Improvement of the Transient Stability of the Grid through the Power Angle Control Strategy of Virtual Synchronous Machine: A Novel Approach to Improve the Transient Stability

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Abstract - *Renewable energies such as wind turbines and solar photovoltaic have gained significance as a result of global environmental pollution and energy crises. These sources of energy are converted into electrical energy and delivered to end-users through the utility system. As a result of the widespread use of power electronics-based grid-interfacing technologies to accommodate renewable sources of energy, the prevalence of converters has expanded as well. Due to this, the power system's rotating inertia is decreasing, endangering the transient stability of the grid. The use of Virtual Synchronous Machine (VSM) technology has been purposed to mitigate the grid stability problem due to low rotating inertia. The grid-connected inverter used in VSM can be controlled to emulate inertia, which replicates the external features of a synchronous generator. As a result, the rotating inertia is increased to support the power system's stability. A power angle control strategy is developed and the model is simulated in MATLAB/Simulink software to analyze the effects of parameter disturbances on the active power and frequency for a VSM. The system consists of synchronous generator, which has been modeled in such a way that the frequency drops is beyond the acceptable range during transient condition due to lack of inertia when VSM is not used. Then, the suggested model incorporating VSM, emulates rotating inertia, injecting a controllable amount of energy into the grid during frequency transients to enhance transient stability.*

***Key Words*: VSM, ROCOF, Transient stability, Inertia–constant, Damping Constant.**

1. INTRODUCTION

The trend of generation and distribution of power using the Renewable Energy Sources (RES) and Distributed Energy Sources (DES) is increasing rapidly in recent years. Distributed Energy Sources (DES) like Photovoltaic-hydro hybrid micro-grid system seems to be suitable in distant regions having enough hydro sources and to those areas lacking electric grid. However, in comparison to traditional bulk power plants, where the synchronous machine is dominant, the DES/RES units have either a very tiny rotational mass or none at all [1-2]. The massive rotational weights of synchronous generators are crucial for delivering the necessary inertia to large power systems. However, when the percentage share of PV in the system increases, the system's overall inertia decreases as the size of the system grows. In these PV-hydro integrated systems, the lower inertia will have a substantial influence on transient stability and dynamic performance [3-4]. Therefore, a large change in load in these systems can cause large frequency perturbation with a significant rate of change of frequency (ROCOF). As a result, more inertial response is required to give superior dynamic performance and stability during frequency deviation transient periods. The employment of a Virtual Synchronous Machine can give this additional inertia.

The goal of this research is to investigate and simulate VSM using the power angle control approach. It has a wide range of applications. It can be implemented in the PV-Hydro micro-grid where the resultant inertia of the system is significantly lower. A VSM is a power electronics device that stores short-term energy and uses a dispatching algorithm to behave like a synchronous generator. VSM can emulate the characteristics of a synchronous generator by providing inertia and damping properties to the grid or electrical network that is connected with VSM. Whenever there is load perturbation there is an exchange of power between the grid and VSM (i.e. VSM either absorbs or injects power to the grid) [5-8]. Having these features, a VSM can minimize frequency changes during transient periods. The VSM consists of an inverter, frequency sensor, and the controller to generate the necessary switching patterns.

In PV-Hydro Micro-Grid shown in fig -1, the resultant capacity of the plant will get increased in comparison to that when PV is not added.

However, $H = H_1 + H_2$ (PV contributes zero inertia)

The system's total inertia has not risen. As a result, the PV-hydro micro-transient grid's stability will be weak. To enhance transient stability, VSM can be utilized in combination with PV-hydro micro-grids as demonstrated in fig -1.

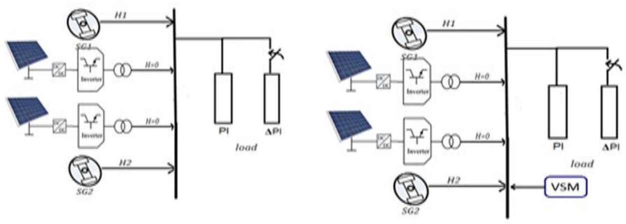

Fig -1: Micro-grid without VSM and with VSM

2. METHOD

2.1 Introduction to Strategy

The technique that has been implemented is the power angle control technique. Here, the frequency of the grid is sensed and compared with a reference frequency. The change in frequency and ROCOF is then passed to an angle controller. The angle controller produces the power (P_VSM) to be injected by VSM and based upon this calculated power, the power angle of an inverter is calculated which is then passed to a sinusoidal reference signal generator. The three-phase sinusoidal reference signals are passed to the PWM generator and the gate signals are given to the inverter from it. The inverter produces the voltage which leads/lags the grid voltage by the same power angle as calculated above. Thus, this difference in phase angle between two voltages is responsible for active power transfer.

Functionally, the operation of VSM is similar to that of an ideal synchronous machine, which can create or absorb active power by adjusting the inverter output. If the load is increased, the frequency of the system will decrease, then the synchronous machine will add extra active power to the system. On the contrary, when the load is decreased, the frequency of the system will increase, then the synchronous machine will absorb surplus power from the grid. From dc voltage source, the converter of the VSM system produces a set of adjustable 3-phase output voltage (V_0) having frequency synchronized with the grid voltage. The active power exchange between the inverter and the ac system is done in a similar fashion to that of the synchronous condenser by adjusting the phase angle of the inverter output voltage (V_0).

i) If $f_{ref}>f_{grid}$, then the inverter generates the active power

ii) If $f_{ref}<f_{grid}$, then the inverter consumes the active power

iii) If $f_{ref} = f_{grid}$, then there is no exchange of active power .

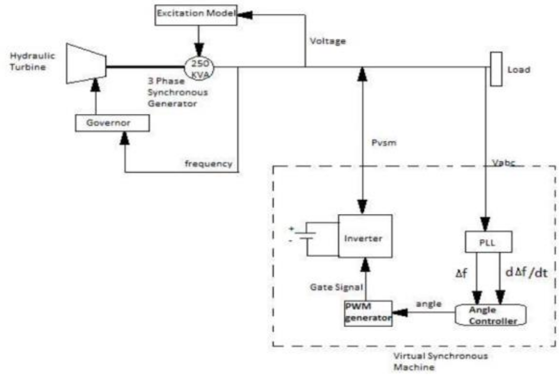

Fig -2: Proposed Scheme of VSM

2.2 Control Strategy

A VSM needs to have an appropriate control mechanism so that it can be able to exchange power with the grid depending on the frequency deviation and ROCOF. The control mechanism should allow the VSM to deliver power when grid frequency decreases and to consume power from the grid when grid frequency increases. The sensed frequency by the frequency sensor is compared with the reference grid frequency, and the change in frequency and the ROCOF are calculated. The power that needs to be exchanged between VSM and the grid is given by,

$$P_{VSM} = K_I \frac{d\Delta f}{dt} + K_p \Delta f \qquad (1)$$

Where K_I and K_p are emulated inertial and damping constants respectively [4].

They are calculated as,

$$K_I = \frac{P_{NOM}}{\left(\frac{d\Delta f}{dt}\right)_{max}} \qquad (2)$$

$$K_p = \frac{P_{NOM}}{(\Delta f)_{max}} \qquad (3)$$

Where P_{NOM} is the nominal power rating of the VSM, $(\Delta f)_{max}$ is the greatest permissible deviation in frequency, $\left(\frac{d\Delta f}{dt}\right)_{max}$ is the maximum permitted ROCOF in the system. The VSM rating should be selected such that, under the worst possible transient condition, it can provide deficient power or consume surplus power set up by boundary conditions for frequency change and ROCOF. The nominal power rating of the VSM, 'P_{NOM}' should be taken 10% of the PV – hydro system's overall size. According to ISO standards, the greatest permissible deviation in frequency during the normal operating condition is ±2.5% in either direction, i.e. 1.25 Hz (for 50 Hz system) and the maximum permitted ROCOF in either direction is ±1% i.e. 0.5 Hz/s (for 50 Hz system). Also, the maximum available allowable frequency deviation during transient operating conditions is ±15% i.e. 7.5 Hz (for 50 Hz system).

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In order to imitate the inertia and damping properties of a synchronous machine, VSM requires the proper selection of the constants K_I and K_p which are calculated using (2) and (3). Inertia and damping emulation control need to be closely analyzed which are described below briefly.

- Inertia Emulation Control:

The inertial power is related to the rate of frequency change. Accordingly, the part '$K_I \frac{d\Delta f}{dt}$' in (1) is responsible for the emulation of inertial property in the system. It directs the inverter to interchange the power with respect to ROCOF in the same way that rotating mass does in a synchronous machine. The rate of change in frequency of the system can be impeded by interchanging the power, and hence inertia can be said to be emulated. The amount of inertia to be emulated can be varied by changing the value of 'K_I' [8-9].

- Damping Emulation Control:

Similarly, the damping effect is related to the deviation of frequency from the reference value. Hence, the part '$K_p(\Delta f)$' in (1) will be emulating the damping effect into the system. This allows the inverter to inject or absorb power into the system according to the change in frequency, in a similar way as the damper winding would have done. By changing the value of 'K_p' the amount of damping to be emulated can be varied.

2.3 Power Angle Control

The primary concept behind power angle control is to change the phase displacement angle between the inverter's three-phase voltage and the grid's three-phase voltage. The voltage difference between the inverter's three-phase voltage and the grid's three-phase voltage will be applied to an inductor in each phase. The larger the phase displacement angle, the larger the voltage difference across an inductor, which results in a higher current through the inductor.

The exchanged active power between inverter and grid is given by:

$$P = \frac{EV}{X} Sin(\delta) \quad (4)$$

Where,

E= Inverter's phase to phase rms voltage

V= Grid's phase to phase rms voltage

δ = Phase displacement angle

X= Reactance in each phase

Various power angle control schemes for VSM are available. Although the basic principle is to generate the reference inverter power angle to produce the calculated P_VSM, the methods of generating this angle can vary from others.

The frequency of the grid is measured using the Phase Locked Loop method (PLL). The sensed frequency is compared with the reference frequency (50 Hz) and the error is produced. The error signal is then passed to the P_VSM calculation block which calculates the power to be injected by VSM. This block calculates the power depending on the change in frequency and rate of change of frequency (ROCOF). The P_VSM and the electrical power from VSM at the instant are then passed to the angle controller which generates the proper amount of phase angle. The angle controller is based on the linearized small-signal model of the swing equation. The phase angle is supplied to the three-phase sine generator which produces the three-phase reference sinusoidal signals and is passed to the PWM generator. The appropriate gate signals are generated from the PWM generator, which will be given to the three-phase inverter. Ultimately, the proper amount of power will be injected into the grid as required.

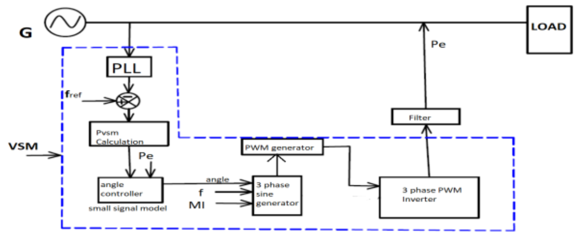

Fig -3: Power Angle Control Using Small-Signal Model Controller

The power angle Controller is based on the swing equation given below:

$$\frac{H}{\Pi f_0}\frac{d^2\delta}{dt^2} = P_m - P_{max} sin\delta - D\frac{d\delta}{dt} \quad (5)$$

Where H = inertia constant

P_m = VSM Power to be injected

$P_{max} sin\delta$ = P_e (power output from VSM)

D = Damping constant

δ= power angle

Using small-signal model, $\delta = \delta_0 + \Delta\delta$

We get,

$$\frac{H}{\Pi f_0}\frac{d^2\Delta\delta}{dt^2} + D\frac{d\Delta\delta}{dt} + P_{max} cos\delta_0\Delta\delta = P_m - P_e \quad (6)$$

Implementing (6) in the block as shown in fig -4, we get $\Delta\delta$ as output.

2.4 MATLAB Simulation

The system consists of a synchronous generator of 250KVA (1pu) along with a hydraulic turbine and generator and excitation system for the generator. It also consists of 100KW (0.4pu) resistive load which is connected all the time and 50KW (0.2pu) load is connected to the system whose switching time is at 10 seconds. A VSM block is present in the proposed Simulink model that contains the PLL (Phase Locked Loop) block which measures the grid frequency and is supplied to the P_VSM calculation block. The P_VSM calculation block calculates the power to be injected by the inverter to the grid. Then, the calculated power would be sent to the power angle controller block which uses small signal model for swing equations and calculates the power angle δ. After this, the power angle would be sent to the three phase sine generator to create necessary sine waves for the PWM generator to create phase shift. The PWM generator provides PWM to the gate of inverter so that inverter will inject the necessary power to the grid.

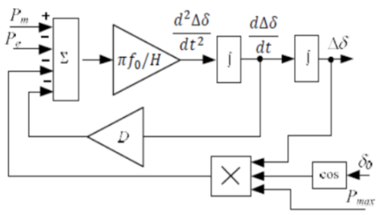

Fig -4: Power angle controller

As the VSM needs to be activated only during the transient period, there needs some activation logic to activate the VSM .This task is done by the activator block as shown in fig -6. This block activates the VSM when the change of frequency is greater than 2 Hz.

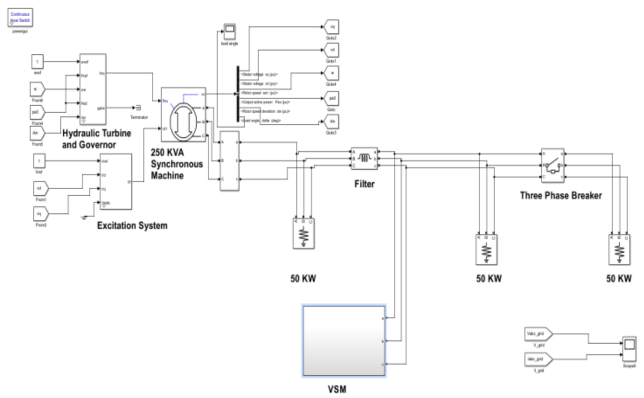

Fig -5: MATLAB Simulation model of VSM with hydro-generating unit

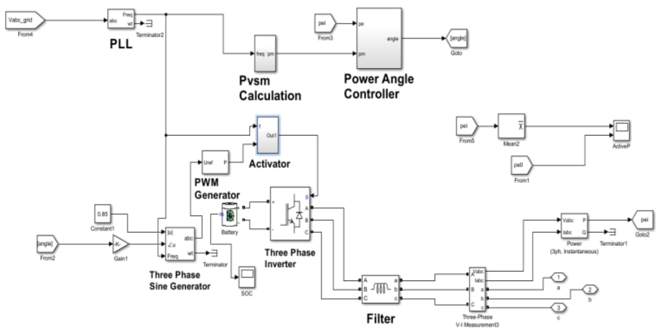

Fig -6: Virtual Synchronous Machine (VSM)

3. RESULTS

Simulink model of VSM has been developed in Matlab-Simulink. Simulation results are shown without and with activating VSM. From fig -7, it is observed that frequency drops to about 0.845pu (deviation is 15.5% from normal value) during transient, the condition which is unacceptable.

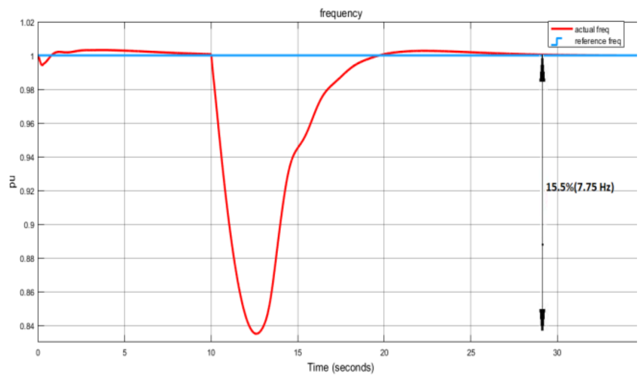

Fig -7: Frequency without VSM

From fig -8, it is observed that the frequency drop is reduced to 0.93pu (deviation is only 7% from normal value) after activation of VSM during transient conditions.

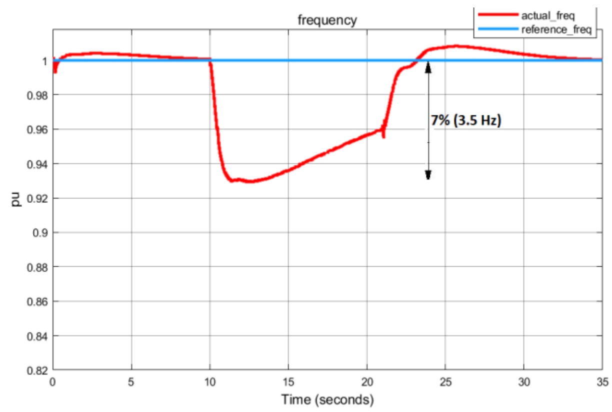

Fig -8: Frequency plot after using VSM

From fig -9, the VSM injects power after 10 seconds as the extra load is switched on at this instant, and after the transient period, the power from VSM is zero where power has been solely provided by the generator.

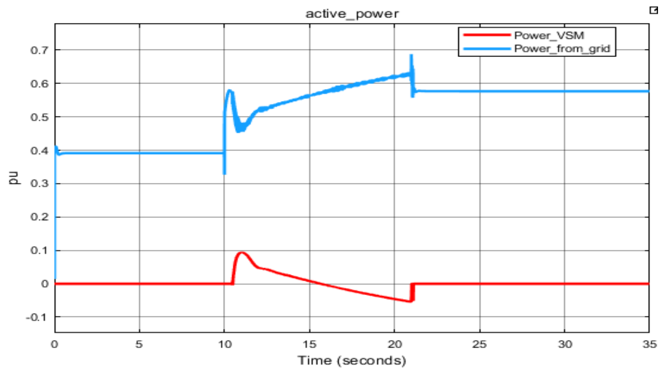

Fig -9: Active Power from grid and VSM

From fig -10, the SOC of a battery needs to be 50% at normal condition. After 10 seconds of operation, the SOC of the battery starts to decrease as the VSM is activated. During this time VSM is injecting power to the grid and the battery is in discharging mode. After some time, VSM starts to absorb power from the grid. During this time, the battery is in charging mode and, thus the SOC of the battery starts to increase.

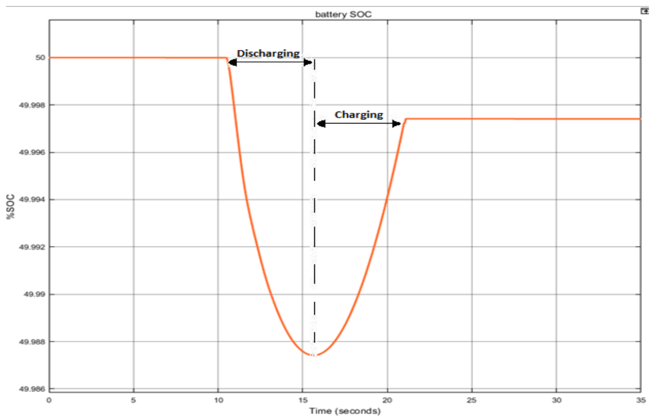

Fig -10: Charging and discharging of battery (SOC)

4. DISCUSSIONS

In this research, the VSM is made to improve the transient stability where the frequency deviation is 15.5%. The frequency deviation of 15.5% is decreased to 7% using VSM, thus improving the transient stability. Indeed, VSM can be accommodated to do so even if the frequency deviation is greater than 15.5%. Instead of the conventional current control technique to control the VSM, a novel strategy using the power angle control method has been used here. The system is modeled (with low inertia) using only the generator to simulate the effect of VSM in transient stability. However, in a real scenario, there will be a large number of PV arrays and other non-inertial sources along with a hydro-generator. Thus, the PV array can also be accommodated in the system during simulation. The SOC of the battery is to be kept at 50% in a normal state. So, there needs some control logic to bring the SOC to this level after the transient condition. This can be incorporated into the project. Thus, the power angle control strategy of VSM is a novel approach to control VSM which can be further explored by incorporating different circumstances.

5. CONCLUSION

From this MATLAB simulation, it is possible to deduce that adding VSM helps to enhance the transient stability of the grid having low inertia. When 50KW load is added to the initial system after 10 seconds of operation, frequency changed is up to a maximum of 15.5% during the transient period without VSM which is unacceptable. With the inclusion of VSM in the system, the maximum frequency change of 15.5% is reduced to 7% (maximum). Hence, it improved the transient stability of the system. Thus, we can penetrate renewable energy sources in higher numbers with the use of VSM which provides enough inertia to the grid.

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