Improvement of Power Quality Using SMES in PV, Wind, Battery, FC and Electrolyzer based AC Standalone Microgrid

Hannah Jessie Rani R, Pankaj Saraswat, Pavan Chaudhary and Kuldeep Singh Kulhar

Hannah Jessie Rani R, Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, JAIN (Deemed-to-be University), Bangalore, India, Email Id-jr.hannah@jainuniversity.ac.in
Mr. Pankaj Saraswat, Scholar, Department of Computer Science and Engineering, Sanskriti University, Mathura, Uttar Pradesh, India, Email Id-pankajsaraswat.cse@sanskriti.edu.in
Pavan Chaudhary, Assistant Professor, Maharishi School of Engineering & Technology, Maharishi University of Information Technology, Uttar Pradesh, India, Email Id-chaudharycaracf6@gmail.com
Kuldeep Singh Kulhar, Professor, Civil Engineering, Vivekananda Global University, Jaipur, India, Email Id-k.singh@vgu.ac.in

Abstract: This paper presents a stand-alone hybrid energy system that utilizes Wind, Solar, Fuel Cell (FC), Superconducting magnetic energy storage (SMES) and Electrolyzer. A novel control methodology has been created to guarantee that the dc-link voltage stays at its designated value by regulating the converters linked to the FC and electrolyzer. The dc-link reference voltage signal is generated by a constant voltage algorithm of a maximum power point tracker (MPPT) for the photovoltaic system (PVS). Consequently, the converters linked to the FC and electrolyzers not only control the dc voltage but also function as an MPPT, removing the necessity for an extra MPPT circuit for the PVS. By properly controlling the dynamics of the FC and electrolyzer, the SMES can charge/discharge instantaneously while the FC/electrolyzer can feed/consume power in a steady state. The proposed control methodology of the dc voltage is simple and requires only a few measurements. Furthermore, a PWM inverter controller was created to uphold voltages at their designated reference level. Extensive simulation results carried out using Simulink on MATLAB platform have demonstrated that the controllers function effectively in both transient and steady state situations.

Keywords- Power Quality, SMES, FC, PV, Wind, Hybrid Microgrid, Voltage control.

Corresponding Author: jr.hannah@jainuniversity.ac.in

1. INTRODUCTION

Numerous nations possess rural regions where the cost or feasibility of connecting to the power grid is high, resulting in the prevalent utilization of diesel generators for electricity generation. In such cases, localized small-scale off-grid generating units can provide electricity to rural areas. Autonomous solar & wind generation systems are commonly exciting and eco-friendly options for remote consumer electrification. A viable strategy is to combine these multiple renewable systems to create a hybrid Microgrid [1-3]. A hybrid system of this nature provides increased reliability and potentially offers greater cost efficiency.

The depicted independent hybrid power supply system (illustrated in Figure 1) comprises a PMSG coupled wind energy unit, a PVS, SMES as a storage unit, FC, and aqua-electrolyzer (AE) serving as a dump load. SMES is a capacity gadget that is straightforwardly connected to the dc transport. For capacity, customary batteries are used. SMES, then again, is one of the stockpiling frameworks that answers rapidly and can infuse both dynamic and receptive power in under one cycle [5-7]. Subsequently, notwithstanding energy stockpiling, SMES assumes a basic part in quickly settling the voltage and in this manner further developing voltage quality. Power generated by wind will be affected by weather, there will be no output from PV during the dark time. In light of these conditions, the incorporation of FC aims to enhance the dependability. The FC is linked to dc-ink by means of a boost converter. In instances where the wind and solar power output remains high for a prolonged duration, a dump load (electrolyzer) is employed to utilize the excess power. The buck converter establishes a connection between the AE and the dc bus. The hydrogen produced by the AE can be stored and used as an input by the FC. Because SMES are expensive, a relatively modest size is employed to consume/supply electricity during transient times, and an electrolyzer/FC is used under steady state operation. AC loads are connected to a dc link through a PWM-based three phase inverter. The recommended framework can control both single stage and three stage loads.

The switched mode rectifier-based control approach [8-9] is optimized for obtaining the most power from wind flow. PVS must be operated at the voltage with respect to their maximum power point for optimal solar power usage [10]. In this case, the PVS is directly linked to the dc bus, and the "Constant Voltage Algorithm for MPPT" [10-12] is implemented with dc-dc converters (connected between the dc-link and the FC; the dc-link and the electrolyzer).

In this paper, standalone power supply module is implemented by using renewable systems with below functions:

a) In order to establish an efficient control system (involving PVS, wind, FC, SMES, load, and AE), a straightforward control method relying on DC voltage is employed, which necessitates only a limited number of measurements.
b) To improve the quality of voltage using SMES.
c) Electrolyzer and FC controllers (i.e., switches S_d and S_s respectively of Figure 1) regulate the voltage at dc-link at its reference command. Furthermore, these switches serve as MPPT circuits for PVSs, eliminating the need for an extra MPPT circuit to optimize power extraction from PVS.

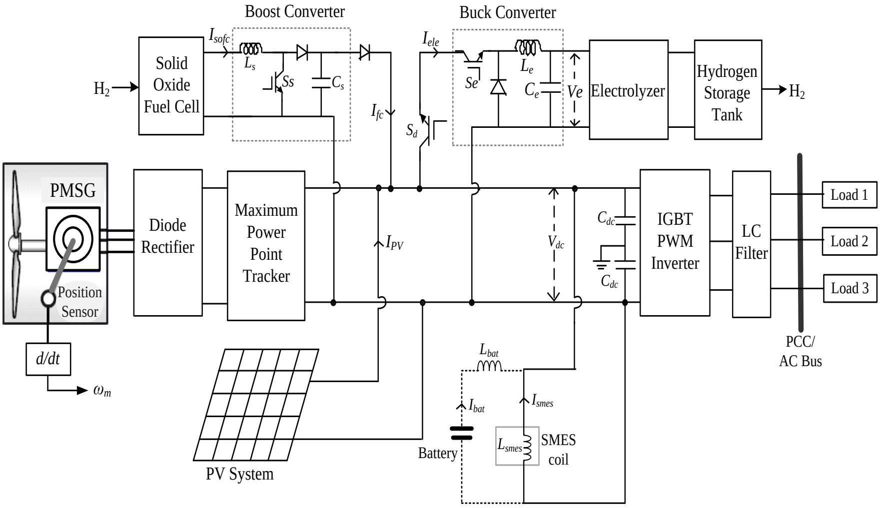

Figure 1: Renewable energy sources based stand-alone hybrid system.

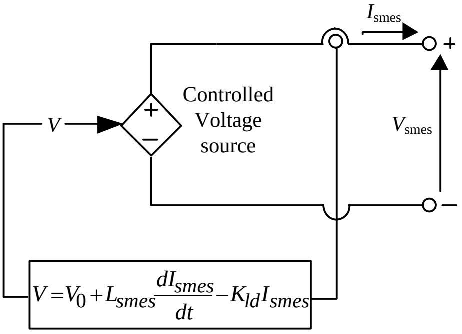

Figure 2: SMES model.

The design of SMES systems involves the utilization of a fundamental controlled voltage source as illustrated in Figure 2 [5-7], as defined by equation (1).

$$V = V_0 + L_{smes}\frac{dI_{smes}}{dt} - K_{ld}I_{smes} \qquad (1)$$

Where
V_0 = voltage at no-load.
L_{smes} = SMES coil inductance.
I_{smes} = SMES current.
K_{ld} = current feedback gain.

2. CONTRO OF DC LINK VOLTAGE

The suggested standalone model is depicted in Figure 1. In standalone operation, the output of inverter must be changed in terms of frequency & amplitude. This is accomplished by regulating the constant voltage at dc-link at its reference command (V_{dc}^*) and the PWM inverter's modulation index within a tolerable practical limit. By adjusting the frequency of the sinusoidal wave during the generation of PWM pulses, it is possible to maintain a constant frequency for the output AC voltage. DC-link voltage varies owing to fluctuations in wind speed, solar irradiation, and load due to power imbalance between sources and loads. As a result, regardless of variations in solar irradiation, wind speed, and load, the dc-link voltage must remain constant. SMES, FC, and AE are used to maintain the system's power balance. However, SMES is only used in this study during the transient phase, and in steady state, the FC and electrolyzer will function based on the power imbalance between generation (wind plus solar) and load.

For best utilization, PVS must be operated at their MPP. According to power-voltage (p-v) curves of PV cells, PV cells can delivered maximum power at particular voltage called as voltage at maximum power point (V_{mpp}). From p-v curves, it is obtained that change in V_{mpp} for change in irradiance from 1000W/m^2 to 400W/m^2 is just 3.9%. Therefore, it is obtained that V_{mpp} is almost constant and hence in this paper constant voltage algorithm [10-12] is implemented. Control method of electrolyzer and FC (S_d and S_s) is incorporated with constant voltage method. Hence, signal of dc-link reference for control methods of FC and electrolyzer will be developed by constant voltage algorithm (i.e., $V_{dc}^{*} = V_{mpp}$). Therefore, S_s and S_d are not only control the voltage at dc-link but also acts as MPPT of PVS, hence additional MPPT converter is not necessary to harvest maximum energy. The control scheme illustrated in Figure 3 showcases the dc-link voltage control. Two PI controllers receive the input of the difference between the desired and actual dc-link voltage. Treating output of PI Controller-1 as reference FC current, it is compared with actual FC current and PWM pulses are generated to regulate switch S_s. Treating output of PI Controller-2 as the reference current of the electrolyzer, a hysteresis band approach is adapted to regulate switch S_d because operation of electrolyzer requires regulation of current. The proposed control technique is very simple and requires just three number of measurements (i.e., V_{dc}, I_{fc}, I_{ele}). Limiters are used to limits the currents of FC and AE.

Effective coordinated control among SMES, PVS, wind, dump load & FC is achieved with the use of dc-link voltage management to maintain power balance between production and consumption. When wind and solar generation exceeds load V_{dc}, V_{dc}* becomes greater than V_{dc}. In this scenario, SMES will be temporarily powered by excess energy, whereas the dump load will utilize the surplus power in a stable state. However, when load demand will be exceed then the generation (wind plus PVS), V_{dc} decreases in comparison to V_{dc}*. In this case, the load is fed via SMES and FC. However, because of the sluggish dynamics of FC, it cannot deliver power instantly and hence cannot stabilize the dc-link voltage during transients [8]. SMES plays a vital function in this situation, supplying load requirement during the transitory time. As a result, in order to properly coordinate SMES and FC, a boost converter control method (i.e., Figure 3) coupled with FC is designed using dc-link voltage. With the aid of controllers linked to SMES and FC, it is possible to accomplish that when there is a fast load shift, SMES gives power instantly, and when FC power increases, SME power continues to dwindle. In steady state, FC supplies the necessary power, and SMES power is nil. The suggested controller enables automated discharging and charging of SMES that are directly linked to the dc-bus. Appendix [5-7] has the SMES parameters.

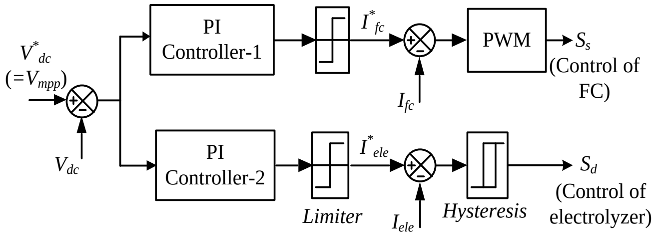

Figure 3: Control of dc-link voltage.

3. RESULTS

MATLAB/SIMULINK is used to simulate the hybrid wind-solar power system depicted in Figure 1. [8] Considers wind turbine, FC and electrolyzer modeling. SME modeling is taken into account in [5-7]. A two-mass drive train model is used to provide a detailed view of turbine dynamic characteristics. With the assistance of sources [8, 13-14], a model of a 10kW SOFC is constructed. The operational voltage of a SOFC is 300 V, which is converted to V_{dc}* via a boost converter. Refer to [15] for statistics on a 5.0kW, 120.0A, 43.0V AE. In this work, an AE with a rating of 10 kW is built with a current rating of 120 A. As a result, the AE voltage is set to 86.0V (achieved by arranging series of 64 cells) and the voltage is decreased from V_{dc}* to 86.0V via the buck converter. The hydrogen storage model is based on references [16-17]. The data of PMSG is derived from [8]. Data for other components is considered from [18-19]. The performance of the suggested hybrid energy system is assessed by considering the following scenarios:

Case-1: *Battery and SME comparison:*

Consider a change in load from 7.0kW to 12.0kW and a change in wind speed from 12m/s to 9m/s at t=2.5 sec, as well as a change in irradiance from 850W/m^2 to 1000W/m^2 and a change in load from 12.0kW to 8.0kW at t=4 sec. Figure 4 depicts the reaction of dc-link voltage with battery and SMES. Figure 4 shows that for the above-mentioned adjustment, the voltage excursion is quite big (i.e., 12%) with battery, which is higher than the allowable limit (i.e., 5%). Furthermore, a huge dc voltage excursion emerges on the inverter's ac side. However, as demonstrated in Figure 4, the excursion with SMES is nearly nil in dc voltage. Hence, apart from storing energy, SMES is playing a key role in power quality improvement.

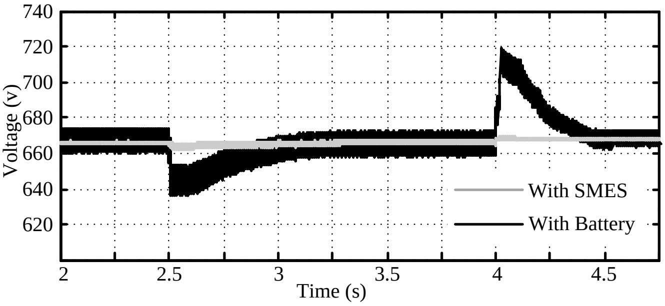

Figure 4: Response of voltage at dc-link.

Case-2: SME & FC Reaction

Let us now examine the procedure with SMES, FC & electrolyzer. In this scenario, the model is run by the load changing but the wind & PV powers remaining constant. Consider a rapid rise in load demand from 10.5 kW to 17.0kW at t=5sec. Following a load shift, SMES discharges instantly to fulfill the needed load demand, as seen in Figure 5. Furthermore, it is noticed that FC steadily feeds power and provides the complete necessary power in steady condition (roughly after 2 seconds). SMES power becomes zero when FC delivers the complete needed power in steady condition..

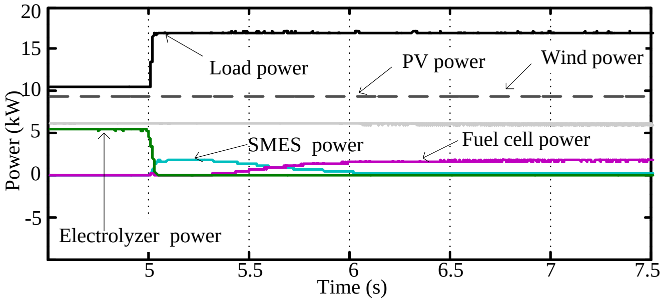

Figure 5: Powers.

Case-3: Wind speed variability, solar irradiation, and load fluctuations

The suggested controller has been evaluated for intermittent wind and solar irradiance fluctuations, as well as load variations (Figure 6). The response of the voltage at dc-link to the aforementioned fluctuations is represented in Figure 7(a), which shows that dc-link voltage is stable for fluctuating powers from wind and PVS. Figure 7(b) depicts the matching rms line voltage at PCC. The output line rms voltage is essentially immune to changes in wind velocity, sun irradiation, and load, as shown in Figure 7(b). Because the rms value of the terminal voltage may not gives a good image of the voltage waveform in a transient state, the instantaneous current waveform is shown in Figure 8. Based on Figure 8, it can be observed that there is no notable increase in the voltage waveform at t=2 seconds during the load transient. The THD is approximately 5% in the voltages of all three phases. Therefore, the proposed method is capable of providing a satisfactory quality of voltage to the loads. The instantaneous current with THD of 5.5% is depicted in Figure 8. The corresponding powers of PV, wind, load, SMES, and electrolyzer are shown in Figure 9. While consuming the surplus power, electrolyzer generates the hydrogen which is depicted in Figure 10 and generated hydrogen can be used by FC as its input power.

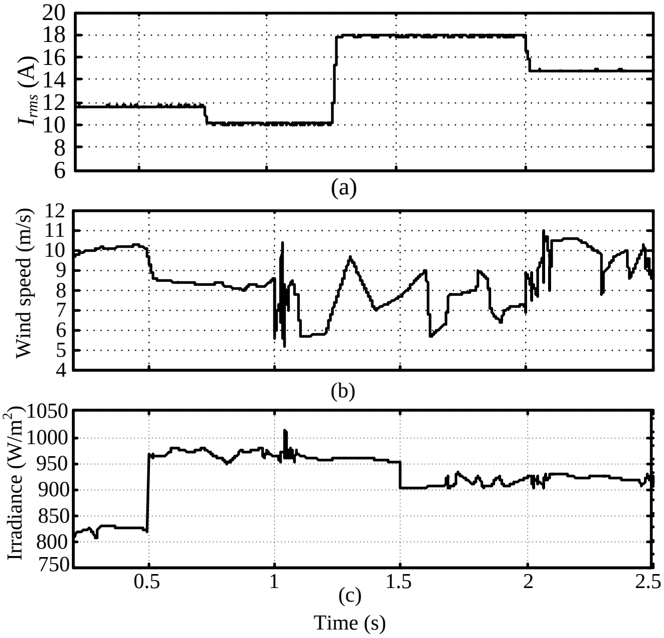

Figure 6: (a) Changes in load, (b) Intermittent speed of wind, (c) Intermittent irradiance.

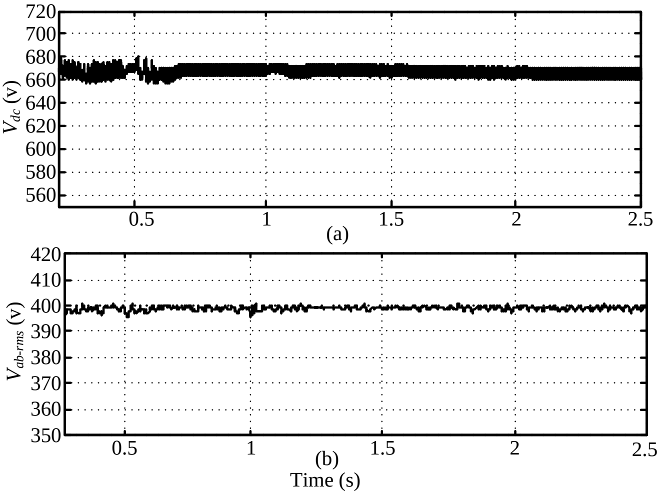

Figure 7: voltage at (a) Dc-link, (b) Line (rms) at PCC.

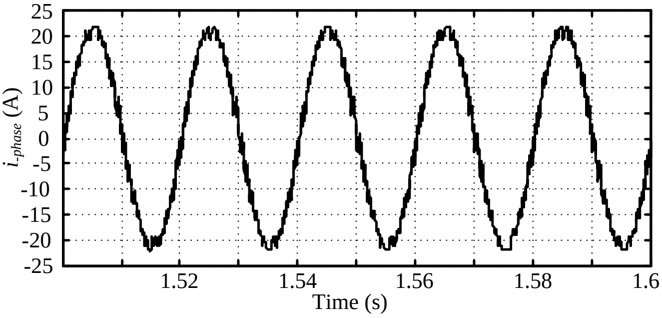

Figure 8: Instantaneous phase currents.

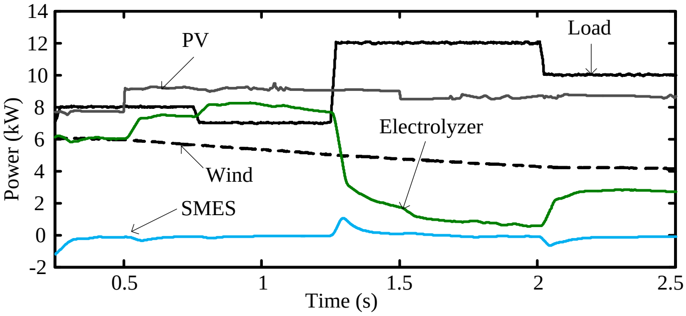

Figure 9: Powers.

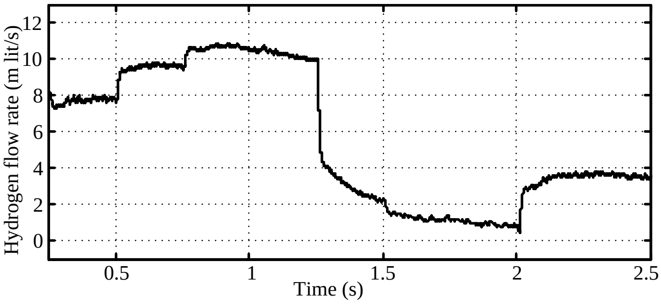

Figure 10: Production of hydrogen.

4. CONCLUSIONS

It is described a control method for regulating the voltage of a stand-alone microgrid composed of a PMSG based variable speed turbine, PV, FC, SMES, & dump load. This article emphasized the advantages of SMES over batteries in transitory circumstances. The inverter maintains a constant output voltage at its rated value by controlling the V_{dc} to its target value and adjusting the modulation indices accordingly. The suggested dc voltage control mechanism is straightforward, requiring just three parameters to be measured. (i.e., V_{dc}, I_{fc} and I_{ele}) They do not necessitate the measurement of any powers (for example, load and source powers, etc.). The use of voltage at the dc-link management is to manage power balance among various components to achieve effective control coordination among PV, wind, FC, SMES, and AE. Because the converters linked to the FC and electrolyzer not only regulates dc voltage but also function as MPPT, there is no need for a separate MPPT circuit for PVS. Because the FC and electrolyzer dynamics are slow, the proposed controller allows SMES to charge/discharge instantaneously while the FC/AE feeds/consumes power in a stable state. The adoption of a two-mass drive train model leads in more realistic wind turbine dynamics. The simulation results demonstrate that the proposed controller can maintain a stable load voltage under dynamic and steady-state situations with changes in irradiation, speed of wind, and loads.

APPENDIX

Parameters of SMES.

Inductance (L_{smes})	6.2H
Feedback gain (K_{ld})	0.18

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