction.

The insulators used for supporting rigid bus for high voltages 115 kV and above and high short circuit currents are made of porcelain which offer higher cantilever strengths in comparison with polymeric type which is a major requirement for such applications. Bus conductors of hollow tubular construction manufactured to NPS standard sizes made of aluminum are used. Bus supports interfacing between station post insulator and aluminum tubular bus are also made of aluminum alloys.

In addition to sizing of tubular bus for meeting required continuous load current, emergency operation load current, and minimum requirement of short circuit current from thermal perspective; rigid bus is also designed to withstand mechanical effects of short circuit loads together with bus supporting insulators for bending stress on bus conductors, maximum span between insulators, cantilever strength of station post insulators and stresses in supporting steel structures. The aspect of mechanical effects of short circuit is required to be assessed on rigid bus as integrated system including all aforementioned elements.

When short circuit occurs; strong electromagnetic forces are generated between phases of rigid bus conductors which are transferred to insulators and supporting steel structures, resulting in strong dynamic mechanical stresses within these elements. The higher the short circuit; the higher are the stresses. Bus conductor, station post insulators, and supporting steel structures are required to be designed to withstand such forces for a safe and reliable design. The duration of short circuit is also a key parameter in assessing mechanical effects of short circuit on rigid bus. Rigid bus associated with line exits usually see short circuit for shorter duration in comparison with main bus; however, line exit bus may see a second stress due to unsuccessful breaker reclosing in case short circuit persist. Breaker failure condition which usually takes longer to clear the fault is usually the most severe short circuit duty for rigid bus mostly applicable to station main bus.

2. Methodology

2.1 Simplified Calculations

The industry standards such as IEEE std. 605 [1], and IEC std. 60865-1 [2] and 60865-2 [3] provide simplified calculations methods for calculating short circuit dynamic forces on rigid bus system elements for their design. Some of the power utilities have developed their own simplified methods based on their internal research and experience spanned over long period of time. These methods are simple to use and produce results faster. Due to these reasons, the approach of simplified method is generally acceptable in utilities and other companies.

However, simplified methods are only applicable in case of straight and parallel runs of rigid bus conductors.

In every transmission station where rigid bus is used; rigid bus conductors cannot always be kept straight. The buses frequently turn at right angles for directing line exits to desired direction, making connections to transformers and folding the diameter; whereas, the simplified method provides solution for designing rigid bus in transmission stations only when the rigid bus is straight. Moreover, simplified method cannot accurately simulate the effect of supporting steel structures. Therefore, due to lack of solution offered by simplified methods for cases when rigid bus changes direction; most of the companies use additional design margins for addressing unknowns associated with the case of direction change.

The challenge in design of rigid bus changing direction lies in the fact that when bus changes direction, the current flowing through the bus does so too. When buses are straight and parallel, electromagnetic field generated by the flow of current is uniform and so are the electromagnetic forces. Contrary to straight bus runs, when buses change direction, the resulting change of current direction causes electromagnetic field produced in the vicinity of corners of rigid bus changing direction not to remain uniform and therefore, it is difficult to predict its behaviour with simplified methods.

Assessing electromagnetic forces due to short circuit current on ‘A’ frame assemblies used in rigid bus at change of bus direction is another challenge for which simplified method also do not provide solution. ‘A’ frame assembly is made of aluminum tubular bus conductor in triangular shape. The base of ‘A’ frame assembly being part of the low-level bus rests on station post insulators, whereas the top of ‘A’ frame formed by two triangular arms supports transverse rigid bus at higher elevation. This implies that ‘A’ frame acts as support for transverse bus which role at other locations is performed by station post insulators. This makes ‘A’ frame a vulnerable component in rigid bus system, however, its response under short circuit cannot be assessed by simplified method.

2.2 Finite Element Analysis Approach

In the absence of design and analysis techniques in simplified method for assessing mechanical effects of short circuits on rigid bus changing direction, the solution is offered by finite element method. An available finite element program capable of performing non-linear analysis of complex problems such as rigid bus including bus direction change and ‘A’ frame assembly will be used for modelling and simulations of selected rigid bus design configurations.

Finite element method is not fast method as simplified method. In simplified method, simple string of data is entered into pre-built spreadsheet which provides results based on calculations for one phase only. Finite element method requires building model of the desired three phase configuration of rigid bus including bus conductors, station post insulators and supporting steel structures along with definitions of physical properties of each component. Furthermore, the connections between bus conductors, insulators, supporting steel structures and their sub-constituent parts are required to be defined in terms of six degrees of freedom for the program to calculate forces, displacements, stress, moments and other parameters at each element. Due to this reason, finite element method takes longer to analyse the rigid bus.

In addition to providing a solution to complex problems, finite element analysis method provides additional advantages over the simplified method. These include permitting application of short circuit current in each of the three phases along with time constant and phase angle to account for dc offset, applying wind and ice loads and ambient temperature.

All this permits a more realistic approach towards solving problems associated with rigid bus. Additionally, finite element method provides detailed results for each phase, each component, and provides history over time of forces, displacements, moments and other parameters.

2.3 Strategy Employed for Finite Element Analysis

The analysis of three (3) rigid bus design configurations will be presented in this paper. Finite element models of all three configurations were built. The design of the models was based on the design typically used in transmission stations at 230 kV voltage level. All configurations consist of three phase arrangement consisting of single tubular conductor 8" NPS aluminum bus per phase changing direction at 90^o and supported on porcelain insulators 900kV BIL and 26.7 KN cantilever ratings. At one end of direction change, bus has phase spacing of 3.8 m, and at other end has phase spacing of 4.8 m. Insulators are mounted on three phase pi and single-phase structures of HSS construction. 'A' frame assemblies made of 8" NPS aluminum bus conductor to facilitate change of bus direction at 90^o and at the same time to elevate the transverse bus to higher elevation permitting crossing over the bus in adjacent bay have been used in configurations 2 and 3. Configuration 1 do not use 'A' frame assemblies, yet, the bus changes direction at 90^o; however, the bus keeps same elevation after direction change. The bus with 3.8 m phase spacing is termed as 0^o bus and that with 4.8 m phase spacing as 90^o bus with respect to direction change. Physical properties of materials of tubular aluminum bus, porcelain insulators and supporting steel structures and their physical dimensions were based on typical design. A comparison of finite element simulation results will also be made with calculations performed using simplified method given in IEEE std. 605 [1] but only for straight bus runs related with bus configuration 1.

2.4 Short Circuit and Wind Loads

Maximum three (3) phase short circuit current of 80 kA was applied on all three (3) phases of each model of bus configurations 1, 2 and 3 for a short circuit duration of 15 cycles i.e. 0.25s for representing breaker failure condition as the worst condition of short circuit stress for system frequency of 60 cycles per second. A time constant of 0.08s and phase angle of 88^o corresponding to an X/R ratio of 30 was used to account for DC component of short circuit current into the simulation of finite element analysis. The phase angle corresponded to the angle by which current lags the voltage at the instant when short circuit occurs. An extreme wind load of 110 km per hour and an ambient temperature of 0^oC were used.

2.5 Short Circuit Force Equations

The simplified method given in IEEE std. 605-2008 uses equation 16 by correcting basic force equation 14 alleviating some of conservatism for calculating electromagnetic force by unit length:

$$F_{sc\_corrected} = D_f^2 K_f \left(\frac{16\, \Gamma\, I_{sc}^2}{10^7 D} \right) \tag{1}$$

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

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

And, the total force 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 per equations given below:

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

3. Analysis of Simulations of Rigid Bus Configurations

3.1 Rigid Bus Configuration 1

The finite element model of configuration 1 involving buses changing direction at 90° at the same elevation on both sides of direction change including aluminum bus, porcelain station post insulators and supporting steel structures was built using finite element program. Clamp, slide and expansion connections at respective bus support locations as part of design were defined in the model. The model was simulated for 80 kA three phase short circuit current with DC offset taken into account, 110 km per hour wind and breaker failure condition. Calculations were also performed for the bus span using the simplified method for straight bus runs only. Calculations for simplified method were performed using method given in IEEE std. 605-2008 for the force in horizontal direction on vertical insulator for the same span length of straight bus run, short circuit current, wind and other parameters as used in finite element model. Simulation results of finite element analysis for bus configuration 1 and simplified method for straight bus run are given in table I along with plan view of bus span arrangement shown in figure 1.

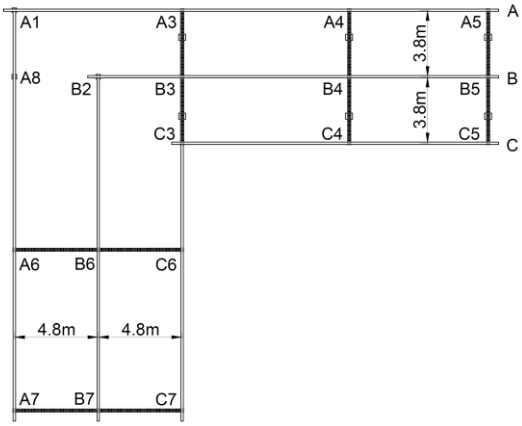

Figure 1 – Rigid Bus Configuration 1

Table I – Results for Rigid Bus Configuration 1

Insulator Location	Peak Cantilever Force on Insulator		Peak Stress in AL. Bus at Bus Support	
	Finite Element Method	Simplified Method	Finite Element Method	IEEE std. 605 - Max. Allowable
	kN	kN	MPa	MPa
A5 at 0° Bus	5.5	28.7	21.4	120.0
A4 at 0° Bus	8.0		22.1	
A3 at 0° Bus	10.0		32.6	
A1 at 0° Bus	17.0		41.3	
A8 at 90° Bus	8.4		22.6	
A6 at 90° Bus	7.1		20.6	
A7 at 90° Bus	6.6		31.3	

The results given in table I show that the simplified method estimated overly conservative force at insulator for straight bus run when compared with those computed by finite element method for the same span of straight bus runs for example at insulators A3 - A5 and A8, A6, A7. Moreover, the result of simplified method is not only conservative in comparison with corresponding finite element results but is even conservative when comparing with finite element result at the corner (bus direction change) at insulator A1. On the contrary, the forces computed by finite element method at insulators along straight bus sections on both sides of the corner (bus direction change) are reasonable and consistent. The force computed by finite element method at the corner (insulator A1) is higher than forces computed by finite element method for straight bus sections which is as expected. Moreover, the results of finite element method in addition to showing the expected pattern also provided more precise values of computed forces. In respect of stress experienced by aluminum bus due to electromagnetic forces, IEEE std. 605 refers to 120 MPa as the maximum allowable stress; whereas the peak stresses computed by finite element method given in table I show precise values much lower than the maximum value specified by IEEE std. 605.

3.2 Rigid Bus Configuration 2

The finite element model built for configuration 2 consisted of same design philosophy of buses changing direction as in case of bus configuration 1. However, the bus configuration 2 additionally used three ‘A’ frame assemblies for facilitating change of bus direction together with elevating the buses at the location of direction change to permit crossing over the buses in adjacent bay. At the other end of bus direction change, the bus configuration 2 used flexible conductor drop leads. This model was also simulated for 80 kA three phase short circuit current with DC offset taken into account, 110 km per hour wind and breaker failure condition. Simplified method was not applicable for this case as it do not provide solution for bus direction change and ‘A’ frame, therefore, calculations were not performed. Simulation results of finite element analysis for bus configuration 2 are given in tables II and III with plan view of bus span arrangement shown in figure 2.

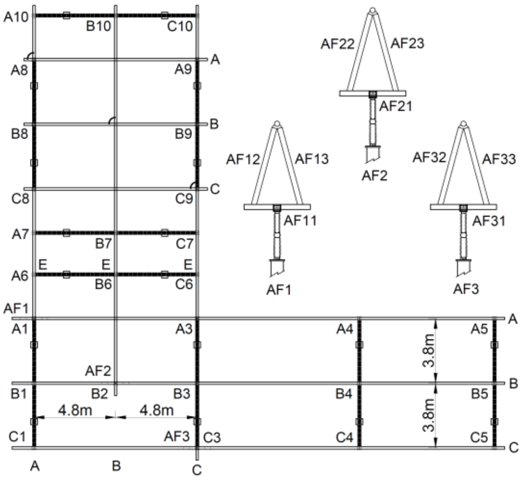

Figure 2 – Rigid Bus Configuration 2

Table II – Results of Rigid Bus Configuration 2

Insulator Location	Peak Cantilever Force on Insulators	Peak Stress in AL. Bus at Bus Support
	kN	MPa
C5 at 0° Bus	10.7	56.2
C4 at 0° Bus	13.5	60.1
C3 at 0° Bus	38.0	99.1
B2 at 0° Bus	30.0	47.3
C1 at 0° Bus	26.2	91.5
B1 at 90° Bus	14.0	52.1
A1 at 90° Bus	28.1	64.5
A6 at 90° Bus	29.6	103.8
A7 at 90° Bus	32.2	105.6
A10 at 90° Bus	15.9	117.8

Table III – Results for Rigid Bus Configuration 2

Peak Force and Stress at mid Span and Displacement of Top of "A' Frames			
'A' Frame Span	Force	Stress	Displacement (Transverse)
	kN	MPa	mm
AF11	13.5	65.2	55.0
AF12	6.0	52.8	
AF13	6.5	36.6	
AF21	13.0	50.2	42.0
AF22	5.0	41.3	
AF23	4.6	40.2	
AF31	21.5	94.4	52.0
AF32	5.5	65.5	
AF33	6.0	70.8	

Bus configuration 2 is much more complex in comparison with bus configuration 1 because of ‘A’ frame assemblies, flexible drop leads and two elevations of buses. Due this reason, the results at corners (bus direction change) do not follow the same pattern as was noted in the case of bus configuration 1. Although the computed forces are higher at corner (insulator C1) which is as expected; however, it has been further noted that the forces at insulators which are supporting the ‘A’ frame assemblies (insulators A1, B2 and C3) are even higher than those at the corner which is also as expected because of ‘A’ frame’s response acting as support for high level transverse bus together with facilitating the bus direction change. From the finite element results given in table II, it has further been noted that computed forces at insulator locations at bus direction change and vicinity are exceeding maximum cantilever rating (26.7 kN) of insulator. Moreover, insulators near flexible drops leads; not shown in tables were also noted to experience even higher forces.

Table II also provides finite element results for stress in aluminum bus at bus support locations mounted on insulators. The results of computed stress indicate that the stress in bus reaches close to maximum allowable stress of 120 MPa. Table III provides additional results for response of ‘A’ assemblies in terms of computed force and stress at mid span of ‘A’ frame bases and arms which are significant. Table III also provides displacement of top of ‘A’ frames under the influence of electromagnetic and wind forces. It is noted that the displacements are large. Moreover, the finite element results also indicated significantly large tensile forces caused by swing of flexible drop leads at other end of bus direction change.

3.3 Rigid Bus Configuration 3

The analysis of finite element results of bus configuration 2 showed that the design with ‘A’ frame assemblies and flexible drop leads resulted in overstressing of station post insulators at locations of bus direction change and vicinity beyond the maximum guaranteed cantilever strength; although the insulator used in the design was selected of the maximum available cantilever rating. The aluminum buses around the corners were overstressed and flexible drop leads also caused extreme forces. This situation may cause insulator and bus failure in case short circuit and wind loads used as design criteria may occur coincidentally which would be a risk to reliability of transmission station and safety of the personnel. From the above, it concludes that the design of configuration 2 does not meet design criteria of 80 kA short circuit with DC offset, 110 km per hour wind and breaker failure condition.

In consideration of the identified risk; a finite element model of reinforced design with three additional ‘A’ frame assemblies replacing flexible drop leads and with two insulators per bus support at overstressed insulator locations was built. The reinforced design also resulted in replacing pi supporting steel structures with single phase support structures at two insulator locations. The model consisting of reinforced design presented as bus configuration 3 was simulated for the same short circuit current, wind and breaker failure condition. Simulation results of finite element analysis for bus configuration 3 are given in table IV and V with plan view of bus span arrangement shown in figure 3.

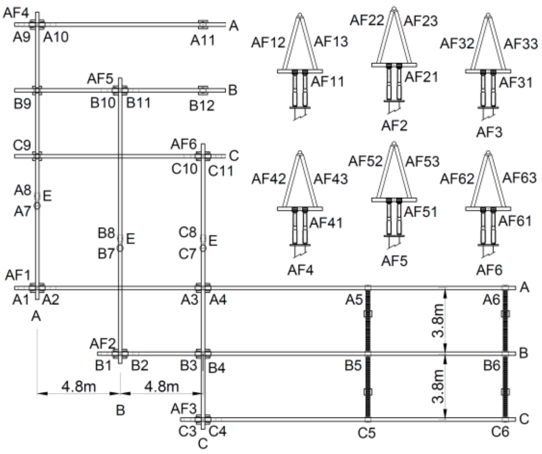

Figure 3 – Rigid Bus Configuration 3

Table IV – Results for Rigid Bus Configuration 3

Insulator Location	Peak Cantilever Force on Insulator	Peak Stress in Aluminum Bus
	kN	MPa
C6 at 0° Bus	7.4	29.4
C5 at 0° Bus	13.6	36.3
C4 at 0° Bus	16.9	48.3
B2 at 0° Bus	13.3	29.3
A2 at 90° Bus	9.0	18.0
A7 at 90° Bus	19.1	62.3
A10 at 90° Bus	13.6	37.9

From the finite element results of bus configuration 3 given in table IV; it is noted that forces on insulators at bus direction change and vicinity are well below maximum cantilever rating of the insulator (26.7kN). The highest force at insulator A7 is about 70% of the insulator rating. Some of the insulator manufacturers recommend for not loading insulators beyond 65% of guaranteed rating in consideration of risk of developing micro cracks. Although this requirement is not warranted by industry standards, however design of configuration 3 provides margin for offsetting such risk. The stress in aluminum bus at bus support locations computed by finite element analysis given in table IV are also well below maximum allowed stress of 120 MPa.

The finite element results given in table V for peak force and stress acting at mid span of 'A' frame bases and arms also indicate that computed forces and stress are significantly lower than those noted in the case of configuration 2. Further, a slight improvement in displacement of top of 'A' frame assembly has also been noticed. Globally, the results confirm that all of the design problems discovered in bus configuration 2 have been rectified in reinforced design of bus configuration 3 which makes the design of rigid bus configuration 3 a reliable, and safe design for 80kA short circuit, 110 km per hour wind and breaker failure condition.

Table V – Results for Rigid Bus Configuration 3

Peak Force and Stress at mid Span and Displacement of Top of 'A' Frames							
'A' Frame Span	Force	Stress	Displacement (Transverse)	'A' Frame Span	Force	Stress	Displacement (Transverse)
	kN	MPa	mm		kN	MPa	mm
AF11	4.0	20.6	45.0	AF41	2.8	22.7	37.0
AF12	4.9	28.0		AF42	4.2	23.4	
AF13	5.3	29.3		AF43	4.5	21.4	
AF21	5.0	28.9	45.0	AF51	2.8	30.1	35.0
AF22	5.1	29.2		AF52	4.0	26.8	
AF23	5.2	29.5		AF53	3.7	30.3	
AF31	5.8	33.3	50.0	AF61	5.8	38.6	45.0
AF32	5.0	34.6		AF62	6.0	36.0	
AF33	4.5	35.6		AF63	5.0	32.3	

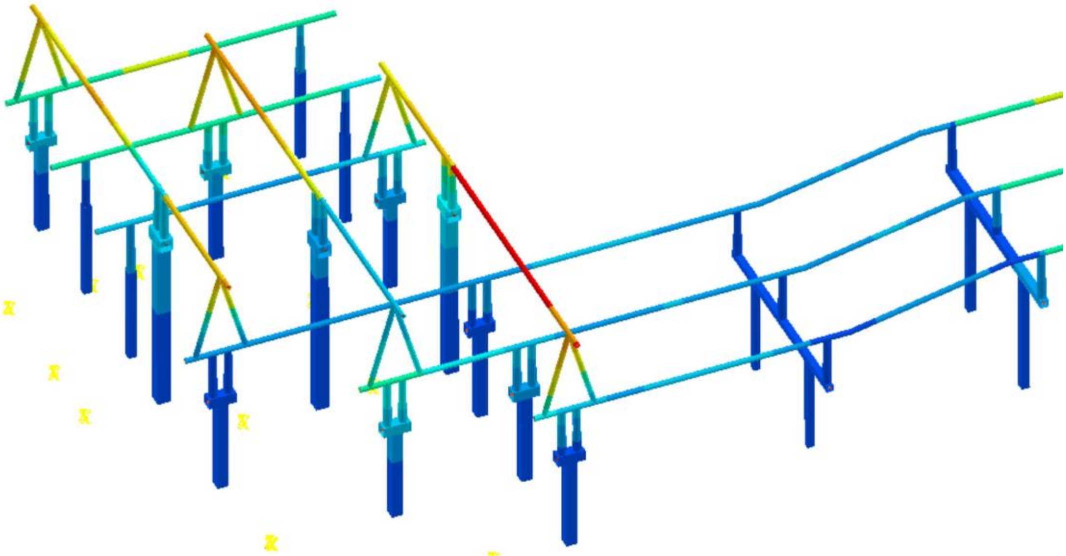

Figure 4 – Finite Element Model of Configuration 3 showing displacement of Bus components

A part of the finite element model of bus configuration 3 is shown in figure 4 for illustration purposes. The model shows displacement of bus components as a result of short circuit and wind loads on a colour scale. The red colour indicates maximum displacement about 50 mm, yellow about 20 mm and dark blue of about 5 mm from the respective rest positions.

4. Conclusion

The non-linear dynamic analysis was performed on three rigid bus configurations 1, 2 and 3 featuring the following specific design characteristics typically used in 230 kV and higher voltage class transformer stations:

- ❖ Buses changing direction at 90^o instead of being straight and parallel only.
- ❖ Bus configuration 1 involved change of direction such that buses after direction change remain at the same elevation.
- ❖ Bus configuration 2 involved change of bus direction as in the case of configuration 1; and additionally, the turning buses were elevated at direction change by using 'A' frame assemblies to permit crossing over the buses in adjacent bay. In addition, flexible conductor drop leads were used at the other location of direction change.

- Bus configuration 3 had the same design concept of bus direction change and elevating of turning buses as in the case of configuration 2; however, it incorporated reinforced design for addressing areas of over stresses identified in analysis of bus configuration 2.

Simulation and analysis of configuration 1 provided the basis for developing confidence that complex electromagnetic forces because of change of current direction due to change in bus direction and its impact on rigid bus components can be solved using non-linear finite element analysis method. A comparison of finite element simulation results with simplified method for a straight part of buses of bus configuration 1 provided an insight into the fact that simplified method although does not provide solution to the complexity associated with change of bus direction but even in a simple case of straight parallel bus provides overly conservative results which can cause investments to be higher even though not providing a complete and confident solution for the design challenge.

After gaining confidence from finite element simulations of bus configuration 1; a more complex design configuration 2 involving 'A' frames assemblies and flexible drop leads was simulated. The detailed analysis encompassing several design aspects associated with each component of rigid bus including each individual insulator, various sections of buses, 'A' frames, connections between components, steel support structures, forces, stresses, displacements helped to analyse dynamic impact of short circuit. The analysis concluded that design of bus configuration 2 do not meet design criteria for withstanding mechanical effects of 80 kA short circuit, 110 km per hour wind and breaker failure condition and hence the design is not safe and reliable.

As a result of conclusions drawn from analysis of bus configuration 2; a reinforced design of bus configuration 3 was developed. The simulations and analysis of bus configuration 3 confirmed its compliance to design criteria which reaffirmed that design of bus configuration 3 rectified design problems identified in configuration 2. This confirmed that design of bus configuration 3 is safe and reliable; however, at the expense of small increase in cost; estimated at 10-15%.

In summary, the finite element analysis presented in foregoing sections guides in arriving at a confident, safe and reliable design solution of complex problem of rigid bus. This paper concludes that an approach of detailed non-linear analysis based on finite element method is the trustable method for addressing challenges associated with aging infrastructure and growing power systems. Moreover, this approach in addition to providing solution to complex engineering problems, in many cases can also result in cost effective solutions providing basis for developing strategies for planning and engineering of capital and sustainment investments in transmission infrastructures.

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