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Virtual Oscillator Control Strategy for Parallel Operated Inverter in an Isolated Microgrid

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Abstract— This study focuses on the application of Virtual Oscillator Control (VOC) to enhance the stability and performance of isolated microgrids in renewable energy systems. VOC operates by generating periodic signals internally using principles of nonlinear oscillation, such as the Lienard theorem and the Van der Pol oscillator. This approach eliminates the need for real-time grid measurements, enabling faster response times. The research investigates VOC's implementation in both single-phase and three-phase microgrids, analyzing its impact on system stability and performance. Simulation models include microgrids with multiple VOC inverters for power-sharing and systems combining VOC with PV inverters to evaluate compatibility. The results highlight VOC's ability to improve stability, enable effective power-sharing, enhance transient recovery, and reduce response times, demonstrating its potential as a robust solution for grid-forming inverters in renewable energy integration.

Keywords— Oscillator, VOC, PV, Grid forming inverter, Stability

Introduction

The evolution of environmentally friendly renewable resources, like solar power and wind power, has brought inverter-based energy resources that are slowly advancing to the front line of power generation. Traditionally, IBRs (Inverter Based Resources) are expected to follow network parameters like voltage, current, and power flow. They are referred to as "Grid-Following Inverters" and typically use Phase Locked Loop (PLL) control mechanisms. Inverters in such an architecture also receive estimates of voltage, frequency, and active and reactive power from the grid network. As a result, the inverter acts as a modified current source that adapts to grid variations in voltage and frequency. A solar farm is a great example of a grid-following inverter application since it does not react to grid voltage and frequency fluctuations the same way alternator-based generating does. Battery technologies have seen a major improvement that has improved their cost-competitiveness with other technologies like synchronous condensers and compensators. Battery storage systems have become much more essential to the electrical grid as a result. The introduction of GFM (Grid Forming), a grid-connected inverter control technique, that uses battery energy storage systems to create and maintain a grid's voltage and frequency, has improved the stability. Based on their respective set points, GFM can control the grid's voltage and frequency.

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The stability of a conventional grid made up of synchronous generators (alternators) cannot be fully mimicked by GFM, even though they can establish and maintain a grid voltage and frequency. This can be a serious issue as transient changes in loading and other faults cause a deviation from set grid parameters, which if not regulated properly can cause the system to spiral out of bounds resulting in permanent damages to various connected devices and infrastructure. In traditional grids, stability is maintained via the inherent inertia of large rotating machines and governing control systems. The tendency of such machines to oppose any sudden changes brought to them is the reason they can maintain constant voltage levels and frequency reliably.

Literature review

The demand for more efficient and dependable control approaches, which are crucial for the systems' maximum stability, exact synchronization, and efficient operation, has spurred several studies and experiments in distributed power generation. One of these control methods that has become very popular is called Grid Forming Control because it naturally creates the voltage reference phasor and offers the required inertial support. Frequency Shaping Control, VOC [1], and machine emulated sub-methodologies like Droop Control and VSM are only a few of the various GFM control sub-methodologies.

The authors of [2] offered two different types of VOCs: nonlinear dead zone-based VOCs (NDZVOC) and nonlinear Vander Pol based VOCs (NVPVOC). In the paper, the design and application of the two control approaches were given. Cases of both even and uneven power sharing were examined. NDZVOC exhibited a higher initial current sharing than NVPVOC. Although there was an overshoot, the voltage synchronization in the NDZVOC during startup was extremely quick. Although NVPVOC's voltage synchronization is slower than NDZVOC's, there is no overshoot. Both control strategies make heavy use of voltage synchronization and current sharing when there are load disruptions.

In [3] a virtual oscillator control application for inverter-based distributed energy resources operating on islands and in grid connections is given. It has been suggested to use a decentralized adaptive battery energy storage system (BESS) primary control mechanism to guarantee reliable oscillator-based microgrid operation in both grid-connected and islanded operations. As a distributed energy source, BESS and photovoltaic systems have been deployed.

The PV resources deliver their available power always and it is hard to control the output power based on our requirements. Researchers are in full gear to achieve power control in inverter-based resources. In this scenario as well, the VOC strategy in inverters has been proven to be vital. Some researchers have proposed and implemented power flow control as well as load sharing between different inverters.

The innovative concept of VOC, which controls the inverter output power by adding a complicated parameter K to its circuit, is presented in the paper [4]. When it comes to synchronizing and controlling VSIs in an isolated grid, the VOC technique has many advantages over alternative methods. Although few papers have discussed VOC in grid-connected mode, power flow control, and grid-connected mode still face significant difficulties. To control the power flow from VOC in a quasi-steady state—a condition in a dynamic system where some variables are thought to be roughly constant or changing very slowly in comparison to other rapidly changing variables—this paper addresses this problem and presents an analytical expression. This paper designed a controller for deriving K based on the reference power set on it. The paper [5] proposed and experimentally verified the power control by current feedback gain (K) which is tuned by the PI Controller. Eigenvalue analysis is used to demonstrate the stability of the system.

The paper [6] outlined the necessity of load sharing among the inverter based on setpoints and presented the solution for it. Synchronization of many inverters is experimentally proven together with the VOC-based inverter's black start capabilities. The paper effectively showcased and verified the grid formation capabilities within the inverter-dominating power system.

A grid-supporting (GS) control system for distributed energy resources (DERs) in power grids is a system that helps to manage the integration of DERs into the grid. These resources, which can include renewable energy sources such as solar and wind power, can provide a valuable source of clean and renewable energy. However, they can also be more unpredictable and variable than traditional power sources, making it challenging to integrate them into the grid without affecting their stability and reliability. Often due to lack of inertia, the grids with large numbers of DERs are considered weaker as they are prone to instability even from small changes, thus the need to support them. There are mainly two types of Grids Supporting mechanisms mostly used today: Grid Forming (GFL) and Grid Following (GFM).

Grid-following inverters are inverters that are used in distributed energy systems to provide alternating current (AC) electricity that the grid can use from direct current (DC) power from renewable energy sources like solar or wind turbines. In high-penetration renewable energy systems, traditional GFL inverters can struggle to maintain the stability and reliability of the grid. This is because these inverters rely on the grid to provide a stable frequency and voltage, and they are not able to respond quickly enough to changes in the grid. As a result, the grid can become unstable or even suffer blackouts if there are too many grid-following inverters connected to it.

On the other hand, "Grid-Forming" (GFM) inverters (which are in rampant research today) can maintain the stability and reliability of the grid, even when a large proportion of the energy being supplied to the grid comes from renewable sources. This is because they can respond quickly to changes in the grid and maintain a stable frequency and voltage. As a result, they can help prevent blackouts and other disruptions in high-penetration renewable energy systems.

Virtual Oscillator Control

Virtual oscillator control (VOC) is a control system that deviates from machine-inspired approaches. In VOC, inverters are configured to mimic the dynamics of weakly nonlinear limit-cycle oscillators, like Van der Pol and dead-zone oscillators. These oscillators, as shown in Figure 1, provide voltage and frequency regulation, power sharing, and communication-free synchronization and synchronization even in the presence of varying initial conditions. They can also generate periodic, self-sustained, and stable oscillations. The VOC-controlled Inverter Based Resource (IBR) shall be connected as a grid-forming power source in the microgrid. This will act as an independent power generation system, capable of operating standalone. IBRs will be able to share the load as well as have a much better frequency response compared to traditional systems with Droop control.

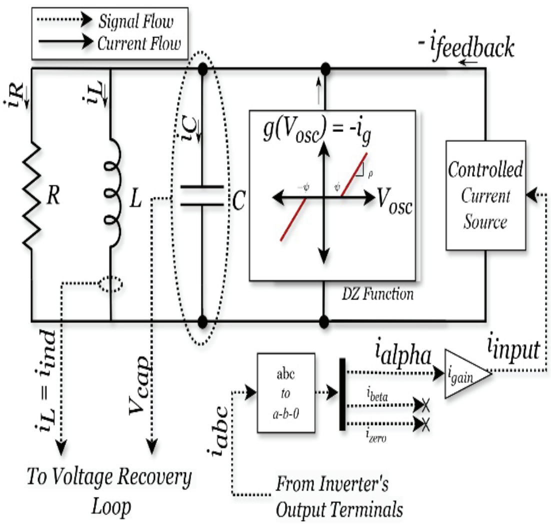

Fig. 1 Dead Zone Virtual Oscillator Control

Methodology

The system of solar photovoltaic and VOC is modelled using MATLAB-Simulink. It provides us with an efficient and flexible way to model all the components of the system with different mathematical features built into it. Simulink provides a better visualization of all the graphs and incorporates a much more user-friendly interface to study the responses during all stages of the simulation.

A. VOC Controlled Inverter

In Figure 2, we can see the VOC-controlled inverters, connected to the load. The different inverter systems have different capacities. The grid is a three-phase system. The VOC inverter is capable of producing and sustaining a 50 Hz AC power which forms the grid; thus, it is a Grid Forming Inverter.

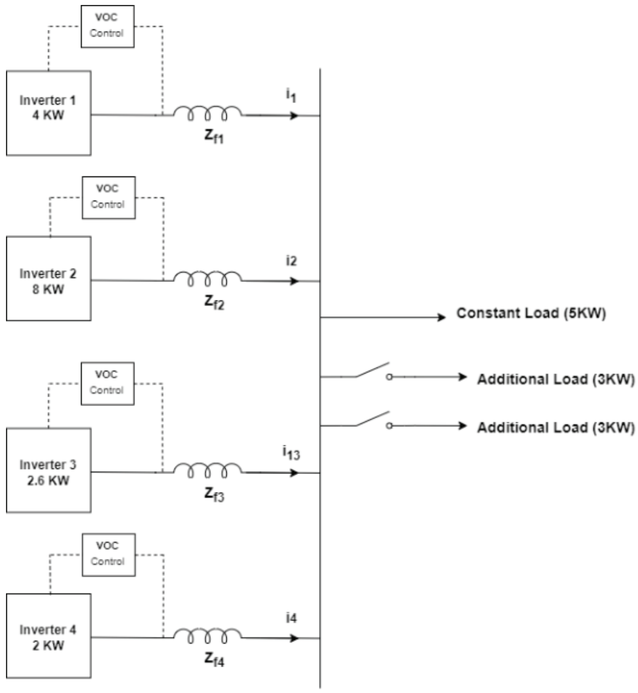

Fig. 2 Parallel inverters with VOC control strategy

B. PV Model

The PV generation system comprises of a DC-DC Boost converter and a PV array with MPPT control. The use of MPPT assures that the PV will produce its maximum power at a given temperature and irradiation level. The MPPT in this system uses the Perturb and Observe (P&O) algorithm to assess the output power at various voltage and current levels. The output voltage of PV array is connected to DC-DC Boost converter which increase the output voltage. The PV generation side is connected to the inverter via a DC-link Capacitor. The voltage across the DC-link Capacitor has to be maintained to a constant value of 600V in order to achieve a DC to 3 phase AC conversion at 400V line to line. In order to do such, there is a need to constantly monitor the voltage across the link and control the current flow at the output of the inverter, i.e. its power injection. If the power injection is lower than the power generated by the PV, then the DC link capacitor starts charging. When the power injection is greater than the power generated, the DC link capacitor starts discharging rapidly.

C. Hysteresis Band Control

Hysteresis Band Current Control method is a type of feedback control system which continually tracks the output current of the PV-Inverter and tries to maintain it within a certain range above and below it. This control system is necessary to maintain a constant DC link voltage by adjusting the power injected to the grid. The PV system that is designed for the system is rated at 30KW with a constant DC link voltage of 600V. This voltage level is required by the inverter to maintain its AC side line-to-line voltage at 400V. When the inverter injects power lesser than 30KW to the grid, the DC link capacitor starts charging rapidly causing an increase in voltage across its terminals, and when the power injection falls below 30KW, the capacitor starts rapidly discharging causing the voltage across its terminals to start decreasing. Both of these phenomena are disadvantageous to the system as a constant voltage level is required in order to meet the grid standards. Thus, this current control system adjusts the current output based on the instantaneous measurements of DC-link voltage. If the voltage is increasing, the reference current is increased and if the voltage starts decreasing, the reference current is decreased as well.

D. VOC Inverter PV System:

For the study of the compatibility of Grid Following Inverters used by various inverters today with a Grid Forming Inverter control, we have a micro-grid with a PV system working in tandem with a VOC controlled battery system. The control system of the PV system has a Hysteresis Band Controller which generates Pulse Width Modulation (PWM) signal for the inverter switches based on the current reference of the PV array output. The frequency and phase of the reference current are obtained from the grid which is maintained by our VOC controlled battery source. In order to maintain the output voltage as 400V L-L on the AC side, the DC link capacitor is maintained strictly at 600V using a voltage control loop that regulates the output power of the inverter. The PV inverter will always output the exact power it generates, and any remaining demand is supplied by our VOC inverter with battery.

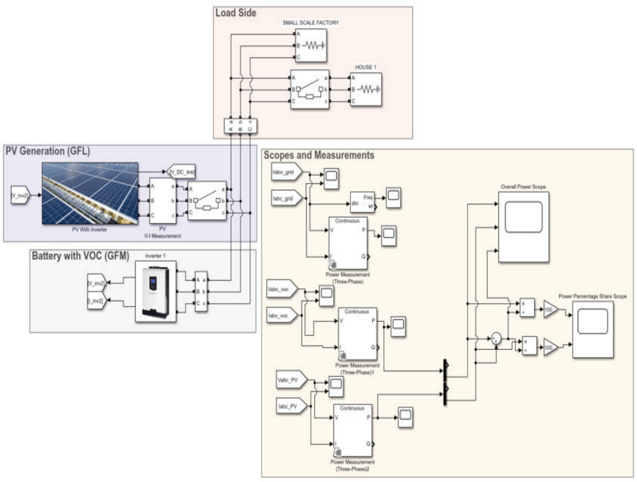

Fig. 3 VOC Inverter PV System

Results

A. Four differently rated inverters with VOC in Parallel

Various grid parameters measured throughout the system have four differently rated inverters controlled with Virtual Oscillator Control supplying a common load in parallel as seen in Figure 2. Load is changed throughout the simulation which can be seen in the graph in figure 4. The initial base load is 5 KW, which is increased by 3 KW (60% load increase) at t = 1 second. A further 3 KW load is added at t = 1.5 seconds. After that, the 3 KW load is disconnected at t = 2 seconds and again at t = 2.5 seconds.

The frequency of the grid during these load changes can be seen in Figure 5. The transients in frequency are very low and last only for a few milliseconds before snapping back to 50 Hz. The grid voltage can be seen in Figure 6. The current supplied by the four different inverters can be seen in figure 7. The largest capacity inverter supplies the most current (blue) while the smallest capacity inverter supplies the least current (green). Even during load changes and transients, the ratio of current supplied is continually maintained.

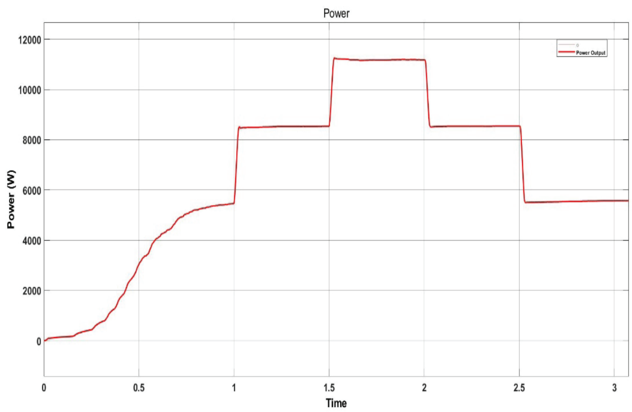

Fig. 4 Load Changes in a 4 VOC invertewr System

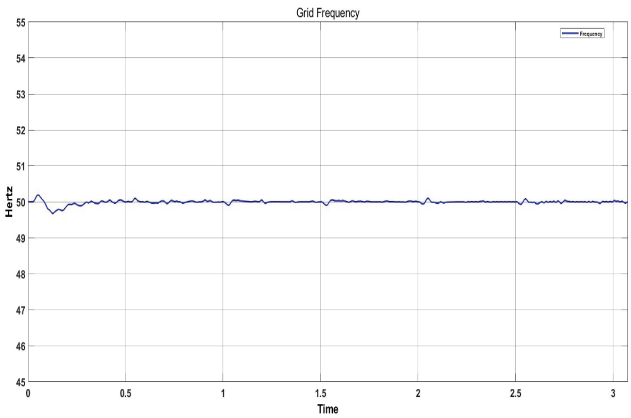

Fig. 5 Grid frequency during load changes at various times

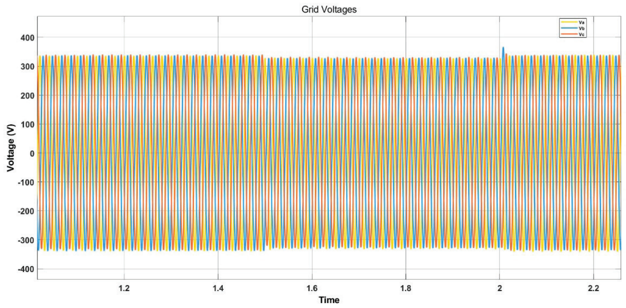

Fig. 6 Grid Voltage maintained during steady state and load changes

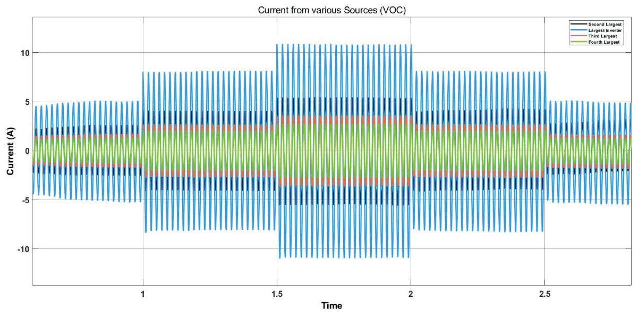

Fig. 7 Load Sharing among 4 different sizes of VOC inverters

B. *PV and VOC*

In the system, as seen in figure 3, a Virtual Oscillator Controlled inverter system is operated normally as a grid forming inverter, and a PV inverter system is connected in parallel to it as a grid following inverter to adjust its switching based on the reference of the grid set by the VOC inverter. Initially, VOC inverter supplies the entire load up to t = 0.5 seconds. At t = 0.5 seconds, the PV system is connected at half capacity, i.e., 2400 W. The PV generation is increased to full capacity by increasing its irradiance at t = 2 seconds. An additional 20% load is connected at t = 5 seconds which is removed promptly at t = 7 seconds.

In Figure 8 we observe that the frequency of the system remains constant throughout the simulation time, even when loading is changed. A slight disturbance can be seen during system transients, i.e., times when load changes or PV generation varies. Figure 9 shows that the current supplied by the GFL inverters of the photovoltaic system is always constant at constant levels of irradiance and temperatures. The output current of the VOC inverter is set based on the power mismatch remaining. As the generation and load demand varies, the output current of the VOC inverter adjusts itself to fulfill the requirements. Figure 10 shows the voltage level and current supplied to the load during the entirety of the simulation. At the instance of load increase, we can observe a slight drop in the system voltage, which is due to increased current flowing through the inverter filter. The voltage droop can be adjusted via the control by adjusting the parameters in the Dead-zone function block of the control system and it also depends on the over-loading of the inverter.

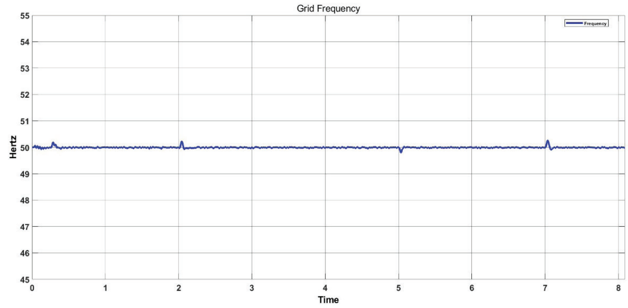

Fig. 8 Frequency during load change in VOC and PV inverter system

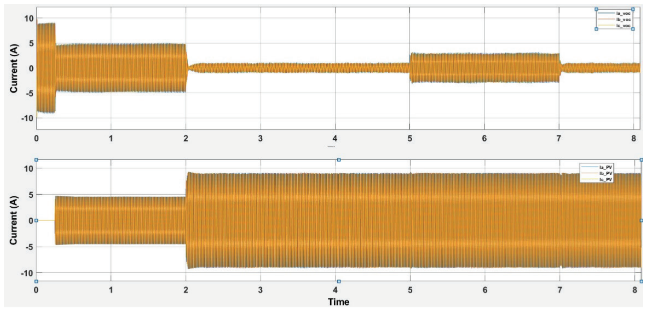

Fig. 9 Current supplied by VOC inverter (a) and PV inverter (b)

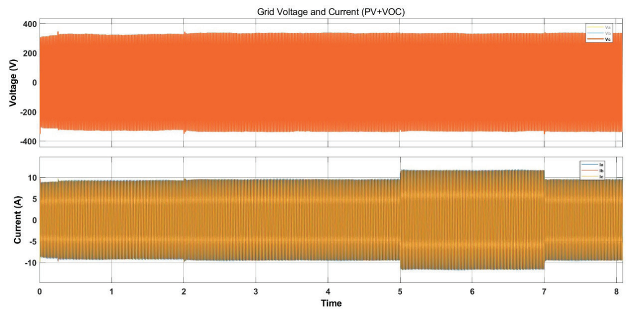

Fig. 10 Grid Voltage and Current of the VOC and PV microgrid

Conclusions

PV requires grid-forming control to operate in fully renewable mode. The droop method operates the system of parallel inverters by sharing power through compensation for the decrease in frequency. The implementation of Virtual Oscillator Control (VOC) strategies enables power sharing between parallel inverters without changing frequency. VOC maintains the system at a common frequency of 50 Hz during any transient loads. The voltage drop in the output of inverters was seen as compensation for the change in supply power while using VOC. VOC has embedded droop control for power sharing, which exhibits more superiority than other conventional methods.

The current system is not compatible with grid-connected mode due to the mismatches in frequency between synchronous generators and inverter-based resources. To enable this capability, further additions to the general control system of the Virtual Oscillator Controller are required. Further, our system is only realized via software simulations. There is also a scope for developing a hardware model that can be used with various Hardware in Loop (HIL) technologies.

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