Flywheels and Power System Stability

Michael Breuhl, Horacio Silva, and Dr.Hector Pulgar-Painemal

***Abstract*—The study looks at impact of flywheels on a power system. This study looks at the effect of inertia and loading on the system. The test system used in this study is a modified 9 bus system, where a FESS is installed to an extra bus. The impact of flywheels with both inertia and loading follow the trend of higher inertia means higher dampening. In this study we also found that the location of the flywheel affects the dampening, such as the damping ratio is higher if the flywheel is with the generator that has the lower inertia. The findings can help lead to possible guidelines on applying flywheels for larger test systems.**

***Keywords*—Power system stability, flywheels, small-signal system stability**

I. INTRODUCTION

Within a power system, there are different methods that help aid in the regulation of a system. Regulation is important because power systems are not perfect, there are disturbances that create oscillations in the system and put the system in an unstable mode. This could cause serious damage to a system, so in order to prevent this multiple methods are used to regulate the system. One method is to regulate the output of the generator. The renewables source reserves some of its power for disturbances, so the generator only outputs a part of its full power to the system [1].This is only part of the total power is generated from a renewable source and a small portion of power is left for dealing with deviations caused from disturbances [1]. Another way to regulate the system is implementing a controller, which will respond to the changes in the system in order to maintain a stable operating point [1]. A third method that helps in the regulation of a system is to implement a device called an energy storage system (ESS) that can store energy for later use [1]. These regulation methods have allowed renewable sources to be added to todays power grid, such as wind turbines and solar panels.

A couple of reasons why renewables are being incorporated into power systems are that there are a limited amount of fossil fuels for future use and the renewable sources are better for the environment. Renewable energy sources do not require fuels and harness natural phenomena to generate power, but due to this we have less control over these devices, since we cannot control how much wind is blowing or the amount of sunlight. As discussed in [1] this leads to an issue of balancing the generation and load due to the variability of renewables. There is also a reduction of inertia with renewable power sources, and the relationship between angular speed (ω) and inertia (H) where the change in angular speed is higher with a lower inertia [1]. This shows that the rate of change of angular speed is faster when the inertia is lower. In order to be able to safely integrate renewables, many studies have been performed dealing with renewables in the power grid and power system stability.

One study dealing with renewables is a study that shows the impact of wind farms on damping related to frequency regulation [2]. This is done by attaching a group of wind turbine generators to a small power system and seeing how the system responded. The study showed the impact of wind turbine generators (WTGs) participating with and without inertial response. The overall results of this study show that the normal behavior of higher inertia, higher damping can be changed with the proper controller [2]. This study shows that the system can be improved even at lower inertia values with the proper controllers. Another study looked at the voltage stability of a power grid with an interconnected wind farm [3]. In this study, wind power is studied because the influence of wind power is increasing in China due to the large wind farm connected to the network. In [3], the power system analysis tool PSCAD/EMTDC is used to simulate short circuit faults within the system and see how time response and reactive power injection affect the systems response. According to [3], the large wind farm has a deficiency of reactive power compensation capacity which would increase the chances for instability, but this can be improved through the following methods: increasing the ability of reactive power compensation of wind farm, raising the speed of protection motion , [and] using doubly fed induction machine in wind farm. A third study dealing with power system stability has talked about using a flywheel energy storage (FES) based on a doubly-fed induction machine to help aid in the stability of a power system with dynamic simulations [4]. The study talks about a Phillips-Heffron model that is used with a single-machine infinite-bus power system that uses the FES system [4]. The results of the study show that the FES system used has very little damping effect, but that they can be improved with a stabilizer [4]. These are a few of the studies concerning the stability of the power grid.

As shown in the case studies above, by implementing devices such as energy storage systems we can improve the stability of the power grid. When looking at energy storage systems, there are many types like the capacitor energy storage systems, battery energy storage systems, and flywheel energy storage system, which take energy and store them to be used later as electrical energy in a power system. Compared to renewable energy sources, which need to have a certain energy potential in an area to be useful, these

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devices can be placed anywhere throughout a power system. Each one has a set of advantages and disadvantages, such as batteries are relatively cheap, but have a small life span where capacitors have a longer lifespan, but have a low amount of energy [1]. Another device is the flywheel which is described as they have a high power density (W/kg) and they have a bi-directional power flow, which means they can absorb or generate power [5] [6]. These devices can help regulate and maintain a stable operating point within a power system and are constantly being improved in order to do so.

As shown with the studies and energy storage systems, there are different techniques to help improve a system with renewables like installing a device to help with power injection or implement a controller to increase the damping of the system, but the main goal of this study is to improve a power systems stability while dealing with the variability and low inertia of renewables. With this in mind, our idea is to use a flywheel energy storage system (FESS) to help impact the electrical mechanical mode in the system. The reason why this particular mode is focused on is many disturbances seen in a power system are dealing with the electromechanical mode. These disturbances are between 1 Hz and 3 Hz and are issues like sudden changes in the loading of the system or line failures [2]. These types of disturbances can severely impact a system quickly, so a scenario where a system can quickly dampen out oscillations is optimal. This is shown with higher damping ratios. One method is to use a FESS, which is desired due to the capability of being able to inject large amounts of power quickly, absorbing or supplying power, and having a much longer lifespan than battery technology.

The goal of this study is to show that the FESS can help aid in small signal stability dealing with the electromechanical mode by increasing the damping ratio as well as how the FESS affects a small test system. Energy storage systems are important to regulate the electromechanical oscillations within a system, where a model for the FESS is used to aid in simulations. Using the model, we are able to test a system by looking at varying inertia and load settings with and without the FESS. By seeing how the system reacts, we wish to be able to generalize our findings and apply them to future systems.

II. Background

A. Energy Storage Systems

There are many different types of energy storage systems, such as capacitors, batteries, and flywheels. These devices store energy for later use [7]. The reason energy storage system is needed is because there is a lack of inertia with renewable source which causes the system to be more susceptible to oscillations. This relation is show by equation 1:

$$\frac{\partial \omega}{\partial t} = \frac{1}{2H}(T_m - T_e) \tag{1}$$

which shows the relationship between angular speed and inertia [1]. Each device has advantages and disadvantages and the proper device needs to be chosen for what is needed. For this study, a high amount of power, a fast response, and a long lasting device is needed. As shown in the table 1, there is a list comparing the devices, where the device that fulfills our requirements is the flywheel [1] [8]. These flywheels will be used to help with our small signal stability analysis of the electromechanical mode in our system.

B. Electromechanical Oscillations

The electromechanical mode is an important oscillatory mode which ranges from 1 Hz to 3 Hz [2]. This mode is shown when there are small disturbances such as short circuits. One way to monitor and view the changes caused by the disturbances is to monitor the eigenvalues. This can be calculated using modal analysis, which is also called small-signal stability analysis, which calculates the eigenvalues for the system under small disturbances [9]. The eigenvalues are then used to calculate the damping of the system by Equation 2:

$$\sigma = -\frac{\alpha}{\sqrt{\alpha^2 + \beta^2}} \tag{2}$$

Where σ is the damping ratio, α is the real part of the eigenvalue, and β is the imaginary part of the eigenvalue. Using this method, we can observe the damping of the system with various scenarios with the FESS.

III. Models of System

A. Flywheel Energy Storage System

The model shown in Figure 1 for the FESS is comprised of a set of measurement devices, controllers, and a flywheel. The measurement devices are compared with reference values within the controllers in order to have the flywheel inject or absorb power as needed, such as if the frequency is higher than 60Hz, the controllers will have the flywheel adjust the power output accordingly in order to bring the system back to 60Hz. The controllers consist of: a charge controller, a FES-based Damping controller, a frequency controller, Idq controller, and a PQ controller. The flywheel is modeled to inject power only when a perturbation occurs, otherwise there is no power injection.

TABLE I. TABLE COMPARING ENERGY STORAGE DEVICES

Device	Advantage	Disadvantages	Power Density (W/kg)	Lifecycles
Electrochemical capacitors	long lifespan	low energy	>1,000	>20,000
Flywheels	high power	low energy	1,000 to 5,000	>20,0000
Lead-acid batter	low cost	reduce lifespan	25 to 100	200 to 2,000
Li-Ion battery	High Power and Energy	High Cost and Temp	100 to 200	500 to 4,000

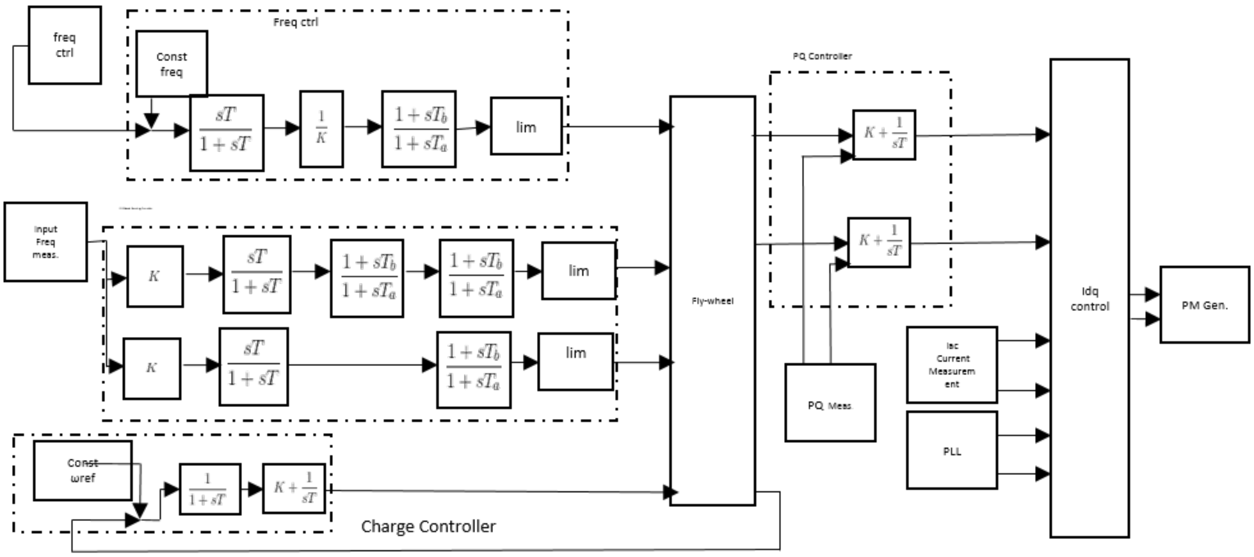

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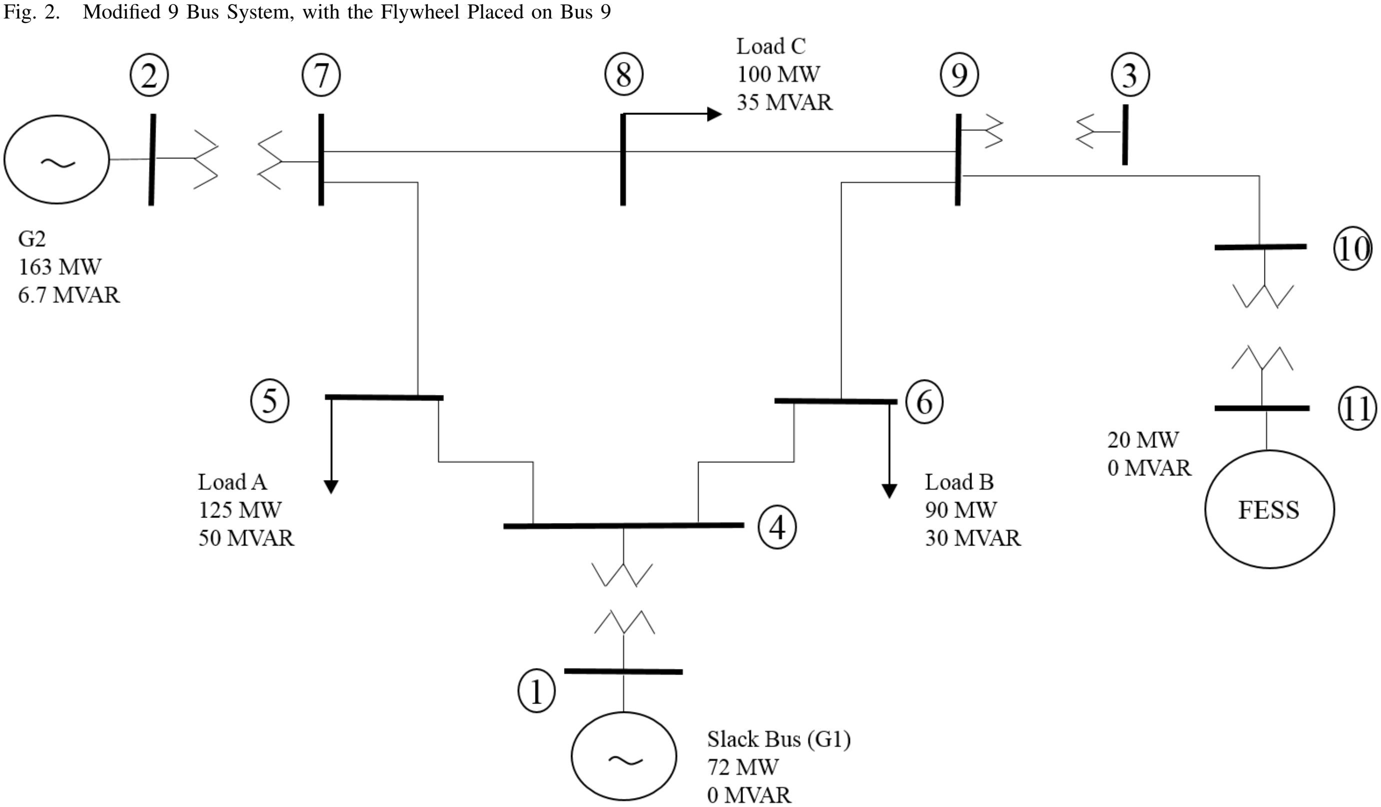
Fig. 1. Model of the FESS

Fig. 2. Modified 9 Bus System, with the Flywheel Placed on Bus 9



1) Charge Controller: This controller keeps the flywheel at the optimal state of charge and change the power as needed to maintain the state of charge.

2) FES-based Damping Controller: This controller uses the frequency as a reference and maintains the active power and reactive power signal output into the flywheel in order to control the damping that should be seen by the system.

3) Frequency Controller: The frequency controller tells when to inject or absorb power into the system in order to balance the generation and loading, which helps regulate the frequency.

4) Idq Controller: This controller compares the d current angle with the voltage angle and makes sure that they are in phase with one another. The q current angle is regulated to be offset by 90 degrees from the voltage angle.

5) PQ controller: This controller adjusts the current seen by the flywheel to produce the proper power.

B. Automatic Voltage Regulator (AVR)

The automatic voltage regulator model used is the IEEEX1 model, which is also called the 1979 IEEE Type 1 Excitation System. The reason this model was used is because this is a general model [10]. The model is simple and allows for the main dynamic responses for a real power system to be seen

C. Governor

The governor model used is the IEESGO model, which is also called the IEEE Standard Governor [10]. This model is another general model that will be able to monitor the main dynamic responses of the system.

IV. Case Study

For this study, a FESS is attached to the standard 9 Bus system as shown in Figure 2, and the generator originally on bus 3 and the FES-base damping controller are removed. This is to make it easier to study the effect of the FESS on the electromechanical mode of the power system. The test system shown in Figure 2 was simulated using a power system analysis tool called DigSilent. DigSilent is used because the software allows for an in-depth analysis of the system such as dynamic simulations. The FESS originally has a rated power of 20MW, which matches the amount of power that is injected to the system during a disturbance. The slack bus with the generator, G1, has an inertia H1= 25s and the generator at bus 2, G2, has an inertia H2 = 10s for the base case. The following cases are looked at for the effect on the damping ratio: changing inertia, changing loading. The reason why the changing inertia case is studied is we wish to see how the inertia of the machines will affect the sensitivity of the system. For the changing load case, although for a real system the loading is constantly changing and is hard to control, we desire to see how the sensitivity is affected and whether or not our conclusions change in comparison with the inertia case.

A. Changing Inertia

In this scenario, the inertias H1 and H2 are stepped from 10secs to 30secs to see how the system changes, such as the eigenvalues of the system. Due to their only being two generators, there is only one electromechanical eigenvalue we need to observe.The following cases are studied while the inertia of each generator is ranged from 10 secs to 30 secs in order to see how the FESS impacts the system: the FESS injects no power, the FESS injects 20MW on bus 7, the FESS injects 20MW on bus 9, and the FESS injects 20MW on bus 4.

B. Changing the Loading

In this scenario, the inertia of the generators are set to H1 = 25 secs and H2 = 10 secs. Each of the loads are varied from 80MW to 250 MW, so Load A = 80MW, Load B = 80 MW, and Load C = 80 MW initially, then in steps of 10 MW each load is increased. So the next step would be Load A, Load B, and Load C are equal to 90 MW, and they are increased until they reach 250 MW. The reactive power of each load was left alone and not incremented. This allowed for the changes in the system to be related to one variable and allowed us to observe the changes more easily. In this case we considered the system without the power injection with bus 1 as the slack bus and G2 has an active power (P) = 163 MW and then repeated this scenario where bus 2 is the slack bus and G1 has P = 163 MW.

V. Results

A. Changing Inertia

1) Base Case: In this case there is no injection from the flywheel into the power system. This case was used to find where the damping ratio of the system is at when the system is running normally. The damping ratio of the base case ranges from approximately 6.05% to 8.84% as shown above in Figure 3.

2) Bus 7,9,3: In this case the damping ratio is found when the FESS is placed at various buses. In Figure 4, the 3 buses used are bus 7, bus 9, and bus 4. The ranges of the damping ratio for buses 7, 9, and 4 are approximately 7.32% to 9.63%, 6.21% to 8.89%, and 6.54% to 9.11%, respectively. In each case the flywheel has improved the damping ratio slightly. This also shows that the location of the flywheel can help improve the damping ratio, if placed well. The graphs for these scenarios depicted in figure 3 and figure 4 show that when the inertia increases then the system damping increases. This is most likely due to the fact that at a higher inertia the generator changes slower when compared to a machine with a lower inertia, so the system does not change as fast with a sudden disturbance. Another observation with the flywheel is whenever the flywheel is attached to a bus with one generator

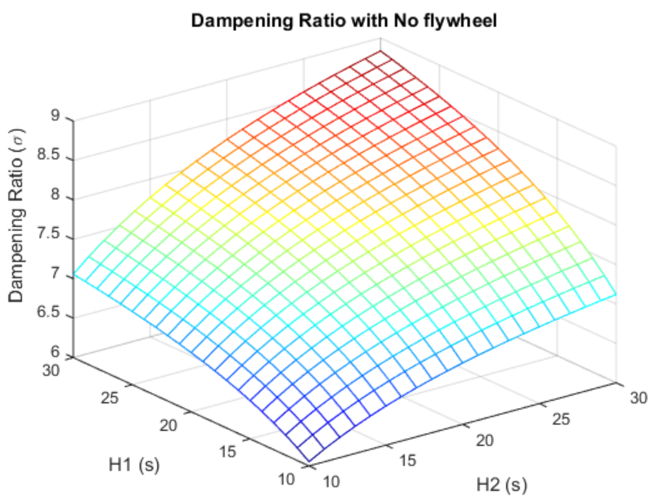


Fig. 3. Damping ratio when there is no injection from the FESS

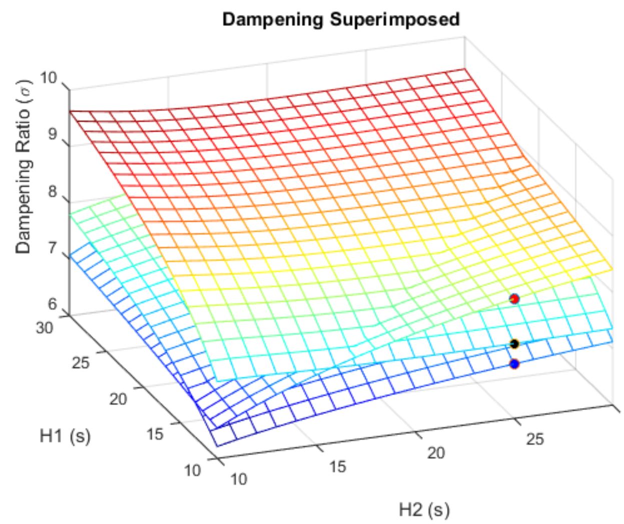


Fig. 4. Damping Ratio at the various buses. The red marker refers to bus 4, the blue marker refers to bus 9, and the black marker refers to bus 7. In order of top to bottom: Top point is bus 4, Middle point is bus 7, and the bottom point is bus 9.

the highest damping occurs when the other generator has a high inertia.

B. Changing Loading

1) Base Case: Like with the changing inertia case, the damping ratio ranges from approximately 6.05% to 9.55%. The trend shown is that with the higher inertia of the generators, the higher the damping in the system. This is consistent with the inertia case above. In some of the scenarios when the inertias of the machine were closer together, there was a minima of the damping ratio in the middle of the load values. An idea is that this occurrence may be due to the generators switching which one has a bigger impact on the system, but this would require further study with the participation factors of the generators.

2) Alternate Slack Bus: This case follows the base case in that the higher damping occurs with higher inertia.

VI. Future Work

From the simulations we were able to see how the flywheel impacted a small system, but due to time constraints we were not able to study a test system consisting of more than two generators. If we were to continue this study we would like to study a system with multiple generators in order to see if the flywheel maintains the behavior exhibited in the small test system. We also want to see if the behavior of increasing the damping ratio by the most when placing the flywheel on the generator with lower inertia changes. Further study would be needed to explain the phenomena where we had a minimum during the changing the loading scenario, where at a constant inertia case the minimum damping value occurred in the middle of the range of the loading.

VII. Conclusion

In this study, we wished to study how a FESS impacted a small test system and see if the device would improve the stability of the system. The reason for this study is that more renewable sources are being incorporated into power grids today, but this lowers the inertia within the system and increases the variability in the generation of power. In order to fix these issues, some methods are to use energy storage systems and controllers to help improve and regulate the system. We desired to see how the FESS impacted the regulating capabilities of a system by observing the reaction of the system when changing the inertia in the machines and the loading of the system. We found that in each scenario the FESS had improved the damping ratio of the system when compared to the system without the FESS installed. An observation seen is the damping of the system was improved further when the FESS was attached to the same bus as the generator with lower inertia. Overall, this shows by integrating a FESS we can improve the regulating capabilities of a power system.

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