**Progress Update:**

Upon completion of the sensitivity analysis, as described in the previous update, I wanted to define an acceptable range for H.

To restate the sensitivity analysis findings, using the values from Anderson’s Low Order SFR paper as the mean for normal distribution, with a standard deviation of 15%, the following correlation graphs were found:

A screenshot of a computer

Description automatically generated

The variables R, K, and Fh are more than 3 times more correlated to the depth of the frequency Nadir, than Inertia.

**Accuracy window Work:**

Methodology:

As mentioned in the previous update, I am unsure if its possible to give a range of H that is “safe” without considering the 3 more correlated values.

The plan was to use a set of fixed values, acquired from the book “Power System Protection”, to define the mean values of the variables in the GSFR model. Using a for loop, values of H could be tested from 1-12 seconds. The for loop works as follows:

1. Find the GSFR using the Estimated Values (the mean values) and the value of H [1-12s] with a Simulink Model.
2. Find the power Injection, referred to in code as SigIn, to completely correct for the transient dip in the GSFR model from step 1.
   1. Adjust the power injection as needed for the “Halved” injection. (See Appendix for Halved vs Ideal Injection)
3. Run two for loops, acting as lower and upper bound finders, which change the value of H by 1 percent at a time, and then reruns the GSFR model with SigIn, checking the statutory limits for each percent.
   1. Store the last percent value, plus or minus, which does not violate the statutory limit boundaries. (1%, or 0.99 and 1.01 Hz pu)

**Initial Results:**

As mentioned, the values for each variable were taken from “Power System Protection”, but for the initial test, the values were taken from Andersons “A Low Order System Frequency Response”.

**Table 1: Values used in GSFR model.**

|  |  |
| --- | --- |
| **Variable** | **Value** |
| R | 0.05 |
| K | 0.95 |
| Fh | 0.3 |
| Tr | 8 |
| D | 1 |
| Pd (Per Unit Loss of Generation) | 0.1 |

The results of using ONLY the mean value for each variable in the models, found that there was no upper bound. This was tested up to a positive inaccuracy of over 5000%, due entirely to curiosity (further tests were limited to 100%, for practical applications). The testing did find a lower bound which violated the statutory limit 0.99 Hz pu.

**Table 2: Upper and Lower Bounds of accuracy of H per value of H using Anderson Values**

|  |  |  |
| --- | --- | --- |
| **Value of H (in seconds)** | **Accuracy Lower Bound** | **Accuracy Upper Bound** |
| 1 | -63% | 100% |
| 2 | -63% | 100% |
| 3 | -64% | 100% |
| 4 | -64% | 100% |
| 5 | -64% | 100% |
| 6 | -64% | 100% |
| 7 | -65% | 100% |
| 8 | -65% | 100% |
| 9 | -66% | 100% |
| 10 | -66% | 100% |
| 11 | -66% | 100% |
| 12 | -67% | 100% |

The results were similar for both the Ideal Injection and the Halved injection, thus only the Ideal Injection results are shown. These early results indicate that for the Average system, as presented by Anderson, there is a minimum accuracy lower bound of 63%, for a Correction factor of B = 1. This indicates that if the real value of H, is within 63 percent of the Estimated value of H, Jesus’ injection will prevent the System Frequency Response from going below the statutory limit.

Below is the Frequency response curves of the first Value of H which violates the Statutory limits, such that it is 1% greater than the values presented in Table 2.

A close-up of a graph

Description automatically generated

Figure 1: Limit Violating Frequency Response Curves

**Investigating the Limits with worst case and best-case scenarios:**

Methodology:

Similar to the previous methodology, except the values of the 3 most influential variables are altered to their Worst Case and Best-Case values, as per the book “Power System Protection”. These 3 variables were identified during the initial sensitivity analysis, based on correlation factor. The greater the correlation factor, the greater impact on the result. These 3 variables are R, K, and Fh.

**Table 3: Values adjusted for the Worst Case and Best-Case Testing**

|  |  |  |
| --- | --- | --- |
| **Variable** | **Worst Case Value** | **Best-Case Value** |
| R | 0.075 | 0.04 |
| K | 0.8 | 1.0 |
| Fh | 0.2 | 0.4 |

**Worst Case Results:**

**Table 4: Upper and Lower Bounds of accuracy of H per value of H, Ideal Injection**

|  |  |  |
| --- | --- | --- |
| **Value of H (in seconds)** | **Accuracy Lower Bound** | **Accuracy Upper Bound** |
| 1 | 15% | 99% |
| 2 | 16% | 99% |
| 3 | 16% | 99% |
| 4 | 16% | 99% |
| 5 | 17% | 99% |
| 6 | 17% | 99% |
| 7 | 17% | 99% |
| 8 | 17% | 99% |
| 9 | 17% | 99% |
| 10 | 17% | 99% |
| 11 | 17% | 99% |
| 12 | 18% | 99% |

**Table 5: Upper and Lower Bounds of accuracy of H per value of H, Half Injection**

|  |  |  |
| --- | --- | --- |
| **Value of H (in seconds)** | **Accuracy Lower Bound** | **Accuracy Upper Bound** |
| 1 | 0% | 99% |
| 2 | 0% | 99% |
| 3 | 0% | 99% |
| 4 | 0% | 99% |
| 5 | 0% | 99% |
| 6 | 17% | 99% |
| 7 | 17% | 99% |
| 8 | 17% | 99% |
| 9 | 17% | 99% |
| 10 | 17% | 99% |
| 11 | 17% | 99% |
| 12 | 18% | 99% |

These results are interesting, due to the fact that the lower bound for the half injection, has a lower bound inaccuracy of 0% until H = 6. The rest of the results are similar to the Ideal injection, but the reason for the difference becomes apparent when graphing the Violating Frequency Response curves.

A graph of a number of different colored lines

Description automatically generated with medium confidence

Figure 2: Worst Case frequency Response - Violating Responses

It can be seen that for the values H = 1 to H = 5, the fact that the Halved Injection does not inject for the same length of time as the Ideal Injection, the GSFR will initially be compensated, but once the injection ends, the system will fluctuate back down, to under the statutory limit. Further investigation should be done, to see if the Simplified Injection I suggested in the Monte Carlo Simulations, has the same result. It is suspected that it will not.

**Best-Case Results:**

**Table 4: Upper and Lower Bounds of accuracy of H per value of H, Ideal Injection**

|  |  |  |
| --- | --- | --- |
| **Value of H (in seconds)** | **Accuracy Lower Bound** | **Accuracy Upper Bound** |
| 1 | 99% | 99% |
| 2 | 99% | 99% |
| 3 | 99% | 99% |
| 4 | 99% | 99% |
| 5 | 99% | 99% |
| 6 | 99% | 99% |
| 7 | 99% | 99% |
| 8 | 99% | 99% |
| 9 | 99% | 99% |
| 10 | 99% | 99% |
| 11 | 99% | 99% |
| 12 | 99% | 99% |

**Table 5: Upper and Lower Bounds of accuracy of H per value of H, Half Injection**

|  |  |  |
| --- | --- | --- |
| **Value of H (in seconds)** | **Accuracy Lower Bound** | **Accuracy Upper Bound** |
| 1 | 99% | 99% |
| 2 | 99% | 99% |
| 3 | 99% | 99% |
| 4 | 99% | 99% |
| 5 | 99% | 99% |
| 6 | 99% | 99% |
| 7 | 99% | 99% |
| 8 | 99% | 99% |
| 9 | 99% | 99% |
| 10 | 99% | 99% |
| 11 | 99% | 99% |
| 12 | 99% | 99% |

In the best-case scenario, the inaccuracy can be up to 99%, in either direction, lower or upper, but cannot be 100% inaccurate for obvious reasons (H cannot be equal to 0).

**Conclusions:**

The lower bound depends on the 3 correlated variables. The Accuracy Window for H is dependent on R, K, and Fh. This research applies only if the settling frequency is above the statutory limit, as if Pd or R is too large, such that the settling frequency drops below the statutory limit, then it will violate the boundary anyway.

the lower bound is smaller for the halved injection BECAUSE after the injection stops, the frequency response can DIP BACK DOWN under the statutory limits. Thus, the difference between statutory limit and the settling frequency will alter the lower bound accuracy window for the Halved. The second dip, due to the shape of the injection, is the reason for this relationship.

practically NO UPPER BOUND VIOLATIONS (tested up to 99% for most runs, up to 50X the value of H for one test).

Lastly, I should investigate what the Simplified Injection results look like. For reference, this is the injection in between the Ideal and Halved injections. It is simpler to employ than the Ideal Injection (which is not a true triangle) and covers the entire length of time of the Ideal injection, thus taking more energy than the Halved Injection.

**Appendix:**

A graph of a power injection

Description automatically generated

Figure 3: Ideal Power Injection, correction Factor 0.8

A graph of a power injection

Description automatically generated

Figure 4: Halved Power Injection, correction Factor 0.8

A graph of a power injection

Description automatically generated

Figure 5: Simplified Power Injection, Correction Factor 0.8