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Comparing Static and Dynamic Analysis of Short Circuit Forces on Substation Rigid Bus: A Case Study

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SUMMARY

Short circuit forces generated by electrical faults on substation rigid bus conductor can have a significant impact to a design of supporting insulators, bus conductors, and steel structures. With increasing fault currents analyzed nowadays, e.g. matching short circuit interrupting rating of circuit breakers, on new or existing substations due to system upgrades or system expansions, the conventional design method that applies fault current as a static load may be found excessively conservative. Short circuit force is a dynamic load in nature that the load varies with time. It has been perceived that dynamic analysis of substation rigid bus design would result in lower stresses in supporting insulators, bus conductors, or steel structures; hence, yielding a longer bus span and potentially providing a cost saving to a project. While the dynamic analysis can provide more accurate results, the level of design complexity as well as the initial design effort of performing the dynamic analysis could be significantly higher than the static analysis.

This paper first briefly discusses short circuit load determination, as outlined in IEEE 605-2008 and CIGRE 105, applied as static load and dynamic load on bus conductor, respectively. Next, advantages and disadvantages on each design approach as well as design considerations are discussed. A case study was performed based on a specific layout and some design assumptions. Several results, including bus conductor stresses, insulator cantilever forces, and steel column stress ratios, from the two design approaches are then compared.

For designing substation rigid bus layout, results showed that the use of dynamic analysis could generally yield a lower force/stress on members compared to the static analysis, especially with flexible configurations. In a more rigid configuration, force or stress determined from the dynamic analysis could be higher than the static analysis. Results from a case study in conjunction with design advantages and disadvantages outlined in this paper provide guidance to engineers to select a design approach that better suits their applications.

KEYWORDS

Short circuit force, Substation rigid bus design, Static analysis, Dynamic analysis, IEEE 605, CIGRE 105

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INTRODUCTION

Short Circuit Force based on IEEE 605-2008

For determining short circuit force to be applied on substation rigid bus, electrical utilities often use the design procedure as outlined in IEEE Std. 605-2008 [1] "*IEEE Guide for Bus Design in Air Insulated Substations.*" The design guideline essentially provides a closed-form equation for computing basic short circuit force for infinitely long parallel conductors, as shown below:

$$F_{sc} = \frac{3.6\, \Gamma\, I_{sc}^2}{10^7\, D} \qquad \text{[IEEE 605-2008 Eq. 15]}$$

Recognizing the conservatism in the basic short circuit force calculated from this equation, the design guideline further provides a corrected equation in an effort to capture the peak fault current and structure responses, as computed by the following equation:

$$F_{sc\_corrected} = D_f^2\, K_f\, F_{sc} \qquad \text{[IEEE 605-2008 Eq. 16]}$$

Where: D_f = the half-cycle decrement factor
K_f = the mounting structure flexibility
F_{sc} = the basic force equation computed from Eq. 15

With only a few design parameters required, it is obvious that the design approach can be easily implemented with minimal effort. However, there are several design limitations as stated in IEEE 605-2008 that cannot be used with this design approach; e.g., unequal bus spans, change in bus horizontal/vertical direction, or corner effect. In general, this computed short circuit force only represents the maximum force that occurs over a period of time. The short circuit force computed from IEEE 605-2008 is typically applied to rigid bus conductors as a static load in conjunction with other applicable loads, such as self-weight, ice, wind, or seismic loads, for designing substation rigid bus layout including insulator selection as well as structure and foundation designs. In most cases, results based on IEEE 605-2008 guideline are overly conservative and could potentially result in a higher project cost.

Short Circuit Force based on CIGRE 105

Short circuit force is a dynamic load in nature. IEEE 605-2008 provides a short circuit current function with time variation including AC component and DC decaying component as shown below:

$$i_{sc}(t) = \sqrt{2}\, i_{sc}[cos(2\pi f t + \delta) - e^{-t/T_a} cos(\delta)] \qquad \text{[IEEE 605-2008 Eq. 17]}$$

The short circuit force function with time variation is then computed from:

$$F(t) = \frac{\mu}{4\pi r^2} i_1(t) i_2(t)[d_1 \otimes (u_r \otimes d_2)] \qquad \text{[IEEE 605-2008 Eq. 13]}$$

Similar to equations provided in IEEE 605-2008, CIGRE 105 [2] "*The Mechanical Effects of Short Circuit Currents in Open Air Substations*" provides short circuit force determination background in great details. Once the short circuit current function, $i_{sc}(t)$, is determined, a generalized short circuit force function with time variation can be expressed as:

$$F_{sc}(t) = \frac{\mu_0}{2\pi}\, i(t) \sum_n \frac{i_n(t)}{a_n} \qquad \text{[CIGRE 105 Eq. 1.7]}$$

The short circuit force function on phase A, B, and C for the case of three-phase fault are defined as:

$$F_{sc\_A}(t) = \frac{\mu_0}{2\pi}\, i_A(t) \left[\frac{i_B(t)}{a_n} + \frac{i_C(t)}{2a_n}\right] \qquad \text{(Phase A)}$$

$$F_{sc\_B}(t) = \frac{\mu_0}{2\pi}\, i_B(t) \left[-\frac{i_A(t)}{a_n} + \frac{i_C(t)}{a_n}\right] \qquad \text{(Phase B)}$$

$$F_{sc\_C}(t) = \frac{\mu_0}{2\pi}\, i_C(t) \left[-\frac{i_A(t)}{2a_n} - \frac{i_B(t)}{a_n}\right] \qquad \text{(Phase C)}$$

For the case of phase-to-phase fault, the short circuit force function for phase A to B, or B to C are derived in a similar fashion. It should be noted that the sum of short circuit force from all phases considered in any specific time period is always equal to zero. Once the short circuit force function is determined, it can be then used in an analysis for designing substation rigid bus layout.

DESIGN ADVANTAGES AND DISADVANTAGES

In addition to short circuit force calculation, IEEE 605-2008 also provides a set of closed-form equations that can be used to design substation rigid bus layout based on insulator cantilever strength, bus conductor stress, and bus conductor deflection criteria. However, these equations are simplified and are only applicable in simple bus configurations. Another design approach that has been increasingly used for substation rigid bus design is static analysis with a finite element software. The peak short circuit force computed from IEEE 605-2008 is still applied as a static load, but the static design approach addresses many design limitations that cannot be analysed with IEEE 605-2008 closed-form equations. The author discussed the static design approach in more details in a previous publication. [3]

As mentioned previously, short circuit force is a dynamic load by nature. There are several studies on analysing substation rigid bus with a dynamic analysis design approach; e.g., Tsanakas and Papadias [4], Bergeron, Trahan, and Budunuch [5], Iordanescu, Hardy, and Nourry [6], and Amundsen, Oster, and Malten [7]. The dynamic design approach offers more accurate results, but it is more complex and time consuming compared to the static design approach. Table 1 compares advantages and disadvantages between the two design approaches.

Design Approach	Advantages	Disadvantages
Static Analysis	• Require minimal design time • Require fewer design parameters/considerations to run an analysis • Reduce design complexity • Widely used by utilities with well-established design guideline	• Provide a more conservative analysis • Potentially require more support structures/foundations (higher project cost) • Applicable with limited bus layout/configuration
Dynamic Analysis	• Provide a more accurate analysis • Potentially requires fewer support structures/foundations (project cost saving) • Applicable with any bus layout/configuration	• Require extensive design time • Increase design complexity • Require several more design parameters/considerations to run an analysis • No industry established guideline available

Table 1: Design approach comparison

CASE STUDY

Because of the conservatism in a substation rigid bus design from the static design approach, it has been long perceived that by performing a dynamic analysis, longer conductor span could be achieved resulting in fewer insulators and supporting structures/foundations; hence, potentially providing a cost saving to a project. From this perspective, a study was performed using a rigid bus configuration, as shown in Figure 1, including a change in rigid bus elevation (high bus to low bus supported by rigid bus A-frame), insulators and steel structures.

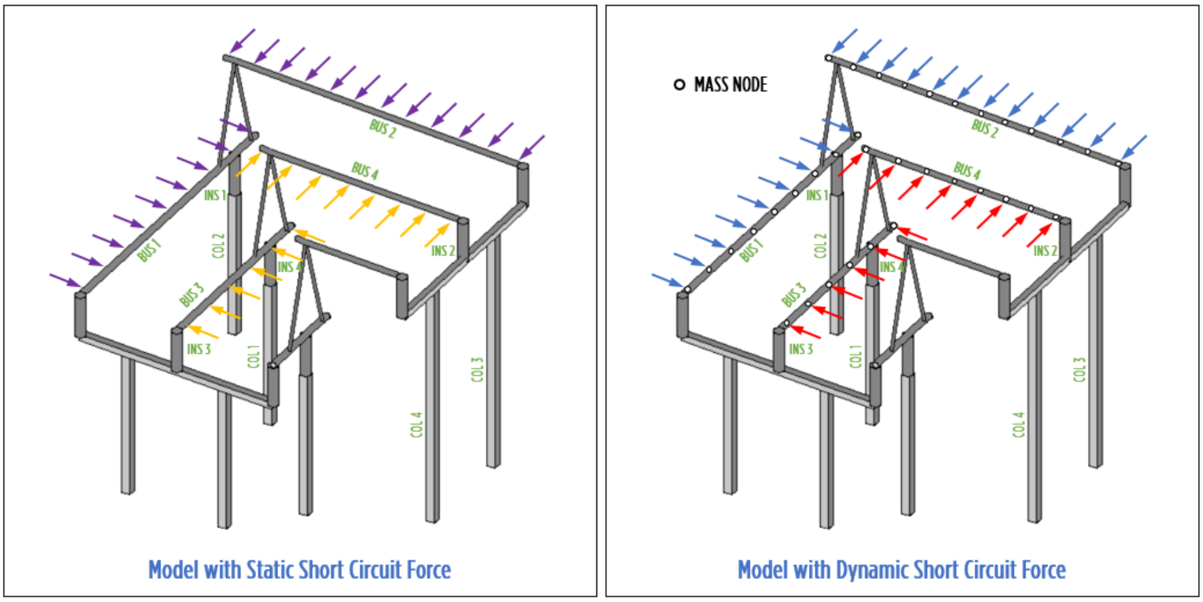

Figure 1: Bus layout analyzed for a case study

Two identical models were created. The first model was subject to short circuit force computed from IEEE 605-2008 closed-form equations and applied as a static load on bus conductors. The other model was subject to short circuit force function with time variation computed from CIGRE 105, and applied as a dynamic load on bus conductors. Short circuit force function with time variation used in the case study is shown in Figure 2. All the analyses were performed utilizing RISA-3D software.

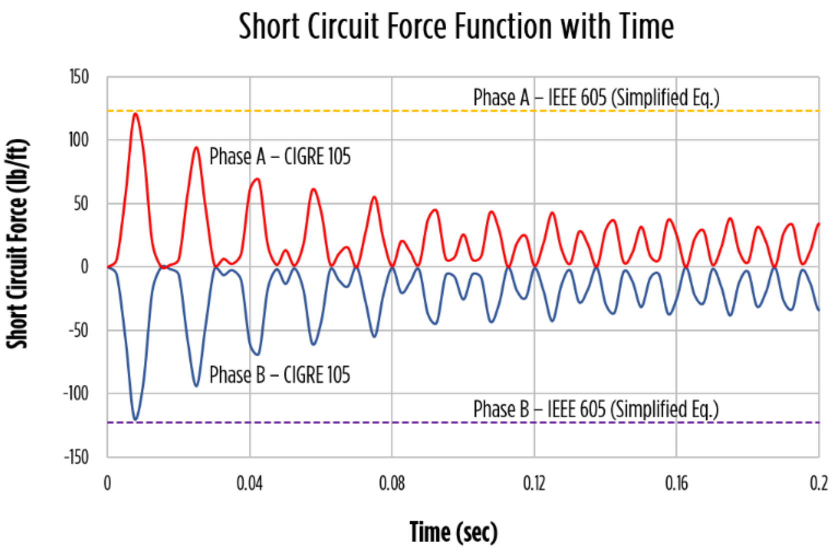

Figure 2: Short circuit force with time variation

Design Parameters

The design parameters/assumptions used for the case studies are as follows:

- Conductor materials: all rigid bus conductors are made of 6063-T6 aluminum schedule 80 with 5” nominal for main bus and 2-1/2” nominal for A-frame.
- No damping wire is used.
- Phase spacing, *D*, of 10 feet, and the system fault current, I_{sc}, of 63,000 A and assumed *X/R* value of 20. System frequency, *f*, is taken as 60 Hz. Support flexibility factor, K_f, is equal to 1.0.
- Fault type: phase-to-phase with short circuit constant, Γ, of 1.0 and 180º out of phase.
- Insulator designation TR 287 with cantilever strength of 2,600 lb.
- Steel structure beams and columns, HSS 8x8x1/4 and HSS 10x10x1/4, respectively.

Based on design parameters/assumptions listed above, computed parameters and short circuit force are as follows:

- Short circuit force using IEEE 605-2008
  - Peak force determined at half-cycle = 122.87 lbf/ft (at 0.0083 sec)
  - Computed fault clearing time, T_a = 0.053 second
  - Computed decrement factor, D_f = 0.927
- Short circuit force using CIGRE 105
  - Peak force computed at half-cycle = 122.45 lbf/ft (at 0.0083 sec)
  - Force computed at 1.5-cycle = 93.92 lbf/ft (at 0.0250 sec)
  - Force computed at 2.5-cycle = 75.47 lbf/ft (at 0.0417 sec)
  - Force computed at 5-cycle = 22.34 lbf/ft (at 0.0833 sec)
  - Fault incident angle, $Ø_A$ = 0º
  - Fault incident angle, $Ø_B$ = 180º

For the static analysis, the peak short circuit force of 122.87 lbf/ft occurred at half-cycle (1/2*f*) was applied to rigid bus conductor and did not change over time. For the dynamic analysis, short circuit force changes over time, the peak short circuit force of 122.45 lbf/ft also occurred at half-cycle (1/2*f*), but the force was approximately reduced by 40% after only two cycles. It should also be noted that the peak short circuit force is dependent on fault incident angle, e.g. at fault incident angles, $Ø_A$ and $Ø_B$ of 45º and 225º, respectively, the peak short circuit force was reduced to 82.8 lbf/ft.

For both models, only self-weight and short circuit load was applied on bus conductors, excluding all other loads such as wind or ice. In the case of the dynamic analysis, short circuit loads were applied over the total time period of 0.5 seconds.

RESULTS AND DISCUSSION

Based on the applied loads described earlier, results from the two models, the static and dynamic analysis, were compared in terms of bus conductor member stress, insulator cantilever force, and structure column stress in different locations.

Figure 3 shows bus conductor member stress comparison under applied loads for bus conductor member BUS1 thru BUS4 from the model layouts shown in Figure 1. In general, bus stress in all members determined from the dynamic analysis was approximately 50% lower than the static analysis, except for BUS3. Among all members investigated, BUS 3 has the shortest span and is supported by insulators on both ends. Although BUS4 has a similar span length but it is supported by insulator on one end and conductor A-frame configuration on the other end, which is more flexible compared to BUS3. Therefore, it was expected that BUS3 configuration having the highest rigidity would experience the least stress reduction from the dynamic analysis.

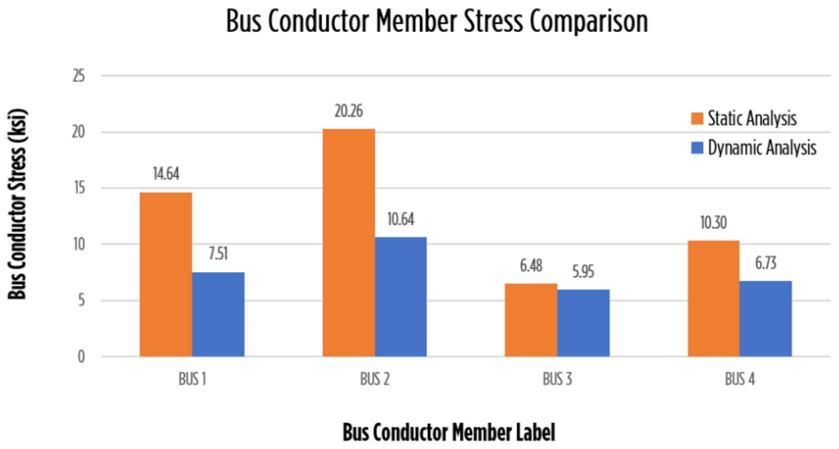

Figure 3: Bus conductor member stress comparison

Figure 4 shows a comparison on insulator cantilever force under applied loads for insulator member INS1 thru INS4. In three insulators investigated, INS1, INS2, and INS4, the dynamic analysis yielded a lower insulator cantilever force compared to the static analysis, with a force reduction ranging from approximately 20% to 50%. Station post insulator conventionally made of porcelain is generally more rigid than bus conductor that is typically made of aluminum. Similar to earlier results, higher system rigidity results in a lower load/stress reduction with the dynamic analysis. In this particular configuration, dynamic analysis results on insulator member INS3 that supports bus conductor member BUS3 having the shortest span (the highest rigidity) even experienced a higher load compared to the static analysis, approximately 25% higher. The increase in load is similar to results analyzed by a simplified dynamic analysis approach proposed by Amundsen, Oster, and Malten [7] with short span bus conductor.

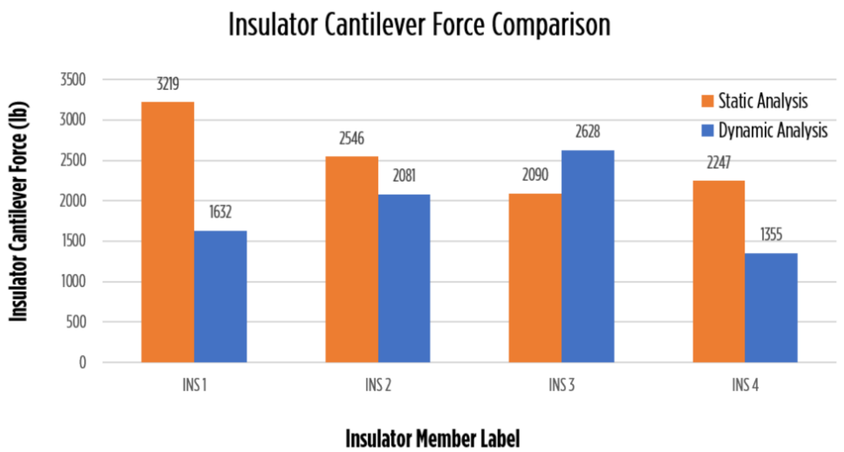

Figure 4: Insulator cantilever force comparison

Figure 5 shows a comparison on structure column stress ratio under applied loads for member COL1 thru COL4. The dynamic analysis generally yielded a lower structure column stress ratio compared to the static analysis. Although the results show that structure column stress ratio in column member COL3 from the dynamic analysis was higher than the static analysis, the stress increase was minimal and did not govern the column design overall.

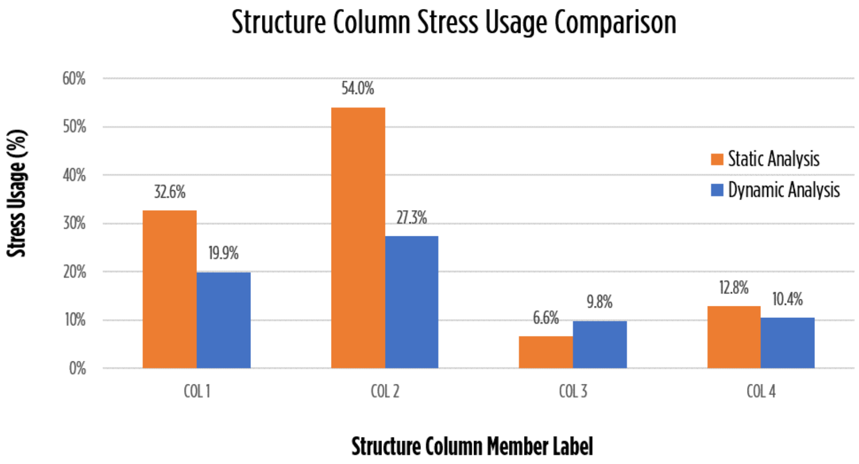

Figure 5: Structure column stress usage comparison

Although a rigid bus layout analyzed with the dynamic analysis generally experienced lower member force/stress compared to the static analysis, there are a couple aspects that should be discussed, 1) design complexity and 2) industry guidelines.

For the static analysis, short circuit load determination based on IEEE 605-2008 is straightforward requiring a few design parameters. IEEE 605-2008 also provides some guidance on factor of safety to be used on rigid bus conductor and insulator strength that have been widely used by utilities.

On the other hand, for the dynamic analysis short circuit load determination based on CIGRE 105 is more complex, e.g. different fault incident angle should be investigated for determining the peak short circuit force. In addition, as a rule of thumb for dynamic analysis the number of modes required to be included in an analysis should result in a mass participation exceeding 90%. For building designs, this requirement could be achieved by including only the first few modes. However, for this case study the design included up to 20 modes to meet mass participation requirement due to low mass in the system, unlike buildings. In this study only one load case was considered, self-weight plus short circuit loads, and results from each mode, total of 20 modes, were investigated. Substation rigid bus design typically includes more than one load case; therefore, one could imagine the amount of results that need to be investigated for the worst case scenarios, compared to the static analysis approach.

Furthermore, there is currently no industry guideline available on acceptable factor of safety to be used on materials (bus conductor or insulator) when using the dynamic analysis. IEEE 605-2008 offers little guidance but mentions that a higher factor of safety should be used when designing with the dynamic analysis. Lower member force/stress means longer bus span. It could have been that at a longer span other failure modes, e.g. local connection failure, bus vibration, etc., could govern the design that are not listed or not covered in current industry guidelines.

CONCLUSION

Short circuit force can have a significant impact to substation rigid bus design, especially that a much higher system fault current has been considered in a design for system retrofits or system expansions. For short circuit load determination, utilities often use IEEE 605-2008 in conjunction with the static analysis due to its ease of implementation, but this design approach could sometimes be excessively conservative since the design is based on the peak short circuit force. Short circuit is a dynamic force that varies with time. CIGRE 105 provides great details how to derive short circuit force in function with time. The dynamic analysis can offer more accurate results. It has been long perceived that the dynamic analysis generally provides a reduction in member force/stress resulting in potential project cost saving from using fewer insulator supports, steel structures, and foundations. A case study was performed to compare the same rigid bus configuration for two different design approaches, static and dynamic analysis. Results showed that at the same peak short circuit force computed from IEEE 605-2008 and CIGRE 105, using the dynamic analysis generally yielded lower bus member stress, insulator cantilever force, and structure column stress ratio, with a reduction in load/stress ranging from approximately 10% to 50%. When a configuration is less flexible, the reduction in load/stress from the dynamic analysis decreased and was more comparable to results from the static analysis. In some configurations, the dynamic analysis could even yield higher member force/stress compared to the static analysis. Other factors discussed in this paper that should also be considered when selecting a design approach were design complexity and available industry guidelines. The dynamic analysis is normally more complex and could require much more design effort compared to the static analysis. In addition, although members typically experience less force/stress when using the dynamic analysis, there is no current industry standard providing a guidance on appropriate factor of safety on materials with this design approach. With results from a case study together with other information provided in this paper, it offers design considerations that could aid engineers to select a design approach that better suites their applications.

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