New droop-based control of parallel voltage source inverters in isolated microgrid

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ABSTRACT

Microgrids, featuring distributed generators like solar energy and hybrid energy storage systems, represent a significant step in addressing challenges related to the greenhouse effect and outdated transmission infrastructures. The operation and control of islanded microgrids, particularly in terms of grid voltage and frequency, rely on the synchronization of multiple parallel inverters connected to the distributed generators. However, to determine the necessary grid parameters for effective control, the presence of circulating currents from unbalanced grid voltages arises as a challenge. This situation necessitates the development of a new approach to achieve phase angle locking for grid synchronization, with the aim of maintaining the voltage within acceptable limits in islanded microgrids. This objective is realized through the creation of a microgrid network model, design of an adaptive filter, utilizing the double second-order generalized integrator–phase-locked loop (DSOGI-PLL), for dynamic voltage transformation. The design is evaluated by simulation using MATLAB/Simulink. The primary goal is to investigate the DSOGI-PLL-based droop control and compare its performance with the conventional synchronous reference frame–phase-locked loop (SRF-PLL) control approach. Notably, the DSOGI-PLL successfully eliminates the ripples in phase angle estimation, consequently enhancing the quality of voltage output in the microgrid.

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1. INTRODUCTION

The power supply challenges in developing countries, along with the shift towards renewable energy sources, have spurred a demand for effective solutions within the energy sector [1]. This necessity has prompted restructuring efforts in countries such as Nigeria, albeit with limited or no substantial improvements [2]. These issues encompass a range of problems, including insufficient generating capacity, outdated transmission infrastructure, and unregulated distribution networks. One potential solution involves the implementation of low-voltage, isolated microgrids, which have demonstrated considerable potential in meeting the electricity requirements of local communities [3]. Such microgrids empower communities to self-generate electricity using renewable energy sources (RES) that are both sustainable and pose minimal health risks to their inhabitants.

In the pursuit of global development and technological advancement, the harnessing and conversion of renewable energy into usable forms, particularly electrical energy, play a pivotal role [4]. Microgrid technology, therefore, presents an avenue for energy generation that accommodates renewable sources, incorporates energy storage systems, enables effective management, and provides sophisticated control mechanisms [5]. Renewable energy sources, such as solar and wind energy, are inherently sustainable and offer a lucrative alternative to conventional energy sources, while also mitigating environmental pollution [6]. The intermittency of renewable energy sources has seemingly become unnoticeable because of the technology of energy storage systems (ESS) [7]. Examples of ESS include flywheel, superconducting magnets, to match up power demand and supply, the control of the output from distributed generators which includes renewable sources and ESS is the concern of electrical engineers [8]. The synchronization of parallel voltage source inverters, connected to multiple distributed generations such as renewable energy sources and hybrid energy storage systems [9], has been a subject of concern for microgrids [10], especially AC islanded microgrids.

Diverse control strategies are proposed from literature ranging from communication-based to decentralized control methods; most of these strategies can be found in [11]. The hierarchical method uses the primary, secondary and tertiary approach creating means for level-by-level control. The level by level control provides strategies for each unit instead of a master-slave control which has the tendency to shut down the system when there is fault in one level [12]. In grid-connected, the grid monitors the voltage and frequency, but for the stand-alone, the reactive and active power is balanced with the energy storage and the load demand [13]. The voltage and frequency control of a microgrid is of high importance, creating a balance between the distributed generators. This is to achieve power sharing, reduce instabilities, and maintain voltage. Controllers have been designed to achieve voltage regulation with the use of droop control. Droop control is a well-tested decentralized, hierarchical, closed loop control for power sharing in a microgrid [14].

Table 1 compares the effect of different phase locked loop systems. Hui *et al.* [15] used an hybrid filter, a combination of SOGI and a moving average filter to block fundamental frequency negative sequence component and other harmonics achieving disturbance rejection and faster transient response of the phase locked loop (PLL). Hao *et al.* [16] carried out an investigation to remove higher order harmonics for accurate evaluation of the grid phase angle using double second-order generalized integrator (DSOGI) for unbalances represented by a single-phase load. The signals were divided into direct current (DC) components which represents the fundamental frequency, positive sequence and quadrature phase signal. To avoid the converters losing their stability, the effect of the use of PLL in microgrid operation which has multiple distributed generators and converters needs to be looked into. DSOGI-PLL is adapted, as compared to the common synchronous reference frame–PLL (SRF-PLL), to remove the harmonics by separating the complex part of the equation from the fundamental voltage component, generating a positive sequence representation. Table 1 compares the characteristics of different types of PLL, '*Yes*' means an advantage and '*No*' refers to a disadvantage.

Table 1. Performances of different types of PLL

Types of PLL/Signal characteristics	SRF-PLL (DD)	DSOGI	Single-phase EPLL	Adaptive filter	Author
Unbalanced voltage	No	Yes	Yes	---------	[17]
High low-order harmonic distortion	No	Yes	Yes	---------	[17]
Phase jump	No	Yes	---------	No	[15]
Frequency step	No	Yes	---------	Yes	[15]
Reference frame	Alpha-beta	Alpha-beta	abc	Alpha-beta	
DC Offset rejection	No	No	---------	Yes	[15]

In situations of unbalance loading in a microgrid, the connected inverters generate unbalance currents, which have large negative sequence currents. One of the major causes of unbalanced currents in a distribution network includes single-phase loads, especially residential and commercial loads, which are the most common in islanded microgrids. Unbalance loading condition increases circulating currents in the operation of multiple inverters. Unbalance loading condition happens in a network when there are unequal currents in a three phase network [18]. One of the effects of circulating current is unbalance voltages which affects the synchronization of multiple voltage source inverters because of phase angle measurement errors [19]. The inaccuracy of the phase angle hinders the synchronization of voltage source converters to the grid, leading to inaccurate load sharing within the microgrid [20]. Although the control of microgrids has been widely studied using predictive control [21] artificial intelligence [22], iterative control, and decentralized; droop control still remains the most viable method without communication losses [23]. However, these methods have not been able to adequately resolve the instability of phase locked loops especially in the case of unbalanced voltages, wherein the magnitudes of the three-phase grid voltages are not the same [24], [16].

The use of PLL was integrated in a single-phase inverter system [25] to improve the system's synchronization. The noticeable challenge with the use of SRF-PLL is in the presence of unbalance loading system, which allows for error in the voltage transformation of the phase locked system. Table 2 shows the state of art methods in microgrid control and their shortcomings.

Table 2. Review of shortcomings in microgrid operation and control

Challenge microgrid	Microgrid operation	Method	Results and advantages	Short-comings	Reference
Control for parallel DG inverters	Voltage and Current control for three-phase inverters	Synchronous reference frame (SRF) for phase locked system	Power sharing between DG inverters in an islanded microgrid for unequal DG rating	Did not consider circulating currents and unbalanced voltage	[26]
PLL Synchronization Stability	Improvement of synchronization stability of weak grid	Comparative evaluation of the synchronization stability of PLLs	Improved PLL with PI control	Used for grid connected converters, not islanded microgrid without droop control	[19]
Power converters tied to fractional frequency transmission system	No microgrid but frequency transmission system	DSOGI-PLL varying voltage amplitude	Design of DSOGI based PLL to achieve satisfactory dynamic and steady state	Not with the use of voltage source inverters	[27]
Output voltage and current control	Alleviating power quality problems	Uses DSOGI-PLL to improve power quality of a single inverter connected to solar	Elicits the fundamental component of highly nonlinear load current	Parallel inverter connections not considered	[28]

In this paper, the use of a modified phase-locked-system is introduced as a filter to help improve the measurement of the system's parameters for microgrid control in case of unbalance loading. The paper designed the use of a DSOGI-PLL based droop control for a hybrid microgrid to compare the effect of SRF-PLL and DSOGI-PLL in eradicating system parameters error in frequency and voltage control. To achieve this objective, hybrid energy storage system (HESS) is connected to a DC-AC converter to form a grid by droop control, and another DC-AC converter from a solar generator is connected in parallel, which helps to balance the grid's stability and improve the output grid voltage and current.

Figure 1 illustrates a three-phase microgrid configuration featuring two parallel-connected voltage source inverters. The purpose of this system is to explore the functionality of the DSOGI-PLL in maintaining synchronization with the grid, particularly under conditions of unbalanced grid loading. The setup allows for a detailed investigation into how the DSOGI-PLL responds to variations in grid conditions and loads.

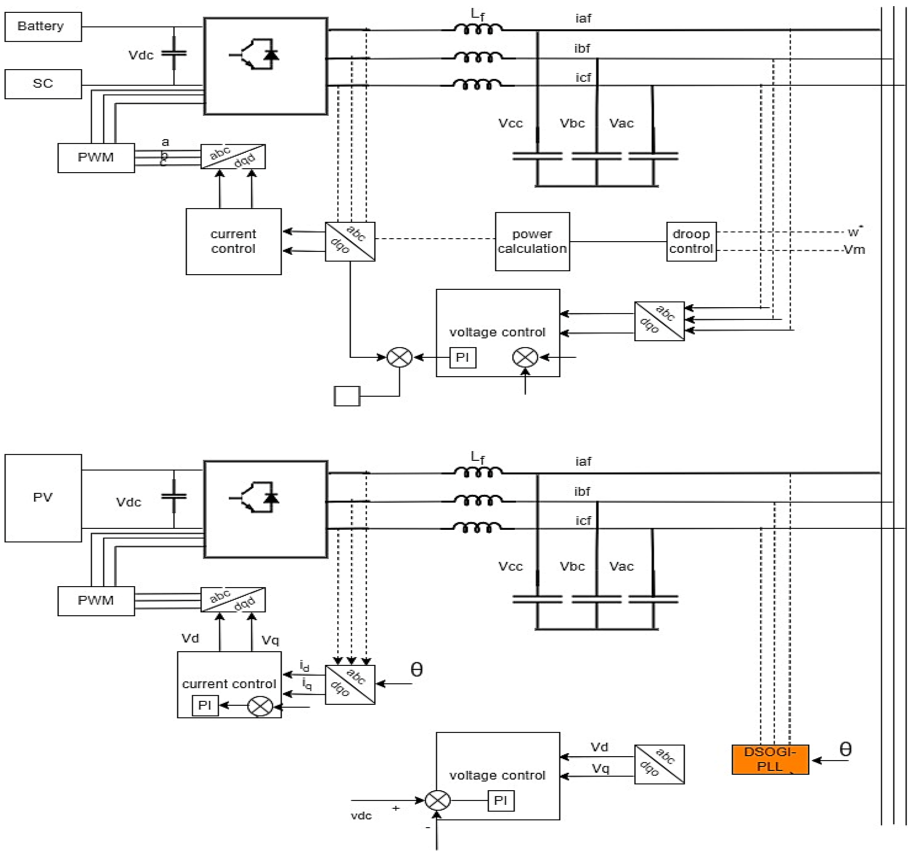


Figure 1. One-line diagram of the microgrid and its component

2. METHOD FOR PROPOSED DSOGI-BASED DROOP CONTROL

Voltage source inverters are known to convert DC voltage to AC voltage and are connected in parallel to reduce voltage stress on switches [29]. With the increase in the use of renewable sources is the dependence on power electronic converters. For the purpose of microgrid control with multiple generating sources, the HESS is connected to a bi-directional converter, and the photovoltaic is connected to a DC boost converter. Figure 2 is a step-by-step approach for the microgrid control with multiple parallel inverters.

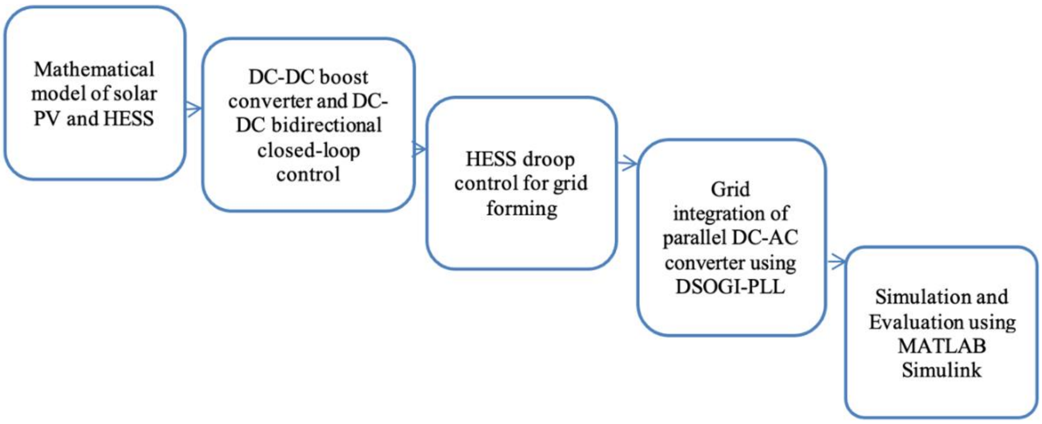


Figure 2. Methodological framework for the research

2.1. Mathematical model of photovoltaic a HESS converters

The photovoltaic system was accurately represented using (1)-(2), while the HESS was characterized using (3)-(4). To ensure synchronization between the battery output voltage (V_{ob}) and the supercapacitor output voltage (V_{osc}), the reference voltage for HESS was derived employing Kirchhoff's voltage law, as outlined in (3) and (4). Definitions for all symbols involved in the equations were appropriately provided, ensuring clarity and precision in the model description. This comprehensive approach enables a thorough understanding of the system's behavior and interactions between its components.

$$I = I_{PV} - I_O \left(\exp\left(\frac{V+R_S I}{aV_T}\right) - 1\right) - \frac{V+R_S I}{N_P R_P} \tag{1}$$

where I_{PV} is photovoltaic current, I_d is diode current, I_O is saturated reverse current, and a is ideal diode constant.

$$V_{T=}N_S kTq^{-1} \tag{2}$$

where V_T: thermal voltage, N_S: number of series cell, N_P: number of series cell, q: electron charge, k: Boltzmann constant, T: temperature of p-n junction, R_S: series equivalent resistance of solar panels, and R_P: parallel equivalent solar resistance of the panels.

$$V_{b.dc} = V_{ref} - R_b . i_{b.dc} = V_{ob} \tag{3}$$

$$V_{sc.dc} = V_{ref} - \frac{1}{sC_{sc}} . i_{sc.dc} = V_{osc} \tag{4}$$

where $V_{b.dc}$: battery DC output voltage, $V_{sc.dc}$: supercapacitor DC output voltage, V_{ob}: battery output voltage, and V_{osc}: supercapacitor output voltage.

2.2. Synchronization and voltage control of parallel converters

The reliability of the microgrid depends on the operational control of the different components used in the microgrid, which is largely dependent on the power electronic converters (PEC). For controllability and the stability study of the system, each component of the microgrid is mathematically modelled and controlled. The proposed control algorithm is also shown in Figure 3, which shows the steps taken for the proposed control and operation of the microgrid layout.

The design of a new control strategy involves the precise modeling of each distributed generator (DG) and the associated PEC. Subsequently, a specific control method is designed for each of these components. These control methods play a crucial role in establishing the relationship between the microgrid components and their interaction with the main power grid. Figure 4 provides a visual representation of the operational modes required to implement the control strategy, encompassing energy management for various DGs, power control, current regulation, and voltage control loops. To ensure a consistent power supply where the load is connected, two parallel DC-AC converters are employed. The control method comprises several key elements, including voltage measurement, phase angle estimation, voltage transformation, and the implementation of droop control for both inner and outer loop regulation.

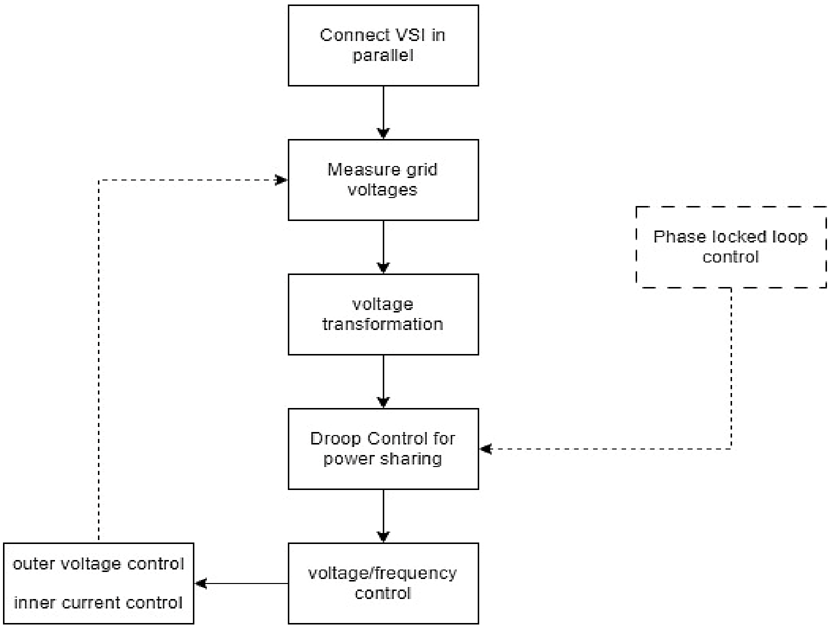


Figure 3. Control flow-chart for stand-alone microgrid

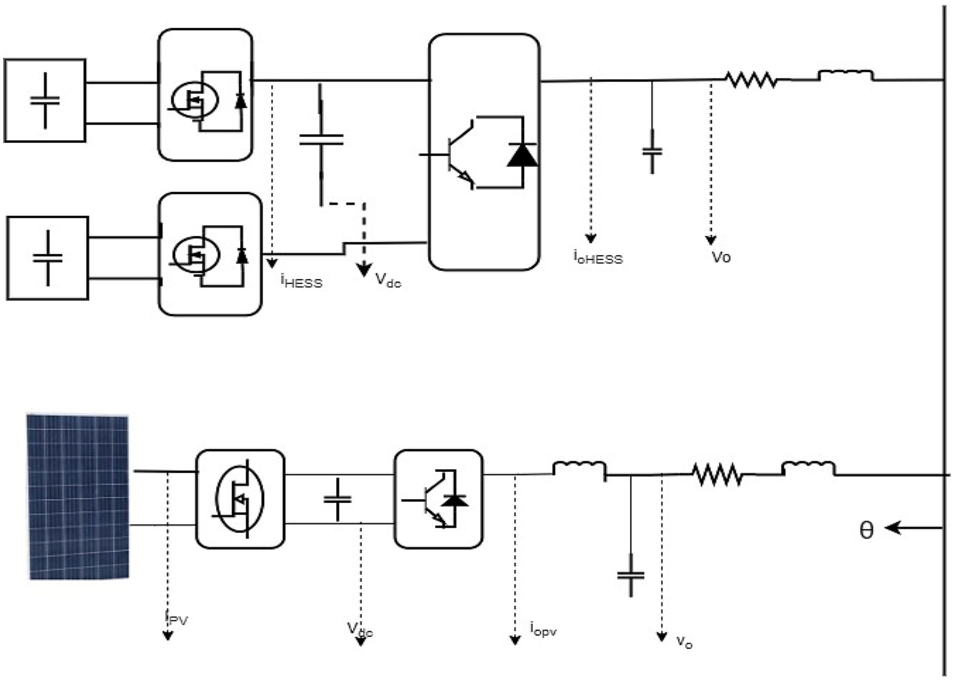


Figure 4. One-line control diagram of the islanded microgrid, control schematic for two parallel inverters

The reliability of a microgrid depends on the control mechanism of the power electronic converters which are a DC-DC boost converter connected to the PV, DC bi-directional converters used for the hybrid energy storage systems and the different DC-AC converters which are either grid-forming or grid-supporting. DC-DC boost converter is used for voltage transformation of the output from the solar panel in connection with a maximum power point tracking (MPPT) technique. A bi-directional converter is connected to each of the energy storage systems to enable charging and discharging when necessary. An inverter (DC-AC) is then used to interconnect to the grid to enable power sharing and for grid synchronization. The reference voltage is derived using Kirchhoff's voltage law so as to have the battery output voltage, V_{ob} equal with the supercapacitor output voltage, V_{osc} as given in (5)-(6).

$$V_{b.dc} = V_{ref} - R_b . i_{b.dc} = V_{ob} \tag{5}$$

$$V_{sc.dc} = V_{ref} - \frac{1}{sC_{sc}} . i_{sc.dc} = V_{osc} \tag{6}$$

where $V_{b.dc}$: battery DC output voltage, $V_{sc.dc}$: supercapacitor DC output voltage, V_{ob}: battery output voltage, and V_{osc}: supercapacitor output voltage.

For two parallel converters, the active and reactive power are shared as in (7)-(11).

$$m_1 P_{PV} = m_2 P_{HESS} \tag{7}$$

$$n_1 Q_{PV} = n_2 Q_{HESS} + V_2 - V_1 \tag{8}$$

where P_{PV}: photovoltaic power output and P_{HESS}: HESS power output. The angular voltage and frequency from the droop equations are used to generate sinusoidal voltage reference for each converter.

$$V_{ref} = V_i sin(\omega_i t) \tag{9}$$

The impedance of each of the converters connected to the energy source is considered in introducing a closed loop control system so as to reduce the effects of circulating currents and harmonics caused by unbalance voltages and sudden load changes.

$$V_{oPV} = V_{ref} - Z_{PV} . i_{oPV} \tag{10}$$

$$V_{oHESS} = V_{ref} - Z_{HESS} . i_{oHESS} \tag{11}$$

where V_{oPV} is photovoltaic voltage output and V_{oHESS} is HESS voltage output.

The droop control offers a balance for power sharing among the converters. The transfer functions serve as the droop coefficient. To set the coefficients, the capacity of the inverters, the maximum voltage and frequency deviation should be taken into consideration.

2.3. Modelling unbalance voltage in a three-phase network

Considering a balanced three-phase system, it can be represented by a two-phase system on the stationary reference frame (i.e., the αβ-reference frame) as shown in (1). For a grid with unbalance voltage, there are harmonics generated at the point of common coupling as shown from (13) to (21). A new filter based on negative and positive sequence separation is used for phase measurement.

$$\begin{bmatrix} V_q \\ V_d \\ V_o \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{12}$$

For an unbalance voltage system,

$$V_{an} = V_{m1} \cos(wet + \delta_0) \tag{13}$$

$$V_{bn} = V_{m2} \cos(wet + \delta_0 - \beta_1) \tag{14}$$

$$V_{cn} = V_{m3} \cos(wet + \delta_0 - \beta_2) \tag{15}$$

if $\delta_0 = 0$

$$V_q = \frac{2}{3}\begin{bmatrix} V_{m1}\cos(wet)\cos\theta + V_{m2}\cos(wet - {}^{2\pi}/_{3}) \\ +V_{m3}\cos(wet + {}^{2\pi}/_{3})\cos(\theta + {}^{2\pi}/_{3}) \end{bmatrix} \tag{16}$$

if $wet = \theta$

$$V_q = \frac{2}{3}\left[V_{m1}\cos^2\theta + V_{m2}\cos^2(\theta - {}^{2\pi}/_{3}) + V_{m3}\cos^2(\theta + {}^{2\pi}/_{3})\right] \tag{17}$$

$$V_d = \frac{2}{3}\begin{bmatrix} V_{m1}\sin\theta\cos\theta + V_{m2}\sin(\theta - {}^{2\pi}/_{3})\cos(\theta - {}^{2\pi}/_{3}) + V_{m3} \\ \sin(\theta + {}^{2\pi}/_{3})\cos(\theta + {}^{2\pi}/_{3}) \end{bmatrix} \tag{18}$$

Using Fourier series expansion,

$$V_q = \frac{1}{3}\left[V_{m1} + V_{m2} + V_{m3} + V_{m1}\cos 2\theta + V_{m2}\cos(2\theta - {}^{4\pi}/_{3}) + V_{m3}\cos(2\theta + {}^{4\pi}/_{3})\right] \tag{19}$$

$$V_d = \frac{1}{3}\left[V_{m1}\sin 2\theta + V_{m2}\sin(2\theta - {}^{4\pi}/_{3}) + V_{m3}\sin(2\theta + {}^{4\pi}/_{3})\right] \tag{20}$$

$$V_o = \frac{1}{3}\left[V_{m1}\cos\theta + V_{m2}\cos(\theta - {}^{2\pi}/_{3}) + V_{m3}\cos(\theta + {}^{2\pi}/_{3})\right] \tag{21}$$

2.4. Mathematical Design of DSOGI-PLL-based droop control for islanded microgrid

From the non-normalized Clarke's transformation [30],

$$V_{\alpha\beta} = [T_{\alpha\beta}]V_{abc} \tag{22}$$

$$V_\alpha^+ = V_\alpha' - qV_\beta' \tag{23}$$

$$V_\beta^+ = qV_\alpha' + V_\beta' \tag{24}$$

The two signals generated by DSOGI [28] is;

$$V_\alpha' = D(s).V_\alpha \tag{25}$$

$$qV_\alpha' = Q(s).V_\alpha \tag{26}$$

$$V_\beta' = D(s).V_\beta \tag{27}$$

$$qV_\beta' = Q(s).V_\alpha \tag{28}$$

The orthogonal signal, along with the direct and quadrature axes, are defined by (14) through (17). These equations establish the basis for understanding the system's orientation and alignment in relation to its components. Furthermore, equations (18) and (19) serve as the mathematical framework for mitigating the double frequency resulting from unbalanced voltage conditions. By incorporating these equations into the model, the system can effectively address and compensate for the challenges posed by voltage imbalances, enhancing its overall performance and stability.

$$D(s) = \frac{k\omega_{raf}.s}{s^2 + k\omega_{raf}.s + (\omega_{raf})^2} \tag{29}$$

$$Q(s) = \frac{k(\omega_{raf})^2}{s^2 + k\omega_{raf}.s + (\omega_{raf})^2} \tag{30}$$

where k is damping factor, ω_{raf} is resonance angular frequency, D is gain for direct axis, and Q is gain for quadrature axis.

Therefore,

$$V_{qd} = [T_{qd}]V_{\alpha\beta}^{+} \tag{31}$$

Equations (16)-(18) with (23)-(24),

$$V_{qd_{sogi}} = V_{qs}^{p} + jV_{ds}^{p} = [T_{qd}]\begin{bmatrix} V_{\alpha}' - qV_{\beta}' \\ qV_{\alpha}' + V_{\beta}' \end{bmatrix}. \tag{32}$$

Inverters utilize switching actions for control. To facilitate control, a system model is presented for DC/AC converters integrated with an L filter, comprising the current controller, PQ controller, and DC-link voltage controller. Figure 5 illustrates the internal current and voltage control processes that influence the inverter's switching decisions based on phase angle measurements. The AC control variables, which include voltages and currents, are transformed into two DC parameters through the Clarke and Park transformations, as depicted in Figure 4.

The outputs of the generators, connected each to an inverter, are connected in parallel and simulated using MATLAB/Simulink. The voltage output of the HESS is used as the reference for the inverter to form a grid, and the inverter connected to the photovoltaics follows the formed grid to achieve phase locked loop for grid synchronization and microgrid control. The parameters for the grid synchronization for microgrid control are shown in Table 3.

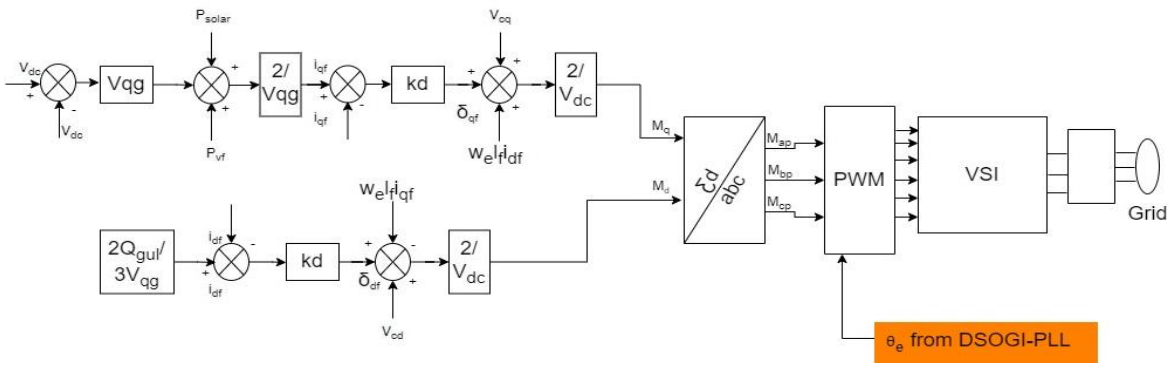


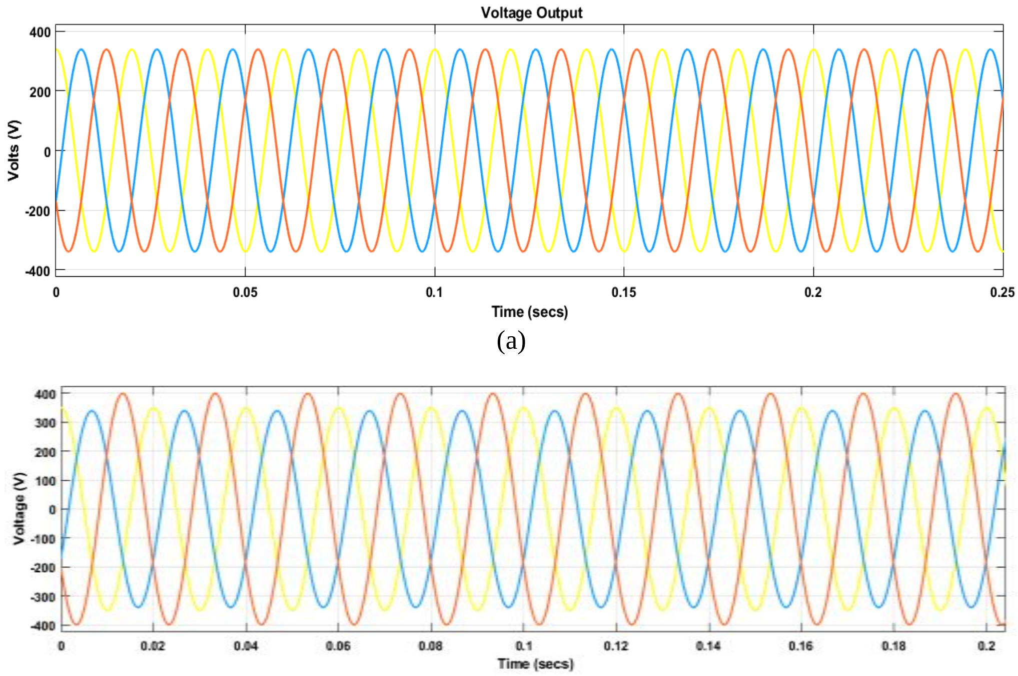
Figure 5. Control loop for DC-AC converter system connected to AC load

Table 3. Parameters for the simulation of parallel inverters

Parameters	Value
V_{hess}	780 V
System frequency	50 Hz
Angular frequency	314.0 rad/s
Switching frequency, *fsw*	10 kHz
Droop gain for P	1e-6
Droop gain for Q	1e-6
Line impedance	50
Line inductance	3.3e-3
Filter inductance	10e-3
Capacitor inductance	5.968e-6
Active power	100e3
Reactive Power	100 Var
Reference Voltage	400 V

3. RESULTS AND DISCUSSION

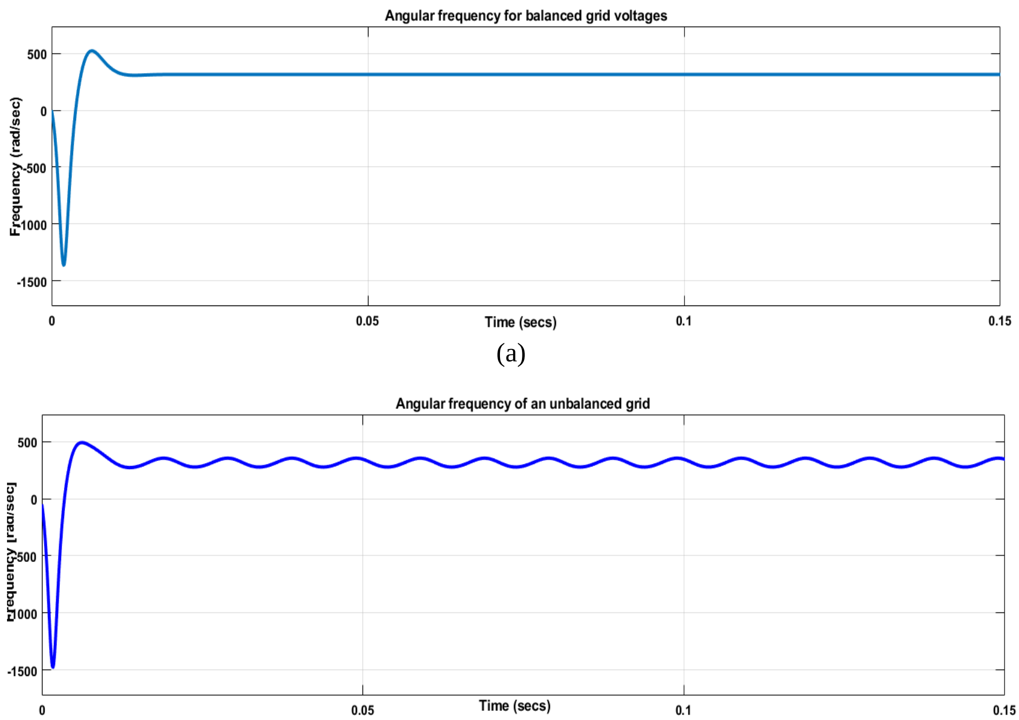
Two DC-AC inverters, one for the hybrid energy storage system and the other for the solar panel are connected in parallel with parameters as given in Table 3. When there is balanced load of the microgrid, the grid voltage is as shown in Figure 6(a), but in the case of unbalanced loading, the grid voltage is given in Figure 6(b). In synchronizing the output from the two voltage source inverters, the frequency of the grid is smooth with no ripples in the case of balanced grid voltage, as shown in Figure 7(a), which shows there was an accurate measurement of the phase angle needed for the voltage and output current control. In the case of unbalance loading, as expressed in (19) and (20), there are harmonics in estimation the phase angle, which allows for ripples in the grid frequency as shown in Figure 7(b). It therefore proves that the harmonics in the voltage transformation affects the output of the microgrid control.



(a)

(b)

Figure 6. Voltage output for (a) balanced and (b) unbalanced loading



(a)

(b)

Figure 7. Frequency measurement for (a) balanced loading (b) and unbalanced loading

3.1. Three phase grid output: unbalance voltage with SRF-PLL and DSOGI-PLL

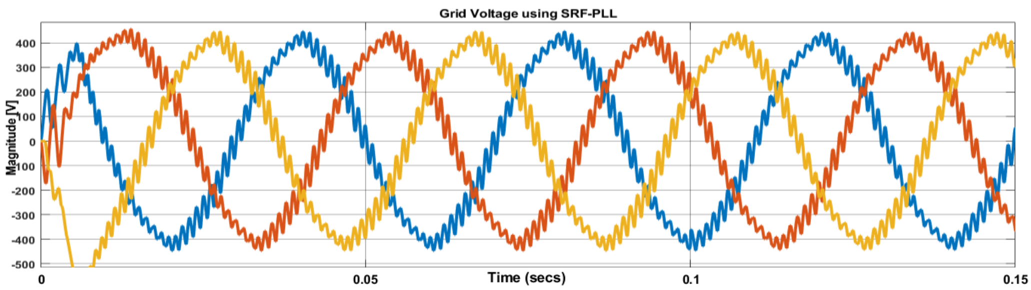
Droop control is used for power sharing within the islanded microgrid. The droop control uses the impact of the output impedance on the inverter to determine accurate power sharing between the inverters. The voltage and current control loops are implemented in various forms according to the influence of the PLL system. A modified phase locked loop system is used to remove the ripples that occur in the grid voltage in the presence of unbalance loading of the microgrid. SRF-PLL is a common phase locked method for microgrid but in comparison with DSOGI-PLL, it is not able to achieve phase angle measurement in the presence of harmonics. Figure 8(a) shows the effect of the use of SRF-PLL which still has some ripples at the grid voltage, but with the use of DSOGI-PLL as shown in Figure 8(b), the output of the grid is smooth.

Likewise, with the use of SRF-PLL for synchronizing the parallel inverters in the microgrid, the grid output current has some ripples which reduce the grid quality as seen in Figure 9(a). But with the use of DSOGI-PLL, the harmonics caused by the circulation current in the presence of unbalanced loading are separated to achieve the phase angle measurement which gives a smooth output grid current as seen in Figure 9(b). The effect of the ripples on the grid output is reduced if there is no error in the phase angle measurement by separating the harmonics using the second-order generalized integrator.

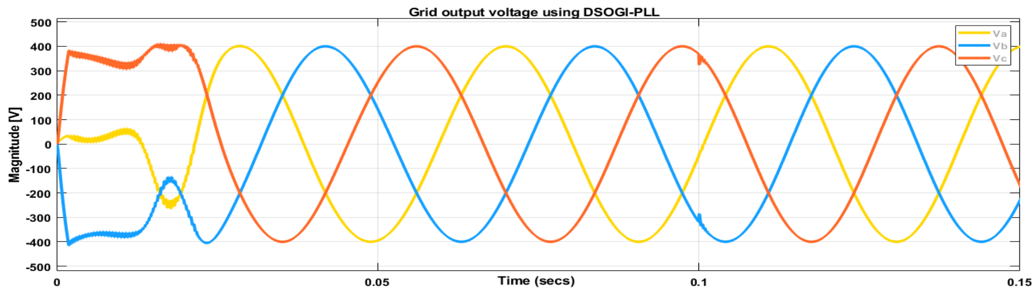
The effect of the harmonic as discussed in (19) and (20) is also seen in the reactive and active power output sharing as shown in Figure 10(a). The ripples show the impact of the circulating current in the synchronization of the parallel inverters because of the unbalance loading of the microgrid. The use of DSOGI-PLL for inverter synchronization is able to remove the ripples from the output active and reactive power in Figure 10(b) as against the output using SRF-PLL.

It is thus observed that the proposed new control method which is DSOGI-PLL based droop control gave a smooth voltage output by reducing the variation of the phase angle measurement. It is observed from the grid output that the DSOGI-PLL is able to measure the phase angle in the presence of circulating currents, to achieve efficient grid synchronization and microgrid control and power sharing without ripples. The grid synchronization using DSOGI-based droop control has been shown to remove the ripples of SRF-PLL droop control in the voltage, current, active and reactive power outputs. This establishes that the DSOGI-PLL based droop control reduces the ripples by separating the positive and negative sequence as discussed in the mathematical method.

The DSOGI-based droop control has shown capacity for more accurate phase angle measurement which is an important system parameter for improved power quality and stable microgrid. This is established with DSOGI separating the positive and negative sequence which correlates with the mathematical development. The control method was able to maintain the power quality even with the load change at 0.1 s as shown in Figure 10. The load is varied to investigate the effect of load changes that may occur in the system.

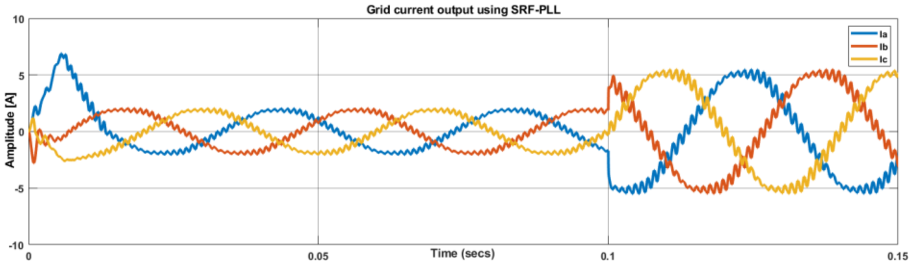


(a)

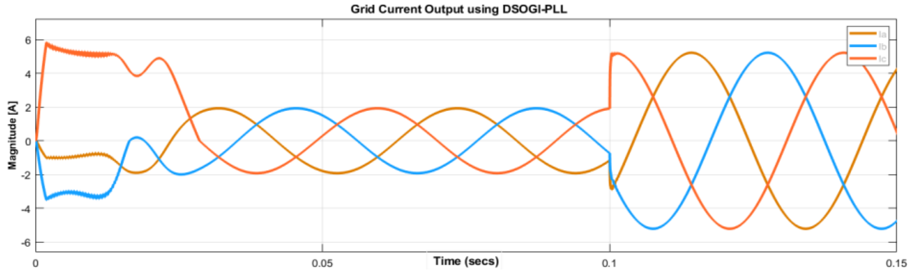


(b)

Figure 8. Voltage output with load variation using droop control with (a) SRF-PLL and (b) PI and DSOGI-PLL

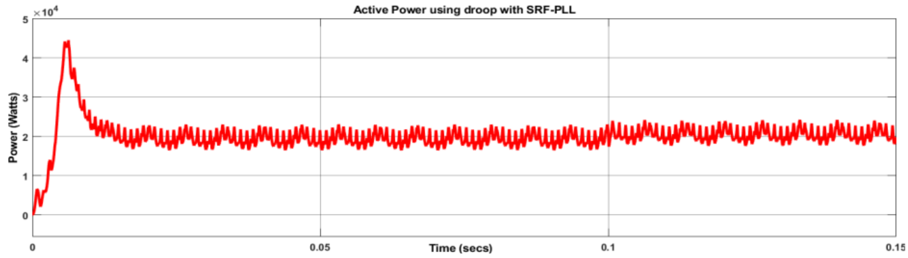


(a)



(b)

Figure 9. Current output with load variation using droop control with (a) SRF-PLL and (b) PI and DSOGI-PLL



(a)

(b)

Figure 10. Active power using droop control with (a) SRF-PLL and (b) DSOGI-PLL

4. CONCLUSION

In this study, a DSOGI-PLL based control method is successfully designed. This controller is specifically tailored to address grid synchronization challenges resulting from unbalanced voltage conditions caused by uneven load distribution. The proposed control methodology was applied to manage two parallel voltage source inverters within an islanded microgrid, featuring solar energy and hybrid energy storage as the distributed generators. To evaluate the performance of our controller, comparative analysis against the traditional SRF-PLL method was carried out. The results obtained demonstrated the remarkable efficiency of the proposed controller, notably in enhancing the quality of power distribution among various energy sources. This improvement is primarily attributed to the elimination of circulating currents that negatively impact the quality of both current and voltage outputs. The results of our study reveal that the DSOGI-based controller offers a substantial enhancement in the dynamic response of voltage and current outputs, particularly in scenarios marked by unbalanced loading, which is common in islanded microgrids at the point of common coupling.

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