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Improving Virtual Synchronous Generator Control in Microgrids Using Fuzzy Logic Control

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***Abstract*—Virtual synchronous generators (VSG) are designed to mimic the inertia and damping characteristics of synchronous generators (SG), which can improve the frequency response of a microgrid. Unlike synchronous generators whose inertia and damping are restricted by the physical characteristics of the SG, VSG parameters can be more flexibly controlled to adapt to different disturbances. This paper therefore proposes a fuzzy logic controller designed to adaptively set the parameters of the VSG during a frequency event to ensure an improved frequency nadir and rate of change of frequency (ROCOF) response. The proposed control method is implemented and tested on the power inverter for the battery energy storage system of the Banshee Microgrid Feeder 2 test case system using MATLAB/SIMULINK. The effectiveness of the adaptive control scheme is validated by comparing its performance with a constant parameter VSG, a virtual inertia only fuzzy controller, and an inertial-less inverter control.**

***Index Terms*—Virtual Synchronous Generator, Virtual Inertia, Virtual Damping, Fuzzy logic control, Microgrid.**

I. Introduction

In recent years renewable energy sources (RESs) have risen to be an important component in modern power systems due to concerns over environmental pollution and the energy crisis. However, these RESs, such as photovoltaic (PV), wind, and batteries, require three-phase inverters to connect to the grid. As more RESs interface and replace the conventional power generators which have a rotating mass and inherit inertia characteristics, the power grid becomes more vulnerable to frequency disturbances that could have catastrophic effects. The conventional control of power inverters uses direct current control. This involves the use of PI controllers for controlling the active and reactive power flow between the inverter and the grid and does not offer inertia capabilities for the stability of the power system. This form of inverter control cannot support microgrid during standalone operation or islanding mode [1-3] unless modified to a grid-forming inverter using droop control which again does not provide inertia support.

A new control method for grid-connected converters called "virtual synchronous generator" has been proposed to solve the problem of inertia loss in the power system and operate as a grid-forming inverter. The goal of the virtual synchronous generator (VSG) is to mimic the inertia and damping and characteristics of actual synchronous generators which can be achieved by using the generator swing equation in the active power loop control [4-5]. Also, like SG, VSGs can regulate the flow of reactive power by using either a voltage droop controller or a PI controller to mimic the winding excitation of SG. However, unlike SGs, the VSG is an algorithm that is implemented in software and as such, it has the flexibility of operating in an adaptive manner which involves tuning its parameters with respect to the perceived disturbance. The performance of the active power loop (APL) of the VSG is dependent on a variety of factors, with the virtual inertia and damping factor parameters playing a significant role in the VSG performance. A step-by-step parameter design method was introduced in [6]. The concept of linear quadratic regulator control was proposed to find the optimal virtual inertia constant for a single VSG [7] and was extended to multiple VSGs [8]. By using this approach, the trade-off between the critical frequency limits and control cost was achieved. By taking into consideration the change of the rotor speed and its differential, [9-10] developed a class of adaptive parameters (virtual inertia and/or damping factor) adjustment.

While these methods show good performance, it would require an accurate system model to set up a good adaptive tuning law. To eliminate the need for such rigorous system modeling, a fuzzy logic controller was used [11] for tuning the virtual inertia of the VSG APL. This approach eliminates the need for accurate mathematical representation, as it only considers the virtual inertia parameter of the VSG APL. In a more recent work [12], the fuzzy logic controller was augmented with the VSG to dampen the perturbation during transients by increasing the inertia of the system. This was achieved by adding a correction term to the governor output power such that the system inertia is increased during transients. However, since the APL is built on imitating the swing equation of the SG, it would be beneficial to explore the influence of its key parameters.

This paper focuses on the APL of the VSG which mimics the SG swing equation to improve inverter response. The two key parameters of interest from the APL loop are the

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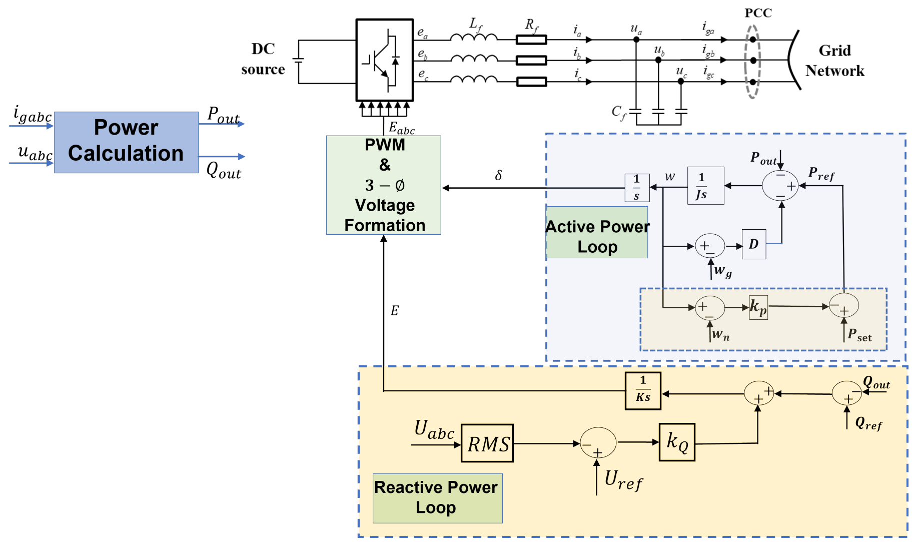

Fig. 1. Conventional layout of the grid-connected inverterwith VSG Controller

virtual inertia constant (J) and virtual damping (D). While both parameters directly influence the VSG frequency response, they have distinct roles. The virtual inertia parameter impacts the ROCOF more significantly than the frequency nadir when increased, while the virtual damping has a more significant impact on the frequency nadir than the ROCOF when increased. Hence, we propose a fuzzy logic control method that dynamically adjusts these parameters during a frequency disturbance to improve the VSG response. Furthermore, we show that as opposed to [11], dynamically adjusting both parameters provide a better frequency response.

The rest of the paper is organized as follows. First, the virtual synchronous generator control is briefly discussed in Section II alongside how the parameters of the VSG influence its response. Section III introduces the fuzzy logic control setup for dynamically setting the VSG parameters. The performance of the proposed fuzzy logic control-based virtual synchronous generator (FLCVSG) controller is evaluated in Section IV and the conclusions and suggested future work are presented in Section V

II. System Modelling

Figure 1 shows a conventional layout of VSG controlled grid-tied inverter which is connected to the utility grid network. A three-phase circuit breaker can be used to island the microgrid and, in such a scenario, the inverter should be capable of forming the voltage and frequency of the microgrid. A low pass filter is used to filter off high switching frequency signals coming from the inverter into the microgrid while allowing low frequency of 50/60Hz to pass through. In this paper, the inverter of concern is connected to a battery energy storage unit which acts as the prime-mover for the VSG.

To control the inverter, the output voltage U_{abc} and current I_{abc} of the inverter are measured and used to compute the output active P_{out} and reactive power Q_{out} of the inverter which are inputs to the VSG controller alongside the active power reference P_{ref} and reactive power reference Q_{ref}. The output of the VSG controller is the inverter voltage magnitude E and the load angle δ which are both necessary inputs for the PWM to generate gate pulse signals to control the inverter.

The VSG controller has two main control loops; Active power loop(APL) and reactive power loop(RPL). The APL is modelled to mimic the SG swing equation expressed as

$$P_{ref} - K_p(\omega - \omega_g) - D(\omega - \omega_g) - P_{out} = J\omega\dot{\omega} \quad (1)$$

From (1) P_{ref} is the active power reference, K_p is the droop gain, D is the virtual damping factor of the VSG, and J is the virtual inertia. The angular speed of the virtual rotor, the angular speed of the grid, and the reference angular speed are all represented by ω ,ω_g ,ω_{ref} and $\dot{\omega}$ being the ROCOF of the VSG angular speed.

The output active power of the VSG can be expressed as

$$P_{out} = \frac{3EV sin\delta}{2X_{eq}} \quad (2)$$

With $X_{eq} = X_{line} + X_{filter}$ being the effective reactance.

The inverter load angle is given by

$$\delta = \int (\omega - \omega_g)\, dt \quad (3)$$

The inverter voltage magnitude E can be computed from the reactive power loop as shown in Figure 1 which can be written as:

$$Q_{ref} - K_Q(U - U_{ref}) - Q_{out} = K\frac{dE}{dt} \quad (4)$$

Where Q_{ref} is the reactive power reference, K_Q is the droop coefficient for the RPL, and K is the voltage regulation coefficient. The measured grid voltage amplitude and the nominal voltage amplitude are given by U and U_{ref} , respectively. The control outputs of the VSG are then fed to a voltage formation (5) block to form the 3-phase voltage which is supplied to the PWM to generate the gate pulse signals to control the inverter.

$$E = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} Esin\delta \\ Esin\left(\delta - \frac{2\pi}{3}\right) \\ Esin\left(\delta + \frac{2\pi}{3}\right) \end{bmatrix} \tag{5}$$

A. Small Signal Analysis for VSG Parameter Influence

Unlike the traditional SG, a VSG offers the flexibility of dynamically setting the virtual inertia constant and damping factor during a frequency event to achieve a smooth frequency response. However, before adopting an adaptive VSG, it is beneficial to study the influence these parameters have on the VSG performance. To analyze the behavior of the VSG under different values of virtual inertia and damping factor, obtaining the necessary transfer-function through small-signal modeling and analyzing the behavior of the poles using root-loci under different parameters is necessary.

Based on (1), (2), (3) and using the approach given in [6, 14-15], the small-signal analysis of the APL can be used to derive the transfer function of the VSG.

From (1) we get,

$$-K_p\Delta\omega - D(\Delta\omega - \Delta\omega_g) - \Delta P = J\omega s\Delta\omega \tag{6}$$

From (2) we get,

$$\Delta P = \frac{3EUcos\delta}{2X_{eq}}\Delta\delta + \frac{3Usin\delta}{2X_{eq}}\Delta E + \frac{3Esin\delta}{2X_{eq}}\Delta U \tag{7}$$

Since δ is small, $sin\delta \approx 0$ and $cos\delta \approx 1$ hence (7) becomes

$$\Delta P = \frac{3EU}{2X_{eq}}\Delta\delta \tag{8}$$

From (3) we get

$$\Delta\delta = \frac{\Delta\omega - \Delta\omega_g}{s} \tag{9}$$

When $X_{eq} >> R_{eq}$, the change in active power directly impacts the grid frequency, hence, the desired transfer function should be the output active power with respect to the grid angular speed $(G(s) = \frac{\Delta P}{\Delta\omega_g})$

Now, from (6), we can deduce that,

$$\Delta\omega = \frac{D\Delta\omega_g - \Delta P}{J\omega s + K_p + D} \tag{10}$$

Also, ΔP can be expressed as,

$$\Delta P = \frac{3EU\Delta\omega - 3EU\Delta\omega_g}{2X_{eq}s} \tag{11}$$

Rewriting (11) in terms of $\Delta\omega$ yields

$$\Delta\omega = \frac{2X_{eq}\Delta P + 3EU\Delta\omega_g}{3EU} \tag{12}$$

Equating (10) and (12) and solving for $G(S)$ we arrive at

$$\frac{\Delta P}{\Delta\omega_g} = \frac{-3EU}{2X_{eq}} \frac{s + \frac{K_p}{J\omega}}{s^2 + \frac{Kp+D}{J\omega}s + \frac{3EU}{2X_{eq}J\omega}} \tag{13}$$

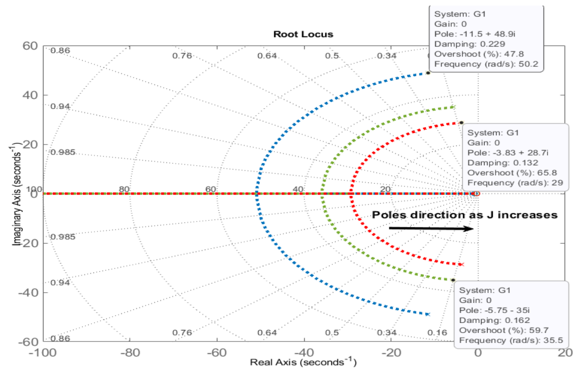

Fig. 2. Poles movement on s-plane with the variation of virtual inertia constant

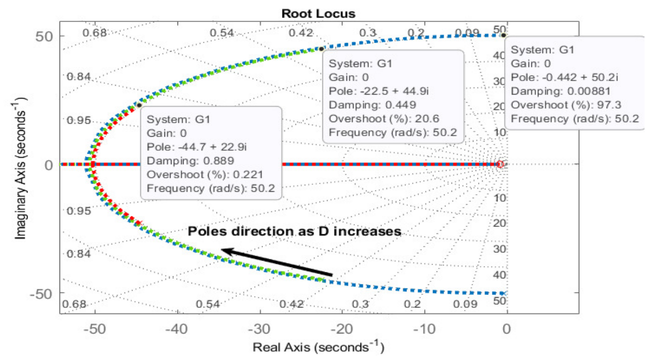

Fig. 3. Poles movement on s-plane with the variation of virtual damping constant

Equation (13) is the desired transfer function for the APL of the VSG. Since this paper primarily focuses on the APL, we only focus on the transfer function for the APL. Based on (13), the roots of the APL are located on the negative left half of the s-plane and are also independent of the RPL droop coefficients as discussed in [14], [15]. To analyze the influence of the APL parameters, the root locus of APL is shown below. Based on Fig. 2, increasing the virtual inertia constant reduces the damping ratio, increases the overshoot, and results in low-frequency oscillations. However, high inertia would also result in a low ROCOF which would be beneficial to the microgrid protection devices. From Fig. 3, increasing the damping factor reduces the oscillations and the overshoot and contributes significantly to the frequency nadir. However, excessively increasing the virtual damping would result in prolonged settling time. Hence, while it is beneficial to increase the APL parameters, it could ruin the system's stability. Thus, it would be beneficial to increase the APL parameters when the frequency event occurs and gradually reduce it as the disturbance fades off.

III. Fuzzy Logic Controller Virtual Synchronous Generator Implementation

The fuzzy logic controller is a rule-based controller that maps the characteristics of the measured inputs to the desired output response using sets of membership functions. Crisp input measurements are collected from the microgrid. In the case of the virtual synchronous generator, the error in the angular speed of the virtual rotor $e = \omega - \omega_g$ and its derivative $\dot{\omega}$ serves as the crisp inputs. The fuzzification unit consists of 5 membership functions for both input parameters. During a frequency disturbance, such as a frequency dip caused by loss of power generation, or load change, the error seen by the fuzzy logic controller would be negative and, depending on its magnitude, would be classified as either zero error (ZE), negative small (NS), or negative large (NL). Similarly, if the error is in the positive region, depending on its magnitude, it would be classified as either zero error (ZE), positive small (PS), or positive large error (PL). The Mamdani fuzzy logic method is applied in this paper. The inferencing stage of the FLC implements the rules by which the controller adjusts its output based on the measured fuzzified inputs. In this work, we desire two outputs from the FLC, the virtual inertia (J) and the damping factor (D) as shown in Figure 4, both of which are updated only during a frequency event. For example, if the error seen by the controller is NL and the derivative of the error is also NL, then, from the rule table shown in figure 5, the FLC would decide to set the virtual inertia and damping factor in the PL region. It should be noted that the FLC only tunes the initial VSG parameters to ensure the ROCOF and frequency nadir has a smooth response, hence, as the error decays to zero, the virtual inertia and damping factor provided by the VSG would also tend to zero leaving the original set of parameters active. Since the VSG requires crisp outputs, the Fuzzy parameters are de-fuzzified first before being fed to the system.

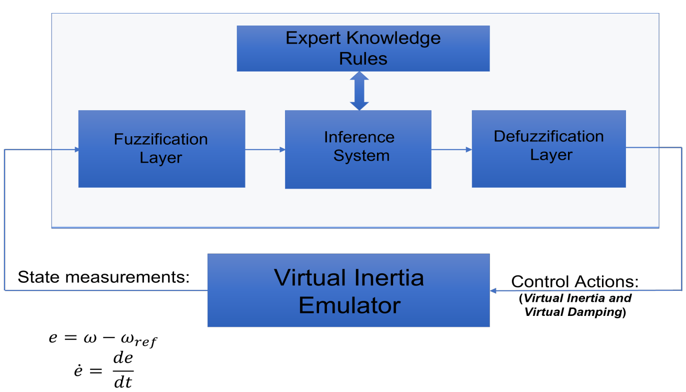

Fig. 4. Fuzzy VSG Controller

IV. Results

To validate the performance of the FLCVSG, feeder 2 of the Banshee Microgrid shown in Fig. 5 was used as the test system. The feeder consists of a 2500KVA BESS located at BUS202 and a 500KW PV located at BUS 203. In grid-connected mode, the loads are served by the utility grid and the BESS-VSG acts primarily in P/Q mode. When the feeder is islanded by opening the breaker at BUS 201, the BESS must

$\dot{e}$ \ e	NL	NS	ZE	PS	PL
NL	PL	PS	PS	PS	PL
NS	PL	PS	ZE	PS	PL
ZE	PS	ZE	ZE	ZE	PS
PS	PL	PS	ZE	PS	PL
PL	PL	PS	PS	PS	PL

Rules For Determining Virtual Inertia (J)

$\dot{e}$ \ e	NL	NS	ZE	PS	PL
NL	PL	PS	PS	PS	PL
NS	PL	PS	ZE	PS	PL
ZE	PS	ZE	ZE	ZE	PS
PS	PL	PS	ZE	PS	PL
PL	PL	PS	PS	PS	PL

Rules For Determining Virtual Damping (D)

Fig. 5. Fuzzy Logic Controller Rules for Adaptive VSG

immediately switch to V/F mode to form the microgrid voltage and frequency. Controlling the microgrid voltage is very important because the PV control performance depends on its PLL to accurately track the voltage phase information. Hence, if the BESS-VSG fails to control the microgrid frequency and voltage, the PV generation would also fail thereby throwing the entire system into instability. Also, according to [16], loads I3 and I4 are considered interruptible loads, hence, once the islanding condition is detected, these loads could be shed if generation capacity does not meet the load demand in the microgrid.

TABLE I
System Key Parameters

Parameters	Values
BESS Inverter Rating	2500KVa
AC BUS Voltage (BUS 202)	480volts
DC-Side Voltage	900volts
Fixed VSG Virtual Inertia	0.00035pu
Fixed VSG Virtual Damping	0.4pu
Inverter Filter Resistance	$1.9m\Omega$
Inverter Filter Inductance	0.05mH
Inverter Filter Capacitance	20uF
Microgrid Frequency	60Hz

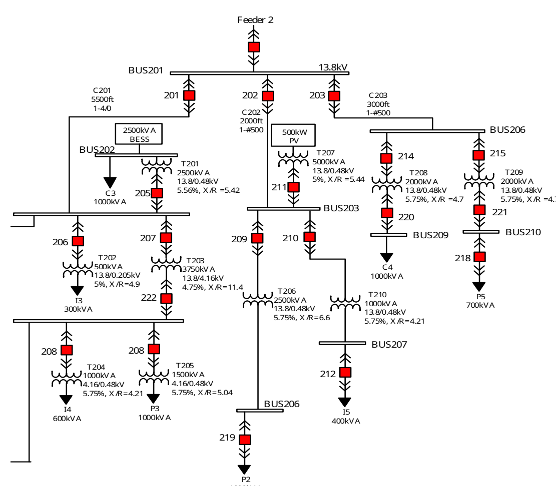

Fig. 6. Modified Feeder 2 Banshee Microgrid

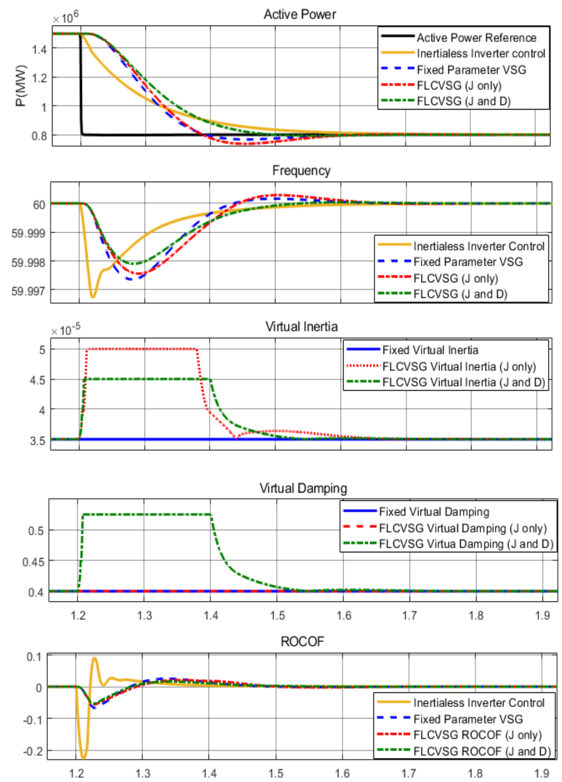

Fig. 7. Simulation results to compare FLCVSG with inertia-less inverter control, constant VSG, and fuzzy VSG (J-Parameter only) under active power reference change

A. Active Power Reference Change

In case 1, the performance of the FLCVSG is evaluated during an active power reference change in the grid-connected mode with the BESS-VSG active power reference changing at 1.2seconds from 1.5MW to 800KW. Fig. 6 shows a comparison of the FLCVSG (J and D tuning) against just tuning J, a fixed parameter VSG, and an inertia-less inverter control method that uses just PI controllers. Based on the rule table defined for the Fuzzy Logic Controller, the FLCVSG can dynamically adjust its parameters to ensure a smooth transition between different levels of the active power reference. This directly improves the frequency nadir and ROCOF, as discussed in Section III, when compared to other listed methods. It should be noted that the inertia-less inverter does not provide the virtual inertia ability hence it experiences the worst ROCOF and frequency nadir. More-so, since the fixed parameter VSG controller can not respond in an adaptive manner towards the disturbance, its performance may also deteriorate in more severe cases.

B. Mode-Transitioning

In this case, the transitioning of the microgrid from grid-connected to islanded mode is considered. According to [16], since there are only renewable energy sources in this feeder, and BESS has more capacity than the PV, the formation of the microgrid voltage and frequency is tasked to the BESS. Hence, for the PV control to work properly, the controller for the BESS inverter must be able to stabilize the microgrid voltage and frequency in islanded conditions.

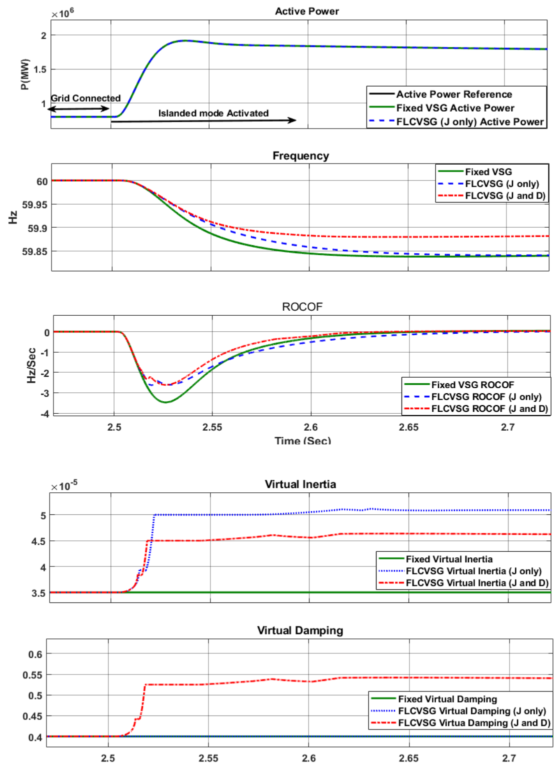

Fig. 8. Simulation results to compare FLCVSG with constant VSG and fuzzy VSG (J-Parameter only) under intentional islanding disturbance

It should also be noted that due to a change in microgrid operation, the grid following inverter can no longer be used unless its topology is changed since it lacks the grid-forming capability of the VSG. From Fig. 8, at 2.5 seconds, the breaker connecting the feeder to the main grid is opened and which automatically triggers the BESS-VSG control to switch from P/Q to V/F mode. As shown, all three forms of VSG control successfully form the microgrid voltage and frequency. However, the frequency nadir and ROCOF obtained by the FLCVSG (J and D) show a better response to the disturbance as compared to the Fixed VSG and just when virtual inertia is tuned. This again is because the FLCVSG can adaptively set both of its parameters based on the disturbance it observes and it confirms that tuning both virtual inertia and damping factor is more beneficial than just focusing on one parameter. It should also be pointed out that a secondary level controller is not used to restore the frequency to 60Hz in this case.

C. Load Change In Islanded Mode

A typical disturbance in an islanded microgrid is load change. Recall in Case 2 that in islanded mode the BESS VSG formed the microgrid frequency and voltage. From Figure 9, prior to 5 seconds, the BESS supplies 1.65 MW of active power to meet the load demand. However, at 5

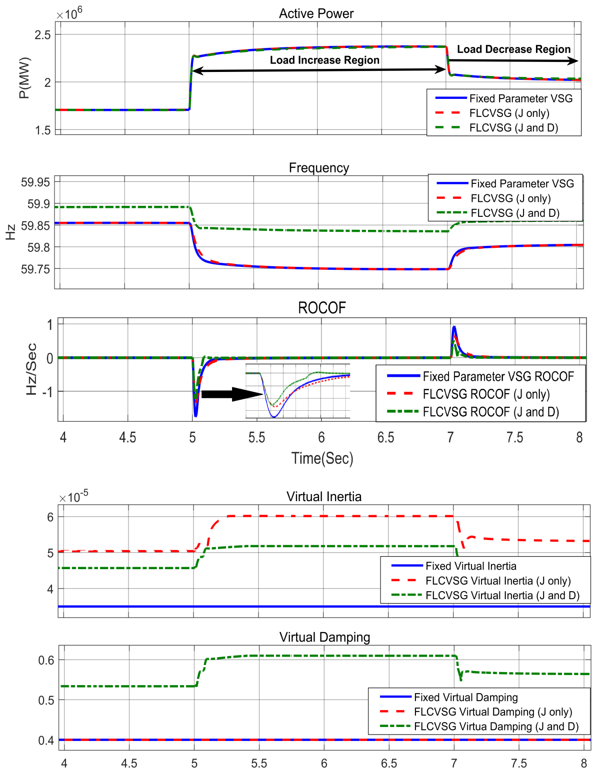

Fig. 9. Simulation results to compare FLCVSG with constant VSG and fuzzy VSG (J-Parameter only) under Load change disturbance in Islanding scenario

seconds, an additional 650KW load was switched on and the BESS increases its output to balance the load demand. Consequently, since the increase in load would result in a dip in the microgrid frequency, the virtual inertia and damping factor of the VSG dynamically increases to guarantee a smooth frequency response. Also, at 7 seconds, some of the loads were tripped off at different locations of the feeder, which causes the frequency to rise. Again, with the dynamic FLC, VSG parameters can adaptively respond by increasing both virtual inertia and damping factor to guarantee a good frequency response.

V. Conclusion

In this paper, fuzzy logic control has been used to improve the inertia response of grid-connected inverter controlled using the virtual synchronous generator control. The proposed fuzzy logic virtual synchronous generator takes as input, the angular frequency of the virtual rotor and its derivative and provides the virtual inertia constant and damping factor parameters as output. Through this process, the VSG-inverter can contribute to improving the frequency response during frequency disturbance. It should be noted that the performance of the FLCVSG highly depends on a good rule selection. Hence, as part of our future work, we look to apply advanced deep reinforcement learning methods which would learn by interacting with the microgrid to obtain optimal VSG parameters. More also, the performance of the reactive power loop has not been investigated in this paper which should also be considered particularly in weak grids.

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