A Novel Controller for Virtual Synchronous Generator with Energy Storage System to Improve Power System Inertia

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***Abstract*— The integration of renewables like wind and solar results in reduced grid stability due to their lack of inertia. In order to increase the renewable energy share in the energy mix, the lack of inertia must be compensated with an alternative method to prevent the reduction of frequency stability of the system due to a reduction of inertia. To improve the inertia in the system energy storage system can be used as a virtual kinetic energy storage to emulate inertia which improves the frequency stability of the system. The main focus of this paper is to evaluate the capability of a virtual inertia system to aid in frequency stability following a disturbance to the grid. In this paper, a novel control strategy is suggested for the virtual inertia controller. This system does not rely on numerically solving the swing equation unlike widely discussed controllers. This can reduce the complexity of the virtual inertia system while still having good performance in improving frequency stability.**

Keywords—Virtual inertia, Virtual synchronous generator, renewable energy, frequency stability

I. INTRODUCTION

Due to environmental concerns and rapid development of the technology integration of RESs to the power system is accelerating fast and replacing the traditional fossil fuel based conventional power plant with power electronics based RESs like wind and solar which lack the inertia [1]. Kinetic energy that stored in rotating synchronous generator provide inertia to the power system which helps to stabilize the frequency of the system. When the system inertia is too low, the ability to withstand a perturbance to the system is reduced [2].

In order to reduce the effect of low inertia in the power system, it is proposed to use VSG with energy storage systems. With a suitable controller technique, the VSG has the ability to mimic the dynamic characteristics of the synchronous generator [3]. Compared with the synchronous generator VSG has more advantages like ability to change characteristics by changing parameters in real-time, operation flexibility etc.

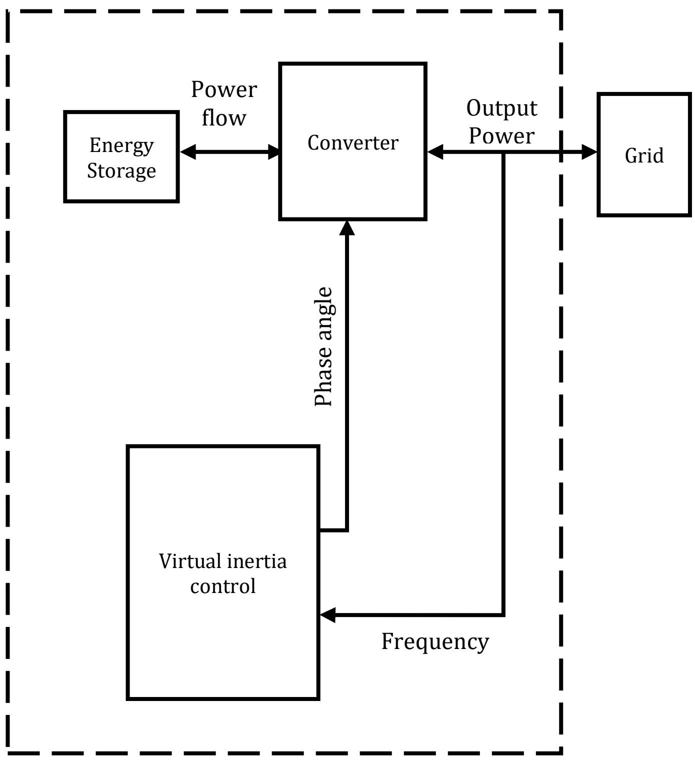
Most literatures available about VSG control techniques uses mainly two approaches. First is to solve the swing equation numerically to calculate the load angle and then inject the power by varying the load angle. The approach used here is to use the rate of change of frequency (RoCoF) to calculate the required real power that needs to be injected to aid frequency stability. In this method, numerically solving the swing equation is avoided and the calculated power is injected by directly changing the phase angle between the inverter output and the grid voltages.

II. PRINCIPLE OF OPERATION

Fundamental block diagram of the proposed VSG controller shows in Fig 1. Controller has the ability to control injected power to the grid according to RoCoF and frequency. Also has the ability to alternate between two preselected inertia parameters according to the measured frequency and RoCoF value in a particular moment.

A. Control Strategy

Fig 1: System block diagram



When the power demand from a grid exceeds the power supplied to the generators, the rotors undergo deceleration, and this results in a drop-in grid frequency. Under these circumstances, the kinetic energy of the rotor is expended to supply the power deficit. The power supplied by expending kinetic energy is given by the following equation.

$$P = J\omega \frac{d\omega}{dt} \tag{1}$$

P – Power supplied by the rotor kinetic energy
J – Moment of inertia of the rotor
ω – Angular velocity of the rotor

Since the fractional/percentage change of angular speed is small, the product, $J\omega$ can be considered a constant. Then, (1) can be rewritten as by replacing angular speed with frequency (Denoted by *f*). Here, k is a negative constant.

$$P = k \frac{df}{dt} \tag{2}$$

In order to inject power to the system, the phase angle between the Voltage Source Inverter (VSI) and the grid needs to be controlled. The "load angle" can be given by,

$$\delta = \ sin^{-1}(sin\delta_0 + K\frac{df}{dt} + D(f^* - f)) \tag{3}$$

$$K = \frac{kX}{EV} \tag{4}$$

E – VSI terminal voltage
V – Grid voltage
X – Reactance between VSI output and the grid
δ – Phase difference between grid voltage and VSI output
f – System frequency
f^*– Steady state frequency after the perturbance
D – Damping parameter

This leading phase angle of the inverter can be achieved by applying a time delay mechanism to the reference of the phase-locked loop (PLL) control of the inverter to alter the phase angle between the grid voltage and the inverter terminal voltage [4]. This method requires significantly less computational requirements compared to the method of numerically solving the swing equation to obtain the load angle [5].

B. Alternating inertia strategy

Increasing system inertia not only resists deviations from steady state frequency, but it also resists returning to the steady state frequency. Having a high inertia when frequency deviates from the nominal frequency and having a low inertia when frequency returns to its nominal value can increase the effectiveness of the controller. This effect can be achieved, and the response of the system can be improved by employing the following criteria [6].

$$if \ \ f < f_0 \ \ and \ \frac{df}{dt} < 0; \ \ select\ high\ inertia$$

$$if \ \ f < f_0 \ \ and \ \frac{df}{dt} > 0; \ \ select\ low\ inertia$$

$$if \ \ f > f_0 \ \ and \ \frac{df}{dt} > 0; \ \ select\ high\ inertia$$

$$if \ \ f > f_0 \ \ and \ \frac{df}{dt} < 0; \ \ select\ low\ inertia$$

Here, f_0 refers to the nominal steady state frequency. According to the above criteria, J and therefore k is selected. In this case, k alternates between 2 pre-selected values to improve the characteristics of the response to a disturbance.

C. Conditions for stability

It is important to consider the effect of the virtual inertia system on the stability of the system. In order to analyze this, the transfer function of the virtual inertia system is obtained.

$$P = K_0 \frac{d\omega}{dt} + D_0(\omega^* - \omega) \tag{5}$$

$$K_0 < 0$$

For a given load step, ω^* is constant therefore this can be modified to obtain the following,

$$\Delta P = \ K_0 \frac{d\Delta\omega}{dt} + \ D_0\Delta\omega \tag{6}$$

Obtaining the Laplace transform gives,

$$\frac{\Delta P(s)}{\Delta\omega(s)} = \ K_0 s + \ D_0 \tag{7}$$

This transfer function of the virtual inertia system can be incorporated into the frequency control block diagram of an isolated power system

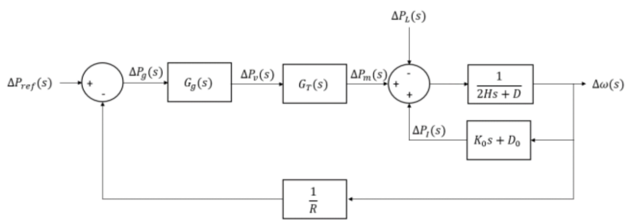


Fig 2: Frequency control block diagram

Considering a constant reference power, the transfer function is obtained.

$$\frac{\Delta\omega(s)}{\Delta P_L(s)} = \frac{-R}{G_g(s)G_T(s) + R(2Hs - K_0 s + D - D_0)} \tag{8}$$

We can conduct a stability analysis using the transfer function of the overall system including the virtual inertia system. Transfer functions representing a delay can also be incorporated when conducting a stability analysis.

D. Modelling

A perturbance/disturbance to a simple grid due to a disconnection of one of its generators can be represented as a load step to the remaining generators. In this simulation model, a load step given to a single synchronous generator is considered. The number of generators in the system does not affect the idea of this since the virtual inertia mechanism relies on the frequency readout of this point of connection.

The 3 phase VSI associated with the virtual inertia system is modelled using a controlled voltage source. A time delay is applied to the reference voltage signal to control the phase angle between grid and the inverter. It can be controlled by varying the reference signal of the Phase Locked Loop system [4]

III. Designed VSG controller and results

A. Designed Virtual Inertia Controller

Fig. 2 in below shows the simplified version of the designed virtual inertia controller. The output of the controller applies a time delay to the reference voltage signal. In this case, under steady state conditions, the virtual inertia system does not inject any real power into the grid, therefore the output voltage of the inverter and output voltage of the grid are in phase. A Phase Locked Loop (PLL) based inverter can be used to perform this task [4]

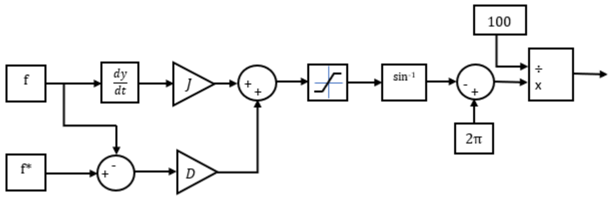


Fig 3: Simplified control block diagram

B. Results and test conditions of the simulation

A load step is applied to a microgrid system to simulate a disturbance and the test parameters are as follows.

Nominal load = 50kW
System voltage = 400V
Inverter/voltage source voltage = 450V
Nominal frequency = 50Hz
J = -0.06s^2
D = 0.01s
Generator inertia = 8.105kgm^2

Here, the settling time is defined as the time it takes for the frequency to settle between 49.9Hz and 50.1Hz after a disturbance. Any other arbitrary criteria can also be used.

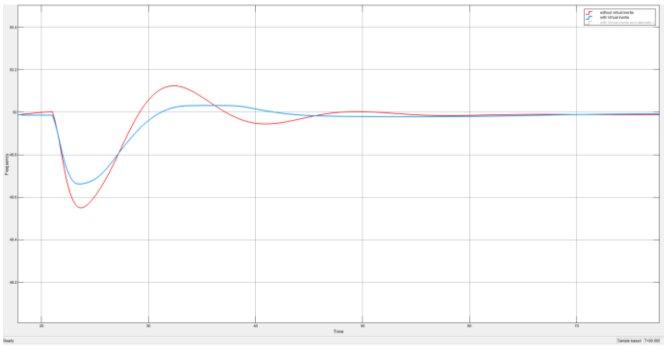


Fig 4: Frequency variation with and without virtual inertia for 5% disturbance (2.5kW load step)

Parameters	With virtual inertia J	Without virtual inertia J
Lowest point (Hz)	49.63	49.55
Highest point (Hz)	50.04	50.12
Settling time (s)	7.49	13.18

Table 1: Performance of the system with and without virtual inertia for 5% disturbance (2.5kW load step)

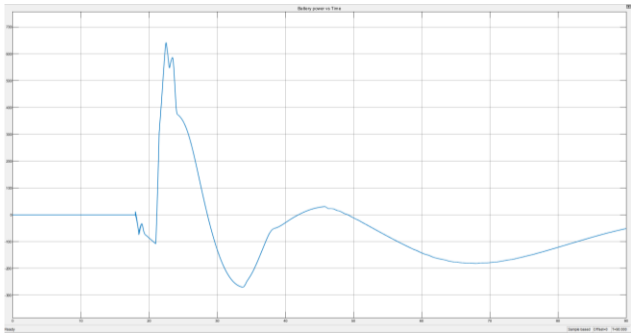


Fig 5: Power output of the system for a 5% disturbance (2.5kW load step)

As shown in Table 1, the peak-to-peak frequency improvement with virtual inertia for 5% disturbance is 28.07%. The settling time improvement in virtual inertia system over default system is 43.17%.

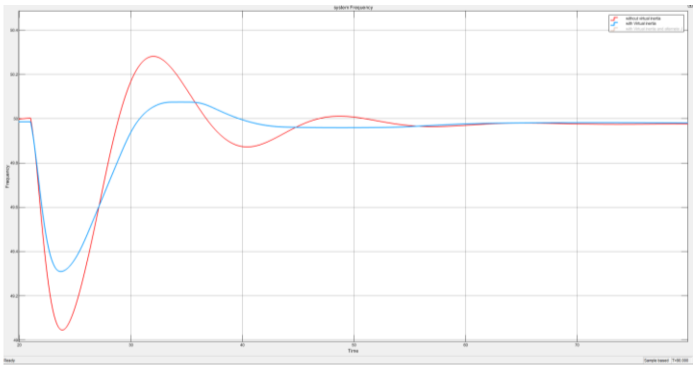


Fig 6: Frequency variation with and without virtual inertia for 10% disturbance (5kW load step)

Parameters	With virtual inertia J	Without virtual inertia J
Lowest point (Hz)	49.24	49.05
Highest point (Hz)	50.09	50.28
Settling time (s)	8.22	21.68

Table 2: Performance of the system with and without virtual inertia for 10% disturbance (5kW load step)

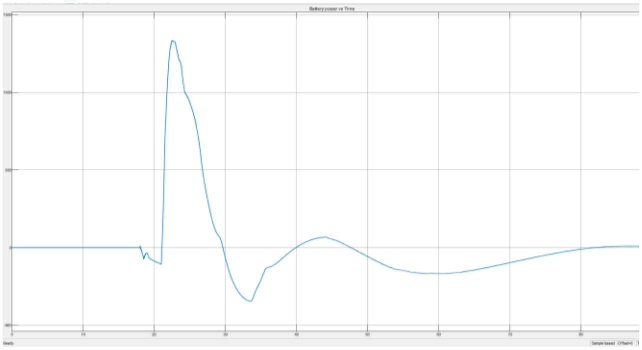


Fig 7: Power output of the system for a 10% disturbance (5kW load step)

As shown in Table 2, the peak-to-peak frequency improvement with virtual inertia for 10% disturbance is 30.89%. The settling time improvement in virtual inertia system over default system is 62.08%.

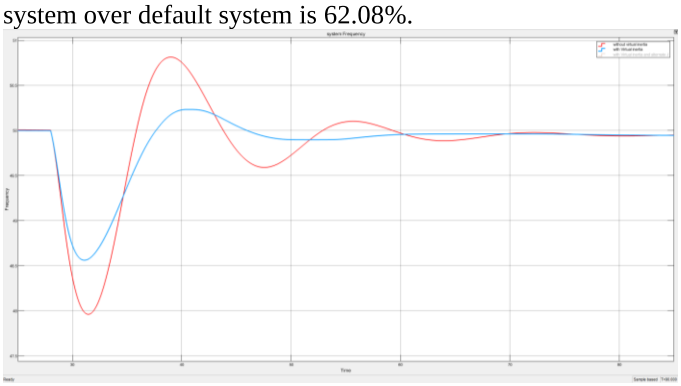


Fig 8: Frequency variation with and without virtual inertia for 20% disturbance (10kW load step)

Parameters	With virtual inertia J	Without virtual inertia J
Lowest point (Hz)	48.56	47.96
Highest point (Hz)	50.23	50.81
Settling time (s)	15.97	22.32

Table 3: Performance of the system with and without virtual inertia for 20% disturbance (10kW load step)

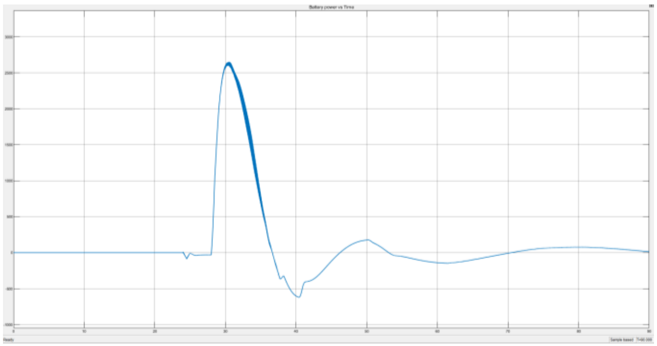


Fig 9: Power dispersion for 20% disturbance (10kW load step)

As shown in Table 3, the peak-to-peak frequency improvement with virtual inertia for 20% disturbance is 41.40%. The settling time improvement in virtual inertia system over default system is 28.45%.

Test results for a sudden disconnection of a fraction of the load is simulated below.

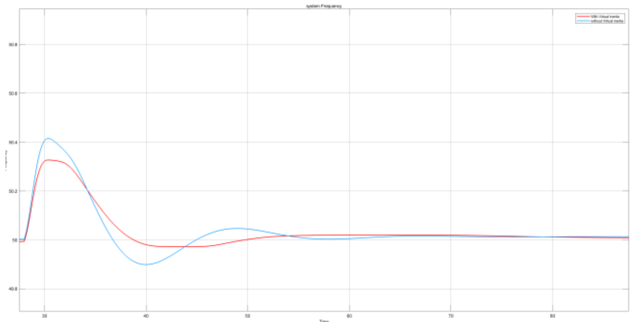


Fig 8: Frequency variation with and without virtual inertia for 5% load decrease (2.5kW load decrease)

Parameters	With virtual inertia J	Without virtual inertia J
Lowest point (Hz)	49.97	49.90
Highest point (Hz)	50.31	50.42
Settling time (s)	7.468	12.309

Table 3: Performance of the system with and without virtual inertia for 5% load decrease (2.5kW load decrease)

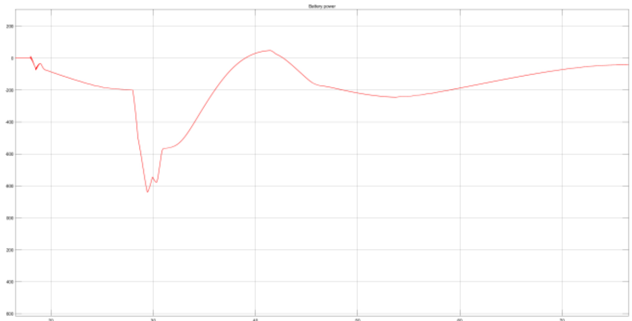


Fig 9: Power dispersion for 5% load decrease (2.5kW load decrease)

As shown in Table 1, the peak-to-peak frequency improvement with virtual inertia for 5% disturbance is 34.62%. The settling time improvement in virtual inertia system over default system is 39.33%.

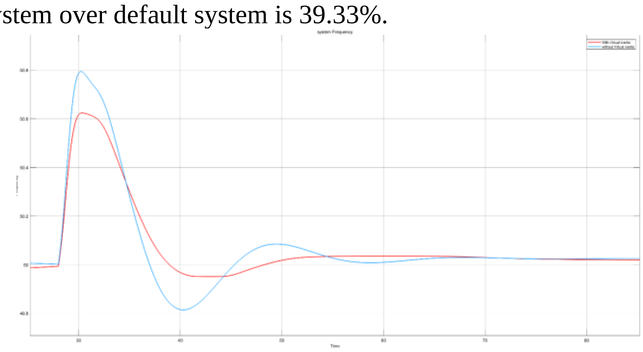


Fig 8: Frequency variation with and without virtual inertia for 10% load decrease (5kW load decrease)

Parameters	With virtual inertia J	Without virtual inertia J
Lowest point (Hz)	49.96	49.81
Highest point (Hz)	50.61	50.80
Settling time (s)	8.767	14.965

Table 3: Performance of the system with and without virtual inertia for 10% load decrease (5kW load decrease)

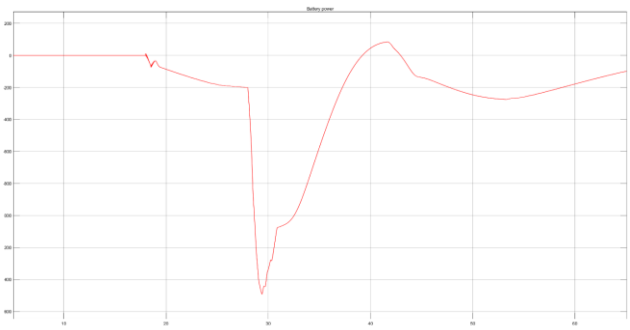


Fig 9: Power dispersion for 10% load decrease (5kW load decrease)

As shown in Table 2, the peak-to-peak frequency improvement with virtual inertia for 10% disturbance is 34.34%. The settling time improvement in virtual inertia system over default system is 41.42%.

A load step is applied to a high-power system to simulate a disturbance and the test parameters are as follows.

Nominal load = 120MW
System voltage = 13.8kV
Inverter/voltage source voltage = 15kV
Nominal frequency = 50Hz
Disturbance = 10MW
Generator inertia constant = 4s
Rated apparent power = 200MVA

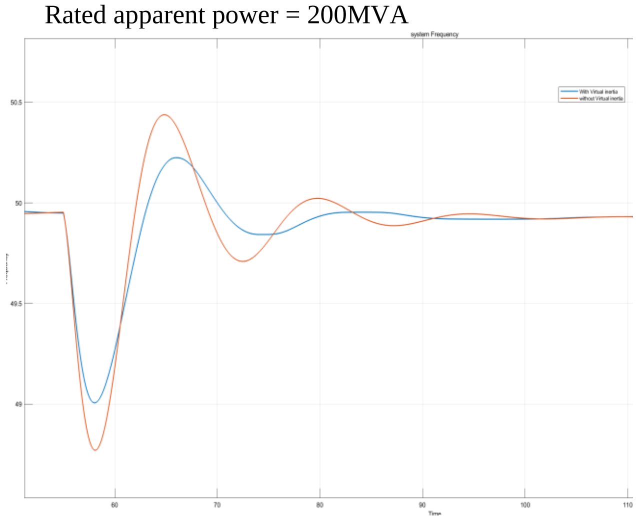


Fig 10: Frequency variation with and without virtual inertia for high power system (10MW disturbance)

Parameters	With virtual inertia J	Without virtual inertia J
Lowest point (Hz)	49.01	48.77
Highest point (Hz)	50.23	50.44
Settling time (s)	23.78	34.94

Table 4: Performance of the system with and without virtual inertia for high power system (10MW disturbance)

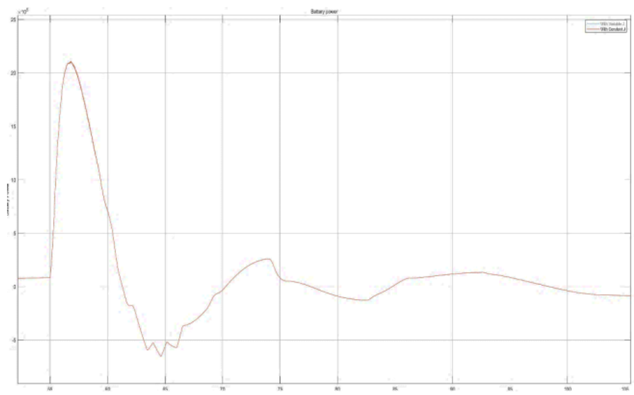


Fig 11: Power dispersion for constant virtual inertia system (10MW disturbance)

As shown in Table 4, the peak-to-peak frequency improvement with virtual inertia for 10MW disturbance is 26.95%. The settling time improvement in virtual inertia system over default system is 31.94%.

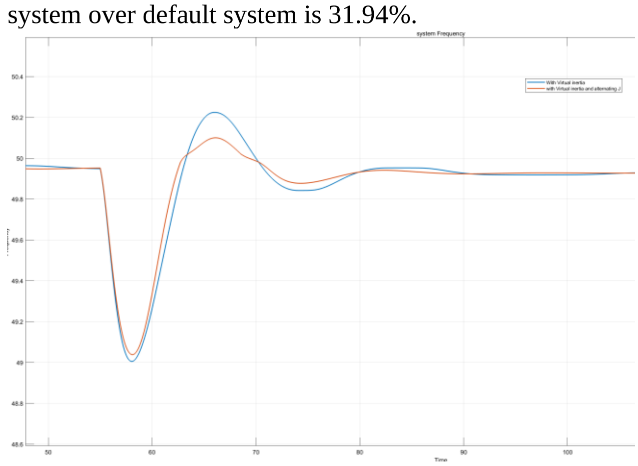


Fig 12: Frequency variation with constant and variable virtual inertia for high power system (10MW disturbance)

Parameters	With constant virtual inertia J	With variable virtual inertia J
Lowest point (Hz)	49.01	49.04
Highest point (Hz)	50.23	50.09
Settling time (s)	23.78	20.28

Table 5: Performance of the system with constant and variable virtual inertia for high power system (10MW disturbance)

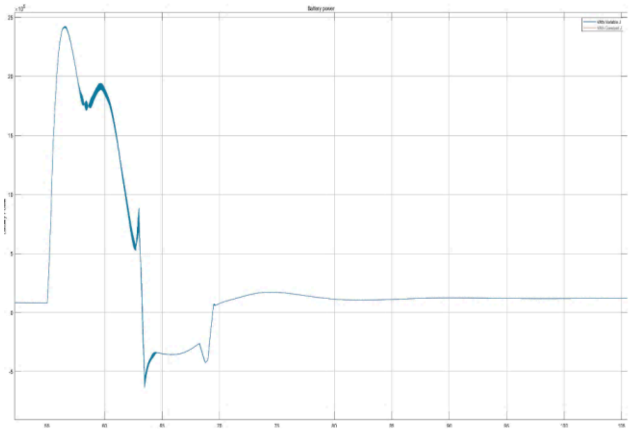


Figure 13: Power output of the alternating virtual inertia system

IV. CONCLUSION

This paper describes a virtual inertia system that injects power into the grid based on the rate of change of frequency and the frequency deviation. And incorporates an alternating inertia strategy. This is less computationally intensive than numerically solving the swing equation as described in the other commonly used method.

From the results we can see the initial frequency drop from the load step, and the subsequent recovery by the governor action and how a virtual inertia system aids in limiting frequency fluctuations and results in an improved response. The performance of a constant inertia virtual inertia system and alternating parameter virtual inertia system was also observed.

In order to test the functionality of the system, different levels of load steps were applied (up to 20% of nominal load) and the frequency plots were obtained. Furthermore, the transfer function obtained for this kind of virtual inertia system allows the system to be incorporated to the frequency control block diagram of a power system for stability analysis.

In conclusion, the simulations conducted on the system demonstrate that a virtual inertia system as described in this report is capable of significantly improve the frequency response of a power system under disturbance due to a load step. The system response to faults were not studies in this paper and would be a topic for future research.

V. REFERENCES

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