Frequency Regulation Scheme Based on Virtual Synchronous Generator for an Isolated Microgrid

Himanshu Grover
Centre for Energy Studies
Indian Institute of Technology Delhi
Delhi, India
email: himanshu.grover@ces.iitd.ac.in

Ashu Verma
Centre for Energy Studies
Indian Institute of Technology Delhi
Delhi, India
email: averma@ces.iitd.ac.in

T.S. Bhatti
Centre for Energy Studies
Indian Institute of Technology Delhi
Delhi, India
email: tsb@ces.iitd.ac.in

M. J. Hossain
School of Electrical and Data Engineering
University of Technology Sydney
Sydney, Australia
email:: jahangir.hossain@uts.edu.au

***Abstract*—This paper proposes a Virtual Synchronous Generator (VSG) based frequency regulation scheme for an isolated microgrid. The conventional VSG scheme is modified using frequency recovery control scheme which reduces the frequency deviation occured in the system due mismatch in power between the source and the load. The isolated microgrid considered in this paper consists of a solar photo-voltaic (PV) generator connected in parallel to HESS with battery and ultra-capacitor. The modified VSG helps voltage source converter (VSC) to mimic the characteristics of a synchronous generator and improves system inertia using hybrid energy storage system (HESS) as energy buffer which ensures faster DC bus voltage regulation. The solar PV generator operates in maximum power point tracking (MPPT) mode using Perturb and Observe (P&O) algorithm. The performance of modified VSG controller was tested using MATLAB/Simulink and compared with conventional controllers under different system inertia parameters with a step load change and solar PV fluctuating conditions.**

***Index Terms*—Virtual Synchronous Generator,frequency deviation, Hybrid Energy Storage System (HESS), Maximum Power Point Tracking (MPPT).**

I. Introduction

Renewable energy sources (RES) based isolated microgrids have gained much attention from the past few years for the locations where grid availability is not feasible, due to the goegraphical and economical constraints. Due to variation in environmental conditions, RES such wind, Solar PV etc. are intermittent and uncertain in nature [1]. Therefore, such isolated microgrids based on RES must be equipped with an energy storage sources that provides an energy buffer and handles RES output power fluctuations. Battery energy storage system (BESS) are generally installed in such off-grid systems to handle intermitent nature of RES. However, such microgrids faces both low-frequency as well as high-frequency power oscillations. Fig. 1 represents the ragone chart for different energy storages with power and energy density [2]. BESS have high energy density and low power denisty. Therefore, they must handle low power fluctuations whereas handling high power fluctuations with BESS suffers stress and reduces life [3].

However, to handle fast power fluctuations ESS must be equiped with a combination of high energy and power densities. A combination of BESS and Ultra-capacitor (UC) as HESS is found to be popular solution to deal with such problems [4]–[7]. BESS handles slow power fluctuations due to high energy density whereas, UC handles high power fluctuations due to its high power density.

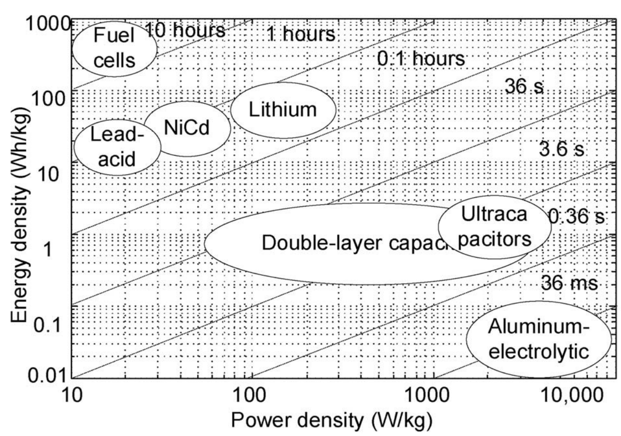

Fig. 1. Ragone chart for different energy storages

Due to intermitent and uncertain nature of RES, isolated RES based microgrid faces a new challenging task in terms of system stability. The microgrid system inertia plays an important task in frequency and voltage regulation during any variation in load or source power [**?**]. The system inertia reduces with high penetration of RES sources, which leads to rise in steady state error in primary frequency regulation [1].

In this paper the VSC controller is reorganised to mimic the characteristics of synchronous generator, which is known as virtual synchronous generator (VSG). The VSG control improves system inertia and helps in frequency & voltage regulation of the system. Various research have been carried out in implementing VSG control scheme for VSC [8]–[14]. Ref. [9] compares the dynamic characteristics of both droop control and VSG control during grid connected and islanded mode of operation. In [10] author proposes an enhanced VSG control scheme using communication-less control method through which proper oscillation damping and proper transient active power sharing is achieved. The reponses of the enhanced VSG control were verified by simulaiton and experiment. An improved VSG control strategy with pre-synchronization was developed by authors in Ref. [1], the results of improved VSG control was compared with conventional VSG and droop control under various transient cases.

Keeping in concern the above mentioned drawbacks in integrating solar PV with battery energy storage system for an isolated/ off-grid low-inertia network, a frequency regulation scheme is proposed. The paper focuses on integrating a frequency regulation scheme based on modified virtual synchronous generator control stragtery for an islanded microgrid. As per the analysis, the conventional droop and VSG control strategy during any transient could not able to regulate the system frequency and voltage to its nominal value and lacks with a steady state error. Hence to overcome the problem a modified VSG control scheme is developed which utilizes a frequency recovery control with an integral controller, which reduces steady state error and retains system frequency to its niominal value.

The major contributions of the paper are summarized below:

1. A modified VSG with a self frequency recovery control have been developed for VSC which reduces the steady state error during any transients.

2. Performance verification of proposed VSG control strategy under different values of inertia constant. Also under differnt cases of variying solar PV power and load variation have been carried out.

3. Faster restoration of DC bus voltage.

The modified virtual synchronous generator scheme for frequency regulation has been tested via MATLAB/Simulink platform and the results are compared with conventional droop and VSG control.

The sequence of paper is organized as follows, isolated microgrid system architecture is provided in Section II, Section III provides details of system modelling and its control of various energy sources.The details of modified virtual synchronous generator scheme is discussed in section IV. Section V provides simulation results and discussion. Finally the conclusion of the research work is drawn in Section VI.

II. Isolated Microgrid System Architecture

An isolated microgrid considered in the paper is shown in Fig. 2. The microgrid contains solar PV generator as a renewable energy source in parallel to Battery and Ultracapacitor as HESS and AC loads. Solar PV generator is connected to DC bus of Voltage Source Converter via DC-DC Boost Converter. Battery and Ultracapacitor is connected to DC bus via DC-DC Bi-directional converter which mantains the DC Bus voltage within specified limit and ensure charging and discharging operation of HESS. The sources and loads are interfaced using VSC which operates in grid forming mode, regulates the system voltage and frequency.

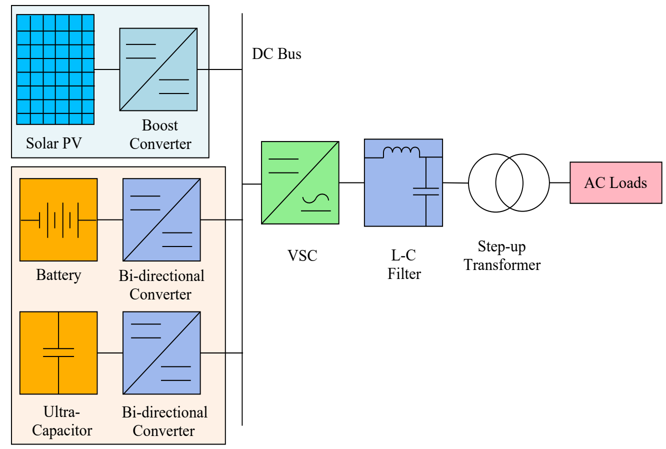

Fig. 2. Block diagram of an isolated microgrid

III. System Modelling and Its Control

A. Solar PV Generator (SPV)

The power generated by solar PV generator majorly depends upon the amount of solar irradiance falling over it and also on its cell's temperature. The relation of output power generated by the solar PV generated is expressed as:

$$P_{PV} = \eta_{PV} A\varphi[1 - 0.005(T_a + 25)] \tag{1}$$

Where, P_{PV} is the power generated by solar PV, η_{PV} is the efficiency of solar PV panel, A is the area of solar PV panel receiving solar radiations at φ (kW/m^2), T_a is the solar PV panel ambient temperature in °C.

However, at constant temperature the solar PV generator inherits the non-linear output characteristics for different irradiance levels. Therefore, the operating point of solar PV generator must be controlled using maximum power point tracking algorithm so as to extract maximum power from solar PV. The control operation of solar PV generator is shown below in Fig.3. The solar PV is connected to DC bus via DC-DC boost converter and the output of boost converter is dependent on the value of duty cycle generated via P&O algorithm,

B. Hybrid Energy Storage System (HESS)

HESS consists of battery and ultra-capacitor connected in parallel using DC-DC bi-directional converter as shown in Fig. 2. HESS regulates the DC bus voltage by handling high frequency voltage oscillation via ultra-capacitor and low-frequency voltage oscillation via battery. The bidirectional DC-DC converter circuit diagram for battery and ultra-capacitor is shown below in Fig. 4. The DC bus voltage control architecture is shown below in Fig. 5. The DC Bus

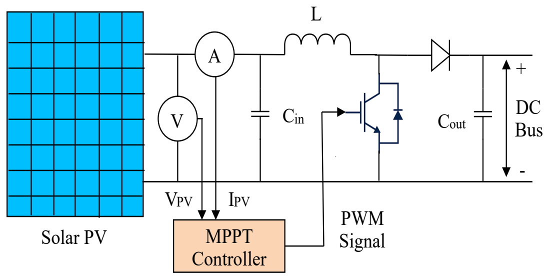

Fig. 3. Solar PV generator control operation.

voltage reflects the power balance between the sources and the load [15]. Therefore, the reference current(I_{ref}) which is supplied or absorbed by HESS is generated by the DC bus voltage control loop, which is given by the equations :

$$I_{ref}(t) = k_{pdc}(V_{DCref} - V_{DC}) + k_{idc}\int(V_{DCref} - V_{DC})dt \quad (2)$$

$$I_{ref}Batt(s) = \left[\frac{2\pi f_{cf}}{s + 2\pi f_{cf}}\right] I_{total}(s) \quad (3)$$

$$I_{ref}UC(s) = I_{total}(s) - I_{ref}Batt(s) \quad (4)$$

where, k_{pdc} and k_{idc} are DC bus voltage control loop proportional-integral (PI) controller gains. The cutt-off frequency of low-pass filter is chosen as 5Hz [16].

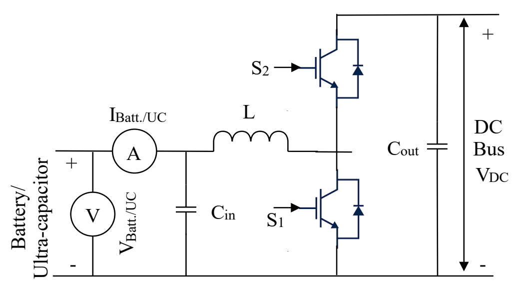

Fig. 4. Bi-directional DC-DC converter for battery/ultra-capacitor

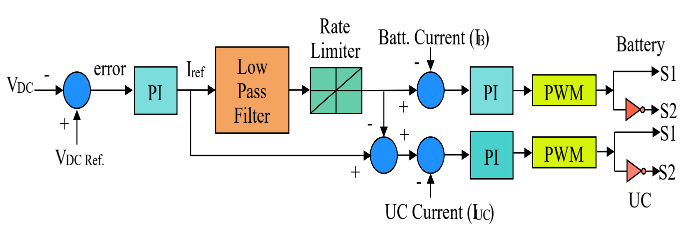

Fig. 5. DC bus voltage control architecture

C. Voltage Source Converter (VSC)

The voltage source converter (VSC) conisdered in the paper operates in grid forming mode and acts as an interface between DC sources and AC loads. The DC bus voltage of VSC input is regulated by HESS, while it regulates the AC bus voltage and frequency within specified limits based on the reference signals generated by MVSG control scheme. VSC delivers the desired AC power to the loads.

The VSC converter can be mathematically modeled on a synchronous rotating frame (SRF) as given below:

$$\begin{bmatrix}\frac{di_d}{dt}\\ \frac{di_q}{dt}\end{bmatrix} = \begin{bmatrix}-\frac{R_f}{L_f} & \omega_{nom}\\ \omega_{nom} & -\frac{R_f}{L_f}\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix} + \begin{bmatrix}\frac{1}{L_f} & 0\\ 0 & \frac{1}{L_f}\end{bmatrix}\begin{bmatrix}v_d\\ v_q\end{bmatrix} + \begin{bmatrix}-\frac{1}{L_f} & 0\\ 0 & -\frac{1}{L_f}\end{bmatrix}\begin{bmatrix}v_{od}\\ v_{oq}\end{bmatrix} \quad (5)$$

The outer voltage and inner current loop of VSC are shown below in Fig. 6 & 7. The reference voltages ($V_{od(ref)}\&V_{oq(ref)}$) are converted to d-q frame using park-transformation, which are fed to PI controller of outer voltage control loop. The reference currents ($I_{od(ref)}\&I_{oq(ref)}$) are generated by outer voltage loop which are further fed to inner current control loop. Based on the output voltage references ($V_{id}\&V_{iq}$) and the reference angle (θ) generated by the MVSG frequency control, the pwm signals are generated which controls VSC operation.

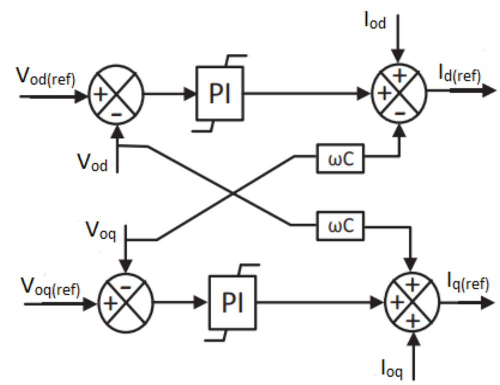

Fig. 6. Outer voltage loop of VSC control

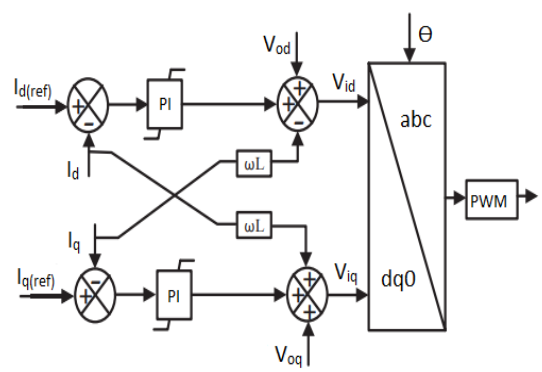

Fig. 7. Inner current loop of VSC control

IV. VSG Control Scheme (VSG)

The control scheme for VSC is shown in Fig. 8, it is modified to mimic the characteristics of a synchronous generator to perform as virtual synchronous generator, which maintains the system inertia. VSG control structure is based on mathematical modelling of three-phase synchronous machine which is described below.

According to ref. [1], the conventional VSG controller lacks with frequency and voltage regulation through primary inertial control during any transient. Therefore, the modified VSG control utilizes a self-frequency recovery control using an Integral controller. The Integral controller minimizes the frequency deviation and retain back the system frequency within its nominal acceptable range.

A. Frequency Control

The VSG based frequency regulation for VSC is based on the following swing equation [8]:

$$2H\frac{d\omega}{dt} = P_m - P_{actual} - K_D(\omega - \omega_{actual}) \tag{6}$$

where, H is the inertia constant, P_{actual} is the real power generator by VSC, K_D is the damping constant, ω is the calculated angular frequency, ω_{actual} is the angular frequency generated by VSC, P_m is the input real power of VSC based on droop characteristics;

$$P_m - P_{ref} = \left[\frac{1}{D_p}\right](\omega_{ref} - \omega_{actual}) \tag{7}$$

where P_{ref} is the reference active power and D_p is the droop coefficient, ω_{ref} is the reference angular frequency.

B. Voltage Control

The voltage regulation by VSC is based on the following equations [8]:

$$V = V_{ref} - D_q * Q + \frac{K_Q(Q_{ref} - Q)}{s} \tag{8}$$

where V is the VSC Voltage, V_{ref} is the reference terminal voltage, D_q is the voltage droop constant, K_Q is the integral gain constant, Q_{ref} is the reference reactive power, Q is the actual reactive power generated by VSC.

V. Simulation Results and Discussion

Simulation was performed on MATLAB/Simulink platform to validate the effectiveness of the modified VSG control scheme. The performance of the system was evaluated under different inertia constant values with a step load change and solar PV fluctuating conditions.

A. Performance under different values of inertia constant

In this case, the system is initially operated at a nominal loading of 1000 W-500 VAR. A step load change of 200 W-0 VAR is given at time t= 4.0 seconds. The frequency response of the MVSG system under different values of inertia constant is shown in Fig. 2. Frequency response verifies the frequency deviation improves with increase in inertia constant value.

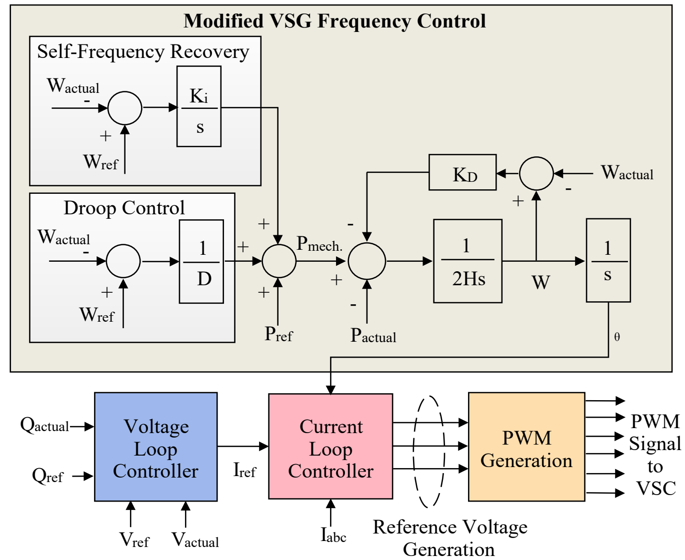

Fig. 8. Modified VSG control scheme

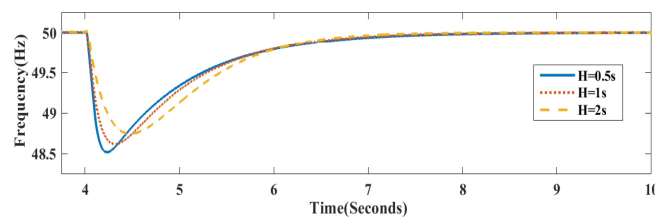

Fig. 9. Load frequency at different values of inertia constant

B. Performance under a step change in load power

In this case, a step load change of 200 W is given at time t= 4.0 seconds as shown in Fig. 10. Fig. 11 shows that constant power is generated by solar PV at constant irradiance of 1000 W/m^2 whereas, the step load change power is supplied by UC as it handles high frequency voltage deviation and gradually the step load change power is supplied by BESS. The frequency response of different control strategies are shown in Fig. 12 and MVSG control regulates the frequency deviation to its mnominal value. The DC bus voltage repsonse is shown in Fig. 13 and HESS regulates the DC bus voltage within the specified range.

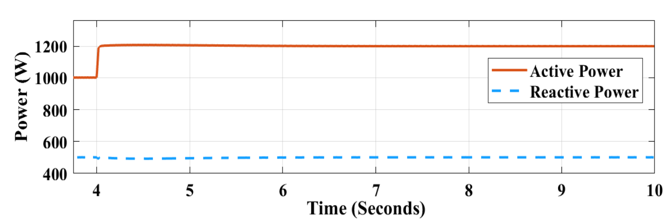

Fig. 10. Load power during a step load change

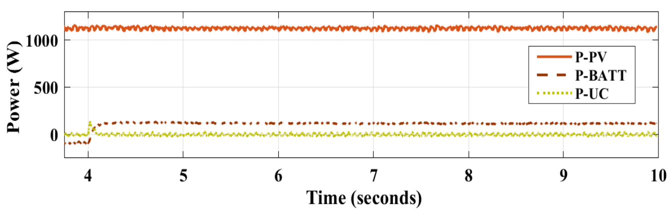

Fig. 11. Source power during a step load change

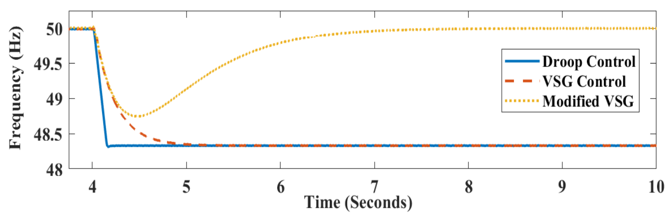

Fig. 12. Load frequency during a step load change

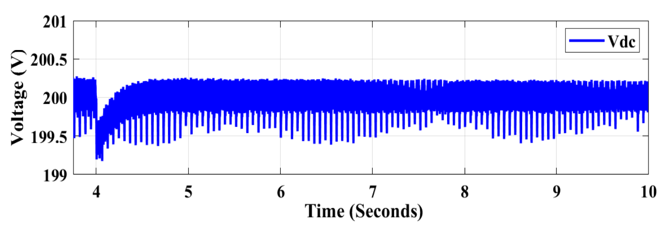

Fig. 13. DC bus voltage during a step load change

C. Performance under varying solar PV output due to varying irradiance

In this case a variation in solar irradiance level is considered as shown in Fig. 14 and Fig. 15 shows the variation in source power. The load power and frequency are kept constant as shown in Fig. 16 & 17, as the DC bus voltage is kept nearly constant with the variation in solar PV power due to HESS as shown in Fig. 18.

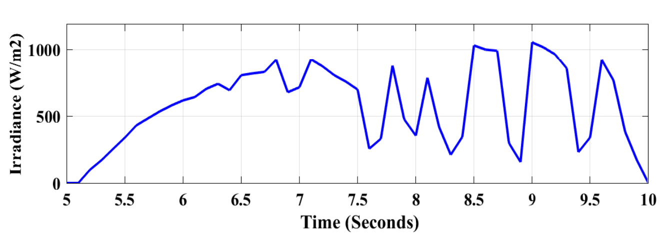

Fig. 14. Variable solar PV irradiance

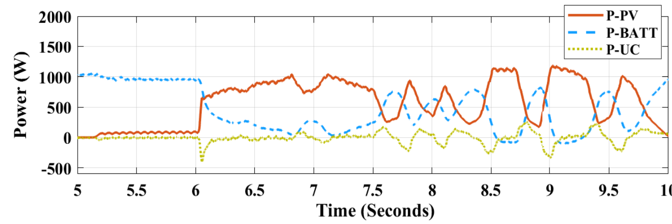

Fig. 15. Source power during changing solar PV irradiance

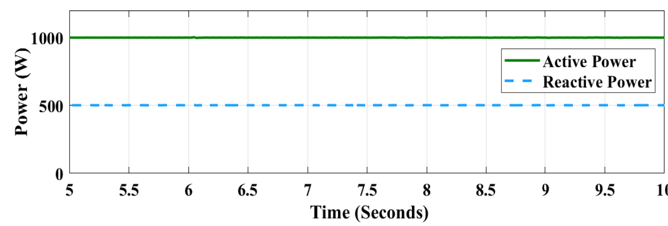

Fig. 16. Load power during changing solar PV irradiance

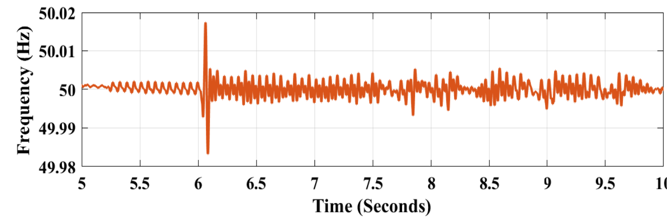

Fig. 17. Load frequency during changing solar PV irradiance

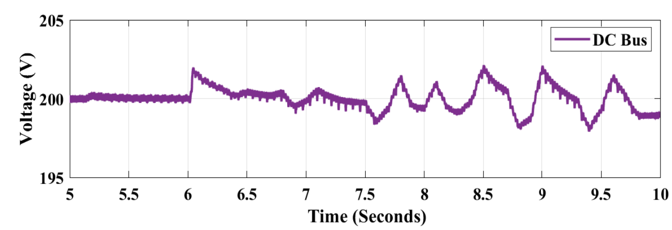

Fig. 18. DC bus voltage during changing solar PV irradiance

VI. Conclusion

A modified virtual synchronous generator scheme developed for a solar PV and Hybrid Energy Storage based microgrid has been presented in this paper. A self frequency recovery control with an Integral controller is applied to conventional VSG control scheme. Moreover, an ultra-capactior is added in parallel to battery which handles high power flucatuations. The developed control strategy mimics the characteristics of a synchronous genertor and improves system inertia. The load frequency change occured due to power mismatch in solar PV generation and/or load is regulated by the self frequency recovery controller. The performance of the developed control scheme is validated on MATLAB/Simulink platform. Hence the developed control regulates the system frequency and provides satisfactory performance as compared to conventional control schemes.

REFERENCES

[1] J. Liu, M. Hossain, J. Lu, F. Rafi, and H. Li, "A hybrid ac/dc microgrid control system based on a virtual synchronous generator for smooth transient performances," *Electric Power Systems Research*, vol. 162, pp. 169 – 182, 2018. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378779618301524

[2] H. Zhou, T. Bhattacharya, D. Tran, T. S. T. Siew, and A. M. Khambadkone, "Composite energy storage system involving battery and ultracapacitor with dynamic energy management in microgrid applications," *IEEE Transactions on Power Electronics*, vol. 26, no. 3, pp. 923–930, 2011.

[3] M. E. Glavin, P. K. W. Chan, S. Armstrong, and W. G. Hurley, "A stand-alone photovoltaic supercapacitor battery hybrid energy storage system," in *2008 13th International Power Electronics and Motion Control Conference*, 2008, pp. 1688–1695.

[4] J. Pegueroles-Queralt, F. D. Bianchi, and O. Gomis-Bellmunt, "A power smoothing system based on supercapacitors for renewable distributed generation," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 1, pp. 343–350, 2015.

[5] D. B. Wickramasinghe Abeywardana, B. Hredzak, and V. G. Agelidis, "A fixed-frequency sliding mode controller for a boost-inverter-based battery-supercapacitor hybrid energy storage system," *IEEE Transactions on Power Electronics*, vol. 32, no. 1, pp. 668–680, 2017.

[6] B. Hredzak, V. G. Agelidis, and M. Jang, "A model predictive control system for a hybrid battery-ultracapacitor power source," *IEEE Transactions on Power Electronics*, vol. 29, no. 3, pp. 1469–1479, 2014.

[7] P. Sanjeev, N. P. Padhy, and P. Agarwal, "Effective control and energy management of isolated dc microgrid," in *2017 IEEE Power Energy Society General Meeting*, 2017, pp. 1–5.

[8] F. Gao and M. R. Iravani, "A control strategy for a distributed generation unit in grid-connected and autonomous modes of operation," *IEEE Transactions on Power Delivery*, vol. 23, no. 2, pp. 850–859, 2008.

[9] J. Liu, Y. Miura, and T. Ise, "Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators," *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3600–3611, 2016.

[10] J. Liu, Y. Miura, H. Bevrani, and T. Ise, "Enhanced virtual synchronous generator control for parallel inverters in microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 5, pp. 2268–2277, 2017.

[11] S. D'Arco and J. A. Suul, "Equivalence of virtual synchronous machines and frequency-droops for converter-based microgrids," *IEEE Transactions on Smart Grid*, vol. 5, no. 1, pp. 394–395, 2014.

[12] Z. Xiaolin, D. Wei, G. Jiatian, and Y. Guangxiu, "Hardware in loop simulation test of photovoltaic virtual synchronous generator," in *2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 2018, pp. 1–4.

[13] X. Hou, Y. Sun, X. Zhang, J. Lu, P. Wang, and J. M. Guerrero, "Improvement of frequency regulation in vsg-based ac microgrid via adaptive virtual inertia," *IEEE Transactions on Power Electronics*, vol. 35, no. 2, pp. 1589–1602, 2020.

[14] T. Pimprikar, O. Pawaskar, and A. Kumar, "Virtual synchronous generator- a new trend in technology for smart grid integration," in *2018 International Conference on Information , Communication, Engineering and Technology (ICICET)*, 2018, pp. 1–5.

[15] U. Manandhar, A. Ukil, H. B. Gooi, N. R. Tummuru, S. K. Kollimalla, B. Wang, and K. Chaudhari, "Energy management and control for grid connected hybrid energy storage system under different operating modes," *IEEE Transactions on Smart Grid*, vol. 10, no. 2, pp. 1626–1636, 2019.

[16] M. Hamzeh, A. Ghazanfari, Y. A. I. Mohamed, and Y. Karimi, "Modeling and design of an oscillatory current-sharing control strategy in dc microgrids," *IEEE Transactions on Industrial Electronics*, vol. 62, no. 11, pp. 6647–6657, 2015.