Enhancing the Transient Stability of PV-Hydro Microgrid using Virtual Synchronous Machine (VSM)

Sanjeev Kumar Sah
Department of Mechanical and Aerospace Engineering
Pulchowk Campus
Tribhuvan University
Lalitpur, Nepal

Dr. Shree Raj Shakya
Department of Mechanical and Aerospace Engineering
Pulchowk Campus
Tribhuvan University
Lalitpur, Nepal

Abstract

Renewable energy sources such as solar, wind, and biomass are being integrated into electrical networks in order to meet demand while reducing dependency on non-renewable sources such as petroleum products, mineral oils, and natural gas is attracting a great deal of attention. The bulk of distributed generators (DGs) are linked to the utility grid through power electronics-based converters, which have either extremely little or no spinning mass and damping property, reducing total system inertia and transient stability. It would cause a significant change in the frequency of the system if large load changes in the system. This may be improved by using a Virtual Synchronous Machine (VSM) to simulate the inertial and damping properties of a real generator. A VSM is a power electronics device that stores short-term energy and has a dispatching mechanism that allows it to operate like a synchronous generator. VSM simulates the inertial and damping qualities of a synchronous machine, and it may either inject or absorb power into or from the grid in a manner similar to the injection or absorption of kinetic energy in synchronous generators This thesis suggests the use of VSM to increase grid stability under transient conditions. Unlike many previous efforts, this study proposes a way of regulating VSM operation utilizing power angle control. An angle controller is built using a small signal model of the swing equation that is linearized round the operating point. The suggested technique was simulated using MATLAB/Simulink to increase transient stability when exposed to substantial load changes. A system of 160 kVA was taken and the transient condition was improved by implementing the VSM.

Keywords—VSM, ROCOF, Transient stability, Inertia–constant, Damping Constant

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ACRONYMS

VSM	Virtual Synchronous Machine
RES	Renewable Energy Source
DES	Distributed Energy Source
ROCOF	Rate of Change of Frequency

I. INTRODUCTION

Infiltration of renewable sources of energy like photovoltaic (PV), wind, etc. into an electrical network to satisfy the heap needs and diminish reliance on non-sustainable sources like petroleum derivatives, mineral oils, and so on involves extraordinary interest [1]. The emerging trend is to use distributed generators (DGs) as the advanced implementation of renewable energy sources (RES) [2]. However, the increase in penetration of these kinds of RES decreases the overall inertia of the system causing a serious impact on the transient stability [3]. A large change in load in those systems can cause large frequency perturbation with a significant rate of change of frequency (ROCOF). Thus, additional inertia must be given to the system during the transient period to improve

the stability of the system. And, this can be accomplished by the employment of a virtual synchronous Machine (VSM) [4]. A virtual inertia can be given to such system by the application of short-term energy storage device with an effective control mechanism. 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 [5]. 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). VSM consists of different power electronics devices such as inverter, controller, etc. combined to act as a synchronous generator.
This can be employed in PV-hydro microgrid whose overall inertia is low. The capacity of the system increases when PV is added in comparison to the system without PV as shown in fig. 1 [6]. However, PV contributes zero inertia and thus, the overall inertia of the system remained the same. This causes a significant impact on the system's transient stability. To solve this problem, VSM can be employed as shown in fig. 1 that provides an increase in overall inertia and hence, providing better transient stability.

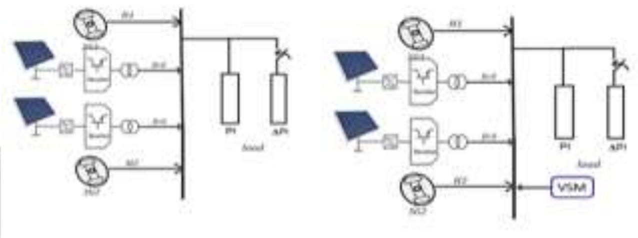

Fig. 1. Micro-grid without VSM and with VSM

There are various types of current control techniques used for the implementation of VSM as in [7]. But, none of those techniques are based on the power angle control that provides direct control of active power share between grid and VSM. The main objective of this paper is to study the active power share between grid and VSM using power angle control strategy resulting in improvement of transient stability of the electrical network.
The paper is organized as follows: Section II presents the method which describes the control strategy and simulink model used in research. Section III presents the simulation results. Section IV presents discussions and section V presents the conclusion.

II. METHOD

A. Introduction to strategy

Power angle control method has been used to control the flow of power between VSM and grid. As shown in fig. 2, the grid's frequency is determined using the Phase Locked Loop (PLL) method. The error is then calculated by comparing this measured frequency with reference frequency where the reference frequency is taken as 50Hz. The change in frequency and ROCOF will be passed to angle controller. Based upon these, the required power to be penetrated by VSM is produced by the angle controller. Contingent on this obtained VSM power, angle of inverter was obtained [8]. Thus, calculated angle is given as an angle input to the three phase sine wave generator which produces the reference sinusoidal signal for the PWM generator. Here, gate signals obtained will be passed to the inverter which produced voltage leading/lagging the grid voltage by same phase angle obtained above, proving that difference in angle between inverter and grid voltage cause the power transfer.

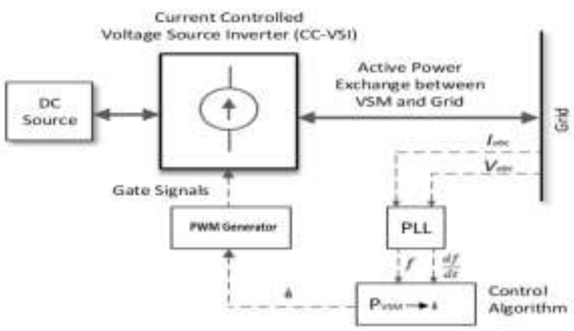

Fig. 2. Proposed Scheme of VSM

VSM emulates the characteristics of a synchronous generator by providing inertia and damping properties to the grid or electrical network that is connected with VSM [9]. Whenever there is load perturbation there is an exchange of power between the grid and VSM. By regulating the inverter output, active power flow can be controlled. When there is sudden increase in load, system frequency will decrease. In this case, active power is supplied by the synchronous machine stored in its rotating part. On the other hand, when there is sudden decrease in load, system frequency will increase. In this case, active power is absorbed by the synchronous machine. Active power interchange between the ac system and inverter is achieved by similar process to that of the synchronous condenser by adjusting the phase angle of the inverter output voltage (V_0) with respect to grid terminal voltage.

i. If reference frequency < grid frequency, active power is generated by inverter
ii. If reference frequency > grid frequency, active power is consumed by inverter
iii. If reference frequency = grid frequency, active power is not exchange

B. Control Strategy

A suitable control technique is required in VSM in order to exchange the power with grid depending on the change in frequency and ROCOF. The control technique must allow the installed VSM to provide the power when the frequency of the grid decreases and to absorb power when frequency of the grid increases. The measured frequency obtained from the frequency sensor was collated with the reference frequency of grid (i.e.1 p.u.) and the frequency change and ROCOF were determined. The required power to be exchanged in between the grid and the VSM is given by [7],

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

Where K_I =emulated inertia constant

K_D =damping constant respectively

They are calculated as,

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

$$K_D = \frac{P_{rating}}{(\Delta f)_{max}} \qquad (3)$$

Where P_{rating} is the nominal power rating of the VSM, $(\Delta f)_{max}$is the maximum change in frequency and $\left(\frac{d\Delta f}{dt}\right)_{max}$ is the maximum ROCOF permitted in the system. The rating of VSM should be selected in such a way that, even in the worst probable transient condition, it can provide deficient power or consume excess power, as set up by boundary condition for frequency change and ROCOF. The nominal rated power of the VSM, 'P_{rating}' should be around 10% of the PV – hydro system's overall capacity. According to ISO standards, the greatest deviation of frequency allowed during normal operating condition was ±2.5% i.e. 1.25 Hz (for 50 Hz system) and maximum ROCOF allowed was ±1% i.e. 0.5 Hz/s (for 50 Hz system). Also, during transient operating condition, the maximum frequency deviation allowed is ±15% i.e. for 50 Hz system, 7.5 Hz [3], [5], [10], [11]. There should be proper selection of the constants K_I and K_D, to emulate the inertia as well as damping properties of a synchronous machine. They are obtained using (2) and (3). For calculation of power, the inertia and damping emulation control is required to be analyzed closely. They are described below briefly.

- *Inertia Emulation Control:*

Inertial power is linked to the ROCOF. In (1), the portion '$K_I \frac{d\Delta f}{dt}$' is the reason behind the emulation of inertial property of the system. It makes the inverter to exchange the power with respect to ROCOF in the similar manner of rotating mass in a synchronous machine. The ROCOF of the system is impeded by exchanging the power, and hence inertia can be imitated. By changing the value of 'K_I', inertia to be emulated can be varied [12].

- *Damping Emulation Control*

Similarly, damping effect is associated with the frequency deviation from the reference value. So, the part '$K_D(\Delta f)$' in (1) will be imitating the damping effect into the system. This makes inverter to penetrate or consume power to the system according to the frequency, as the damper winding would have done. By altering the value of 'K_D', the damping effect can be varied [13].

C. Power Angle Control

The fundamental idea for power angle control is to vary the phase angle between two voltages at the inverter terminal and at the grid terminal. Assuming that, the impedance between inverter is grid is purely inductive type, the difference in voltage is applied across the inductor. The amount of current (power) injected/absorbed to/from grid is dependent on the phase angle difference. Greater the difference, more will be the current flowing through inductor and hence, the power injected to grid also increases [14].
The active power drawn to grid from inverter is,

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

where
E=Magnitude of inverter terminal voltage
V=Magnitude of grid voltage
$\delta =$ Phase angle difference between E and V
X = Reactance between inverter and grid.

Although the fundamental idea for power angle control is to find the phase angle of voltage of inverter terminal with respect to grid voltage and then injecting the calculated P_{VSM} to grid based upon this angle, approach of generating this angle varies from one method to another. The novel approach that has been used here is shown in fig. 3.
The grid's frequency is determined using the Phase Locked Loop (PLL) method. The error is then calculated by comparing this measured frequency with reference frequency where the reference frequency is taken as 50Hz. The P_{vsm} calculation block takes this error signal and outputs the required power (P_{vsm}) to be injected into grid as shown in fig. 3. It calculates P_{vsm} based on (1) which is dependent on the ROCOF and change in frequency. The required power to be injected (P_{vsm}) and the power actually injected by VSM at the instant are passed as inputs to angle controller block which is based on linearized model of swing equation. The output angle from the angle controller block, along with modulation index and grid frequency is then passed to the three phase sine generator which produces reference signals to generate the PWM signals. The modulation is fixed constant as this paper is ideally dealing with active power control only rather than reactive power. After this, the PWM generator generates six gate pulse signals using sinusoidal reference signal and triangular carrier wave, which is then input to inverter for its switching operation. Finally, the inverter injects/absorbs necessary calculated power (P_{vsm}) to/from grid based upon its switching pattern which is determined by gate pulse signals.

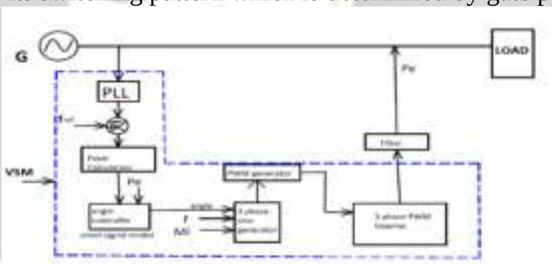

Fig. 3. Angle controlling scheme based on small signal model

Angle controlling scheme is based on swing equation as mentioned below [14], [15]:

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

Where H is inertia constant due to mass of rotating body, D is damping constant due to damper winding, δ is power angle in electrical radian, P_m is the mechanical power, which is actually the power (P_{vsm}) to be injected by VSM,
$P_{max}sin\delta = P_e$ is the electrical output power.

Linearizing (5) at $\delta = \delta_0 + \Delta\delta$,

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

Block shown in fig. 4 [8] is constructed using (6) which gives the $\Delta\delta$ as output.

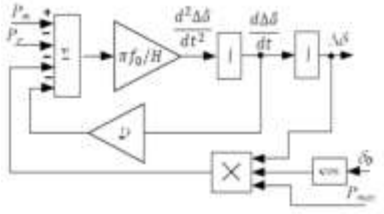

Fig. 4. Power angle controller

D. MATLAB Simulation

The simulation consists of system combining hydro and PV with 150kVA and 10 kW rating respectively. Generator is excited by excitation system. A load rated 0.4 pu (resistive) is connected every time. An extra load rated 0.2 pu is added after three seconds. PLL measures the frequency of grid which is in VSM block. Then it passes the grid frequency to block named P_VSM calculation. This block calculates amount of power that inverter needs to supply to grid. The power obtained is received by block which calculates power. This block calculates the angle which is phase difference between grid voltage and inverter voltage (i.e. power angle) with the help of model of small signal. Then 3-phase sine generator receives this angle which is responsible for generation of proper 3-phase sine waves. PWM generator receives these 3-phase sine signals and generates proper PWM. These PWM signals excites gates of inverter accordingly which produce proper voltages with proper phase difference that is sent to grid. VSM must be turned on only in transient period due to which a proper logic called activation block is implemented. This block turns on VSM only when the frequency change is sensed greater than 2.5%.

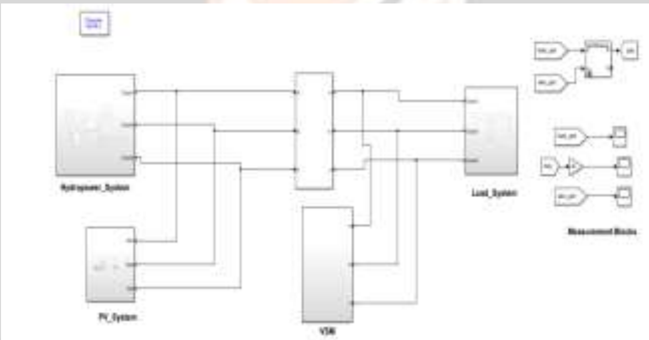

Fig. 5. MAT-LAB Simulation model of the system

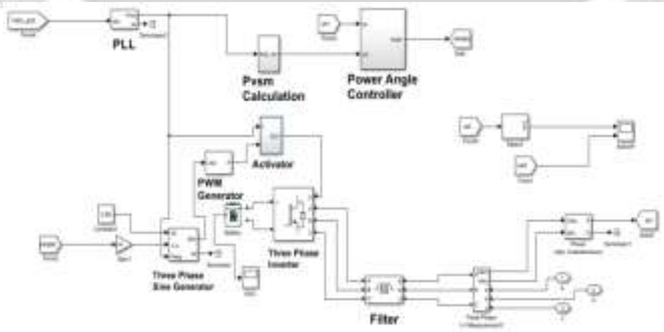

Fig. 6. Virtual Synchronous Machine (VSM)

III. RESULTS

The Simulation of proposed strategy has been conducted with the software MATLAB/Simulink and simulation results are shown when the VSM is not used and, when VSM is used in system for same transient condition.

Fig. 7 presents the frequency plot of system where the VSM is not used. Till 3 seconds, the system is in steady state and, when a step load of 0.2pu is switched on at t=3 s, frequency drops to 0.81 pu. Thus, frequency deviation is about 19% from reference value which is unacceptable as a result transient stability is poor.

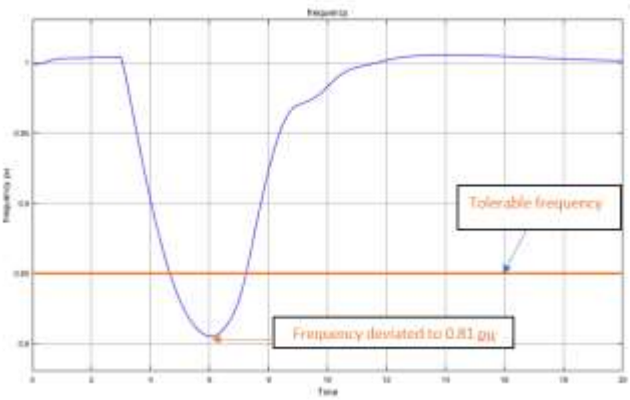

Fig. 7. Frequency plot of system when VSM is not used

Fig. 8 presents the frequency plot of system where the VSM is incorporated to improve the transient stability. Up to three seconds, the system is in steady state and, when a step load of 0.2pu is switched on at t=3 s, frequency drops to only 0.93pu after activation of VSM during transient period. There is only 7% of deviation in frequency from reference value which is acceptable during transient condition thereby improving the transient stability.

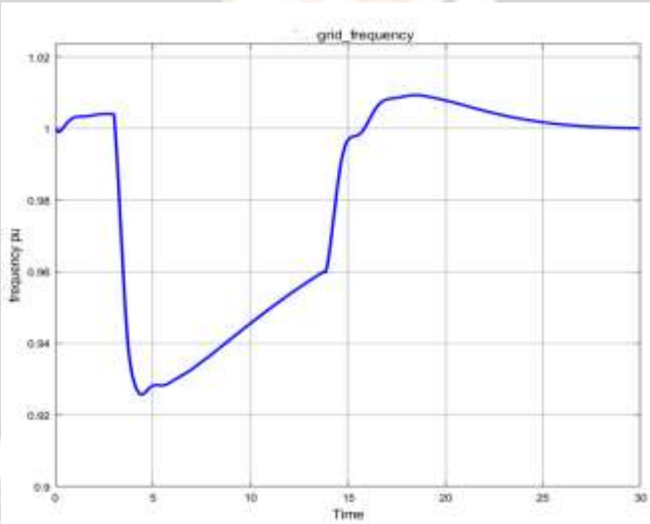

Fig. 8. Frequency plot of system when VSM is used

Fig. 9 presents the active power given to load from VSM and from grid when VSM is incorporated in system. Up to three seconds, the grid is delivering 0.4pu power (shown in blue curve) to load and the system is in steady state condition. So, VSM is not activated at this period and the power (shown in red curve) from VSM is thus 0 pu. At t=3 seconds, 0.2 pu load is switched on and transient period starts. Then, VSM is activated and starts giving power to system. At t=14s, system again comes to steady state period and VSM is inactive from this period.

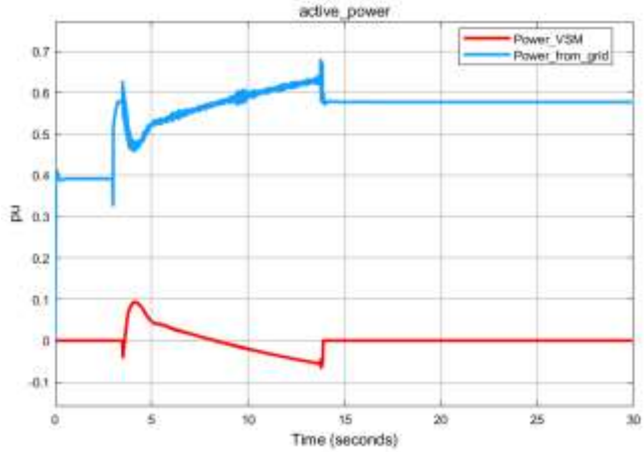

Fig. 9. Power delivered from VSM and grid

IV. DISCUSSIONS

The VSM is able to improve stability during transient period of the system by reducing change in frequency from 19% to 7%. VSM can improve transient stability even if the change in frequency without VSM is much greater than 15%. Traditionally current was controlled in VSM with different control methods but here we used method which controls the angle of power. Only generator and PV system was used with huge change in resistive load to show the frequency change during transient condition. But actually, in real life a large amount of solar plants are connected to the grid which contributes zero inertia and huge change in frequency occurs during transient condition. We can add more solar arrays in simulation. The strategy of controlling power angle is new method of controlling VSM which has a lot more to be researched.

V. CONCLUSION

From this simulation project we came to know that we can increase the stability during transient condition in grid with low inertia by use of VSM. When VSM was not used, the change in frequency was about 19% which cannot be tolerated but after using VSM the change in frequency was decreased to 7%. This helped to increase the stability during transient condition. With the proper use of this project of VSM, we can add a large amount of renewable energy in the grid.

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