VOL. 07 NO. 5,
FEBRUARY, 2025
E-ISSN 3027-1339
P-ISSN 3026-8257

African Scholar Publications & Research International
www.africanscholarpub.com

Journal of Systematic, Evaluation and Diversity Engr. (JSEDE)

Design Of A Hybrid Energy Storage System For Improved Voltage And Frequency Control In A Multi Energy Resource Isolated Microgrid Power System Using An Enhanced Dynamic Droop Control Method

Kenneth Ugo Udeze; & Mezue Francis Canice Tochukwu

Department of Electrical & Electronics Engineering, Federal Polytechnic Oko, Anambra State. Nigeria.

Corresponding Author: princeken2003@gmail.com

DOI: https://doi.org/10.70382/ajsede.v7i5.005

Abstract

This study was conducted basically to improve the voltage and frequency control system of hybrid energy storage system (HESS) microgrid using iteration method of dynamic droop gain control strategy. Six (6) Hybrid Energy Storage System (HESS) arrangement were considered and they were formed by different combinations of Battery Energy Storage System (BESS), Superconducting Magnetic-based Energy Storage (SMES) and also Supercapacitor (SUPCA) system as the new introduction into the HESS microgrid. The use of existing constant and dynamic droop-controlled technique on these arrangements were then compared with the new and enhanced constant and dynamic droop-controlled technique using MATLAB and iteration method. The results showed that the introduction of SUPCA in the HESS help to achieve; one, good frequency control and voltage-stabilization, two, improved and extended service

time and lifespan of battery due to improvement in state-of-charge (SOC). The results also revealed that the improved HESSs showed better frequency and voltage regulation capabilities. Thus, it was concluded that the proposed enhanced dynamic droop-control technique significantly exploits the different features of SUPCA, SMES and BESS to form a sort of complementing HESS. Hence, it was recommended that the BESS in the new control system would significantly protect it from short-term frequency change cycles, Voltage changes and sudden change in currents, lifespan.

Key words; Enhanced Dynamic Droop Control Strategy, voltage control, frequency, control, Hybrid Energy Storage System (HESS), Multi-energy Resource, Microgrid Power System, Battery Energy Storage System (BESS), Microgrids (MGs), Supercapacitor (SUPCA), Superconducting Magnetic-based Energy Storage (SMES), state-of-charge (SOC), Primary Frequency Control.

Introduction

Microgrids (MGs) are localized set of electricity power sources and loads which function as controllable system with respect to their grid. It could be utilized in providing electricity in small community or building, and could combine several energy sources like solar, wind, and normal generators. One key issue in designing and using MG is the challenge on ensuring that voltage and frequency of power that is supplied remain within workable ranges, which can be achieved by combining different energy sources know as Hybrid Energy Storage System (HESS) (Solomon et.al 2014). The HESS involved combination of several types and forms of energy storage arrangement like Battery Energy Storage System (BESS), Superconducting Magnetic Energy Storage System (SEMES) and Supercapacitor (SUPCA). Each arrangement has its individual capabilities and weaknesses, and by combining them, it becomes possible to overcome some weakness and limitations that are peculiar to a single arrangement thereby creating more robust, efficient and effective system. For instance, BESSs are better in providing quick and faster response to alteration in power demand, but their

limitation lies in their overall lifespan and they are equally expensive (Solomon et.al 2014).

In order to enhance voltage/frequency control, the hybrid system of energy storage should be used to provide controlling services to MG which could be achieved by using stored energy to provide active power to the grid to help maintain voltage and frequency within acceptable limits. In conclusion, a HESS with SUPCA can be an effective solution for improving voltage and frequency control in a multi-energy resource microgrid system. By combining the strengths of different energy storage technologies, it is possible to create a more robust and efficient system that can respond quickly to changes in power demand while also being able to store energy for longer periods of time. Additionally, the system can be used to provide regulation services to the MG, helping to maintain voltage and frequency within acceptable). Nayar et.al 2008) limits.

The dynamic droop method is used to control the output of the HESS in order to maintain the desired frequency and voltage levels. In order to ensure reliable operation of the HESS, it is important to properly design the system for the required power and energy requirements. This includes determining the amount of energy required for each storage technology, selecting the appropriate type of storage technology, and sizing the system components. The system must be designed to ensure that there is sufficient redundancy and fault tolerance in case of a failure of one of the components. Finally, the system must also be designed to ensure that it meets the safety and environmental requirements Ma et.al (2014).

From recent ideas for global promotion of integrated Renewable Energy Source (RES) in smaller, medium and larger scale systems and having different power grids being expanded and become complex, the advancement of novel technologies for effective RES integration and usage is of massive concern globally. Several nations globally are concentrating on achieving their RES targets in order to minimize emission of pollutant gases and to reduce energy-consumption in their societies. The power deviation and variation of RES along with their unpredictability reduces reliability of power grids making them very prone and sensitive to stability problem at frequency and voltage level, estimation of power reserve is made more and more harder and power supply security could be affected in areas concerning inductive load. Being that stable supply of electric power is

crucial requirement for nearly all human activities and operations; people that dwell in local islands do not have better access to power Ma et.al (2014). Because fossil-fuel resources are gradually becoming insufficient, people in rural area and people connected to general national power grid are confronted with massive cost for power bills Solomon et.al (2014) and Chua et.al (2014). Nayar et.al (2008) stated that using renewable power generators along with normal diesel-powered generators will aid in reducing expenses on electricity". With continual advancement in renewable power techs, the expense on technologies and devices of renewable energy has dropped appreciably recently. Thus, it is technically and economical compelling to design a micro-grid based on renewable energy in local places also these forms of power generation could be linked to national power-grid like Nigeria to enhance amount of power generated and lined to national power lines.

Renewable energy source systems like solar-panels and wind-turbines required numerous control units designed using power-electronic interfaces are massively needed Barklund et.al (2008) and these devices are very prone and sensitive to alteration in frequency thereby makes MG sensitive and prone to erratic changes and disturbances. In grid-linked conditions, MGs could interchange power with major grid and such process aids to maintain frequencies of the system Trujillo et.al (2010). However, due to massive cost and investment in systems for power transmission, MGs sited within local areas are mostly meant to operate like off-grid systems Bekele and Tadesse (2012). Thus, main frequency/voltage controls are crucial in local area with MG. several solutions are already examined to handle this frequency alteration issues in micro-network system and they include, introducing more rotating mass to elevate MGs inertia, hence to sustain frequencies of MG system Cho et.al (2011) and Bomer et .al (2010) mentioned that more uses of non-Reserved *Power* Generation (RPG) like gas-engines and diesel-powered engine to enhance frequency stability of the system is practicable. The Díaz-Gonzále et.al (2014) and Shalabi et.al (2009) equally examined variable-velocity wind-based turbines meant for MG in frequency-control mode. But all technique mentioned showed same or similar weakness in that dynamic response velocity of more devices is slow, therefore could not meet requirement for frequency control

and regulation requirement in MG Aghamohammodi et al. (2014), Mercier et.al (2009) and Delille et.al (2012).

Review of Recent Literatures

BESS system for energy storage which possess high efficiency and massive energy density according to Cho and Kleit (2015) are supposed and considered as effective means for resolving power balancing in island MGS. Several preceding works have examined possible incorporation of BESSs into micro-power networks with aim of mainly to control frequency. To optimize BSSs for frequency control in rural power-network system Mercier et.al (2014), they initiated adaptable condition of charging limits. Dynamic technique of frequency control is employed in French Guadalope island aimed at increasing renewable energy system penetration for Micro-power systems Delille et.al (2012). BESSs used for plug-in electric-vehicles are examined to be utilized in micro-power network and this has shown to have better capacity for frequency regulation. Vachiresricirikul and Ngamroo (2011). Three-phase BESS was used by Serban and Marinescu (2014) to achieve power balance function in Micro-power network with no load shed. But there were two major issues and problems that limit use of BESS in this case. (i) BESS service life cycle is limited and this problem is worse if the BESS is utilized in renewable-power, due to BESS undergoing several short-time cycle Li. et.al (2015). (ii) Compare to other system of storing energy like super-capacitor and SMES, BESS have low power density and this implies that BESS systems cannot quickly respond to short time issues. Although power-discharging ability of BESS could be increased to handle massive frequency power alterations, but massive matrix of BESS cells is required Cao and Emadi (2012).

Moreover, bigger BESS-banks also undergo several short-time charge/discharges procedures that could trigger severe BESS lifecycle deterioration. The benefits of massive power density are non-limited lifecycles, and massive charge/discharge effectiveness Luo et.al (2015) made SMES and SUPCA for storing energy an ideal complementing device for BESS. Several previous studies used SMES/BESS in numerous applications to enhance system effectiveness in wind-power applications Li. et.al (2015) to compensate for altering loads for railway-system Ise et.al (2005) and to extend battery lifecycle in electric buses Li. et.al (2016). However, no

literature published has noticed that introducing SUPCA, SMES & BESS in Micro-power network for frequency/voltage regulation procedure is better. Hence, to handle such problems, a novel idea of SUPCA, SMES and BESS employed in main frequency control is presented in this work. Micro-power network is designed in SIMULINK to confirm the HESS design with novel technique for droop control.

Li. et.al (2016) stated that droop factor is usually given as fixed values by existing arrangement or pattern which is already reviewed. In HESS, SMES possess higher power rating but poor energy density thus, SMES must be regulated to meet short time high-power needs at commencement of their function. The sharing capacity of SMES should be regulated to decrease while sharing capacity of BESS need to increase. Constant droop factor, therefore, couldn't meet the needs of synergetic activities of these two forms of energy storages due to the inherent or inbuilt features of BESS and SMES. To settle or handle this issue new method based on using dynamic droop factor was initiated by introducing SUPCA.

In designing and building this micro-power network, the BESS lifecycle extension and enhancement of frequency/Voltage variations are among major indicators to evaluate HESS; therefore, BESS lifecycle, SUPCA & SMES is forecasted and compared to BESS-only system. The results of these simulations revealed that compared to BESS-only system, SMES and BESS only, that SUPCA, SMES and BESSs have faster regulation and control for frequency/voltage disturbance. Compared to HESS employing SUPCA, SMES and BESS technique, using an enhanced dynamic droop control accomplishes better PFC/Voltage control, and due to the Dynamic droop gain, the SOC is also shown to have improved from 48 to 74%. Hence, the life cycle of the BESS.

So many solutions are already examined to resolve frequency/voltage alteration issues in micro-power networks system and some of these solutions are adding more rotating weight and increasing MG inertia, thus to maintain frequency/voltage of MG systems, generating better reserve power like gas-engines and diesel-generators to enhance stability of power-system frequency. Several works also examined variable-velocity wind-based turbines employed in micro-power network for controlling frequency.

However, the entire technique explained in literature possess same weakness and pointed that dynamic response velocity of more devices is slow, therefore not able

to meet their requirement of frequency control in MG procedure. BESS which possesses high effectiveness and massive energy density are usually opined to be effectual solution for balancing power within MGs system. Several forms work have worked on integrating BESS into micro-power network aimed at controlling main frequency. BESSs in plug-in electric auto-systems are examined in order to employ in micro-power network and are confirmed to possess better ability for frequency control. Three-phased BESS system is imitated by achieving power balance operation in MG with zero loading shed. But there exist three main issues that hinder BESS usage; one, BESSs have limited-service lifecycle and this condition is made worse when BESSs are utilized in renewable-power, being that batteries undergo several short-time cycles. two, As compared to other HESS like SUPCA and SMES, batteries have lesser power density and that implied that they cannot respond faster to short time frequency/voltage changes, in BESS though their battery power capacity could be increased to handle changes in high-frequency power thus bigger matrix of BESS cells are required. Also, massive battery banks undergo many short-time charge/discharges procedure which could trigger severed deterioration of BESS lifecycle. three they cannot provide enough improvement on power factor when required. The advantages which larger power density, unhindered lifecycles, highly enhanced power-factor, operates in low and high temperate area and high efficiency of charge/discharge make SMES and SUPCA energy storing system ideal complement for BESS.

Several studies used SUPCA, SMES and BESS as a HESS in several applications to improve general efficiency of wind-based systems, compensate for changing loads for railway system, and extend BESS lifecycle in electric-based auto-system even in primary frequency control PFC. But, none of this work published was found to introduce SMES/SUPCA/BESS in Micro-power network as improve methods of handling frequency/voltage control operation in HESS. Hence, to handle these issues above, a novel idea of new technique using an enhanced dynamic-droop control was introduced to control SMES/SUPCA/BESS used in main frequency/voltage control and this entire system was model in a SIMULINK environment as presented in this work.

Methodology

Microgrid Hybrid System Voltage and Frequency Control Equations

In this study, the voltage and frequency control equations for the microgrid using the hybrid system can be represented as follows:

Voltage control equation; Equation 1 calculates the microgrid voltage by summing up different components. It starts with the voltage reference and adds the voltage droop component which adjusts the microgrid voltage based on the frequency deviation from the reference. Then, it subtracts the voltage droop components related to the battery, SMES, and supercapacitor currents. These terms account for the voltage droop caused by the current flow through each energy storage component in the hybrid system.

$$V_{mg} = V_{ref} + Droop_V \times (f_{mg} - f_{ref}) - Droop_{V_{BESS}} \times I_{BESS} - Droop_{V_{SMES}} \times I_{SMES} - Droop_{V_{SUPCA}} \times I_{SUPCA} \quad (1)$$

Where V_{mg} represents the microgrid voltage, V_{ref} is the voltage reference, $Droop_V$ is the voltage droop coefficient, f_{mg} is the microgrid frequency, f_{ref} is the frequency reference, $Droop_{V_{BESS}}$ is the voltage droop factor for BESS, $Droop_{V_{SMES}}$ is voltage droop factor for SMES, $Droop_{V_{SUPCA}}$ represent voltage droop factor for supercapacitor, I_{BESS}, , is the currents flowing through the BESS, I_{SMES} , is the currents flowing through the SMES, I_{SUPCA} , is the currents that flow in the SUPCA.

Frequency control equation; In thus study, Equation 2 calculates the microgrid frequency by summing up different components. It starts with the frequency reference and adds the frequency droop component, which adjusts the microgrid frequency based on the power deviation from the reference. Then, it adds the frequency droop components related to the battery, SMES ($Droop_{V_{SMES}} \times I_{SMES}$), and SUPCA ($Droop_{V_{SUPCA}} \times I_{SUPCA}$) currents. These terms account for the frequency droop caused by the current flow through each energy storage component in the hybrid system.

$$f_{MG} = f_{ref} + Droop_f \times (P_{MG} - P_{ref}) - Droop_{f_{BESS}} \times I_{BESS} - Droop_{f_{SMES}} \times I_{SMES} - Droop_{f_{SUPCA}} \times I_{SUPCA} \quad (2)$$

where: P_{MG} is the microgrid power, P_{ref} is the microgrid power reference, f_{MG} represents the microgrid frequency, f_{ref} is the frequency reference, $Droop_f$ is the frequency droop coefficient, $Droop_{f_{BESS}}$ represent frequency droop factor for battery, $Droop_{f_{SMES}}$ is frequency droop factor for SMES, $Droop_{f_{SUPCA}}$ represent frequency droop factor for supercapacitor, I_{BESS} represent currents that flow through the BESS, I_{SMES} is the currents that flow through the SMES, I_{SUPCA} is the currents that flow through the SUPCA.

The Figure 1 shows the complete model of PFC and this was done by putting Equation 3 below.

$$\frac{df}{dt} = \frac{f_0}{2\sum H_i}\left(\sum P_{G_i} - \sum P_{L_i}\right) + D_{SMES}\Delta P_{SMES} + D_{BESS}\Delta P_{BESS} + D_{SUPCA}\Delta P_{SUPCA} \quad (3)$$

into a MATLAB/SIMULINK model where in which the D_{SMES}, the D_{BESS} and D_{SUPCA} are the droop coefficients of the SMES and BESS and SUPCA systems respectively, and in which $\sum H_i$ is summation of all the inertia index of rotating parts, the f_0 is frequency setting of the system P_{G_i} is energy generated in i section and P_{L_i} is demanded load from i section The proposed dynamic droop gain control approach was codded in a MATLAB file. The code is represented as in Algorithm 1. The algorithm code is contained in the MATLAB function block in Figure 1 the dynamic droop controller is further optimized by multiplying each dynamic power drift obtained as control output, with a set of gains, which were optimized using MATLAB genetic algorithm toolbox.

For the Algorithm on The Dynamic Droop V-F Controller, it will be available on request.

Just as stated in the theoretical work, produce power must continually align with load, and fluctuation or alteration in this possible balance could trigger frequency alteration in this system. In normal and conventional power system, short time power misalignment is mostly covered using kinetic energy from power generators known as main frequency control. Modeling of the PFC system was done by the use of Equation 3. the circuit diagram is shown in Figure 2

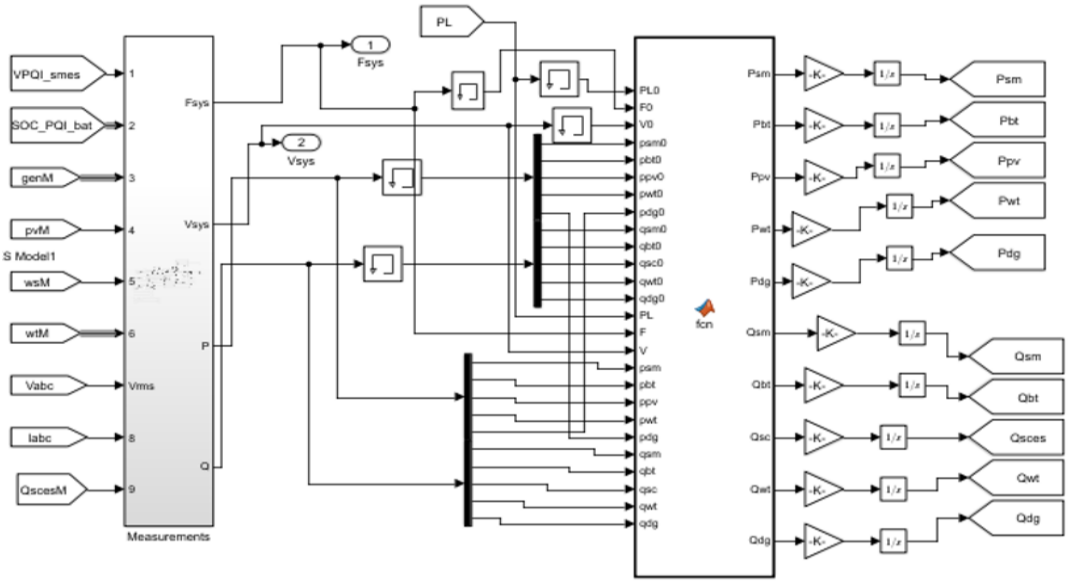


Figure 1 MATLAB SIMULINK Diagram of Proposed Dynamic V-F Droop Controller

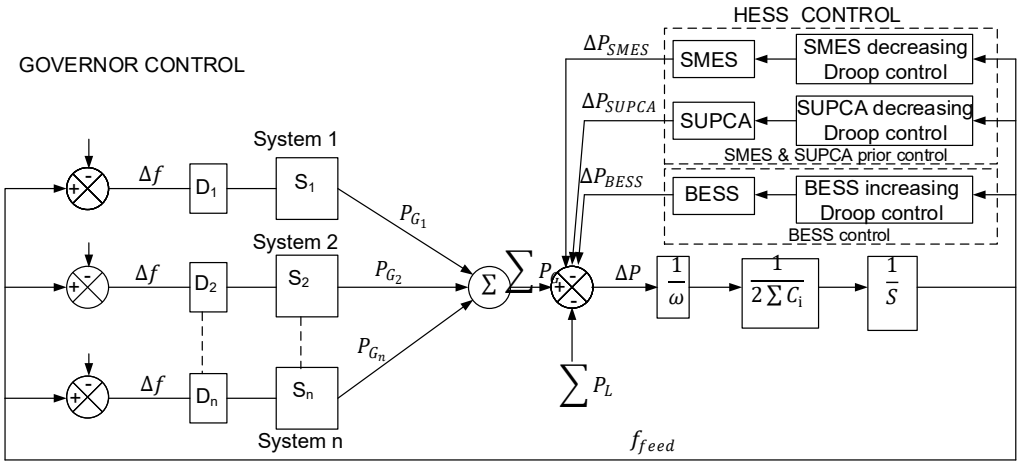


Figure 2 Circuit Diagram of Main frequency control for MG system with HESS

Since D_{SMES}, D_{SUPCA} and D_{BESS} represent droop index for SMES, SUPCA and BESS arrangement respectively. The voltage of this system could be maintained and sustained by controlling reactive power with SMES, SUPCA and BESS. see Figure 3 for reactive power control. Based on this, reactive power discrepancy DQ, creates Voltage error for this system and this error is analyzed by controller and

then return the refenced reactive component Vq_ref. Then, Vq_ref will be employed in generating PWM signals needed to control SMES/SUPCA/BESS HESS compensation reactive power.

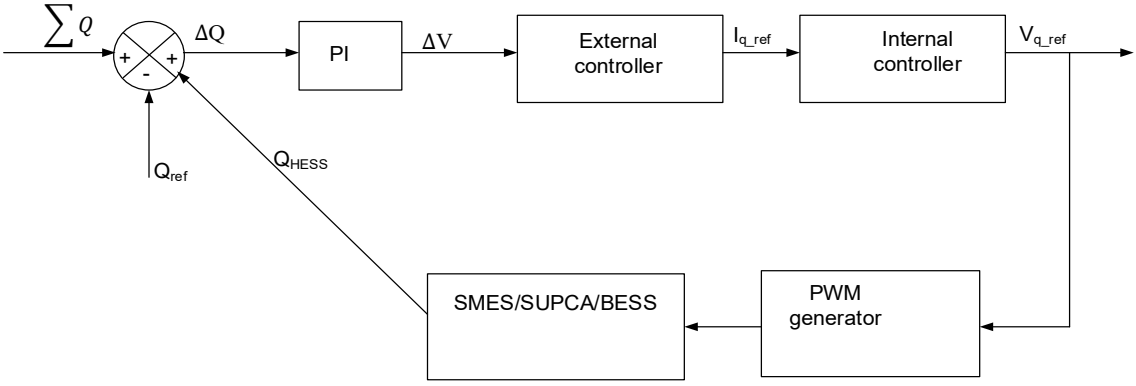


Figure 3 The Reactive Power Regulation using SMES/SUPCA/BESS as a HESS.

Model Equation for A Microgrid that Incorporates Diesel Generator (DG), Wind Turbine (WT), Photovoltaic (PV) System

The general equation for a MG that incorporates a DG, WT and PV system, and HESS is given in Equation 4. Here, the equation states that the total power output of the microgrid is determined by the summation of the power outputs of the DG, WT, and PV systems. This total power is then adjusted by subtracting the power used or utilized by load and any power losses within the microgrid.

$$P_{MG} = P_{DG} + P_{WT} + P_{PV} + P_{BESS} + P_{SMES} + P_{SUPCA} - P_{Load} - P_{Loss} \quad (4)$$

Where: P_{MG} represents the total power output of the microgrid, P_{DG} represents the power output of the Diesel Generator, P_{WT} represents power output of Wind Turbine, P_{PV} represents power output from PV system, P_{BESS} is power output from battery, P_{SMES} is the power output from SMES, P_{SUPCA} is power output from SUPCA system, P_{Load} represents total power consumed by the load within the microgrid, P_{Loss} represents any power losses within the microgrid (e.g., transmission losses). For this work the losses are taking to be about 3% of output power.

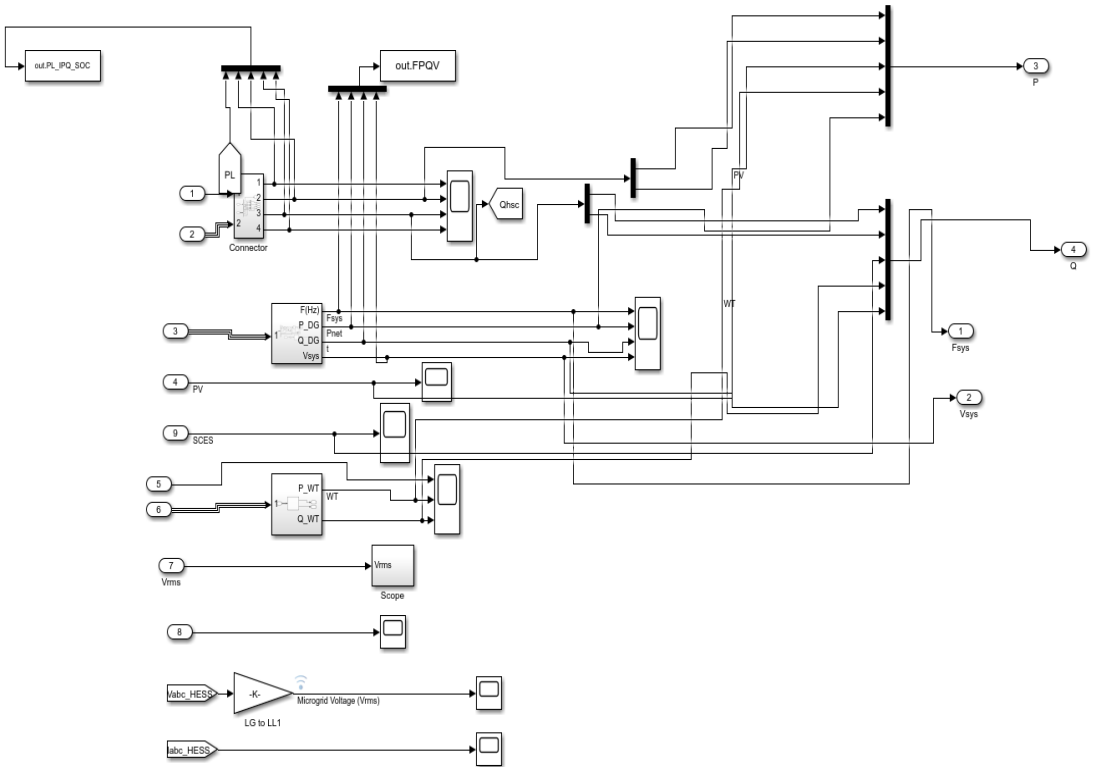


Figure 4 Model Showing the Microgrid that Incorporates A (DG), (WT) & (PV) System

Figure 4 was done using Equation 5 in the MATLAB/SIMULINK model. It shows the different blocks for each of the generators with the scopes that can display what each generator is producing at any given time.

Diesel Generator Simulink Diagram

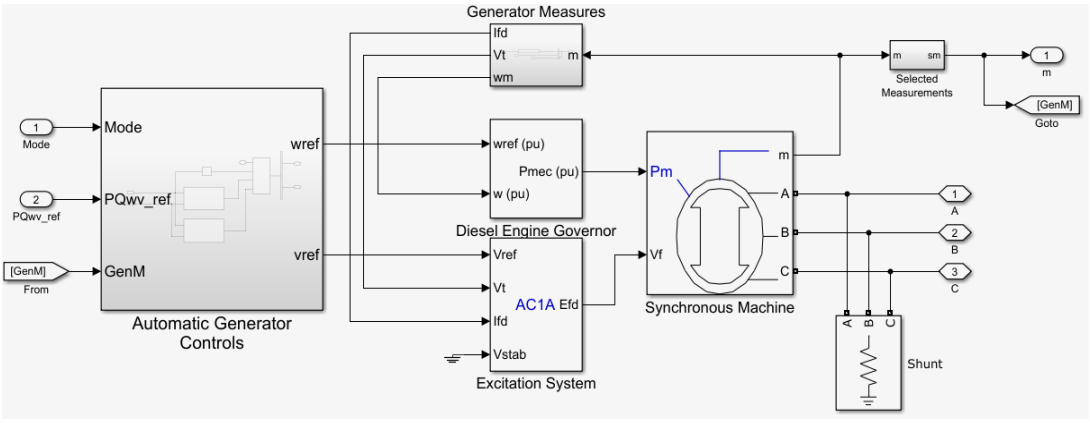


Figure 5 Diesel Generator (Full Genset Control)

From Figure 5, the key part of diesel-based generator included: Diesel-based Engine. Alternating-Current Alternator. Base-frame, along with tank. The benefit of "proton exchange membrane fuel cell (PEMFC)" are good efficiency that could reach 45%, better energy density from smaller dimensions like 2 W/cm^2, silent functions, lower temperature in operation, faster start-up, and robust, Larminia and Dicks (2003) & Gebregergi and Pillay (2010). The most crucial benefit of this PEMFC is reduced pollutants since where hydrogen fuel has no negating pollution effects. Mwinga et.al (2015) & Tremblay and Louis (2009). Not minding these benefits of FC, it also has some demerits such as slow response time to changes in load, unsteady or varying output voltage, short lifespan due to increase in rippling current and expensive. The overall ECM for FC discussed by Outeiro. (2011). The mathematical models of synchronous machines can also be seen in the literature on synchronous generator designs.

Wind Turbine Model Simulink Diagram

This study used equations that consider the available wind speed and cell irradiance (Irradiance) as input parameters. Here are the model equations are as follows:

$$P_{WT} = 0.5 \times \rho \times A \times C_p \times V^3{}_{wind} \qquad (5)$$

Where: P_{WT} represents the power output of Wind Turbine, ρ represent density of air, A represent swept area of turbine rotor, C_p represent power index which depends on wind turbine design and characteristics, V_{wind} is the wind speed. The Figure 6 shows the modeling of the wind turbine. Simple Wind Turbine that serves as an Active and Reactive Power Source depending on the Wind Power Curve. The Wind Turbine Power Curve can be defined by:

-Dimensions of the wind turbine

- Simple cubic power curve

- Look-up vector from a wind turbine data sheet.

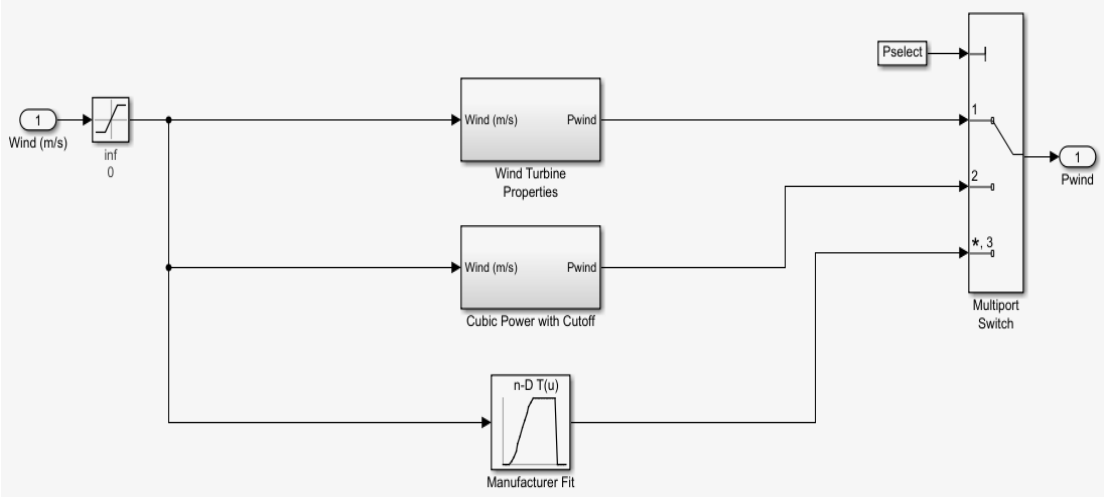


Figure 6 Wind Turbine PQ Model

The Figure 6 shows the modelling of the Wind Turbine system; Wind turbine comprises of rotor positioned on nacelle and tower having at least two blades connected mechanically on electric-generator. Gearbox arrangement in the mechanical system transforms or changes slower rotation velocity from wind turbine to high rotation velocity on electric-generator. The rotation movement of shaft generates electric power whose output and it's maintained by control system. Two design models are commonly used for wind turbines and this classification is made based on the axis on which turbines moves or rotate, thus we have, "Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT)". VAWT is equally known as Darrius rotor credited to the inventor Mukund. (2012). HAWT possess the capacity to absorb optimum volume of wind power for day time and all season and their blades could be easily adjusted to prevent massive wind storm. Wind turbine's function based on two major modes; constant or changing speed. In constant speed mode, turbine rotor is designed to move or rotate at fixed angular speed not minding incoming wind changes hence, the main reason for its application on the modeling on this research work. One benefit of this mode is based on fact that it doesn't involve costly power electronics like inverters/converters arrangement. But its demerit is that it limits rotor speed to allow the turbine to operate only at its optimum efficiency at all time. Thus, a fixed turbine wind speed generates less energy when speed of wind is low compare to changing wind-speed arrangement which are normally designed to move and function at speed corresponding to wind speed lower than rated wind-speed. The torque or power output of wind turbine is ascertained by different factors which are (i) speed of turbine, (ii) tilt angle of rotor-blade (iii) pitch angle of rotor-blade

(iv) shape/size of turbine, (v) turbine area (vi) rotor geometry either HAWT or a VAWT, (vii) wind-speed. The connections between power output and these factors establishes mathematical model for involved wind turbine. This mathematical model for wind turbine is crucial in attempt to understand features of wind turbine over its operation area and also this modelling help control for performance of wind turbine. Mathematical model for wind turbine was explained in thoroughly in Manyonge. W et.al (2012).

Photovoltaic (PV Array) Modeling Simulink Diagram

The Photovoltaic system Modeling Equation is expressed as

$$P_{PV} = A_p \times Irradiance \times \eta_{PV} \qquad (6)$$

Where: P_{PV} represents the power output of the PV system, A_p is the surface area of the photovoltaic panels, Irradiance represents the solar irradiance received on the PV panels, η_{pv} is the efficiency of the photovoltaic system, which represents the conversion efficiency of sunlight into electrical power. The modeling of the PV system was achieved in the MATLB/SIMULINK as shown in Figure. 7. The Figure 7 represents grid-linked solar arrangement using 3-Phased Dynamic Load arrangement. It is system-level arrangement that doesn't involve power electronics; however, it is essential for load-flow, phasor, and hybrid phasor simulation processes. The input on this model arrangement is output for grid linked PV arrangement, not irradiance.

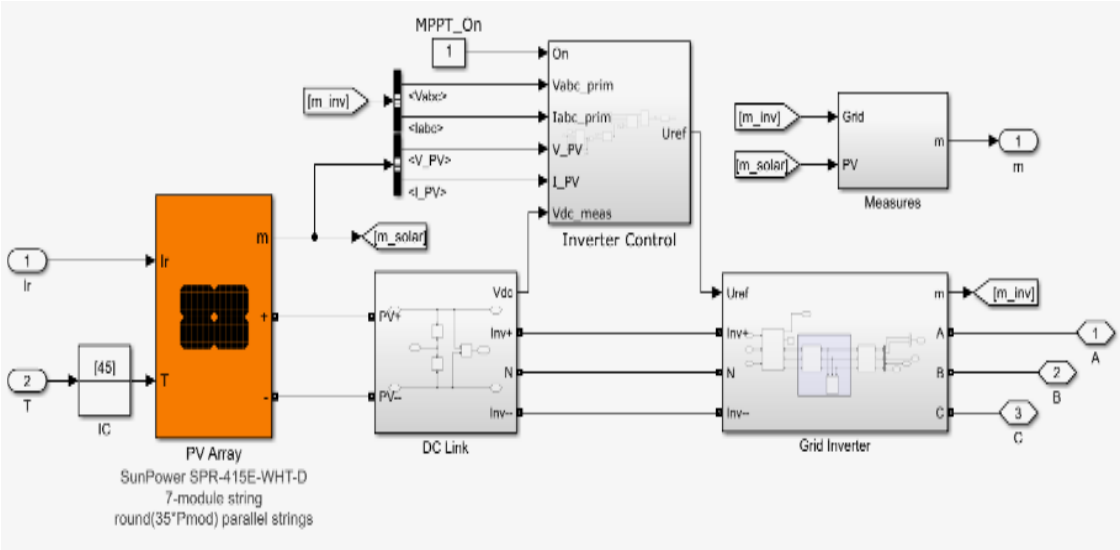


Figure 7 The PV System PQ Model

For thorough PV arrangement, consider PV Array block in Renewables library.

The Controlled Mechanism of the Modified HESS Designed System

Figure 8 is a modification of model used by Li. (2016). But at this time, SUPCA was introduced in the control system.

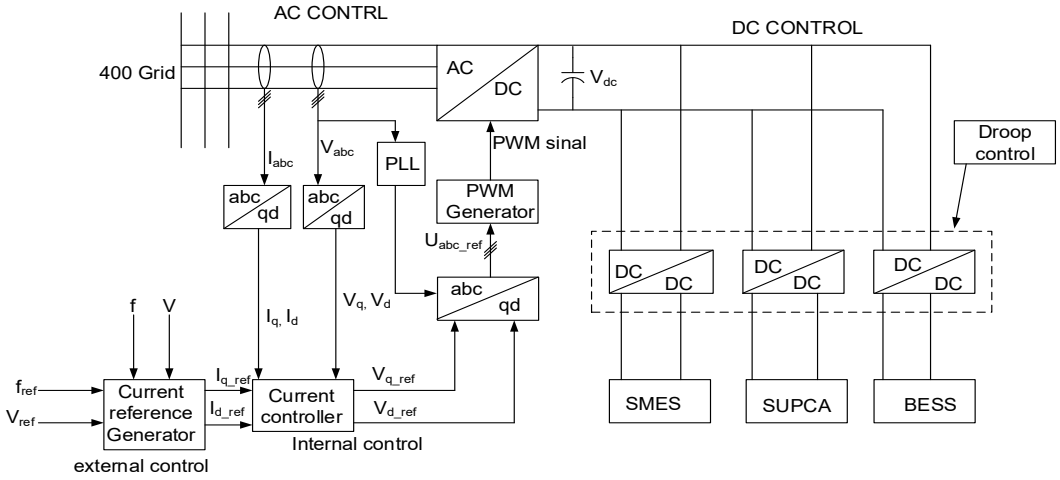


Figure 8 Control system for proposed MG along with HESS.

Control technique is accomplished in two sections revealed in Figure AC-end voltage control and DC-end droop control. Based on this schematic, HESS is arranged as voltage source to recompense for system change and variation. Three DC/DC converters were utilized to cover this BESS, SUPCA and SMES in DC-bus, so that their droop features could be designed

Voltage Source Conversion System Controls for HESS.

The AC-end control comprises of external-leveled control and was done by the modification of expressed in Equation 7, 8 and 9

$$\Delta P_{SMES}\begin{cases} -\frac{1}{k_{SMES}}\left(f - f_{non_up}\right) \quad (charge\ mode) \\ -\frac{1}{k_{SMES}}\left(f - f_{non_low}\right)(discharge\ mode) \end{cases} \tag{7}$$

$$\Delta P_{BESS}\begin{cases} -\frac{1}{k_{BESS}}\left(f - f_{non_{up}}\right) \quad (charge\ mode) \\ -\frac{1}{k_{BESS}}\left(f - f_{non_{low}}\right)(discharge\ mode) \end{cases} \tag{8}$$

$$\Delta P_{SUPCA}\begin{cases} -\frac{1}{k_{SUPCA}}\left(f - f_{non_up}\right) \quad (charge\ mode) \\ -\frac{1}{k_{SUPCA}}\left(f - f_{non_low}\right)\ (discharge\ mode) \end{cases} \tag{9}$$

where ΔP_{SMES}, ΔP_{BESS} and ΔP_{SUPCA} are power alteration triggered due to SMES, BESS, SUPCA $^1/_{k_{SMES}}$, $^1/_{k_{BESS}}$ and $^1/_{k_{SUPCA}}$ are droop index for SMES, BESS and SUPCA.

Dynamic Droop Loop Control for HESS Using iteration Method

The new DDG method developed was adopted by the application of iteration method. The iteration method is a root-finding algorithm, used in numerical analysis. It is a recursive method for finding the root of polynomials by successive approximation.

The general iteration method formula is defined as follows:

$$x_n = x_{n-1} - f(x_{n-1})\frac{x_{n-1} - x_{n-2}}{f(x_{n-1}) - f(x_{n-2})} \qquad (10)$$

For the above recurrence relation, two initial values, x_0 and x_1 are required.

The Algorithm is as shown below:

1. Start.
   x_{new} represents the updated droop gain for the next iteration.
   x_1 is the current droop gain guess.
   x_0 is the previous droop gain guess.
   $f(x_1)$ and $f(x_0)$ represent the errors associated with the corresponding droop gain guesses.
2. Get values of x_0, x_1 and ε, where ε is the stopping criteria. i.e., Get values (Define) for x_0, x_1 and ε
3. Compute $f(x_0)$ and $f(x_1)$. Equations for Errors ($f(x_1)$ and $f(x_0)$):
   $$f(x_1) = desired_value - actual_value(x_1)$$
   $$f(x_0) = desired_value - actual_value(x_0)$$
   These equations define the errors ($f(x_1)$ and $f(x_0)$) associated with the corresponding droop gain guesses (x_1 and x_0). The errors are calculated as the difference between the desired value and the actual value of the parameter being controlled, evaluated at the respective droop gain guesses.
4. Compute $x_2 = x_{new} = x_1 - f(x_1) \times \frac{x_1 - x_0}{f(x_1) - f(x_0)}$
   This equation calculates the updated droop gain (x_{new}) for the next iteration using the current droop gain guess (x_1), the previous droop gain guess (x_0), and the errors associated with these guesses ($f(x_1)$ *and* $f(x_0)$).

5. Test for accuracy of x_2: If $\left|\frac{x_2-x_1}{x_2}\right| > \varepsilon$?
6. Let $x_1 = x_0$ & $x_1 = x_2$; then, goto Step 3
7. Display required root.
8. Stop.

   The iterations of this method converge to a root of f, if the initial values x_0 and x_1 are sufficiently close to the root. Where x are functions of frequency and voltage and any specified time. The iteration method application code is available on request.

Frequency-droop featured of these units of power generation are already reported to show appreciable impact on stability of system MG. Droop-control that could explore benefits of different type of power sources to recompense for instantaneous system variation or alteration, has reported to possess fast response and highly efficient Majumde et.al (2010), Guerero et.al (2011) and Kabir et.al (2014). Therefore, droop-control was designed based on several features of SUPCA, SMES and BESS to achieve a complementing hybrid system using iteration method. The fundamental ideas of HESS frequency droop-control could be initiated in six conditions expressed under stable condition, frequency/voltage for microgrid is within normal value f_0 in continual service condition which implies distortion is small such that energy storage arrangement don't need to act. Díaz-González et.al (2014).

The Flow Chart of the Designed MATLAB/SIMULINK Model

As revealed in Figure 9 is flow chart for microgrid system arrangement in MATLAB/SIMULINK which will generate produced Power $\sum P_G$ and $\sum Q_G$. The system starts by generating reactive power and actual power. The net power which is the deficit power for Net Real Power, we have Net $P = \sum P_{G_i} - P_L$ and also, for the Net Reactive, $Net\ Q = \sum Q_{G_i} - Q_L$. The generated P and Q are used to control voltage and frequency of this designed model respectively. In the constant droop gain (CDG) method, an initial value is assigned while the dynamic droop gain (DDG) control is set to 1 for both frequency and voltage control processes. The constant gain is initialized using particle swamp optimizers (PSO). Generally, the gain is set between $\pm$ 200 for both frequency and voltage control. The PSO is use to tune the frequency and vorlage gain. The PSO technique is used to optimize the CDG in the absent of DDG and after tuning the system to the best value you can get the result was taking for the CDG and this value is used permanently throughout the simulation processes. For the DDG method, an algorithm was developed see

appendix. This algorithm is modified according to the system behavior. From Figure 9, the power deficit is calculated by subtracting the generated power from the load power. Then after that this power is feed into the control scheme generates the appreciate droop control to regulate the whole system and this process is repeated until the simulation process is completed.

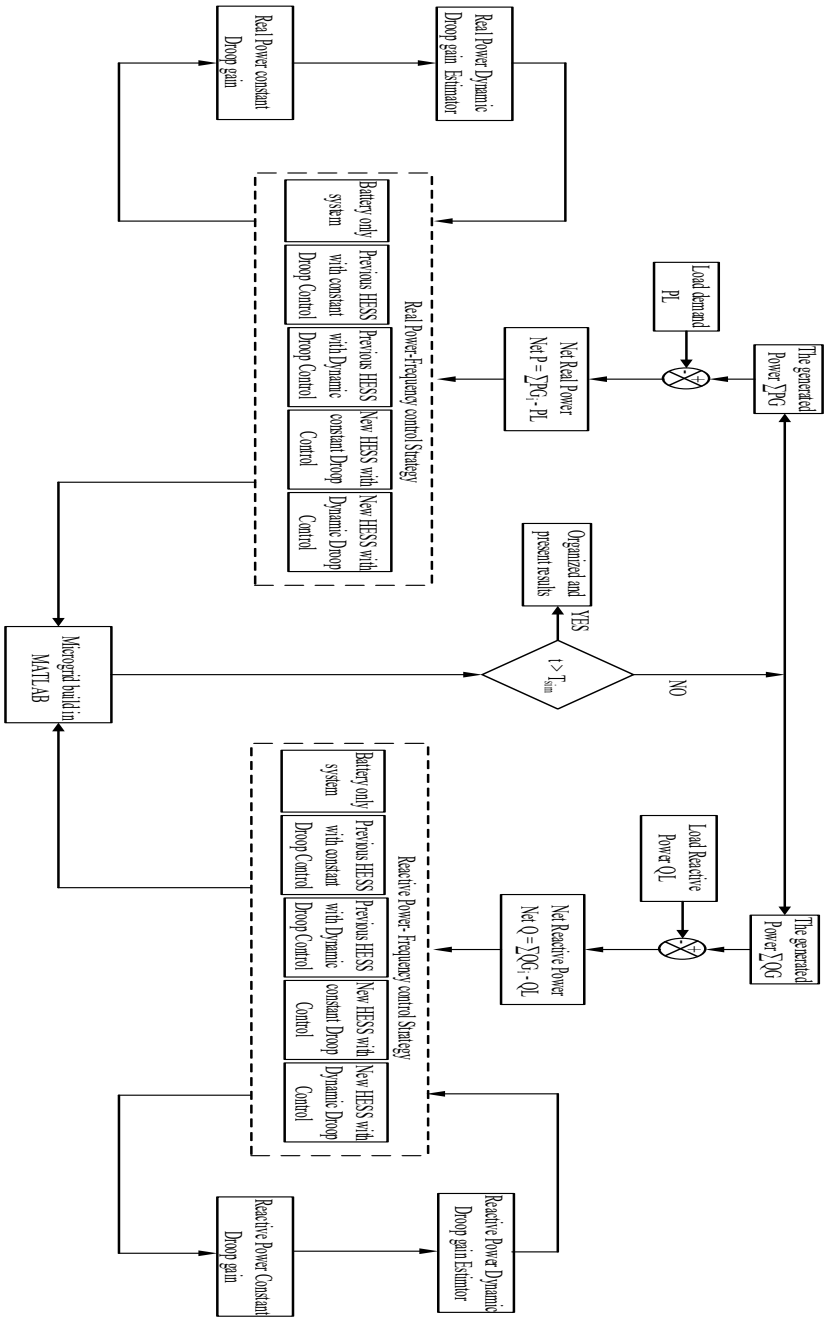


Figure 9 The flow chart of the model system

3.6 Simulation Set-Up

The MG was model with DG, WT and PV systems with the following ratings, SMES, BESS, SUPCA. The solar, wind, and load data for the modeling are based on design from Nayar et.al (2008) and Li et al (2016) previous studies which are WT (48 kW) and the PV (17 kW) respectively while the rating of the DG is 100 kW.

The system simulation parameter		
MG generator parameters		
	Diesel generator output power	100 kw
	Wind turbine output power	48 kw
	Solar PV output power	17 kw
BESS parameters		
	Type	60 Ah lead acid
	Voltage	12 V
	Matrix size	4 x 20
	Bank terminal voltage	4 x 12
	Max. discharging current	30 A
	Power rating	10 kW
	Max energy	100 kW h
The SUPCA parameters		
	Reactive Power	10 KVAR
	Time Constant (τ)	1×10^(-4) sec
The SMES Subsystem ratings		
	Rated power	10 kW
	Inductance	1.4 H
	Standard current	150 A
	Critical current	250 A
	Energy capacity	20.23 kJ
	Highest power	202.3 kW

Furthermore, simulation of the model on this work considered six (6) cases by the obtained result indicating the variations of frequency, voltage and currents, SOC and Total Harmonic Distortions (THD) with respect to time when the system is loaded. These cases are when Battery only is use as BESS, BESS and SMES using constant droop gain, BESS and SMES using dynamic droop gain, BESS, SMES and SUPCA using constant droop gain and finally BESS, SMES and SUPCA using dynamic droop gain.

Results and Discussions

BESS only System

When BESS only is used as the Energy storage system, fluctuating with respect to time was about 40A max just as can be seen in Figure 10. it is only the BESS that can generate the current needed by BESS; the distorting was high due to the fact that the droop control was not considered and the state of charge represented in the Figure 11 in almost between 5 to 92%. This shows the charge and discharging rate is very high which is actually a danger to the life span of the battery. Also, the THD is 303.152%. referring to Figure 12, the harmonics are zero after 1 Hz. The mean current is 6.1681A the fundamental Harmonics is 0.027778 Hz.

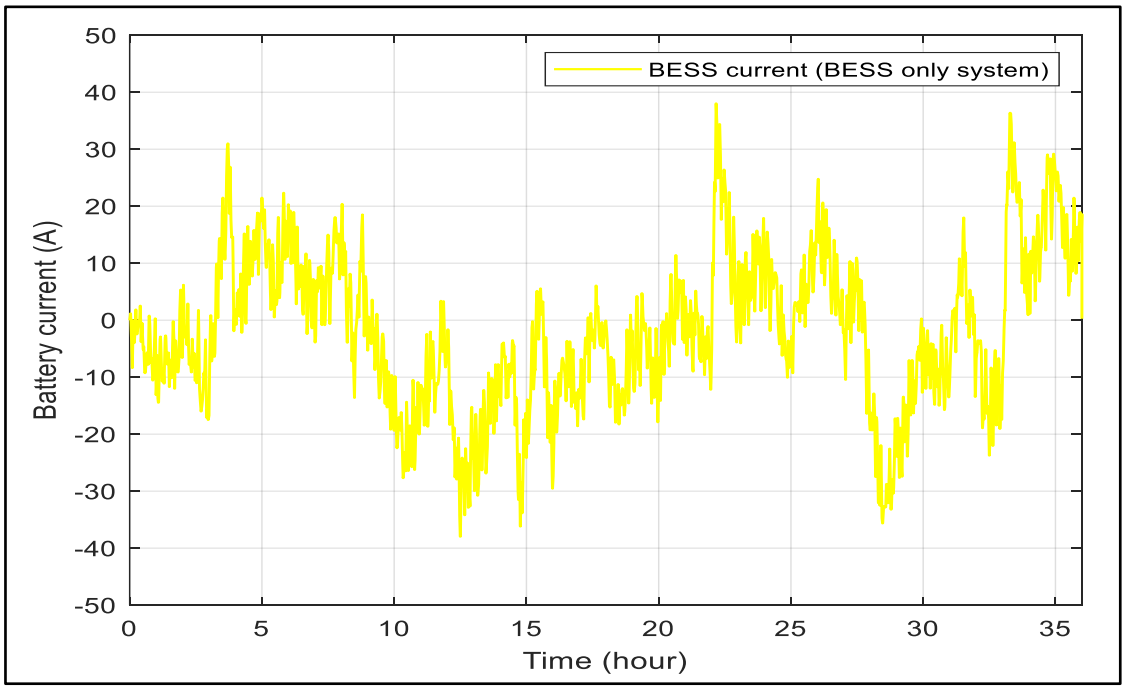


Figure 10 Shows BESS Current in Ampares changes with time

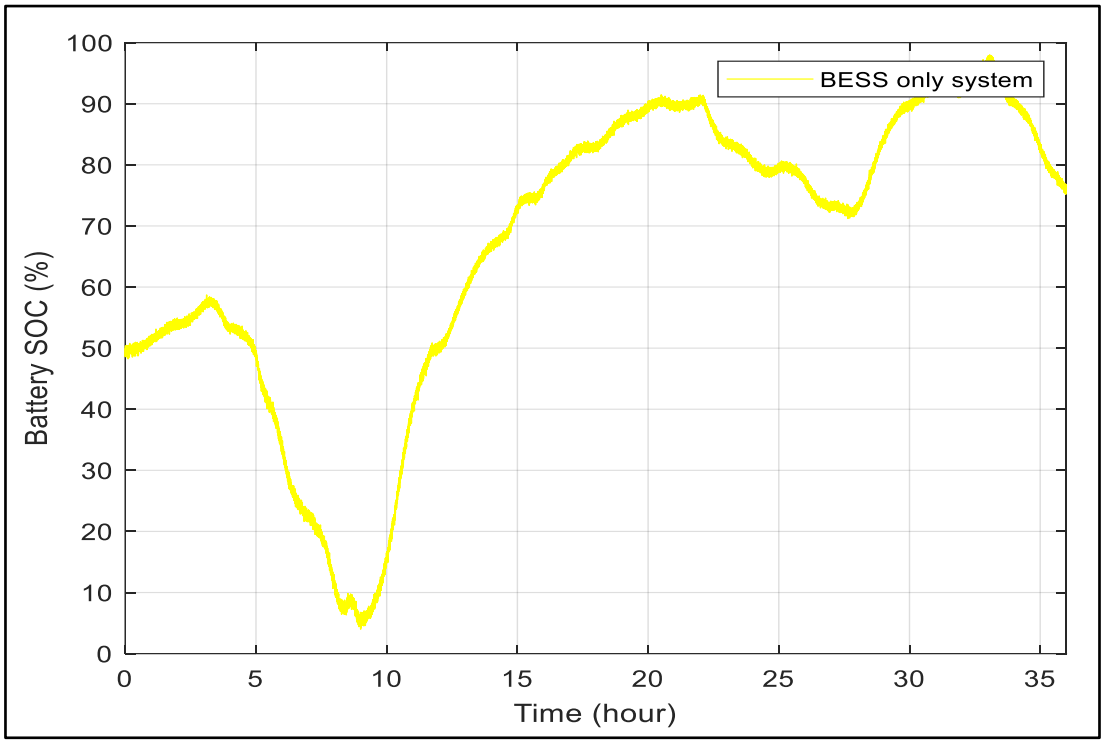


Figure 11 Showing the BESS State of Charge variation with time

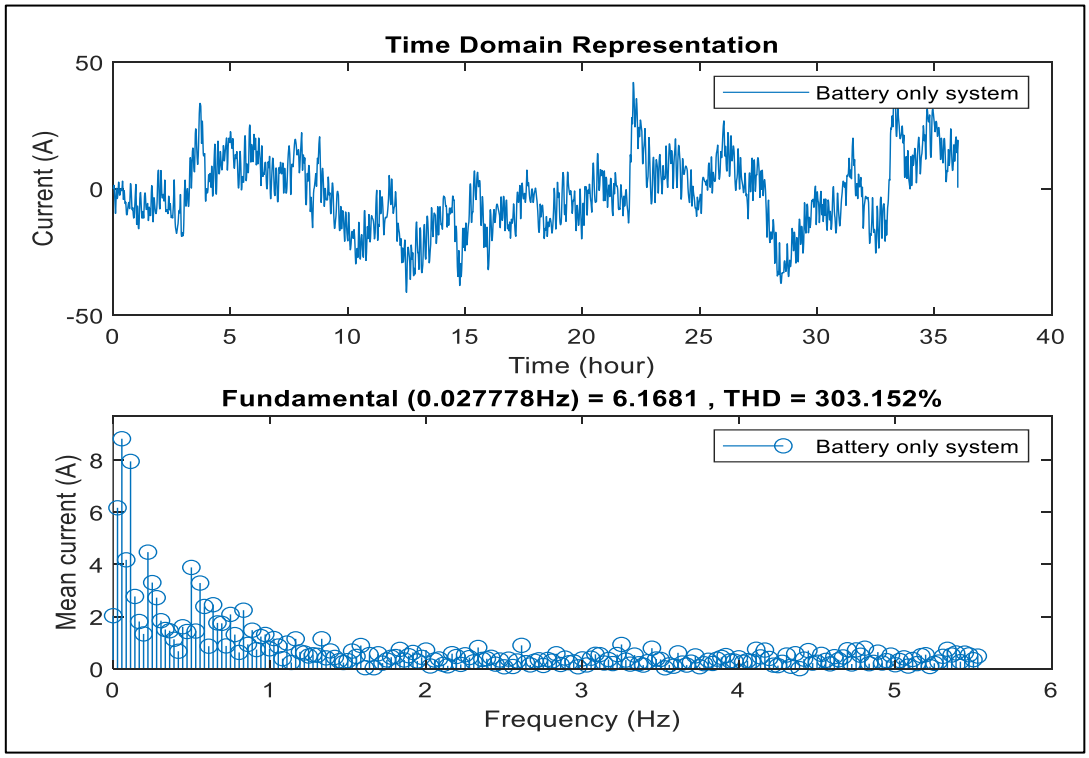


Figure 12 Harmonic on BESS only system

BESS and SMES using constant droop gain

In Figure 13, for BESS and SMES using constant droop gain the Energy storage system is better than when only BESS is used because the current needed by the system was generated by both the BESS and SMES, due to the constant droop gain, the SOC from Figure 14 is almost between 25 to 82%. This shows that charging and discharging rate is significantly reduced. Again, the THD is 290.491%. referring to Figure 15, the harmonics are zero before 2 Hz. The mean current is 5.7108 A the fundamental Harmonics is 0.027778 Hz.

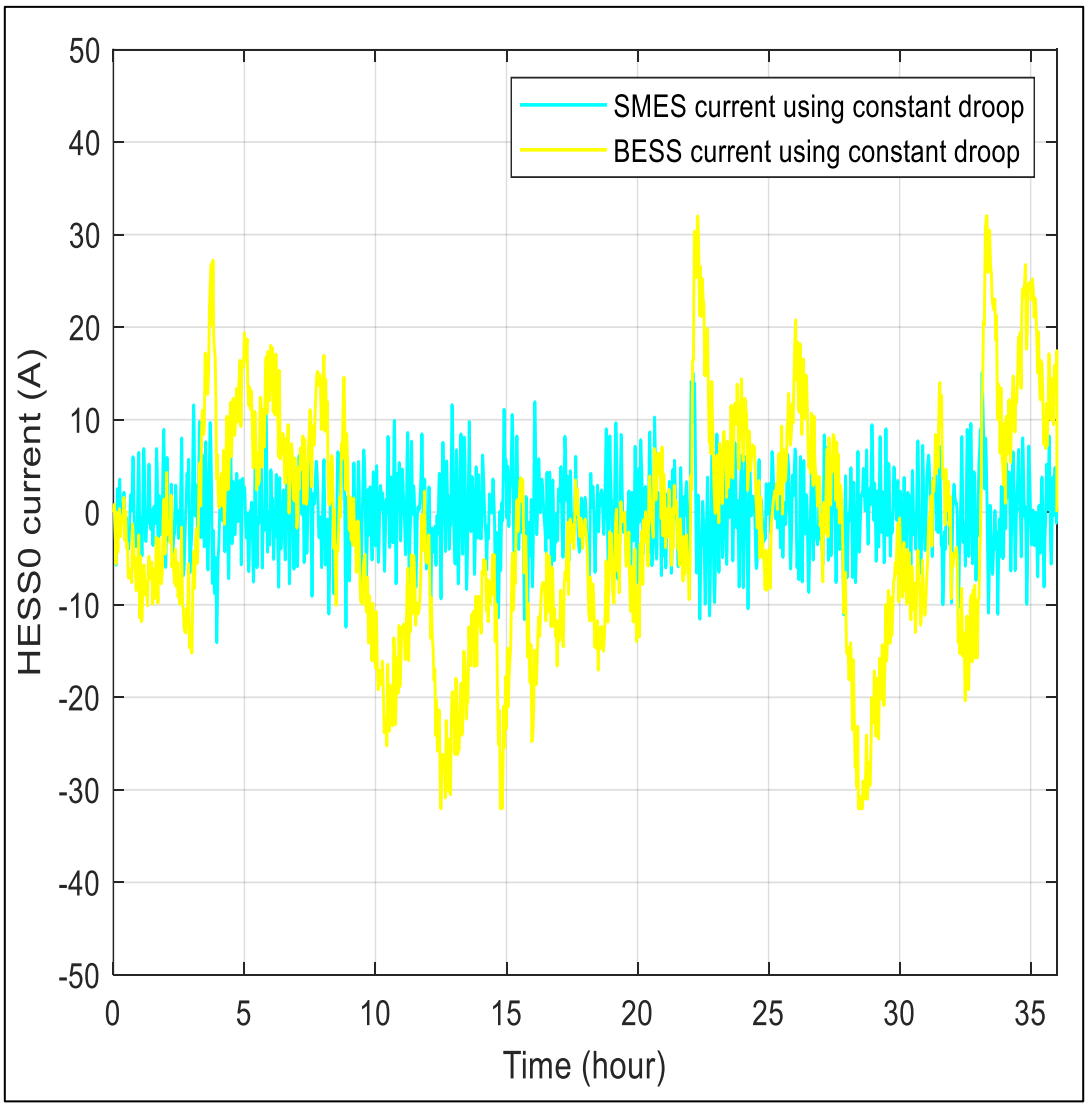


Figure 13 Current variation with time on BESS and SMES using constant droop gain

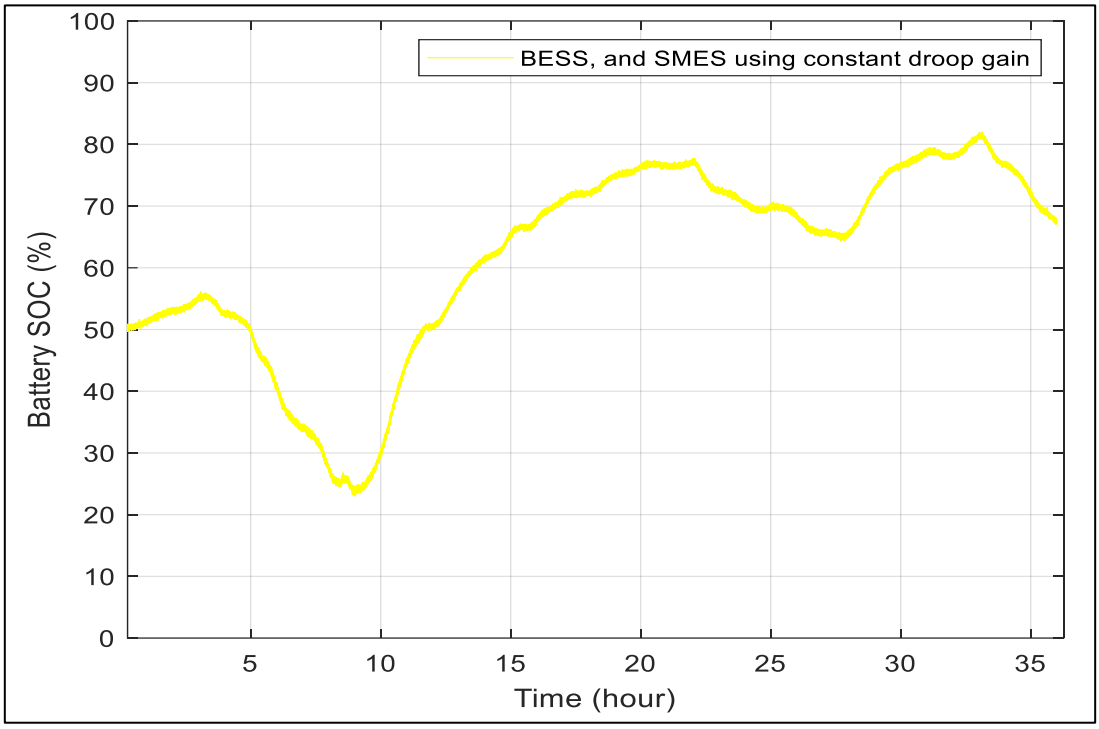


Figure 14 SOC variation with time on BESS and SMES using constant droop gain

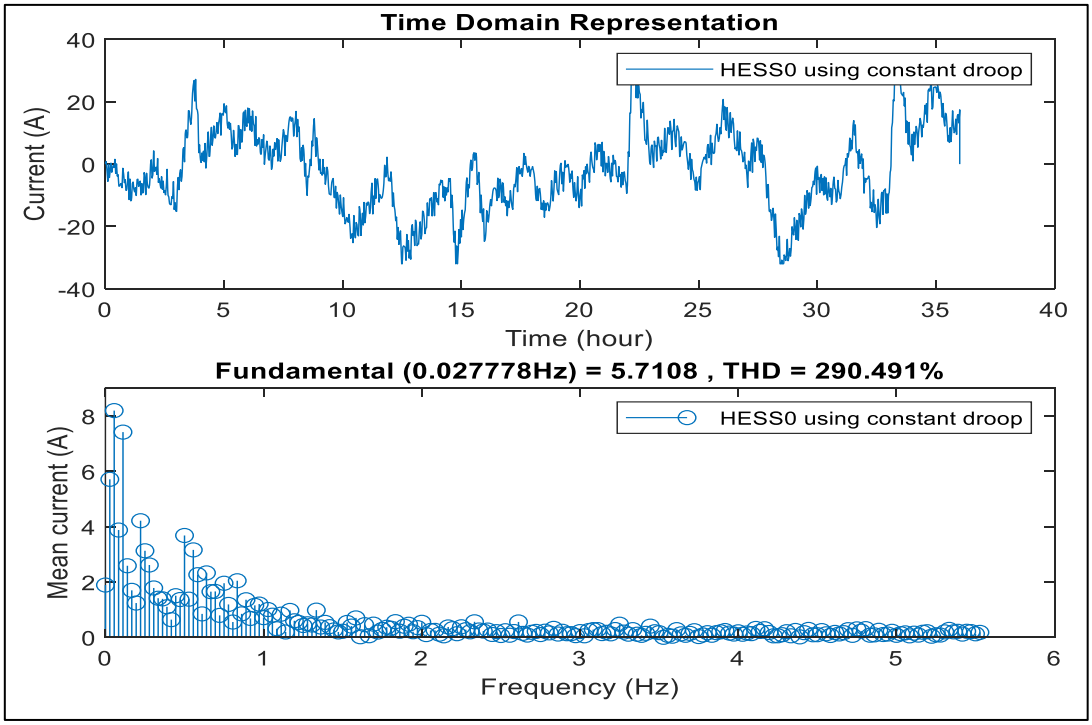


Figure 15 Harmonic on BESS and SMES using constant droop gain

BESS and SMES using Dynamic Droop gain

In Figure 13, for BESS and SMES using Constant Droop gain, the gain does not change. So, when there is need for additional power to be generated so as to stabilize the system frequency, the system will be affected since the gain is fixed meaning that their gain cannot be change and as such any additional power required cannot be met and hence the generated current remains constant. Meanwhile, for Dynamic Droop it means that the gain can be varied to meet any variations on the frequency to produced extra power required because the current needed by the system was generated by both the BESS and SMES dynamically. Due to the Dynamic droop gain, the SOC from Figure 17 is almost between 28 to 80%. This shows that charging and discharging rate is significantly reduced. Again, the THD is 289.987%. referring to Figure 18, the harmonics are non-zero at 1.5 Hz. The mean current is 6.3551 A the fundamental Harmonics is 0.027778 Hz.

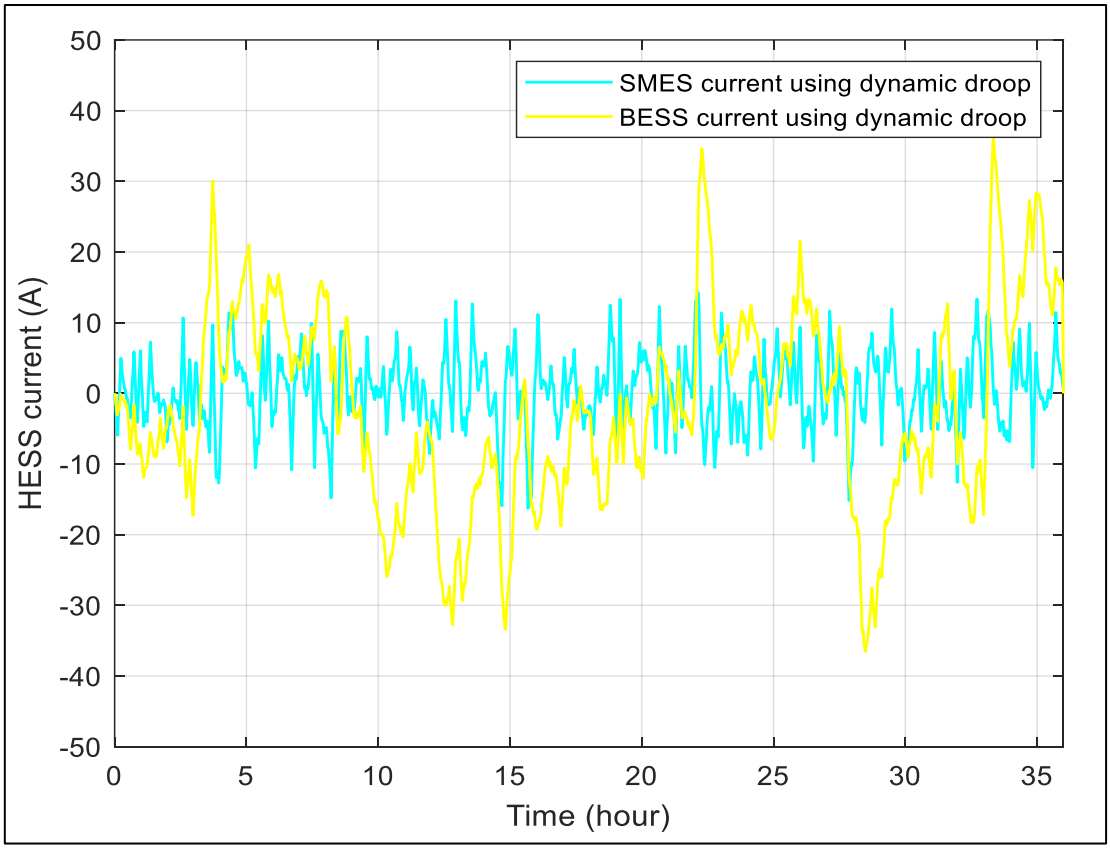


Figure 16 Current variation with time on BESS and SMES using Dynamic Droop gain

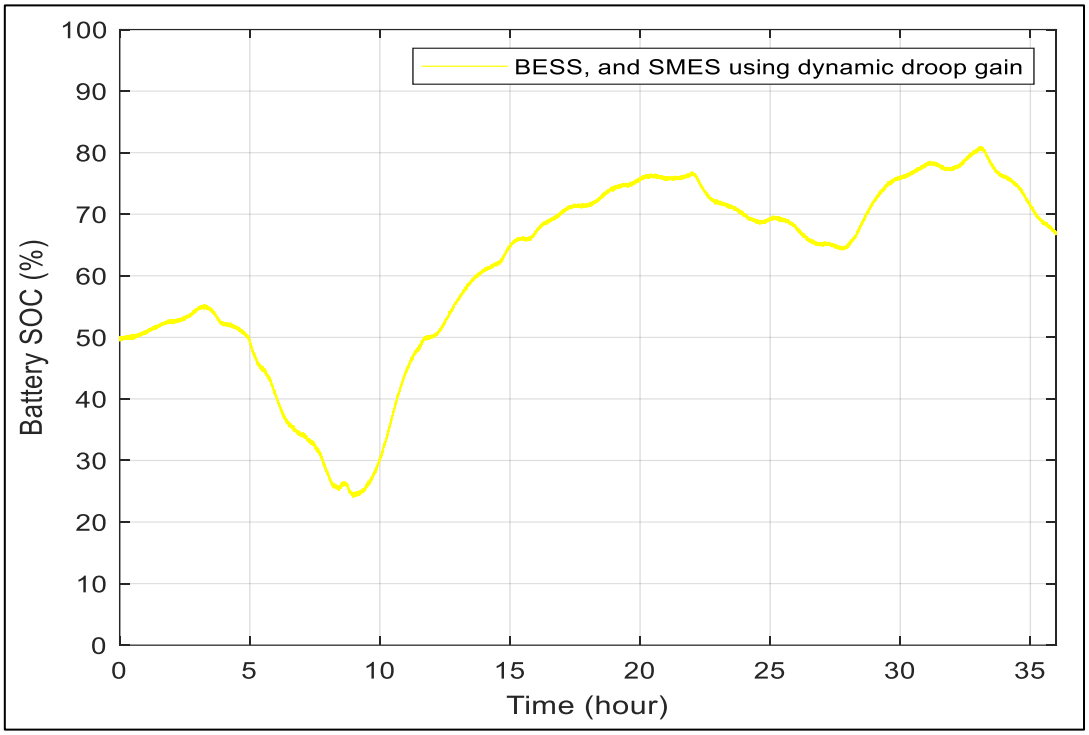


Figure 17 SOC variation with time on BESS and SMES using Dynamic Droop gain

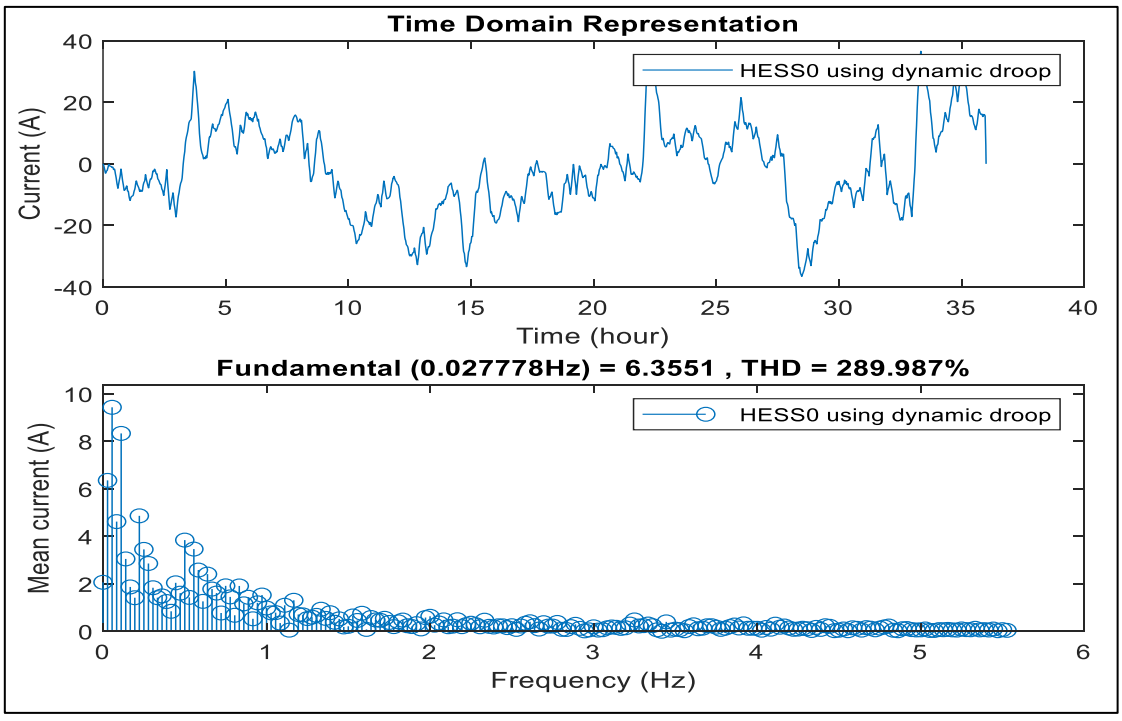


Figure 18 Harmonic on BESS and SMES using Dynamic Droop gain

BESS, SMES and SUPCA using Constant Droop Gain

In Figure 19, for BESS, SMES and SUPCA using constant droop gain the HESS current needed by the system was generated by both the BESS, SMES and SUPCA, due to the constant droop gain, the SOC from Figure 20 is almost between 29 to 72%. This shows that charging and discharging rate is significantly reduced. Hence, an improvement in the life span of the Battery system. Again, the THD is 287.973%. referring to Figure 21 the harmonics are zero before 3 Hz. The mean current is 5.1625 A the fundamental Harmonics is 0.027778 Hz.

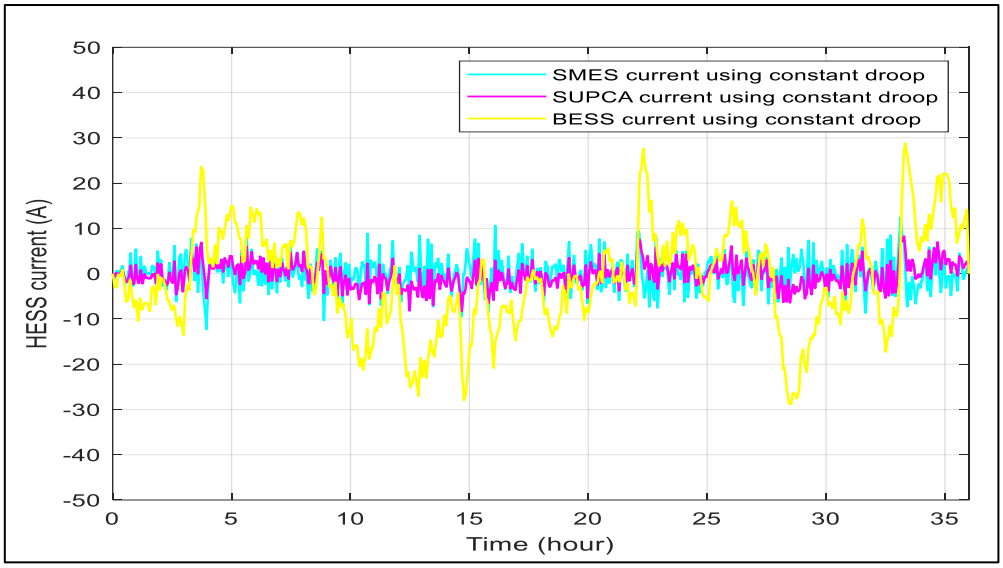


Figure 19 Current variation with time on BESS, SMES and SUPCA using Constant Droop gain

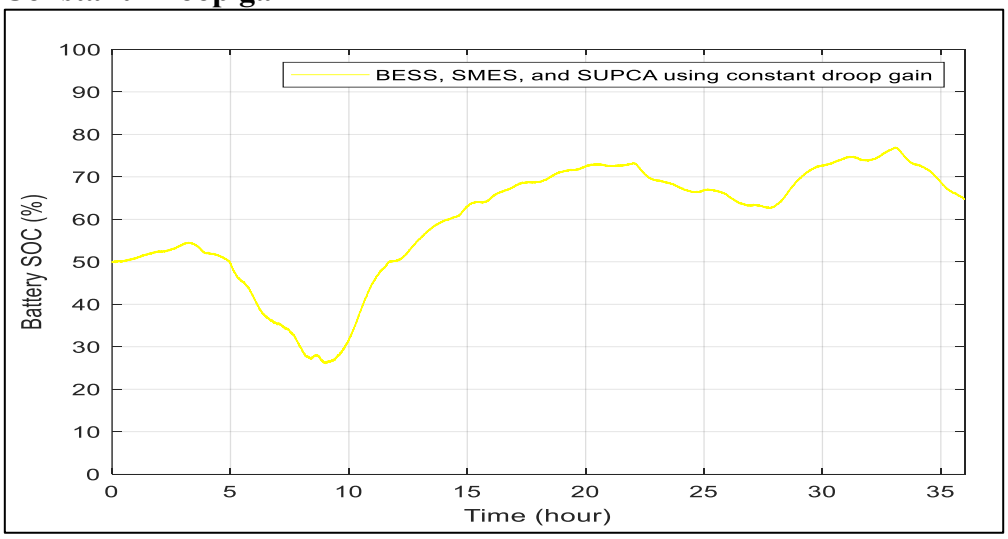


Figure 20. SOC variation with time on BESS, SMES and SUPCA using Constant Droop gain

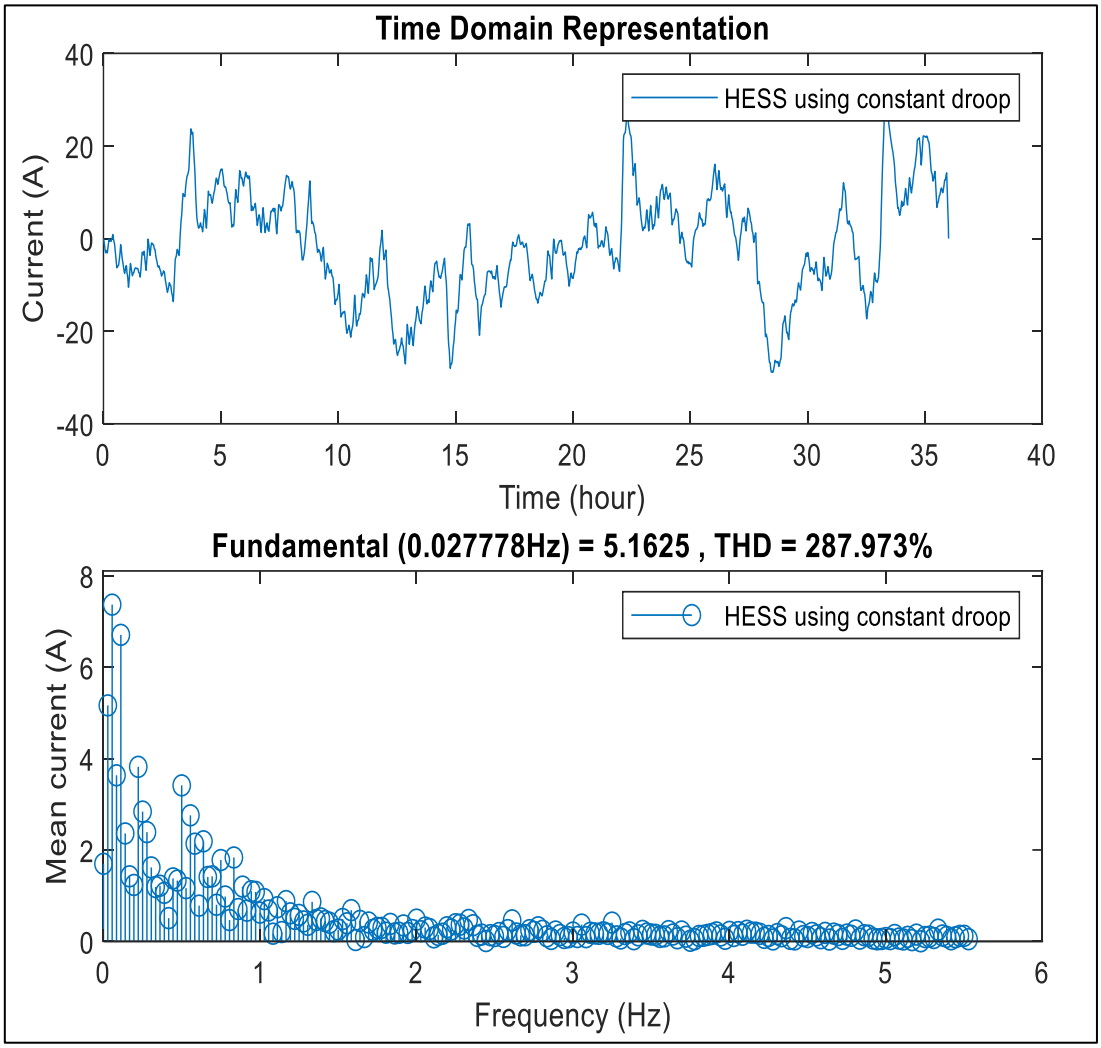


Figure 21, Harmonic on BESS, SMES and SUPCA using Constant Droop gain

BESS, SMES and SUPCA using Dynamic Droop gain

In Figure 19, for BESS, SMES and SUPCA using Constant Droop gain, the current gain does not change. So, when there is need for additional power to be generated so as to stabilize the system frequency, the system will be affected since the gain is fixed meaning that their gain cannot be change and as such any additional power required cannot be met and hence the generated current remains constant. Meanwhile, in Figure 22 for the Dynamic Droop gain, it means that the current gain can be varied to meet any variations on the frequency to produced extra power required because the current needed by the system was generated by both the BESS and SMES dynamically. Due to the Dynamic droop gain, the SOC from Figure 23

is almost between 48 to 74%. This shows that charging and discharging rate is significantly reduced. With the introduction of SUPCA and dynamic droop gain, the whole of the system designed earlier has generally be improved and the rate of charge and discharged has equally be improved, hence, an improvement on the life span of the BESS. From Figure 24 it is clear that current signal is pure without distortions. This is due to the application of the SUPCA on the grid to provide the needed reactive power to improve power factor since the SMES in an inductive device that consumes the reactive power. To offset the effective of the reactive power, a balance system with capacitive characteristic needed to be introduce and hence, the SUPCA to balance the system. Again, the THD is 277.258%. referring to Figure 25, the harmonics are non-zero at 5 Hz. The mean current is 6.4095 A the fundamental Harmonics is 0.027778 Hz.

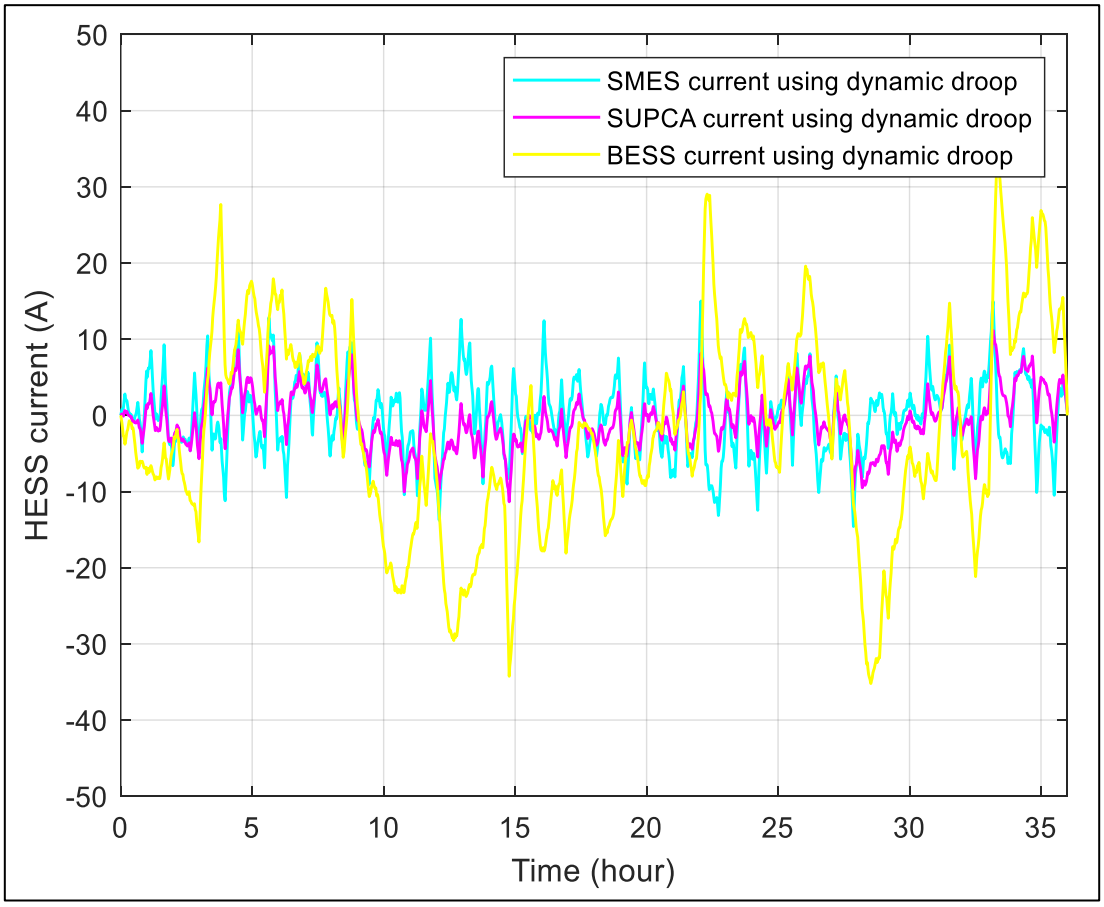


Figure 22 SOC variation with time on BESS, SMES and SUPCA using Dynamic Droop gain

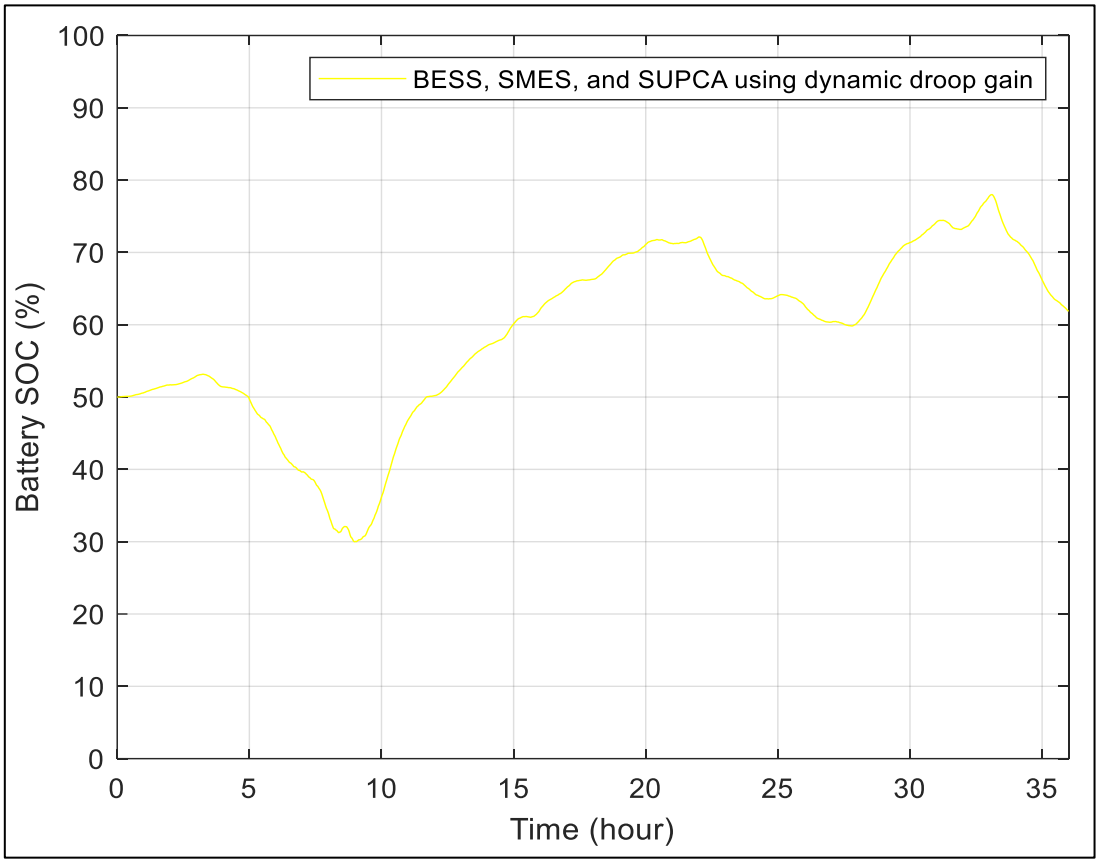
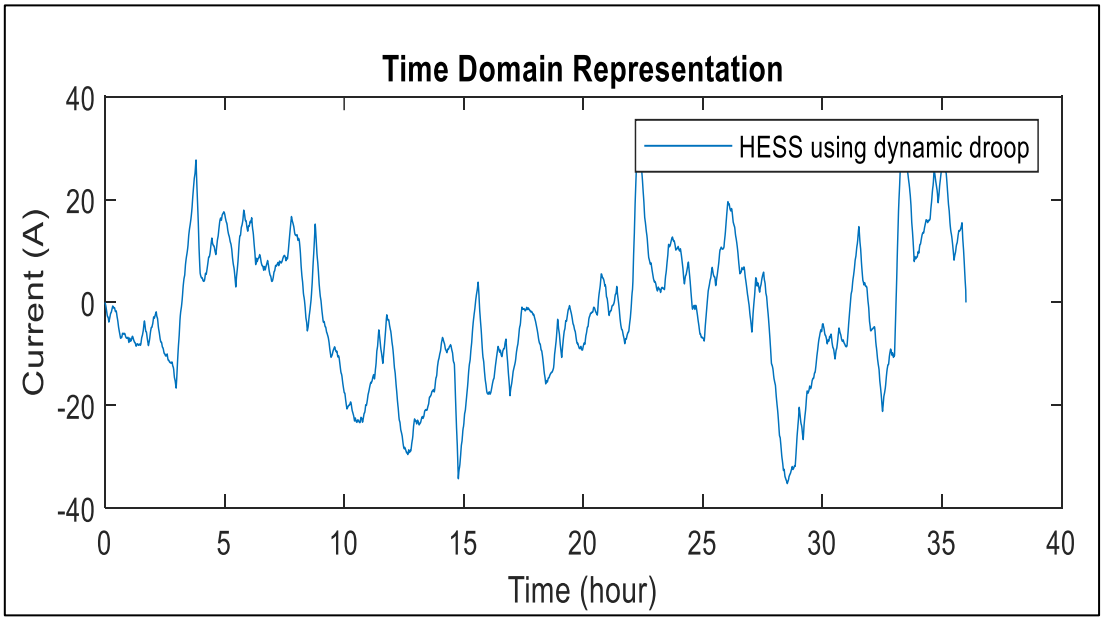


Figure 23 SOC variation with time on BESS, SMES and SUPCA using Dynamic Droop gain



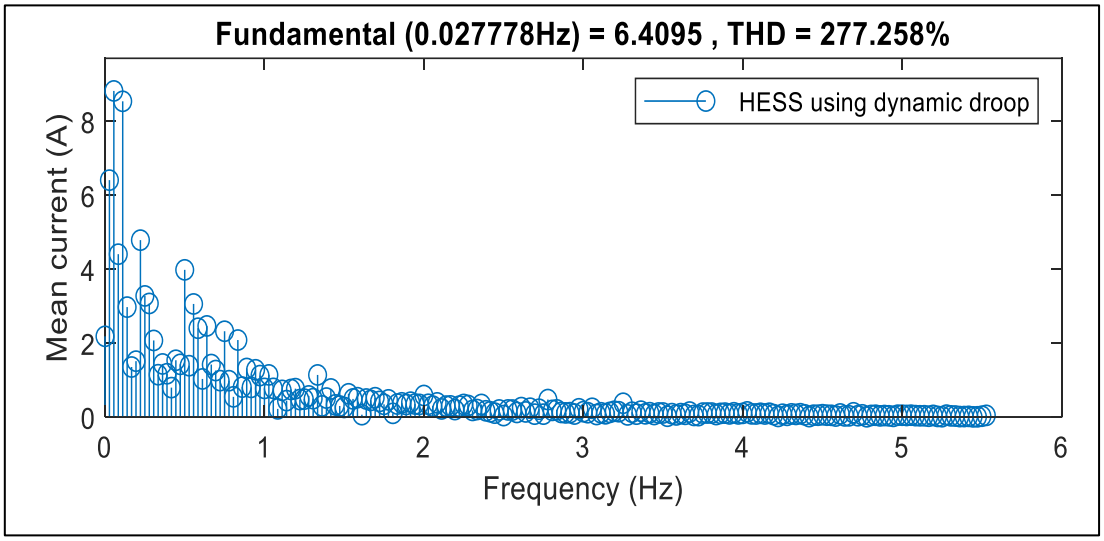


Figure 24 Harmonic on BESS, SMES and SUPCA using Dynamic Droop gain

Frequency and Voltage Control

The impact of this proposed SUPCA/SMES/BESS as a HESS, operating as frequency stabilizers and/or control in MG system are revealed in Figure 25 The voltage changes or alteration are expressed in Figure 26 and random alteration of load are expressed in Figure 27. These are used in six different conditions:

- Microgrid system that has no system of energy storage.
- Microgrid that function with only BESS.
- Microgrid that has SMES/BESS as a HESS and also uses CDG.
- Microgrid that has SMES/BESS as a HESS and also uses DDG.
- Microgrid that has SUPCA/SMES/BESS as a HESS and also uses CDG.
- Microgrid with the SUPCA/SMES/BESS as a HESS and also used new DDG.

Figure 25 represent simulation results for frequency fluctuations for proposed six conditions. It is clear that frequency vacillations in normal MG that one with no energy storages are highly severe compare to those in other 5 conditions. Also, this frequency alterations are notable reduced in microgrid that has HESS compare to the one that has BOS. Peak or maximum fluctuation values in MGs that has HESSs are equally small compare other 4 arrangement. The MG systems that have HESSs along with CDG and DDG showed better changing power recompence capacity

which implied that this novel technique performs with good frequency control similar to formal one. But, this new droop-control showed certain benefits over normal droop-control in battery, SMES and SUPCA performances which is shown in sub-sections 4.7

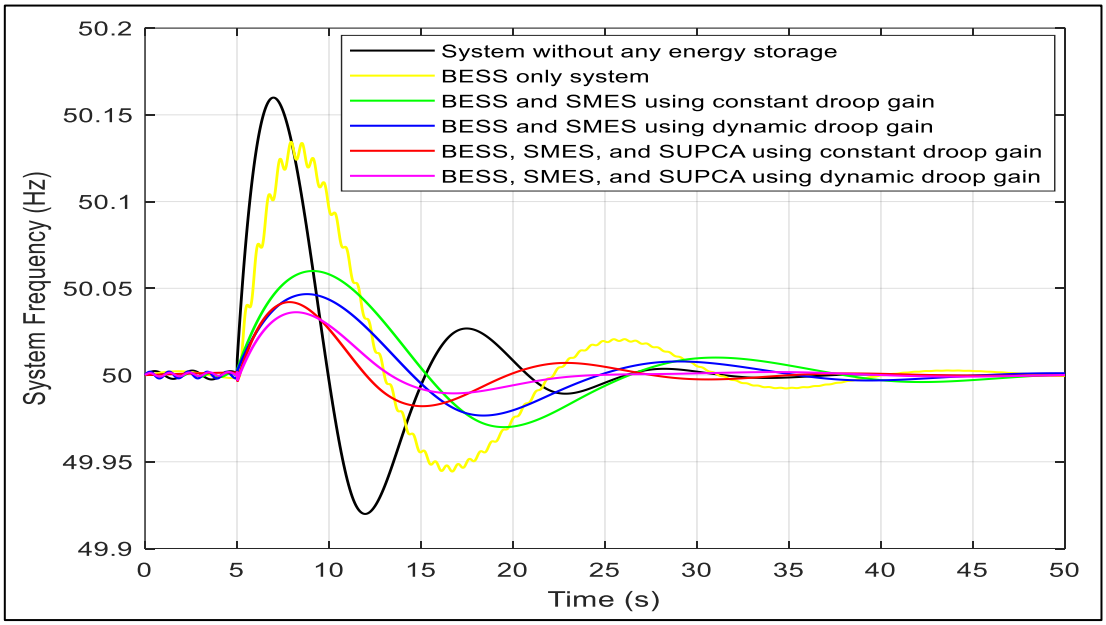


Figure 25 Frequency Oscillations in the five cases.

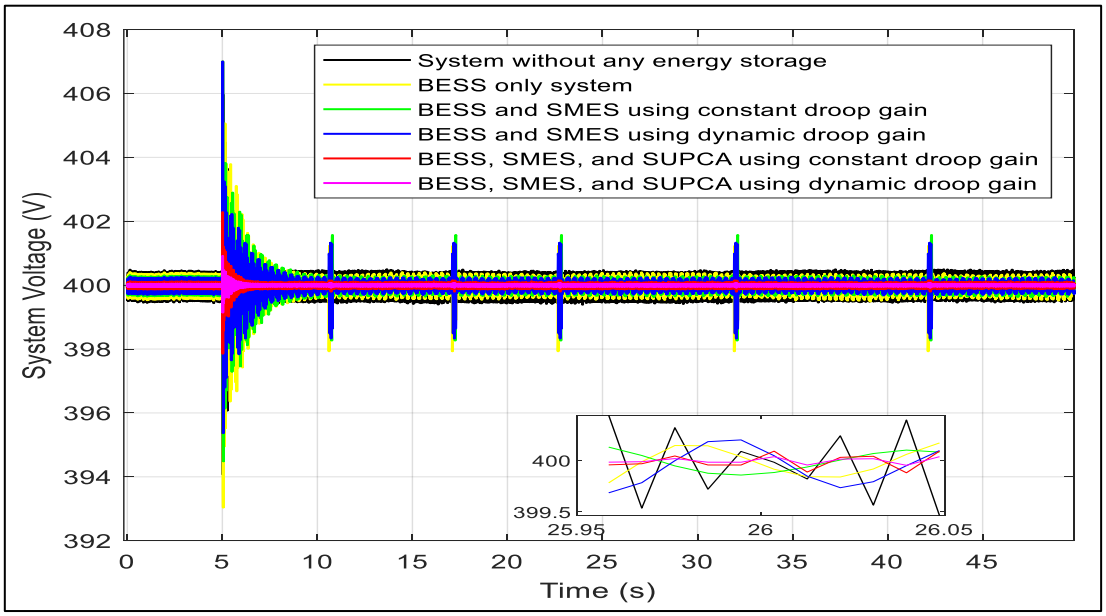


Figure 26 Voltage Variations the five cases.

Figure 26 represent simulation outcome of voltage changes and alteration in proposed six conditions. It became that voltage alteration in normal MG that with no energy storages are more serious compare to those in other 5 conditions. Also, Voltage alteration are appreciably reduced in microgrid that has HESS than that with BOS. Peak or maximum oscillation in MGs that has HESSs are equally small compare to other 4 arrangement. MG systems that have HESSs with CDG and DDG have good alteration power decompensation capacity which imply that this novel technique performs better voltage control similar to previous one. But, this new droop-control showed certain benefits over normal droop-control in battery, SMES and SUPCA performances.

SUPCA, SMES and BESS Performance

The SUPCA/SMES/BESS performance in MG; Figure 22 revealed the BESS/SMES/SUPCA charge/discharge currents along with battery SOC in 35h in five different conditions based on similar situation of system power. Battery currents in HESS expressed in Figure 22, SUPCA/SMES/BESS currents with DDG and SUPCA/SMES/BESS currents with CDG, undergo little polarity showed and high-frequency changes compare to that with BOS as represented in Fig. 4.9. also, battery using DDC delivers smoother current compare to one that use formal control. Also, peak current values for local battery in DDC device are smaller compare to that one in the other two conditions. SUPCA and SMES are controlled and respond in preferred way to high-change in frequency which could be noticed from blue and pink line expressed in Figure 22; SUPCA and SMES current are 0acillating in higher frequency compare to what is observed in battery. Consequently, as expressed in Figure 27 i.e., battery SOC for BOS, battery SOC for HESS with CDG and battery SOC for HESS with DDG, batteries showed varying SOC curves in three situations. As revealed in zoom-in windows, battery SOC in BOS unit has most serious frequent polarity setbacks which imply that this battery undergoes most charge/discharge oscillation cycles in BOS. Though, there are notable and little variations in SOC curve expressed in Figure 27 battery SOC for HESS with DDG, the situation is better compared to BOS unit. HESS with DDC device has most curving battery SOC. Also, peak-values in HESS are small compare that in BOS unit. As summary for Figure 27, first, batteries in HESSs units have appreciably better conditions compare to what is noticed in BOS and the DDC device showed better performance compared to CDC. Second, SUPCA/SMES could enhance the battery lifespan by protecting their battery from frequent charging and discharging cyclic pattern and high battery currents rate.

Battery State-of-Charge (SOC)

In Figure 27, we introduced SOC lines for these five conditions considered. The SOC profile of their battery based on these five different conditions and SOC profiles serve as input to model of battery lifetime. From Figure 27, is shown the five conditions carried out on this project, i.e., (a) MG that function with only battery (b) MG that has SMES/BESS as a HESS and also uses CDG, improved effect on life cycle of Battery than the one with Battery only. (c) MG that has SMES/BESS as a HESS and also uses DDG (d) MG that has SUPCA/SMES/BESS as a HESS and also uses CDG and (e) MG with the SUPCA/SMES/BESS as a HESS and also used new DDG. From Figure 27, the yellow color curve shows that condition (a) has the worst effect on the life cycle of the Battery SOC, the color Green shows the condition (b) whose SOC is better than that of (a). In the SOC of (c) condition, represented in blue color, its SOC is far better than that of (a) &(b). however, the condition (d) SOC represented in red shows that it has a much better SOC that (a), (b) and (c). Finally, Condition (e) showing the introduction of SUPCA and DDG control mechanism shows a much better SOC than the other four conditions and hence the modified system is far better in improving the life cycle of the battery as a result of better SOC which in turn defines the life span of the Battery.

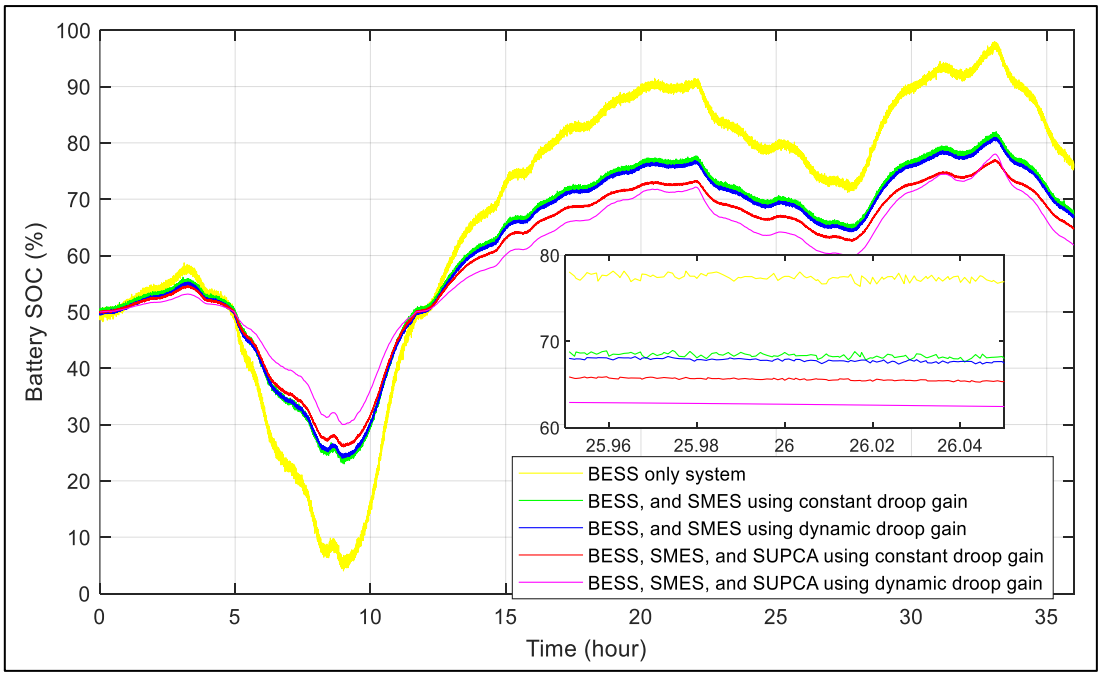


Figure 28 State of Charge in the five cases

Conclusions and Recommendations

Based on the analysis and the results generated it was discovered that introduction of SUPCA as a component in HESS showed better results in its PFC in terms of frequency control, voltage stabilization and improved SOC; hence, better life span of the BESS. Further investigation on the application of CDG and the DDG was conducted. In the CDG, particle swamp optimizer was used to optimized the constant droop gain of the system, while in the DDG, a new improved DDG was developed using iteration method in which it tries to predict future frequency oscillation and voltage deviation by the using previous values of frequency and voltage Oscillation/deviations respectively. It compares the previous frequency/voltage deviation droop control gain and predict the future voltage/frequency droop control gain. This means that when the frequency changes, the system will use the result gutting before to get a newer result or better result. The developed system is a dynamic droop controller that uses numerical approximations based on the conventional iteration method.

Conclusion

Based on the findings of this study, it was concluded that;

- **a.** The developed model presents a novel PFC method by combining SUPCA/SMES/BESS as a HESS to separate microgrid system.
- **b.** A new technique for power sharing was used which was able to control and handle power between SUPCA/SMES and BESS, and control charging discharging rates of these three systems of energy storage by using the benefits contained in dynamic-droop gains.
- **c.** A microgrid system developed with MATLAB/SIMULINK to confirm the performance and efficiency of PFC and voltage control using HESS. showed better stability in term of frequency variation compare to BOS.
- **d.** Compared with formal DDC device from Li. et al, this new technique was able to regulate droop-gains for SUPCA/SMES and BESS, hence helping the system for energy storage to give optimum power output within several power conditions.

e. Finally, in the analysis carried out on the battery lifespan, the battery in the new control system was better secured from short-time frequent unexpected currents, hence confirmed to have better battery lifespan.

Recommendations

Based on these findings and conclusions from this study, it was therefore recommended that SUPCA should be integrated into HESS system in order to; (i) Improve the energy storage capability of the HESS system, (ii) To develop a better dynamic and static voltage and frequency stability during power and loan fluctuations. (iii) Improve the SOC of the battery and in turn improve the lifespan of the BESS. However, lower harmonic currents are still present in the system, and as such future researchers can consider the development of an active power filters to further minimize the harmonic current in the system.

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