



Stability Assessments on Inertial Response for Automatic Generation Control System

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ABSTRACT

Integration of more renewable energy sources (RES) undoubtedly bring more impact into power system. The distributed generation of RES in grid-connected knowingly will interfere frequency system's stability due to decoupling to at point of common coupling. Inertia plays main role for bringing up frequency regulation at very early stage of frequency responses. Thus, to include RES such as solar photovoltaic (PV) and wind turbine (WT) could be a good idea but ideally PV has no inertia while WT only partially inertia. Therefore, the objective of this paper is to do an assessment on frequency stability specifically on inertial response with regard to unit commitment e.g. synchronous generator and RES participation. However, to know certainly the inertia constant (H) for each generator with respect to its rating ultimately difficult as it can varies depending to several factors i.e. unit type and manufacturer. Hence, an equation is proposed and yielded to facilitate for H determination of synchronous generator. The proposed equation is tested with other IEEE systems for its accuracyness. The estimated values are then simulated in various scenarios and cases i.e. increment of inertia, splitting of unit commitment and RES participation toward inertial response. MATLAB Simulink software is used to simulate and analyze the end results. Finally, the famous Kundur's 4 Machine Two-Area Test system is used to verify the effectiveness for entire findings.

Key words : Inertia constant, inertial response, power system stability, frequency response

1. INTRODUCTION

Lately, the generation of electricity using fossil fuel cause harm to our environment [1]. This environmental deterioration stimulated the integration of renewable energy generation in our power system. According to [2], solar photovoltaic (PV) and wind turbine (WT) systems are among the two resources that gained the most attention and interest. The increment of renewable energy sources (RES) in the power system will harm the dynamic performance especially frequency stability [3]. This is because most of the non-synchronous generation, including solar PV and wind

turbines, rely on power electronics to convert primary energy into electricity [4]. However, replacement of a large number of a conventional power plant to this RES power plant will decrease the number of generators operating hence will reduce the amount of overall inertia of the power system [5] [6].

The power system stability refers to the capability of the power system to return to its steady-state without losing synchronism when subjected to a disturbance. [7]. Meanwhile, frequency stability in [8], is defined as the ability of the power system to maintain its steady-state of the frequency following severe disturbance. According to the research [9], one of the main cause power system instability is when a distributed generation of RES is interconnected to the main grid or power system. An uncontrollable drop in system frequency and voltage can happen when there is suddenly high demand for load by the consumer. Hence, it will trigger a high rate of change of frequency (ROCOF) which causes the system operator to have less time to respond to disturbance [10].

After power imbalance occurs during contingencies, a power frequency response will take place to retrieve the system into its balanced state. According to [11], there are three types of frequency response name inertial response, primary frequency response and secondary response as shown in Figure 1. Inertial response is the ability of the objects to change in frequency due to resistance delivered by kinetic energy from rotating masses [12]. Inertia is basically a parameter that represents the capability of a rotating machine to store and derive their kinetic energy into the system.

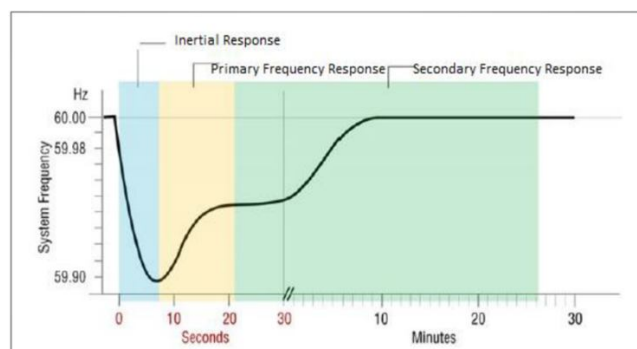


Figure 1: Frequency Response and Their Time Scale [13]

In the previous literature review, most of the researcher does consider the inertial response for their stability studies. This is because the frequency problem regarding inertia in the power system is not really an issue as the most system is still relying on a synchronous generator. Apart from that, the inertial response occurs in a short period of time and often neglected by the researcher. Therefore, in this manuscript, the inertia response is fully considered, and the inertia constant value is determined for study.

2. METHODOLOGY

2.1 Stage 1: verification of inertia constant, H with the generator's rating

For simulation purpose, the value of inertia constants, H need to be set. However, there is no specific way to determine the value of the inertia constants of the generator with their respect rating. After several studies, the data for the IEEE bus system is accumulated and has been analyzed. Based on the data, it is possible to do an estimation by using IEEE-118 busses. IEEE-118 bus is chosen because it has the most synchronous generator unit compared to other IEEE systems. Even though the IEEE- bus system does not correlate with each other, the relationship between the generators rating and the inertia constant is almost the same. To proves this, the data is then plotted on the scatter chart. This chart clearly shows the trend of the inertia constant and MVA is non-linear, using the mathematical logarithmic regression fit, the equation is developed and used to estimate inertia constant for the next simulation purpose.

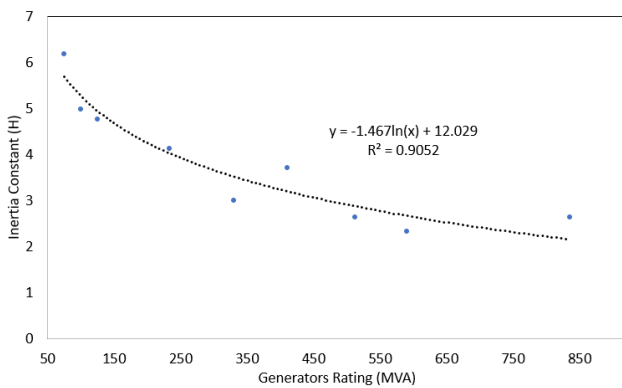


Figure 2: Estimation of Generators Rating with Inertia Constants

Figure 2 shows the score for the R-squared plotted graph. The score for R-squared is 0.905 out of 1 which significantly accurate. R-squared is a statistical measurement which is used to test the data whether it fit for the regression line. Meanwhile, for formula validation purposes, the data acquired from all IEEE buses test system is tested using the discovered estimation method. Below are the tabulated data in all IEEE buses test system with respect to its error.

Table 1: Estimated Inertia Constant and Error for IEEE-Busses

Generator rating (MVA)	Inertia Constant, H (s)	Estimated Inertia Constant H (s)	Error (%)
51.2	5.078	6.25527	-23%
51.2	5.078	6.25527	-23%
75	6.187	5.695245	8%
100	4.985	5.273215	-6%
100	4.985	5.273215	-6%
125	4.768	4.945864	-4%
125	4.768	4.945864	-4%
125	4.768	4.945864	-4%

Based on the result in Table 1, the generator with rating 51.2 MVA has a percentage of 23% error. The error that exceeds 20% is considered inaccurate. Meanwhile, for the generator rated from 75 MVA to 270 MVA and 448 MVA to 512 has an error below 10%. Therefore, for the simulation purpose, this range of generators rating will be used. Overall, the error for the estimation method shows an error below 20% except for the 51 MVA generator.

2.2 Stage 2: Effect of increment of Inertia Constant

For this assessment, the value of 200MVA is chosen as the estimation value of its inertia constant with only 2% of error. The inertia constant, H for the first case is obtained from the equation (1). Then, the inertia constant is increased by 10%, for every simulation as tabulated in Table 2. All the parameters in the generators and load remain unchanged except the value of the H.

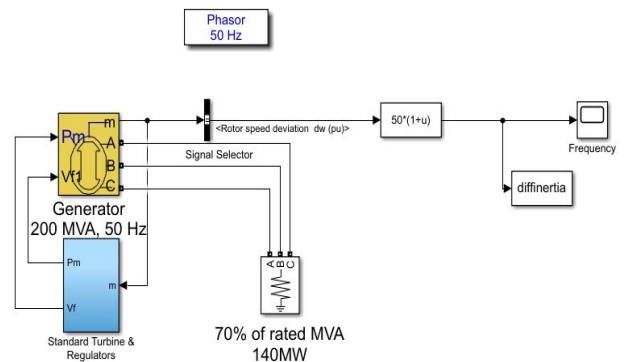


Figure 3: Stage 1 Simulation Diagram

Table 2: Value of Inertia Constant Increment

No.	Inertia Constant, H (s)
1	4.256
2	4.681
3	5.1072
4	5.5328

2.3 Stage 3: Inertia in Renewable Energy

The previous chapter stated that the renewable energy source like wind turbine has partially inertia meanwhile solar PV have no inertia at all. Normally droop control method would come into action for small grid application [14]. For this stage, a simple simulation is carried out with two sets of synchronous generators. The main generator (G1) or is rated at 300 MVA with 3.66s inertia constant value estimated from stage 1. Second generators (G2) rating is 100 MVA with inertia constant value 5.27s. Then the G2 is replaced with WT and solar PV. The details of stage 3 simulation are tabulated in Table 3.

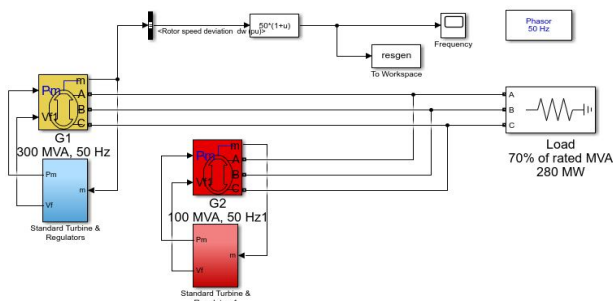


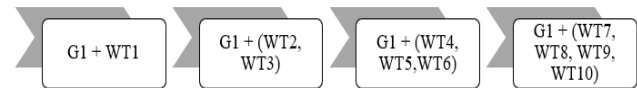
Figure 4: Simulation set up for stage 3

Table 3: Details of Each Case in Stage 3

Case	Type of Generator	Rating (MVA)	$H_{sys} = \sum (H^* MVA)$
1	G1+ G2	300 + 100	3.662 + 5.273
2	G1 + Wind Turbine	300 + 100	3.662 + 5.273
3	G1 + Solar PV	300 + 100	3.662 + 0
Total		400	

2.4 Stage 4: Splitting of Unit Commitment

Based on the plotted graph on the IEEE-118 bus, the trend of the curve shows that the inertia constants increase as the rating decrease. Subsequently, the inertia constants of the same total MVA possibly be increased by splitting the unit of the generators. This also applies to wind turbine because it has inertia (partially). Since the solar PV has an absence of



inertia, the splitting unit of PV will not carry out for this stage.

Figure 5: Hierarchy of Generator Split

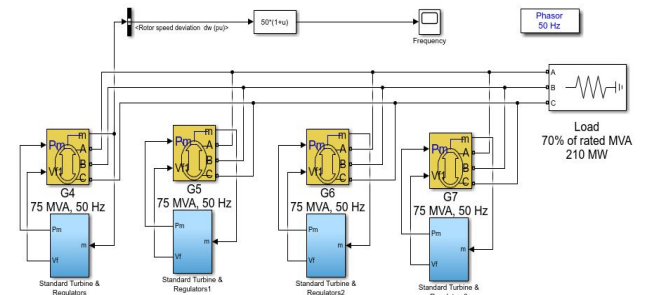


Figure 6: Splitting unit of 4 generators



Figure 7: Hierarchy of Wind Turbine Split

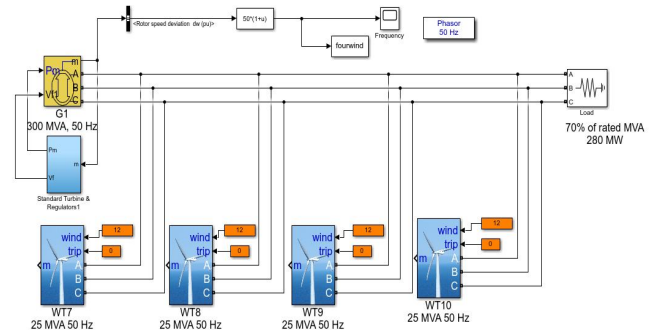


Figure 8: Splitting unit of 4 wind turbine

2.5 Stage 5: Verification of Test System

After all the assessments that have been done in the previous sub-topic, the input of the simulation needs to be verified. For the verification process, the Prabha Kundur’s Two-Area Four-Machines is selected for the test system. At this stage, the simulation is divided into 4 scenarios. The first scenario, the original simulation model of Kundur two area is used. The first scenario is the reference or base case study for this stage. Then on scenario 2, the machine 1 (M1) from the Kundur’s is

replaced with on bulk Wind Turbine (WT) with the same rating as the M1, 900 MVA. Since Kundur’s test system does not have WT, the parameter of the WT is manipulated to match the system. The same parameter of the wind turbine is used for all the scenario to get the fair result. On the third scenario, the machine 4 (M4) is replaced with two generators to mimic the splitting unit of commitment. Lastly, in the fourth scenario, the Wind turbine is replaced with two other wind turbines with half of the capacity of WT in the second scenario. The value of the inertia constant inn each machine that is used in this simulation is changing according to the estimated value for the equation. In conclusion, the fourth scenario containing all the assessment on each stage and is applied in this case scenario.

3. RESULTS AND DISCUSSION

3.1 Stage 1: Estimated Value from the Equation

All the findings in every stage will be discussed. Every stage is tested with different approaches, thus the result of each subtopic does not relate to each other except for the estimation method which is used in all stages. Here are the tabulated estimation values of inertia constant with their ratings.

Table 4: Inertia Constants Estimation value for Simulation

No.	Rating (MVA)	Inertia Constant H, (s)
1	25	7.3069
2	33.33	6.8850
3	50	6.2900
4	75	5.6952
5	100	5.2732
6	200	4.2563
7	300	3.661
8	450	3.0667
9	900	2.0498

3.2 Stage 1: Inertial Response of an Increment of inertia Constant

The generator inertia constants are based on estimation in Table 4 above. The value of the inertia constant increases by 10% for every simulation. The objective of this procedure is to find the relationship between the inertia constants value and inertial response behavior. The value of the generator’s rating with respect to the inertia constant is tabulated in Table 5 below. The generators rating for each simulation is fixed at 200 MVA.

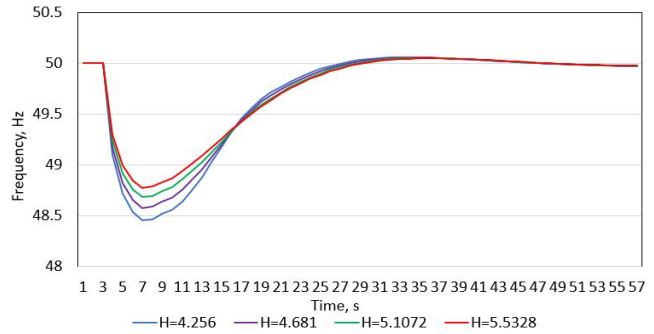


Figure 9: Effect on inertia increment toward inertial response

Table 5: Result on inertia increment toward inertial response

No	Rating (MVA)	Inertia Constant, H (s)	Frequency Nadir (Hz)	ROCOF (Hz/s)
1	200	4.256	48.453	-0.3092
2	200	4.681	48.579	-0.2840
3	200	5.1072	48.685	-0.2629
4	200	5.5328	48.777	-0.2445

The outcome of this stage simulation shows that as the number of inertias increase from H= 4.256 to H= 5.5328, the inertial response of the frequency after a disturbance occurs would be better or getting closer to the steady-state value. This statement is supported by the frequency nadir value which is the lowest point of the frequency response reach after a disturbance occurs. This shows that the bigger the value of inertia constant, the faster the frequency to return to its steady-state condition and the frequency drop is less severe. The rate of change of frequency (ROCOF) of the generators with the highest inertia response has the slowest rate of change compared to the other. Therefore, the system has more time to respond to the disturbance thus make the generator with the bigger inertia value more stable and robust than the generator with smaller inertia.

3.3 Stage 3: Inertial Response of Renewable Sources with Same Inertia Value

The purpose of this stage 3 simulation is to proves that the RES participation in generation unit replacing the conventional generator can reduce the frequency stability of the system after an outage or power interruption. The statement in the previous chapter stated that wind has partially inertia and solar PV have no inertia. For this assessment, the synchronous generator with three times power rating than the RES generation would prevent the system from lost synchronism after replacing the 100MVA with the RES. The details of each simulation are documented by case study as tabulated in Table 6 below.

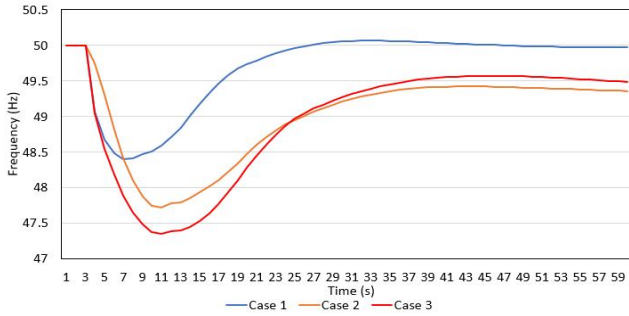


Figure 10: Frequency Response with Renewable Energy

Table 6: Result for Frequency Response with Renewable Energy

Case	Type of Generator	Rating (MVA)	Frequency Nadir (Hz)
1	G1+ G2	300 + 100	48.3977
2	G1 + Wind Turbine	300 + 100	47.7180
3	G1 + Solar PV	300 + 100	47.3515
TOTAL		400	

Based on the result, it is clearly shown that case 1 shows the most stable frequency response as its frequency nadir is the lowest. The settling time of the synchronous generator is faster than WT and solar PV. Apart from that, the generation using both synchronous generator in case 1 is the only frequency that manages to meet the steady-state value after the disturbance occurred. The frequency response of case 2 shows a better response compared to case 3. Solar PV also took more than 50-sec for the frequency to settle down. With many powers system control and techniques in real life, the settling time for the solar PV and wind would be faster but cannot match the settling time of the synchronous generator. From this discussion, it is proven that solar PV has no inertia and WT has less inertia.

3.4 Stage 4: Effect of Splitting Unit Commitment

Based on Figure 12, the single generator with the inertia constant of 3.66s shows a severe frequency drop than other after the disturbance occurs. However, it takes lesser time to reach the steady-state error. The inertial response of the 75 MVA x4 generator shows the best frequency response after disturbance. Theoretically, the fewer H_{sys} or kinetic energy stored in the generator turbine, the easier the inertia effect to return to its steady states. The trend of the graph in Figure 12 indicates that the more unit of generator used to generate the power the nearer the frequency deviates. The ROCOF of the frequency of 4x 75 MVA generator is slower and have more time to respond to the disturbance. In addition, the nadir of the frequency is increased as the lesser number of the generator is used. The wrap up of this stage assessment is the more generator used to make the same amount of power, the better the inertial stability of the system.

Figure 11: Effect on inertia to split generator

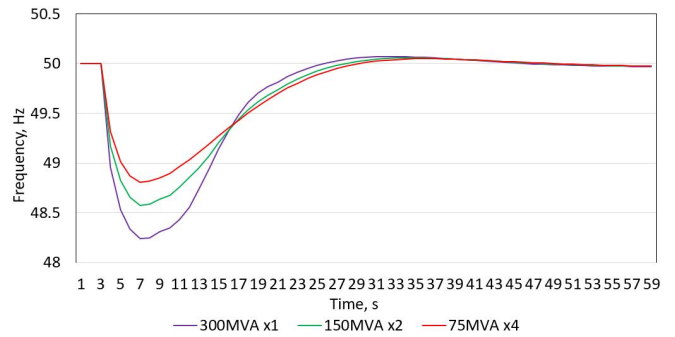


Table 7: Result for frequency response with renewable energy

No.	Type of units	Hsys (MW.s)	Frequency Nadir (Hz)	Inertia Constant (H)
1	G1	1098.6	48.2371	3.6615 x1
2	G2, G3	1403.4	48.5762	4.6784 x2
3	G4, G5, G6, G7	1708.5	48.8034	5.695 x4

Next, this simulation shows the behavior of the inertial response like the splitting unit of the generator in the previous discussion. Splitting wind turbine (WT) unit into the smaller unit with the same total 100 MVA value shows positive results in improving the frequency response after a disturbance occurs. However, on the last simulation, splitting WT into 4 units with a rating of 25 MVA each shows a response diverging from the expected result. Even though it has a better inertial response than a combination of G1 and WT, it still does not meet the expectation. The response should be better than the third simulation which is the combination of G1 and WT4, WT5, WT6. In short, there is a limitation on splitting the WT unit. Based on the simulation, the WT will display a positive response if and only if the rating of the WT is more than 10% of the Total Load Capacity (TCL). Nonetheless, the conclusion is too early to be made as the observation is made only based on this simulation only.

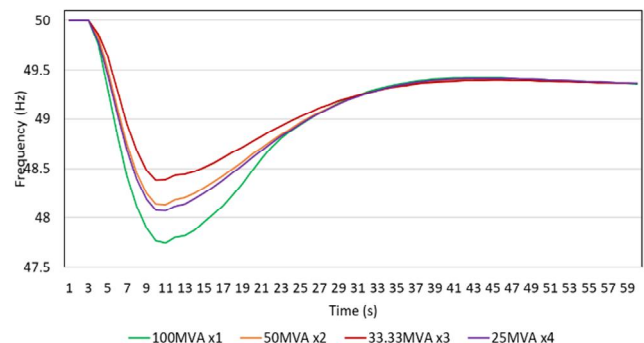


Figure 12: Effect on inertia to split wind turbine

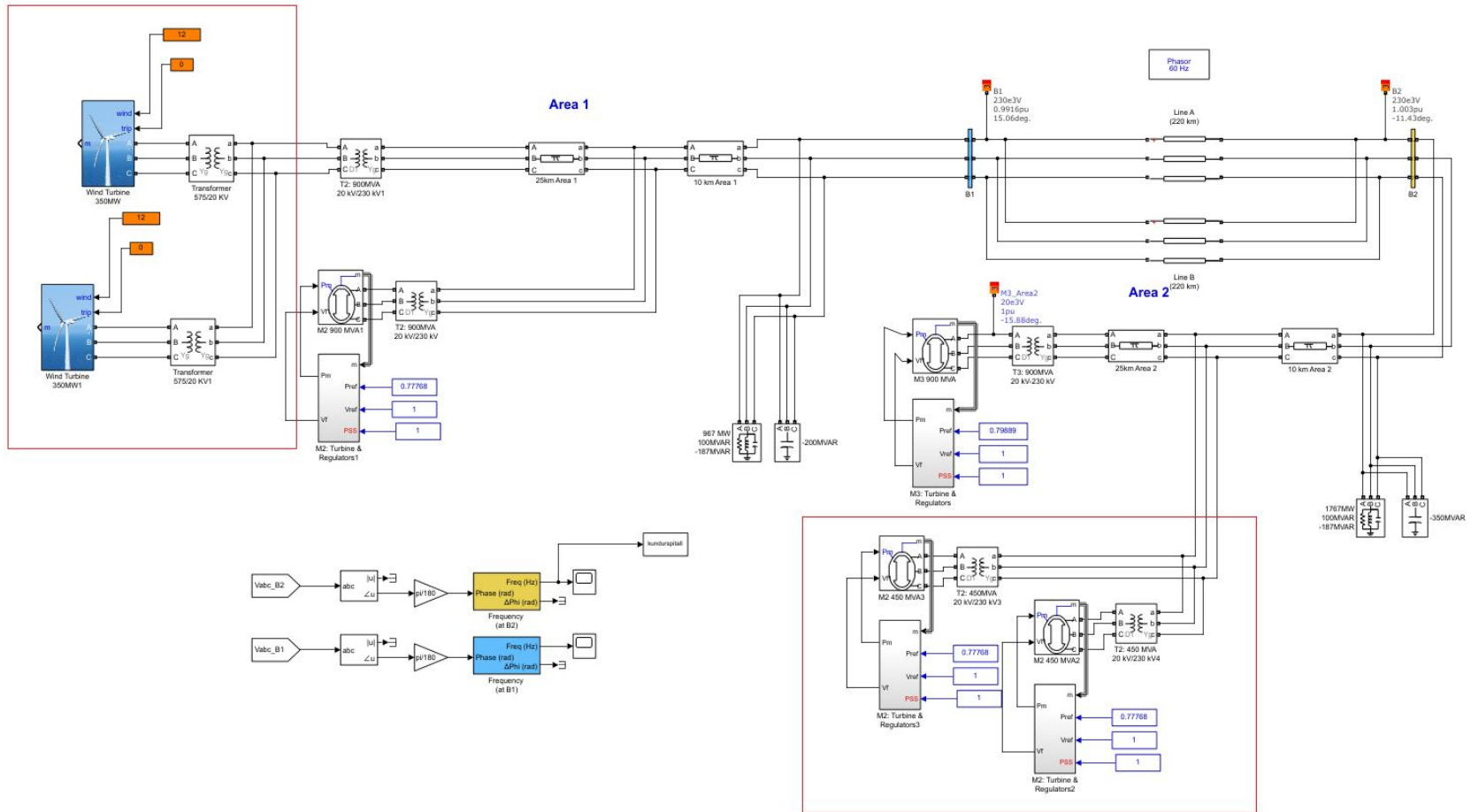


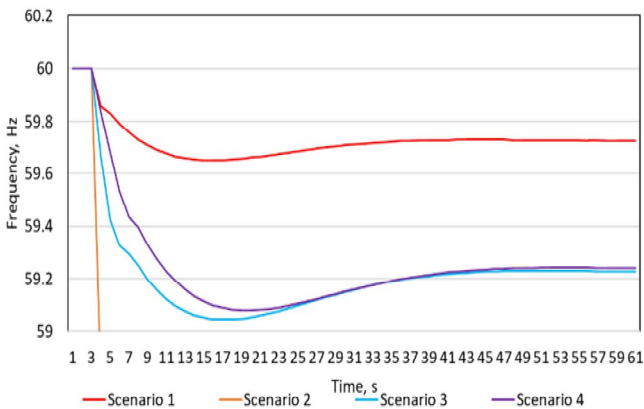
Figure 13: Kundur's scenario 4

Table 8: Result on inertia to slit wind turbine

No.	Type of units	Hsys (MW. s)	Frequenc y Nadir (Hz)	ROCOF (Hz/s)
1	G1 + WT1	1625	47.7431	-0.2507
2	G1 + (WT2, WT3)	1727	48.1337	-0.2073
3	G1 + (WT4, WT5, WT6)	1786	48.3854	-0.1793

3.5 Stage 5: Verification on Test System (Kundur 2-Area)

Scenario 1 stage 5 simulation result shows the original frequency response of the Kundur’s Two Area test system. this response is acted as a reference line for the other scenario. After replacing the M1 with the WT, the frequency drops too much and causing the system to collapse. The frequency does not return to the steady-state value. This indicates the generators lose its synchronism other to support the inertia loss. After the M4 is replaced with two generators with a total rating of 900 MVA in scenario 3, the system gains its synchronism again and the frequency manages to stable at 45 seconds. On the other hand, the frequency steady-state value is lesser than the reference line. Finally, on the scenario 4, the inertial response is better than scenario three after substitute the WT into two smaller units with the total rating as in scenario 3. The frequency drop is lesser and the ROCOF of the would-be slower or have more time to respond. Scenario 4 result shows the nadir of the frequency near the steady-state frequency. It also took lesser time to stable compared to the scenario. As a test in the real test system, scenario 4 shows a positive result, in conclusion, the stability assessment for this thesis is valid and can be further investigated. There are also modern high technology such Flexible AC Transmission System (FACTS) available to be used for abovementioned discussion however it was not favorable with its high price



and after maintenance [15].

Figure 14: Inertial response on Kundur’s Test System

Table 9: Result of all 4 scenarios

No.	Scenario	Frequency Nadir (Hz)	ROCOF (Hz/s)
1	Scenario 1	59.6509	-0.3092
2	Scenario 2	-	-
3	Scenario 3	59.0456	-0.2629
4	Scenario 4	59.0805	-0.2445

4.CONCLUSION

This paper addressed that the increasing number of renewable energy generation substituting the conventional generator which trigger a problem in power system stability. The system with more RES involvement will have a worse frequency response after contingencies occur. This is due to less total system inertia in the system which plays an important role in restoring the frequency to its steady state. The depletion of total system inertia arises as PV has no rotating mass while WT has partially or even no inertia depends on its type. Hence stability assessment on the inertial response of power system needs to be done.

The first objective is to investigate the frequency response on the power system. To achieve this, the classification of generator and RE’s parameter have been investigated thoroughly for frequency stability assessment. The development of a system with considering inertial response for stability assessment study is performed with several assessments on few scenarios and cases. The overall system performance of frequency stability on Kundur Two Area Test System was successfully conducted to further verify the effectiveness of proposed method. The H values for all the simulation were all embedded using the equation proposed. The estimation method proposed was also successfully tested with other IEEE test system for validation.

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