Proportional Load Sharing in Parallel-Connected Inverters Using Droop Control

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The increasing integration of inverter-based distributed energy resources into modern power systems has made the parallel operation of inverters essential for improving system capacity, flexibility, and reliability. However, parallel operation of unequal-rated inverters can result in inaccurate power sharing, circulating currents, voltage deviations, and synchronization problems. This study presents a decentralized droop-control strategy for achieving proportional load sharing between parallel-connected voltage source inverters without requiring communication links. The proposed control architecture combines conventional active-power–frequency (P–f) and reactive-power–voltage (Q–V) droop characteristics with voltage and current control loops and virtual impedance to improve synchronization, voltage regulation, power sharing, and circulating-current suppression. The system is modeled and evaluated in MATLAB/Simulink under no-load and loaded operating conditions. Under load, the two inverters supply approximately 7.00 kW and 3.069 kW, corresponding to 69.52% and 30.48% of the total active power, respectively, resulting in a load-sharing deviation of approximately 0.48 percentage points from the intended 70%/30% sharing ratio. Under no-load conditions, the phase voltage remains approximately 232 V compared with the nominal value of 230 V, corresponding to a voltage deviation of approximately +0.87%. The steady-state operating frequency remains approximately 50 Hz, with only slight droop-related variations, while the circulating current remains below 2 A under no-load conditions and is reduced to approximately zero under loaded operation. These results demonstrate that the proposed droop-control and virtual-impedance strategy can provide stable voltage and frequency operation, proportional power sharing, effective synchronization, and significant circulating-current suppression, making it suitable for decentralized inverter-based microgrid and distributed-generation applications.

Keywords: Droop Control, Parallel Inverters, Proportional Load Sharing, Microgrid, Virtual Impedance, Circulating Current.

Introduction:

The increasing penetration of renewable energy resources (RESs), distributed energy resources (DERs), and energy-storage systems has significantly transformed modern electrical power networks. Voltage source inverters (VSIs) have become an essential interface between distributed energy sources and AC power systems because of their high efficiency, fast dynamic response, flexible controllability, and capability to support both grid-connected and islanded operation [1].

In microgrid applications, several inverter-based distributed-generation units are often connected in parallel to increase power capacity, improve reliability, provide redundancy, and enable modular system expansion. Proper coordination of these parallel-connected inverters is essential for maintaining voltage and frequency stability while ensuring appropriate active- and reactive-power sharing. Hierarchical and decentralized control structures have therefore been widely adopted for inverter-based microgrids [2].

Droop control is one of the most commonly employed decentralized techniques because it allows parallel-connected inverters to operate without requiring high-bandwidth communication. By establishing relationships between active power and frequency (P–f) and between reactive power and voltage magnitude (Q–V), each inverter can regulate its operating point according to locally measured quantities. This enables autonomous synchronization and proportional load sharing among parallel units [3].

Despite these advantages, conventional droop control may experience inaccurate active- and reactive-power sharing when the parallel inverters have unequal ratings or mismatched feeder and output impedances. Complex network impedance can also introduce coupling between active and reactive power and may result in undesirable circulating currents. Virtual-impedance techniques have therefore been introduced to modify the effective inverter output impedance and improve power-sharing performance and circulating-current suppression [4].

The stability and power-sharing performance of droop-controlled inverter networks depend strongly on appropriate controller design and selection of the droop coefficients. Although stable decentralized operation can be achieved through suitable controller parameters, simultaneous achievement of proportional power sharing, voltage regulation, frequency stability, and low circulating current remains challenging, particularly for unequal-rated parallel inverters [5]. Therefore, this study investigates a decentralized control architecture combining P–f/Q–V droop control, voltage and current control loops, and virtual impedance for unequal-rated parallel-connected inverters. The proposed system is modeled in MATLAB/Simulink and evaluated under no-load and loaded operating conditions for voltage regulation, frequency stability, synchronization, proportional power sharing, and circulating-current suppression.

Research Objectives:

The objectives of this study are:

To design and implement a decentralized P–f/Q–V droop-control strategy for unequal-rated parallel-connected inverters without communication links.

To evaluate the voltage and frequency stability of the proposed system under no-load and loaded operating conditions.

To assess the proportional active-power sharing performance of the unequal-rated inverters under load conditions.

To evaluate the effectiveness of virtual impedance in reducing circulating current and improving coordinated inverter operation.

Novelty and Contribution:

The main contribution of this work is the integrated application of decentralized P–f/Q–V droop control, voltage and current regulation, and virtual impedance for proportional

power sharing between unequal-rated parallel-connected inverters without communication links. Unlike conventional approaches that may suffer from power-sharing errors, voltage deviations, and circulating currents under unequal inverter ratings and impedance mismatches, the proposed framework combines these control elements within a unified MATLAB/Simulink model to improve coordinated operation. The proposed system is quantitatively evaluated under both no-load and loaded conditions, demonstrating stable voltage and frequency, proportional active-power sharing close to the intended 70%/30% ratio, and circulating-current reduction from below 2 A at no load to approximately zero under load. Therefore, the contribution of this study is a practical and communication-free control framework for unequal-rated parallel inverters that **integrates** proportional power sharing, voltage/frequency regulation, and circulating-current suppression within a single control architecture.

Literature Review:

An early communication-free load-sharing approach for parallel-connected uninterruptible power supply inverters was presented in [6]. The study demonstrated that the effective output impedance of an inverter has a significant influence on load-sharing accuracy and showed that appropriate output-impedance design can improve coordinated operation between parallel inverter units.

A decentralized control strategy based on resistive output impedance was subsequently investigated in [7]. The proposed approach enabled parallel distributed-generation inverters to operate without critical communication links and demonstrated the importance of controlling the inverter output impedance for achieving satisfactory active- and reactive-power sharing.

A flexible microgrid control architecture based on parallel line-interactive UPS systems was developed in [8]. The proposed scheme supported both grid-connected and islanded operating modes and incorporated small-signal stability analysis to assist in the selection of suitable control parameters.

The effects of feeder impedance and distributed load locations on power-sharing accuracy were investigated in [9]. The study showed that unequal network impedances can significantly deteriorate conventional droop-control performance and introduced a virtual-inductance approach to improve active- and reactive-power decoupling.

Adaptive virtual impedance for improving reactive-power sharing in islanded microgrids was investigated in [10]. The proposed method dynamically adjusted the inverter output characteristics to compensate for feeder-impedance mismatch and improve reactive-power distribution among distributed-generation units.

An adaptive voltage-droop method was further proposed in [11] to improve reactive-power sharing under unequal feeder voltage drops. By modifying the droop characteristics according to operating conditions, the method improved reactive-power distribution compared with fixed-coefficient droop control.

An adaptive virtual-inductance loop for autonomous microgrids was proposed in [12]. The method addressed active/reactive power coupling, proportional reactive-power sharing, and circulating-current mitigation without requiring direct communication between primary inverter controllers.

Distributed secondary frequency and voltage regulation was studied in [13]. The proposed distributed averaging method restored the microgrid frequency while maintaining active-power-sharing characteristics and provided improved coordination between voltage regulation and reactive-power sharing.

A distributed adaptive virtual-impedance method based on consensus control was introduced in [14]. The approach adjusted the virtual impedance of individual distributed-generation units to compensate for mismatched feeder impedances and improve reactive-power sharing while suppressing circulating currents.

A comprehensive survey of conventional and modified droop-control techniques for parallel inverter operation was presented in [15]. The study discussed the advantages of communication-free droop control and identified limitations associated with voltage regulation, power-sharing accuracy, output-impedance mismatch, and transient response.

Power-sharing behavior among parallel inverters supplying different types of loads was investigated in [16]. The findings demonstrated that inverter-control parameters and load characteristics can significantly influence the distribution of active and reactive power.

Accurate power sharing in islanded multibus microgrids containing harmonic loads was addressed in [17]. The work showed that conventional fundamental-frequency power-sharing approaches may not provide satisfactory sharing when nonlinear loads introduce significant harmonic power components.

An improved droop-control strategy incorporating virtual complex impedance was proposed in [18]. The method was designed to improve active- and reactive-power sharing, voltage and frequency regulation, and dynamic performance under variations in load conditions.

A virtual-impedance-based droop-control method for voltage-source-inverter-dominated microgrids was investigated in [19]. The study demonstrated that appropriate virtual-impedance design can improve system stability, power quality, and coordinated inverter operation.

Adaptive negative-sequence virtual impedance for improving unbalanced power sharing was investigated in [20]. The method extended virtual-impedance concepts to unbalanced operating conditions and improved power distribution among inverter-based distributed-generation units.

An adaptive virtual-impedance droop-control strategy for mismatched line impedances was proposed in [21]. The communication-free controller dynamically modified virtual impedance according to local operating quantities to improve reactive-power sharing and reduce circulating currents.

A decentralized virtual-impedance and conventional droop-control strategy for inverter-based distributed energy resources was investigated in [22]. The study demonstrated coordinated power sharing among multiple parallel grid-supporting inverters in an islanded AC microgrid.

An intelligent virtual-impedance-based control method for improving islanded-microgrid stability was presented in [23]. The proposed approach employed adaptive impedance characteristics to enhance voltage stability and overall system performance under changing operating conditions.

An improved adaptive droop-control strategy combined with an equivalent-input-disturbance approach was investigated in [24]. The method addressed power-sharing errors caused by impedance differences, voltage drops associated with virtual impedance, and circulating-current fluctuations among parallel inverters.

More recently, an adaptive virtual-impedance droop-control method for parallel inverters in islanded microgrids was presented in [25]. The controller dynamically adjusted the inverter virtual impedance using local measurements to improve reactive-power sharing and suppress circulating current without requiring communication links.

Overall, studies [6][25] demonstrate the progressive development of parallel-inverter control from conventional droop and fixed virtual impedance toward adaptive droop, distributed control, and adaptive virtual-impedance techniques. Nevertheless, proportional power sharing between unequal-rated parallel inverters while simultaneously maintaining voltage/frequency stability and suppressing circulating currents remains an important control problem. The present work therefore evaluates an integrated P–f/Q–V droop-control and

virtual-impedance architecture for unequal-rated parallel-connected inverters under no-load and loaded operating conditions.

Methodology:

System Modeling:

The studied system shown in Figure 1 consists of two unequal-rated three-phase voltage source inverters connected in parallel to a common AC bus. The inverter ratings are selected according to the intended 70%/30% power-sharing ratio, and both inverters are controlled using decentralized P–f/Q–V droop control with virtual impedance.

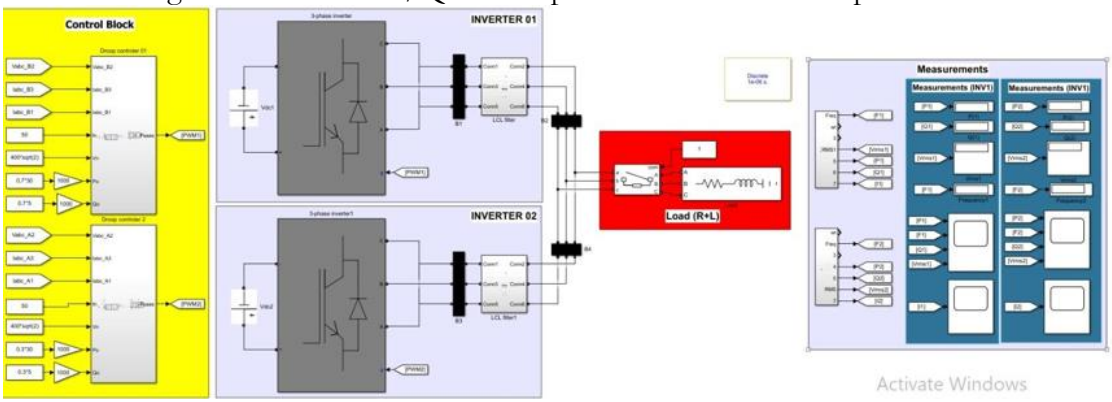


Figure 1. Two parallel inverters System

Droop Control Strategy:

The droop coefficients are selected according to the inverter power-sharing requirements so that Inverter 1 supplies approximately 70% and Inverter 2 approximately 30% of the total active power demand. In this approach, each inverter adjusts its frequency and voltage according to its measured active and reactive power. This allows multiple inverters to operate in parallel while maintaining stability and synchronization.

The droop characteristics are given as:

$$f = f_n - m_p(P - P_o) \quad (1)$$

$$V = V_n - m_q(Q - Q_o) \quad (2)$$

where fn and Vn are the nominal frequency and voltage, respectively; P and Q are the measured active and reactive power; Po and Qo are the reference active and reactive power; and mp and mq are the droop coefficients. This control allows each inverter to automatically regulate its output frequency and voltage to meet the load demand. With an increasing load, the output frequency and voltage will go down slightly, enabling parallel inverters to share the load equally without having to communicate and operate in a stable and synchronized manner.

Power Calculation:

Accurate calculation of active and reactive power is essential for droop control. In this work, the three-phase AC voltage and current signals are transformed into the synchronous d–q reference frame using the Park transformation. In the d–q frame, the sinusoidal AC signals become DC quantities under steady-state conditions, making power calculation simpler, more accurate, and easier to control.

The active and reactive power are calculated as:

$$P = \frac{3}{2}(V_d * I_d + V_q * I_q) \quad (3)$$

$$Q = \frac{3}{2}(V_q * I_d - V_d * I_q) \quad (4)$$

where Vd and Vq represent the d-axis and q-axis voltages, respectively, while Id and Iq denote the corresponding d-axis and q-axis currents. These equations provide a decoupled representation of active and reactive power, simplifying the control of parallel inverters. The calculated active power (P) and reactive power (Q) are then supplied to the droop controller to adjust the inverter frequency and voltage references for proportional load sharing and stable

operation. Figure 2 illustrates the power calculation block used in the inverter control structure for extracting the instantaneous active and reactive power from the measured output voltage and current signal.

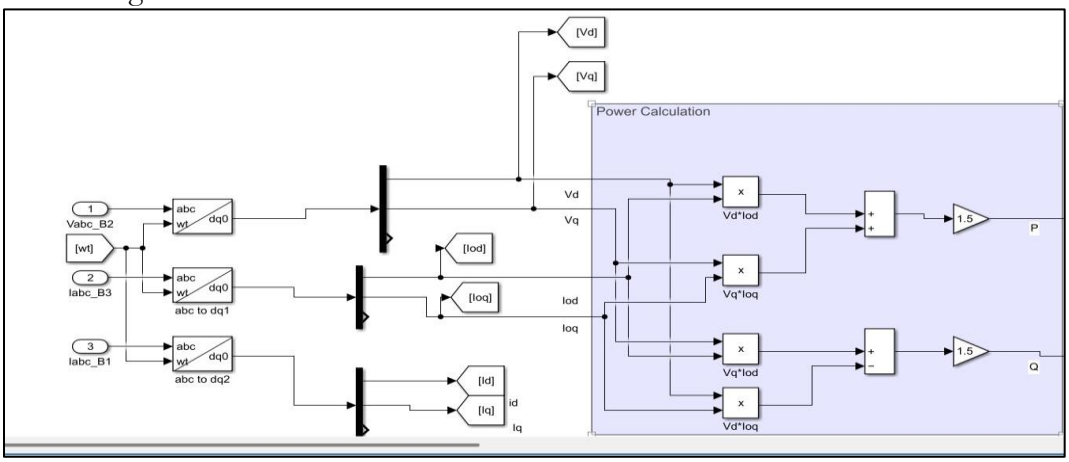


Figure 2. Power Calculation Network Model

Droop Control:

Droop control adjusts output frequency and voltage of the inverter based on the measured active and reactive power with the help of:

$$f = fn - mp(P - Po) \quad (5)$$

$$V = Vn - mq(Q - Qo) \quad (6)$$

The droop coefficients, mp and mq, relate the power and the corresponding frequency and voltage changes. In (1) and (2), fn is the nominal frequency and Vn is the nominal voltage; P and Q are the measured active and reactive power, respectively; and Po and Qo are the rated active and reactive power, respectively. For this work, it is decided to use the frequency deviation of ±0.5 Hz (49.5-50.5 Hz) and the voltage deviation of ±5% (395-405V) to calculate the droop coefficients. The implemented droop characteristics make it possible to automatically synchronize and load share the parallel-connected inverters, as well as to operate them in a stable manner without using communication links as illustrated in Figure 3.

Power Sharing Using Droop Coefficient :

The conventional P–f and Q–V droop control strategy is employed for power sharing between the parallel connected inverters. The frequency and output voltage of the inverter are set based on the measured active power and reactive power, respectively, as follows:

$$Mp = \frac{\Delta P}{\Delta f} \quad (7)$$

$$mq = \frac{\Delta P}{\Delta f} \quad (8)$$

In which Δf and ΔV are the maximum permitted frequency and voltage deviations respectively and ΔP and ΔQ are the rated active and reactive power. The droop coefficients are chosen based on the inverter ratings, thus automatically realizing proportional load sharing. The proposed system will have the 100kVA inverter and the 30kVA inverter to cover about 70% and 30% of the total load. This decentralized control strategy provides proportional power sharing, synchronized operation and stable voltage and frequency regulation on the inverters without the need for communication between the parallel-connected inverters.

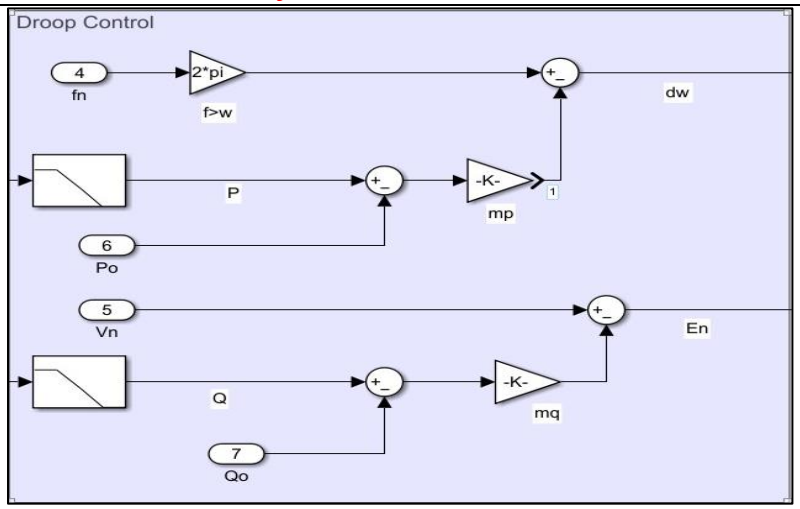


Figure 3. Network Model of Droop Control

Reference Signals:

The balanced three-phase sinusoidal voltages for the voltage source inverters (VSIs) are generated by reference signals. The reference voltages are given by:

$$Va(t) = E\sin(\omega t) \quad (9)$$

$$Vb(t) = E\sin(\omega t - 120°) \quad (10)$$

$$Vc(t) = E\sin(\omega t + 120°) \quad (11)$$

where E is the voltage amplitude, ω is the angular frequency and Va(t), Vb(t), Vc(t). These balanced signals are used as voltage references for the inverter controller to keep the inverter synchronized and to track the voltage accurately. The reference signals generated are shown in Figure 4, which guarantees stable three-phase operation and proper inverter control. The three reference signals are balanced and displaced by 120°.

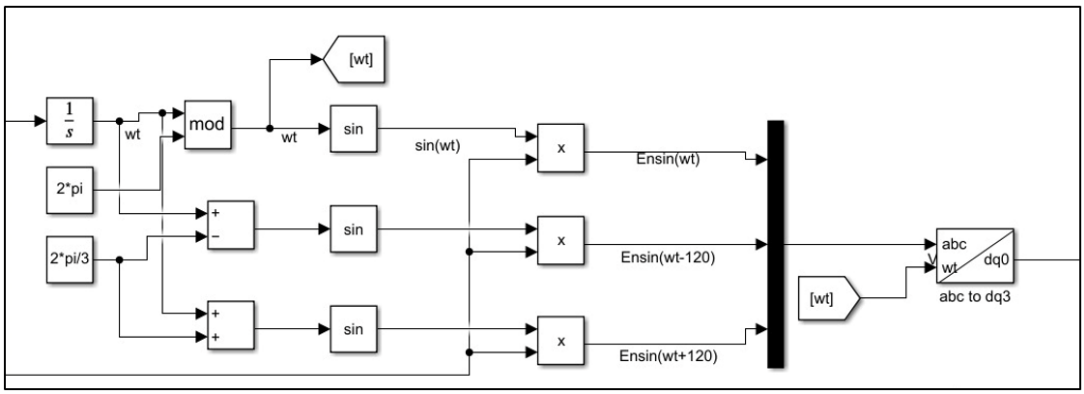


Figure 4. Network Model of Reference Signals

Voltage Control Loop:

The voltage control loop is realized in the dq reference frame to control the output voltage of the inverter. The measured Vd and Vq components are compared with their reference values and the resulting errors are passed to the PI controllers to produce the reference currents Idref and Iqref. The purpose of the decoupling terms is to enhance the dynamic response and system stability. The voltage control loop provides stable voltage regulation under variable-load conditions as demonstrated in Figure 5.

Virtual Impedance:

Virtual impedance is a control method that simulates the effect of actual impedance at the inverter output without the addition of actual components. It is used in the control loop by adding voltage drops proportional to the inverter output currents. The virtual impedance is achieved by current feedback of the voltage reference in the dq reference frame. This results

in an artificial resistive and/or inductive behavior at the inverter output. In this project the use of virtual impedance is mainly for enhancing the performance of parallel inverter operation. It offers the following advantages:

Eliminates circulating currents between inverters

Enables load sharing that is proportional to the number of users

Improves system stability particularly when conditions are unequal

The virtual impedance tuning allows the inverter output characteristics to be effectively controlled, resulting in smoother power sharing and stress reduction in the system. The Network Model of Voltage Control and Virtual Impedance is shown in Figure 5.

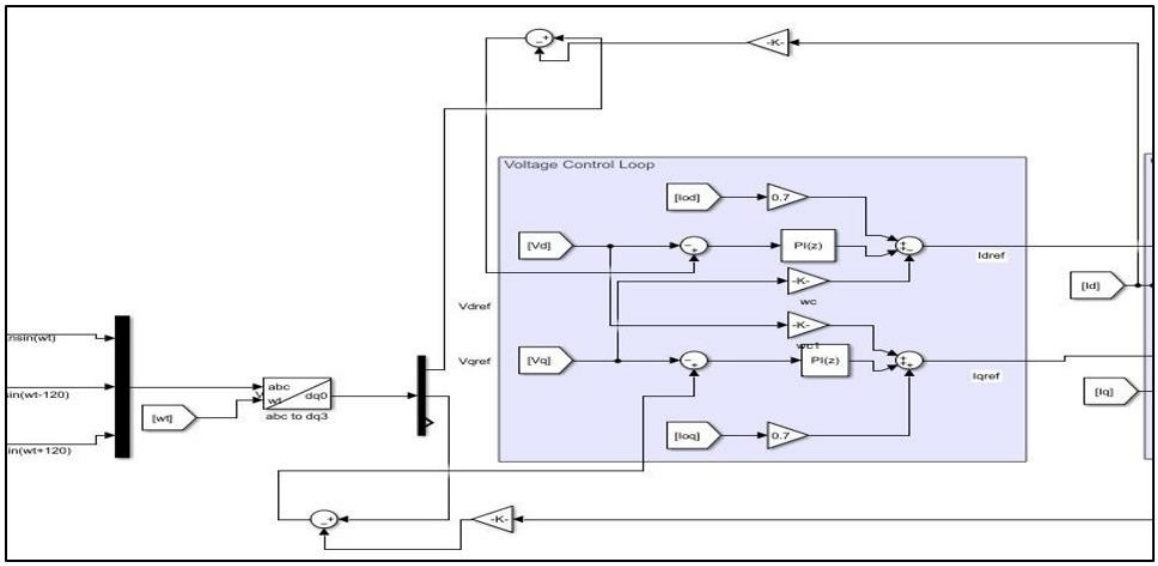


Figure 5. Network Model of Voltage Control and Virtual Impedance

Current Control Loop:

The current control loop is used to control the inverter output currents. The measured Id and Iq currents are compared with their reference values, and the errors are used to drive PI controllers to produce the control voltages Vd and Vq. To account for the cross-coupling between the d- and q-axes, decoupling terms are added, which enhance the dynamic response and stability. The generated control signals are then converted back to the abc frame to generate PWM switching signals as shown in Figure 6, allowing current tracking, stable operation, and effective load sharing between parallel inverters.

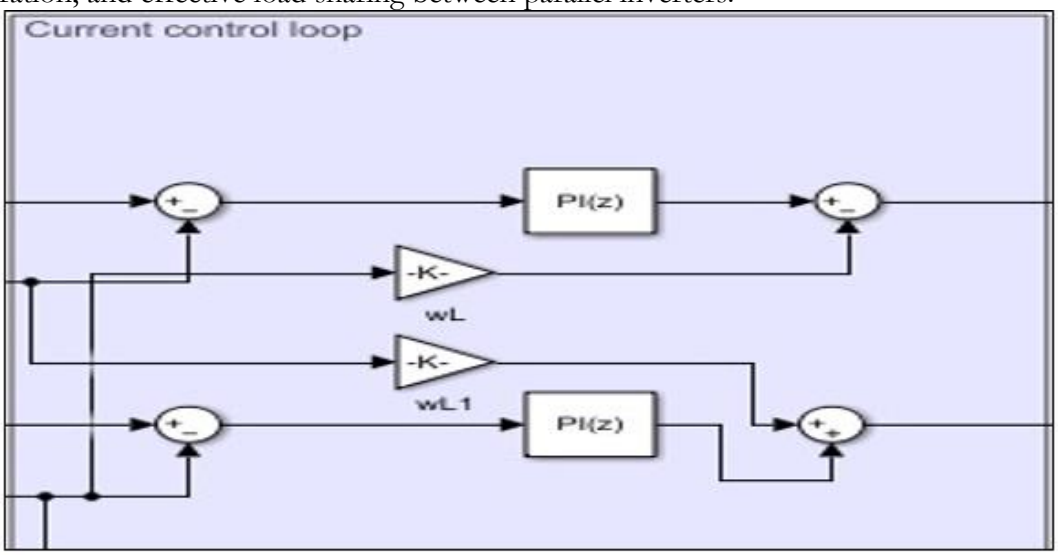


Figure 6. Network Model of Current Control loop

Final Reference Voltage:

The final reference voltage UrefU_is created by the droop, voltage and current control loops. The measured active and reactive powers are then passed through the droop controller to get the reference frequency and voltage. These signals are used to create the reference voltages Vdref, Vqref, which are used by the voltage and current controllers to provide the voltages Vd, Vq needed for control. Finally, the dq voltages are converted to the abc reference frame to get the final reference voltage Uref. Using the Uref voltage to feed into the PWM generator, as illustrated in Figure 7, the voltage is regulated accurately, synchronized and equally shared over all loads

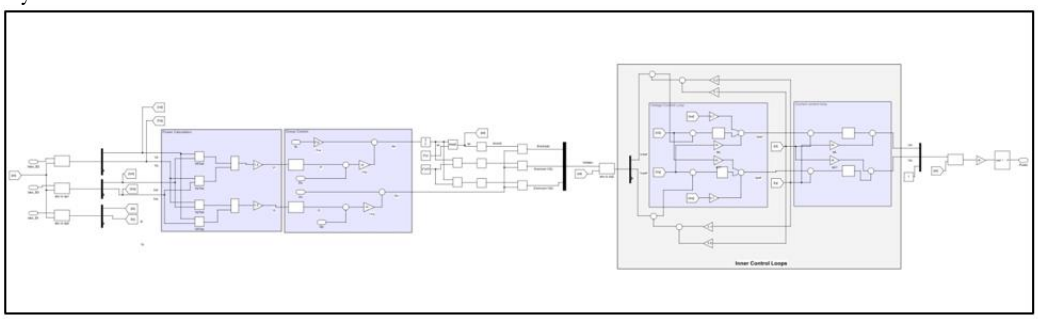


Figure 7. Network Model of Final Reference Voltage Signal

Results and Discussion:

Simulation Results at No-Load Condition:

The proposed parallel inverter system was simulated in MATLAB/Simulink to analyze the performance of the system under no load condition as shown in Figure 8. The main purpose of this test was to examine the quality of the voltage wave and the circulating current in the absence of an external load.

Output Voltage Waveform:

From the simulation results, it can be seen that the three-phase output voltages are perfectly balanced and sinusoidal. The angle of each phase is shifted by 120°, showing proper three-phase operation and synchronization between the inverters. The voltage waveform remains constant at about 232V (phase) which is the rated operation voltage. The waveform is unchanged and has no distortion or irregularity, suggesting:

Appropriate operation of control system

High accuracy reference signal generation

Efficient dq transformation and control loops

This proves the performance of the inverter system without loading. For a no load condition, the results of the simulation are shown in Figure 9, where the voltage magnitude, frequency stability, and the synchronization performance of both inverter systems are shown, confirming that the droop control strategy is able to provide stable output voltage and balanced operation without load demand.

Circulating Current Analysis:

The circulating current between parallel inverters is found to be very small when the machine is not loaded and is less than 2A. The beginning of the simulation shows a small transient, which is caused by the initialization and synchronization of the system. But the present flow is soon limited and restricted to a low level. This indicates that the circulating current is low:

Effective application of droop control strategy

Proper coordination between the two inverters.

Significant impact of virtual impedance in reducing circulating currents

The outcomes show that the system effectively reduces the power exchange between the inverters which is crucial for the system working in an efficient manner.

System Stability:

The system is stable during the whole simulation time. The steady state response of both voltage and current occurs rapidly following initial transients. There are no signs of:

Oscillations

Instability

Frequency deviation

This confirms that the proposed control strategy can provide reliable and stable inverter operation under no-load conditions.

Discussion:

The simulation results prove the effectiveness of the proposed control approach for parallel inverter operation. Perfect sinusoidal voltage waveform indicates that voltage and current control loops are designed and tuned correctly. Furthermore, the circulating current does not exceed 2A, a good sign of the effectiveness of load sharing control and correct impedance matching. Virtual Impedance is a key element in reducing circulating current and enhancing system performance. If this is not included, higher currents in the circuit will result in power loss and decrease efficiency. In general, the outcomes show that the system can achieve:

High power quality

Stable operation

Minimal circulating current

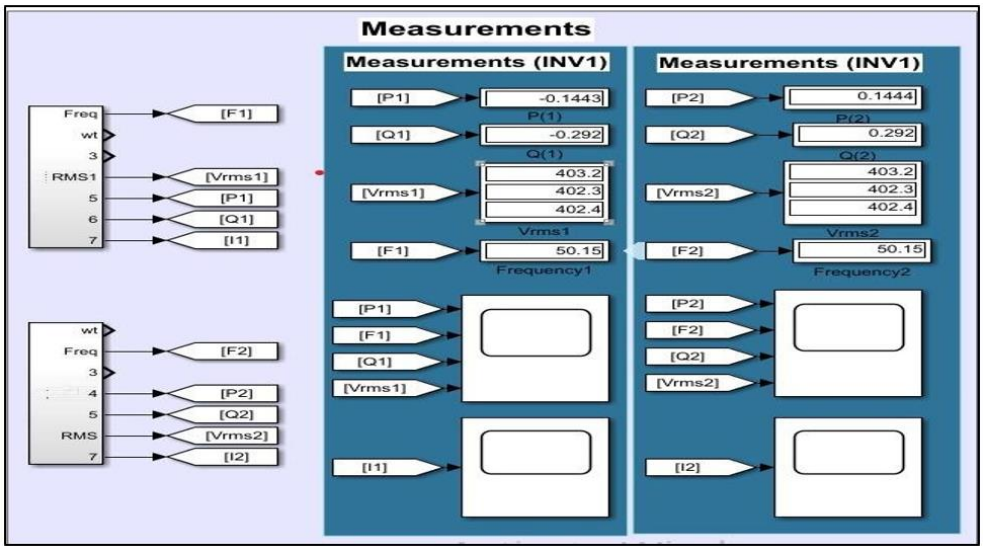


Figure 8. Network Model at No Load Condition

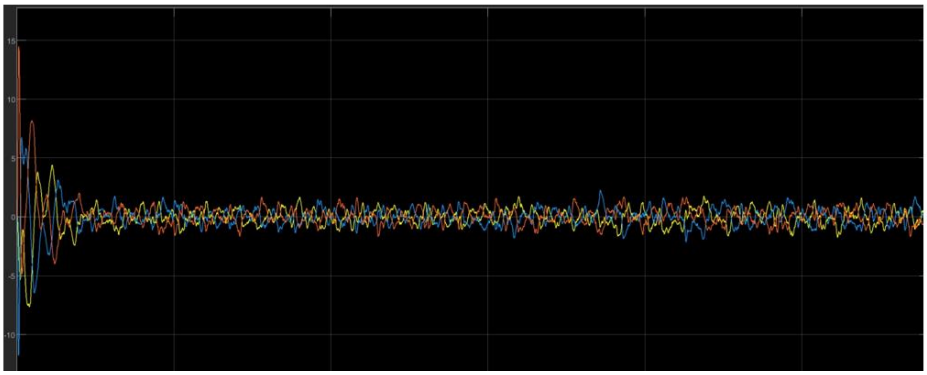


Figure 9. Simulation of Current Under No Load Condition

Based on the simulation analysis, it can be concluded that the proposed parallel inverter system is effective in no load condition. The voltage waveform is both clean and

balanced and the circulating current is very low (less than 2A). The results showed the validity of the proposed control strategy and its applicability in the actual implementation in microgrid and distributed generation systems.

Simulation Results under Load Condition:

The proposed parallel inverter system was also tested under load conditions to further assess the performance of the system. This analysis aims to analyze the voltage stability, load sharing capability and circulating current behavior of the system when supplying power to the connected loads.

Output Voltage Performance:

The three-phase output voltage is stable and sinusoidal under load conditions. Proper phase displacement (120°) and little distortion in the waveform. This indicates that:
The control system ensures voltage regulation even when loaded.
Synchronization of the inverters is maintained
The system has high power quality

Load Sharing Performance:

The simulation results presented show that the load is distributed in the correct ratio between the two inverters based on their ratings, which almost show 70% and 30% of power shrining.
Inverter 1 (100 kVA): Active Power ≈ 7.00 kW
Inverter 2 (30 kVA): Active Power ≈ 3.069 kW
This demonstrates that:
The larger inverter supplies more power, as expected
The smaller inverter supplies less power proportionally

The power sharing is according to the ratio of inverter ratings, which indicates effective power sharing and operation of the droop control strategy. Likewise, the distribution of the reactive power is also distributed between the inverters, which shows that the Q-sharing behavior is correct.

Circulating Current Analysis:

It is found that the circulating current between the inverters is small (and almost zero) under load conditions. This is a significant improvement compared to no-load condition and indicates:

- Proper synchronization between inverters
- Effective droop control implementation
- Strong impact of virtual impedance in eliminating circulating currents
- The absence of circulating current ensures:
- Reduced losses
- Improved efficiency
- Enhanced system reliability

Frequency Stability:

System frequency is kept close to the nominal frequency (≈ 50 Hz) and has only slight deviations caused by the droop characteristics. This means that the machine is operating normally and is maintaining the correct frequency.

Discussion of Results:

The results of the proposed system under the load condition clearly showed that the proposed system is effective in the real operating scenario.
Key observations include:
Stable and high-quality voltage waveform
Accurate and proportional load sharing between inverters
Negligible circulating current
Stable frequency response

The droop control solution does not need communication between the inverters and successfully distributes active and reactive power. Further, the presence of virtual impedance greatly improves the performance of the system by reducing circulating currents. The Network Model under Load Condition is illustrated in Figure 10, which represents the entire model of parallel inverter system for the load condition.

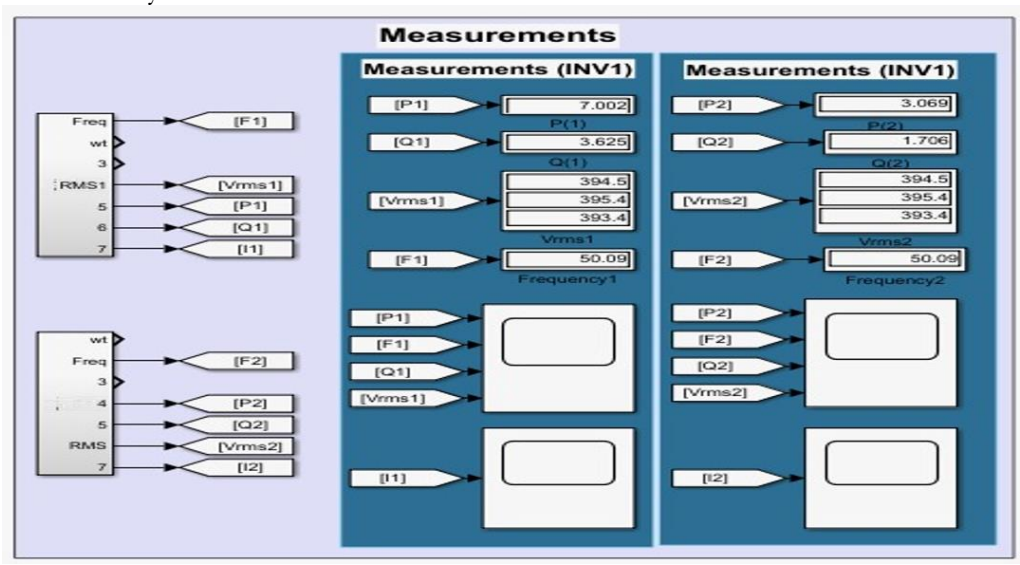


Figure 10. Network Model under Load Condition

Figure 11 depicts the simulation waveforms of the parallel inverter system under full load condition, which shows the current which almost sinusoidal.

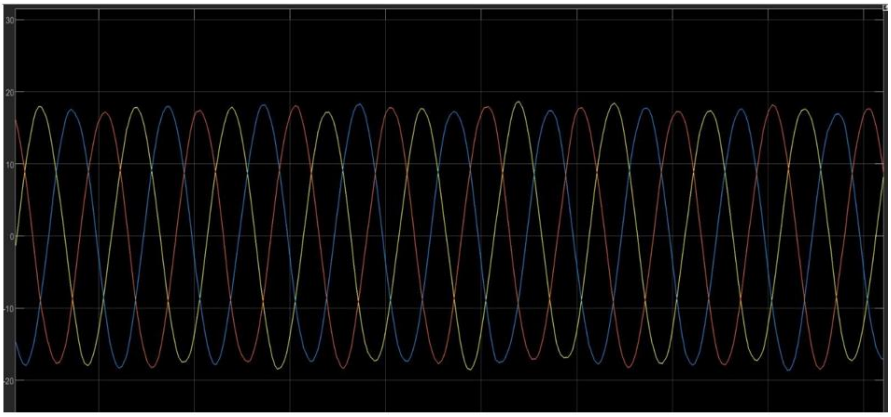


Figure 11. Simulation of Current under Load Condition

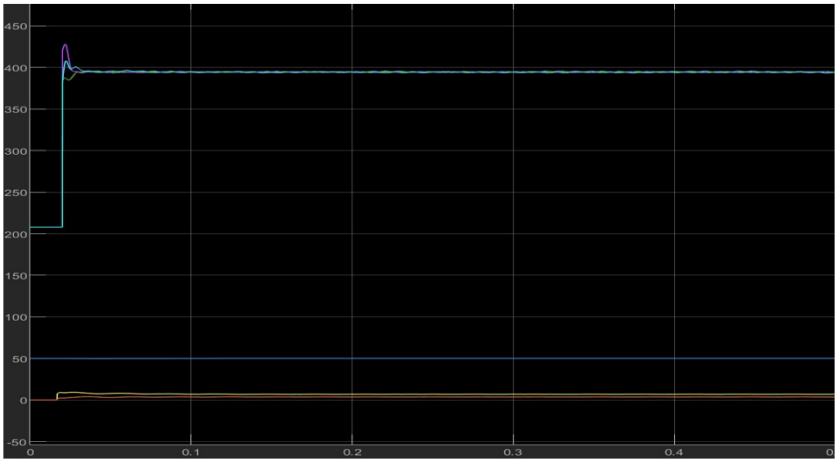


Figure 12. Simulation of voltage, frequency, Active and Reactive power Under Load

Figure 12 illustrates the simulation waveforms of the parallel inverter system operating under full-load conditions, including the output voltage, frequency, active power, and reactive power.

Overall System Performance:

The overall performance of the proposed parallel inverter system under both no-load and load conditions is summarized in Table 1. The results show that the system maintains stable and sinusoidal output voltage and stable frequency in both operating conditions. Under no-load operation, the circulating current remains below 2 A, while under load it is reduced to approximately zero. Moreover, proportional load sharing is successfully achieved under loaded conditions, confirming the effectiveness of the droop control and virtual impedance strategy for stable parallel inverter operation.

Table 1. Overall System Performance under No-Load and Load Conditions

Parameter	No-Load Condition	Load Condition
Voltage	Stable and sinusoidal	Stable and sinusoidal
Circulating Current	< 2 A	≈ 0 A
Load Sharing	Not applicable	Proportional
Frequency	Stable	Stable

Conclusion:

This study developed a decentralized droop-control strategy for proportional load sharing among inverters connected in parallel in a microgrid. The proposed method combines P–f and Q–V droop control with voltage/current control loops and virtual impedance, allowing stable operation without communication links. The simulation results showed that the two inverters shared the active power at approximately 69.52% and 30.48%, close to the intended 70%/30% ratio, while the output voltage remained stable and sinusoidal. The system frequency stayed close to 50 Hz, and the circulating current was maintained below 2 A under no-load conditions and reduced to approximately zero under load. Overall, the proposed strategy achieved stable voltage and frequency regulation, proportional power sharing, effective synchronization, and circulating-current suppression, demonstrating its suitability for inverter-based microgrid applications. Future work may extend the system to three or more inverters and include experimental hardware validation under wider operating conditions.

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