Wireless Communication between Inverter Modules in a Smart Micro-Grid with Reactive Power Compensation

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This project implements low-cost Wi-Fi microcontrollers to manage inverter modules in a smart micro-grid. This was achieved by fabricating and simulating a testbed for a solar-powered smart micro-grid with reactive power compensation. This testbed with two single-phase inverters operating in parallel represents a smart micro-grid that can operate grid-tied, or in isolation to supply power to a load with the ability to locally supply reactive power and reduce losses within the system. Reactive power compensation is implemented with a passive network of capacitor banks to increase the efficiency of the system. The results obtained suggest that low-cost Wi-Fi microcontrollers are a viable option to manage distributed generation in smart micro-grids when integrated with Blynk; however, a local server should be established for zero latency and an increased wireless transmission rate.

Contents

I. Introduction 2
II. Project Scope 3
III. Project Aim 3
IV. Literature Review 3
   A. Inverters 3
   B. Smart Grids 4
   C. Synchronisation and Load Sharing 4
   D. Wireless Communication and Modern Wi-Fi Microcontrollers 4
   E. Reactive Power Compensation 5
V. Project Design 5
   A. Inverters in the Smart Micro-Grid 5
   B. Wireless Communication 6
   C. Reactive Power Compensation Unit 6
VI. Results and Discussion 7
   A. Inverter Simulation 7
   B. Inverter Operation 8
   C. Smart Micro-Grid Testbed Operation 9
   D. Power Factor Measurement Simulation 10
   E. Reactive Power Compensation Unit Operation 11
VII. Conclusion 12
VIII. Future Work 12

Acknowledgements 12
Deliverables 12
References 13

APPENDICES
Appendix A. Reactive Power Compensation Unit A1
Appendix B. Arduino Sketches A2
Appendix C. Blynk Application A3
Appendix D. Simulink Schematics A4

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I. Introduction

The need to convert electricity from direct current (DC) to alternating current (AC) is prevalent in the conversion of renewable energy sources for use in household and commercial applications or exportation to the electricity grid. This is exemplified by the increased demand for clean renewable energy to reduce emissions and the carbon footprint, ultimately leading to a reduction in the cost of renewable technology [1]. Australia’s National Energy Market (NEM) has seen an increase in the production of renewable energy and from 2016 – 2017, there was a 5.3 per cent increase in net production from renewables over that period [2]. During the same period, there was a decrease in the production of energy from non-renewable sources, with oil having the largest percentage reduction. Solar accounted for 3.0 per cent of the total electricity generation in 2017, with the majority of this coming from small scale photovoltaic (PV) systems resulting in the rise of distributed generation (DG) and small-scale power grids known as micro-grids [2]. Micro-grids are a network capable of operating in isolation to supply power to a small load, such as a rural town; or they can be grid-tied with the capability to export back to the energy grid [3]. Micro-grids can have multiple inverters operating in parallel; this configuration relies on synchronisation and load sharing for stable power transfer. However, it does not adequately integrate DG units and does not allow for useful information exchange within the network [2], [4].

Figure 1. Application of load sharing in a smart grid network requiring power information exchange between DG systems [5].

A smart micro-grid achieves power information exchange between DG units using wireless communication as shown in Fig. 1 to effectively integrate the network [6]. All wireless communication networks have varying communication delays that depend on a variety of network factors [5]. Therefore information exchanged over a wireless network may be delayed or lost, this exemplifies the need for time-stamped measurements and commands to detect missing information packets [5], [7].

In a traditional electricity network, the grid supplies frequency and voltage references, which changes with the supply and consumption of power in the network. However, in a smart micro-grid, a reliable frequency reference is required to manage generation and voltage profile, which can be achieved using centralised control [8]. The management of reactive power is equally important to maintaining a stable voltage profile [9]. During low load, the capacitance of the transmission network dominates, however once fully charged there will be a net inductance resulting from the electrical loads. A net reactance will result in reactive power oscillating between a source and load, causing internal losses; this can be offset by introducing a local reactance.

In light of modern microcontrollers having Wi-Fi processors to access the cloud, they communicate over a wireless network using Internet of Things (IoT) platforms [7]. To potentially bridge the gap in open architecture and user flexibility for the low-cost management of DG in smart micro-grids Wi-Fi microcontrollers can be integrated with IoT platforms.
II. Project Scope

Energy is generated by various renewable energy sources and storage devices in DG systems for load sharing in a smart micro-grid, as shown in Fig. 1. To meet reactive power requirements in a smart micro-grid, reactive power compensation is typically used to supply a local reactance. In addition to this, a smart micro-grid requires a reliable reference to manage DG generation; this can be achieved using centralised control and wireless communication.

IoT platforms such as Blynk enable wireless communication between modern Wi-Fi microcontrollers to achieve a centralised control configuration [7]. The Blynk server and application also provides a functional user interface to potentially control and monitor the smart micro-grid operation.

This project innovates existing centralised control configurations by integrating Wi-Fi microcontrollers using Blynk for the management of inverter modules in a smart micro-grid.

III. Project Aim

This project aims to experimentally implement low-cost Wi-Fi microcontrollers using Blynk to manage inverter modules in a smart micro-grid testbed.

IV. Literature Review

The literature review contains the background information pertinent to inverter technology, smart micro-grid operation, wireless communication between modules and modern Wi-Fi microcontrollers. Reactive power compensation will also be discussed as a method to reduce losses while increasing stability in power systems.

A. Inverters

Inverter technology allows for the conversion of DC energy to AC energy for use in household and commercial applications or for the electricity grid as a single-phase or three-phase system. A single-phase inverter uses a single-phase to convert DC energy to AC energy over a period and can export energy back to a three-phase grid by connecting to a single-phase, however residential supply is generally single-phase. Modern power inverters often use sinusoidal Pulse Width Modulation (sPWM), with unipolar sPWM and bipolar sPWM being the two main sPWM switching schemes [10]. Unipolar sPWM can offer up to a 30 per cent decrease in switching losses when compared to bipolar sPWM; there is also an increase in harmonic components [11, 12]. Unipolar sPWM uses a triangular carrier wave and compares two modulating sinusoidal waves 180 degrees out of phase to generate the switching for the positive and negative half-cycles. The output amplitude of an sPWM inverter is adjusted by varying the amplitude modulation ratio, which is the ratio between the amplitude of the modulating sinusoidal waves and the triangular carrier wave [13].

A H-bridge is commonly used to increase sPWM switching amplitude and it switches the sPWM signal between the ground and the magnitude of the DC inverter input [11]. The sPWM signal is passed through a low pass filter to attenuate the switching noise and obtain a sinusoidal AC waveform. Control of the H-bridge output is essential for effective synchronisation between inverters operating in parallel [14].

When multiple inverters are operating in parallel this forms a small-scale power grid, known as a micro-grid; however, this configuration relies on synchronisation and load sharing for stable power transfer [2], [4]. Grid-tied micro-grid configurations can also have the ability to island and continue to operate autonomously when disconnected from the grid; however, they must be able to reconnect and synchronise with the grid [15]. Advanced control, sensing techniques and two-way communication between DG systems allows the for flow of information within the network to create a smart micro-grid.

B. Smart micro-grids

Smart micro-grids present options to enhance grid functionality by effectively integrating DG systems and loads. With access to real-time data, the smart micro-grid can adapt and intelligently manage generation and voltage profile using two-way communication between modules. Advanced sensing techniques, control systems and integrated communication can be implemented to an existing electricity grid to transform it into a smart micro-grid [6], [16]. While many renewable energy solutions have been around for decades, the electricity market and grid lacked infrastructure and techniques to integrate these systems in a meaningful way. Therefore, DG systems should be effectively integrated using modern technological advancements to harness the full potential of renewable energy [6].

In traditional grid configuration, production is centralised with little interaction with consumers; however smart micro-grids introduce active participation of consumers and allow for bidirectional power flow such that a consumer can also be a provider to the grid [6]. The DG systems can assist in reducing the peak demand on the network by exporting back to the grid; however there be effective power management for synchronisation and load sharing [17], [18].
C. Synchronisation and Load Sharing

Inverters in smart micro-grids are a network capable of operating in isolation to supply power to a small load, or they can be grid-tied with the capability to export back to the energy grid [3]. The synchronisation is essential in both cases, and if this does not occur, it can lead to imbalances with the load, resulting in damage to the connected equipment, or instability in the grid for grid-tied smart micro-grid configurations [19]. It has been reported that inverter synchronisation and parallel operation can be achieved using a master inverter and a slave inverter [4]. The slave inverter will sample the output of the master inverter and match its output to obtain synchronisation, for grid-tied configurations the master inverter must first synchronise with a grid reference signal. A master-slave control scheme provides effective current sharing, but a failure in the master has the effect of possibly shutting down the system [20]. Furthermore, this configuration does not offer flexibility as it is challenging to add new DG units, and the grid is always the master, it also does not provide effective information exchange between units.

Centralised control is regarded as a fundamental approach to support the foundation and evolution of effective power management in a smart micro-grid, as well as providing a reliable frequency reference to manage generation and voltage profile [8]. There have been inverter synchronisation schemes by proposed by [15], [21], [22] that utilise Phase-Locked Loops (PLL) for frequency and phase tracking of a reference signal. Every inverter has a local feedback that is given by the PLL at its terminal. Local phase information is combined with the central information to control the inverter output.

The dynamics of a power system can change at a very rapid rate and if there is not sufficient data then it may give incorrect information about the power system or possibly result in the loss of information describing the characteristics of the network [23]. Load sharing control between inverters can be achieved with near real time information.

When inverters are operating in parallel, load sharing control is critical in maintaining the current balance. If this is not done, the output may contain circulating currents that can result in instability and damage to the system [24]. Therefore, sharing a load and balancing active power and reactive power between inverter units is a fundamental problem for parallel operation [25], [26]. Without a physical connection between DG systems in a smart micro-grid, two-way communication needs to be established over a wireless network to exchange information.

D. Wireless communication and modern Wi-Fi microcontrollers

Smart micro-grids require two-way wireless communication between all modules to maintain effective synchronisation and control of the system. However, information exchanged over a wireless communication network may be delayed or lost as a result of network factors, including the network connection and network traffic [5]. This has the potential to have a significant impact on the performance of DG systems connected to the smart micro-grid as they respond to unsynchronised commands; however, short transmission delays will not affect load sharing control. Therefore the time-varying communication delays must be taken into account using time synchronised measurements and commands with a common time source. Centralised control of a smart micro-grid can provide a traceable common time source for DG units to synchronise commands [16].

ESP32 microcontrollers are used to manage DG units within the smart micro-grid testbed and an Arduino Uno Rev 2 is integrated with the reactive power compensation unit as they pose an effective and powerful solution for low cost Wi-Fi microcontrollers.

There are various IoT platforms such as Blynk, Cayenne and Thingsboard enable a bridge to forward messages between microcontrollers over a wireless network. While Blynk requires a more complicated coding setup, it is a highly adaptive platform with a customisable user interface that can be configured to monitor and control the smart micro-grid operation.

E. Reactive Power Compensation

Reactive power oscillates between a source and load resulting in internal losses but does not contribute to net energy transport through a system or load [9]. This differs from the amount of real power that is dissipated and used by a load; the apparent power is the vector sum of reactive power and real power as shown in Fig. 2. The power factor describes the efficiency of a system and is the ratio between the real power in Watts (W) that is used to do work and the apparent power in volt-amps (VA) that is supplied; it is also the related to the phase angle, $\theta$, between the current and voltage waveforms as described in Eq. (1) [27].

$$ \text{Power factor} = \frac{\text{Real power (W)}}{\text{Apparent power (VA)}} = \cos \theta $$  \hspace{1cm} (1)

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The power factor is usually calculated by locally measuring real and apparent power data, or by implementing a current sense circuit with a current transformer and a zero-crossing detector, to detect the phase angle between the zero-crossing points of the current and voltage waveforms respectively.

Distribution companies and consumers seek to improve the power factor to the ideal case of one, to increase the active power that can be used by the load. This can be achieved with reactive power compensation, which has widespread use for its ability to reduce losses within a system, as well as other benefits such as increased voltage stability and system efficiency [27].

A residential network will have a net inductance resulting from transmission line properties and induction motors. If a load is inductive, it will consume reactive power, resulting in a phase shift between the current and voltage waveforms; parallel capacitor banks can supply a local reactance and reduce this phase angle, \( \theta \) [28].

The testbed in this project will adopt automatic reactive power compensation by switching parallel capacitor banks managed by an Arduino Uno Rev 2 Wi-Fi microcontroller to supply reactive power locally.

V. Project Design

A. Inverters in the Smart Micro-Grid

The configuration of a single inverter in the smart micro-grid testbed is shown in Fig. 3. While a smart micro-grid can integrate multiple DG units, the testbed integrates two parallel inverters and a reactive power compensation unit. A single-phase supply was chosen over a three-phase supply to cater for a residential network.

![Figure 3. Configuration of a single inverter in the smart micro-grid testbed with reactive power compensation.](image)

The CN3787 DFRobot Solar Power Manager is used to integrate an 18V solar panel with a floating 12V lead-acid battery acting as an energy storage device. The module features MPPT tracking to maximise the output of the PV array under different environmental and loading conditions.

The floating battery storage allows for excess PV power to be stored and drawn from the battery when needed. The load will draw the amount of current required, meaning that if the PV array cannot meet the supply demand, then the storage battery will supply the difference. To provide a stable 11V DC input into the inverter, a DC-DC Buck converter is used to regulate the output from the solar power manager and storage battery as their respective outputs can drift under varying conditions.

An Arduino Nano microcontroller was chosen as the inverter control device due to the compact size and true PWM output [29]. The sPWM switching scheme is generated using a timing register to compare a triangle waveform with a control sinusoidal waveform to change the duty cycle of the PWM signal. Two output pins are used to represent the positive and negative half cycles of the sPWM waveform. The code implemented was sourced from [30], and modified to allow the amplitude modulation ratio and fundamental frequency to be changed dynamically by interfacing an ESP32 microcontroller on the I2C bus. The ESP32 microcontroller is the master device on the I2C bus and sends a frequency reference required to manage generation and requests output inverter information from the Arduino to ensure the inverter output is meeting this reference.

The amplitude modulation ratio and amplitude of the inverter fundamental output voltage is adjusted by varying a DC voltage level on an Arduino Nano analogue input pin between zero and five volts. This is implemented using the Adafruit DS3502 digital potentiometer is used to accurately adjust the voltage at the Arduino Nano analogue pin. With the low pin connected to ground and the high pin of the digital potentiometer connected to the +5V supply of the Arduino, the wiper voltage is adjusted by the ESP32 microcontroller using the I2C communication protocol.

The output of the inverters is connected to the grid on secondary side of the transformer at the point of common coupling (PCC). A reactive power compensation unit is integrated to locally supply reactive power and reduce losses within the system.

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B. Wireless Communication

A Blynk server is used to bridge the communication network between Wi-Fi microcontrollers and the Blynk application is used to provide a functional user interface to control and monitor the smart micro-grid operation. Authentication tokens are issued to register individual Wi-Fi microcontrollers to bridge unique access to the cloud and enable communication between desired devices. Grid and inverter information, as well as the information from the reactive power compensation unit, can be accessed and controlled within the application Blynk developed. The testbed can operate in grid-tied or islanded mode, which is controlled from the user interface in Blynk and if the conditions are right then the testbed will respond accordingly.

ESP32 microcontrollers were chosen as the IoT devices to be interfaced with the Arduino Nano inverter modules as they present a viable solution to wireless communication and can communicate with the Arduino Nano microcontrollers using the I2C bus.

The centralised control networking configuration between the central IoT controller and the inverter IoT devices for parallel inverter control and power information exchange is shown in Fig. 4. The central IoT controller supplies frequency and voltage profile reference information to the inverter IoT devices using the Blynk server at regular time intervals. The inverter IoT devices relay this frequency and voltage profile reference information to the Arduino Nano inverter modules as gate signals on the I2C bus and requests feedback signals of the output inverter information.

The inverters output power information is exchanged over the wireless network to all devices connected to the smart micro-grid, including the central IoT controller. To achieve a traceable common time source within the smart micro-grid testbed, a real-time clock is implemented with the central controller IoT device and the other IoT devices synchronise with this common time source.

C. Reactive Power Compensation Unit

Power factor information is used by the Arduino Uno Rev 2 in the reactive power compensation unit to control switching of two relay modules, each with four relays and corresponding capacitors. The power factor is measured using a high-side current sense circuit, zero-crossing detector and an exclusive or (XOR) integrated circuit (IC) as shown in Fig. 5.

The zero-crossing detector detects the phase of zero-crossing points in the voltage waveform by referencing the inverting input to ground. An isolation transformer is used to isolate the circuitry from the supply. The high-side current sense circuit uses a differential amplifier to monitor the voltage drop across the shunt resistor and the phase of zero-crossing points of the current waveform. The outputs of the zero-crossing detector and the high-side current sense circuit produce square wave outputs, which are inputs into an XOR IC. The duty cycle of the XOR IC output is used to calculate the power factor as described by Eq. (2).
\[ \text{Power factor} = \cos \left( 180 \cdot \frac{XOR \text{ duty cycle}}{100} \right) \]  

For a resistive load, the voltage and current are in phase, and therefore the XOR output will remain constant with a duty cycle of zero per cent, this corresponds to a power factor of one. For a purely inductive load, the voltage and current are 90 degrees out of phase, this corresponds to an XOR output with a duty cycle of 50 per cent. Comparators with a DC voltage reference to the inverting input are placed after the zero-crossing detector and the high-side current sense circuit to ensure a clean switching signal and ensure the inputs to the XOR IC are of the same amplitude.

The Arduino measures the duty cycle of the XOR output, by measuring the amount of time that the XOR output is high and comparing this to the amount of time that the XOR output is low. The Arduino uses Eq. (2) to calculate the power factor once the duty cycle of the XOR output is obtained. If the power factor is one, the unit will do nothing as the maximum power factor has been achieved. If the power factor is measured to be between 0.01 to 0.99, the unit will turn on relay one to connect the first capacitor in parallel with the load. There is a one-second delay to allow the capacitor to charge before recalculating the power factor. Once again if the power factor is measured to be between 0.01 to 0.99, the unit will turn on relay two connect the second capacitor in parallel with the load. This process is repeated up to eight times.

An 8000mAh power bank is used to power the Arduino Uno Rev 2 and the five volt rail on the Arduino is used to power the relays. Arduino digital pins two to nine are used as inputs to control the eight relays. An Arduino IO expansion shield is used to increase the number of five volt and ground pins required for the two relay modules.

VI. Results and Discussion

A. Inverter Simulation

The in-built MATLAB Simulink sPWM generator and H-bridge block were used to create the unipolar sPWM switching scheme. This represents the Arduino generating a sPWM output and the H-bridge switching the sPWM signal between the ground and the DC inverter input of 11V, which increased the sPWM switching amplitude as shown in Fig. 6. The sPWM frequency modulation ratio is set to 27 to reduce subharmonics and the sPWM amplitude modulation ratio is set to unity to obtain the maximum sinusoidal output from the inverter.

Switching occurs between ground and the positive (+VDC) for the positive half cycle and between ground and negative (-VDC) for the negative half cycle, where (+VDC) and (-VDC) are the positive and negative terminals of the DC source respectively.

The sPWM signal from the H-bridge is passed through a low-pass filter (LPF) to attenuate the switching noise and obtain a sinusoidal waveform. A first order RC and a second order LC LPF were considered, the cut-off frequency for the respective filters are as follows:

\[ f_{cRC} = \frac{1}{2\pi RC} \]  
\[ f_{cLC} = \frac{1}{2\pi \sqrt{LC}} \]  

Equations (3) and (4) were used to calculate the required component values for a given corner frequency. Bode plots for the RC and LC LPF were generated to analyse the system response.

A corner frequency of 100Hz for the RC filter and a corner frequency of 60Hz for the LC filter is chosen to provide sufficient attenuation of higher frequency components without substantially attenuating components at the inverter operating frequency of 50Hz.
The frequency response for the RC and LC LPF is shown in Fig. 7. The LC filter exhibits a low phase margin and a low damping factor, resulting in a spike in the frequency response. This spike in the frequency response can be reduced by using a resistor to increase the damping factor. The LC filter has two poles and provides 40dB attenuation per decade, thus providing more significant harmonic elimination than the RC filter.

The results show two viable options for filtering. It must also be noted that that inductor and capacitor components will have an effective resistance, this will have the effect of decreasing the spike in the frequency response of the LC filter. Therefore power losses and component selection will significantly impact the operation of the fabricated testbed. Resistive losses in the RC filter will increase as the current is increased, and thus its use is not desirable in high power applications. For this reason, the LC LPF was chosen.

The inverter output was simulated using MATLAB Simulink, for a LC filter with a corner frequency of 60Hz and can be seen in Fig. 8. A series resistance of 0.5 ohm was used for the inductor to represent an approximate component resistance. MATLAB Simulink verifies the operation of the filter and inverter design, resulting in a 10.7V output at 50Hz. The experimental inverter testbed will be discussed in the next section.

B. Inverter Operation

The Arduino Nano microcontroller generates a unipolar sPWM switching scheme at a fundamental frequency of 50Hz, with the sPWM amplitude modulation ratio set to unity to obtain the maximum sinusoidal output from the inverter. Two output pins are used to represent the positive and negative half-cycles of the sPWM waveform, and the L-293D H-bridge IC increases the switching amplitude and generates a high powered sPWM signal [31]. The two sPWM outputs from the H-bridge representing the positive and negative half-cycles must be coupled using a transformer to isolate the lower potential before grounding. Without isolating the lower potential output, the H-bridge will be shorted, and the sinusoidal output cannot be obtained. The sPWM signal from the H-bridge is filtered with an LPF to attenuate the switching noise and obtain a sinusoidal waveform, using the same component values from the MATLAB Simulink simulation.

An MM2534 1:1 isolation transformer was chosen to keep the output voltage at a safe level; however, there is a voltage drop across transformer coils and induced non-linear distortion resulting from the Magnetostriction Effect. This is caused by the expanding and contracting of ferromagnetic materials when exposed to a magnetic field [32]. The output from the transformer is filtered with a second LPF of the same corner frequency to reduce the transformer noise.

A second LPF effectively reduces the high-frequency distortion, without substantially attenuating the components at the operating frequency of 50Hz, as shown in Fig. 9. This is necessary to obtain a clean AC output, as this distortion would affect inverter synchronisation.
The amplitude of the inverter output is adjusted by varying the amplitude modulation ratio of the sPWM signal, which is achieved varying a DC voltage level on an Arduino Nano analogue input pin between zero and five volts, as shown in Fig. 10. The testbed implements an Adafruit DS3502 digital potentiometer and the wiper position is adjusted using the I2C communication protocol to adjust the voltage at the Arduino Nano analogue pin.

When five volts is applied to the Arduino Nano analogue input pin, the amplitude modulation ratio is unity resulting in a maximum inverter output. When the voltage applied to the Arduino Nano analogue input pin is decreased, the amplitude modulation ratio decreases and hence, the inverter output also decreases, as shown in Fig. 10. However, as the amplitude ratio is decreased, the distortion in the inverter output appears to increase.

The Adafruit DS3502 digital potentiometer has an adjustable wiper with 127 values, as the high terminal is connected to a positive five-volt rail, this results in a 0.04V DC precision on the analogue input to the Arduino. The precision in the AC inverter output was tested by changing the Adafruit DS3502 digital potentiometer wiper position by one value; this resulted in a 0.09V variation in the inverter output when being operated at an amplitude modulation ratio close to one.

The central IoT controller in the centralised control configuration sends a frequency reference required to manage generation and voltage profile; the Inverter IoT device receives this reference over the wireless network and relays it to Arduino Nano using the I2C bus. The frequency reference allows for the fundamental frequency of the sPWM switching and hence the fundamental frequency of the inverter output to be varied. This presents a configuration which is sufficient to synchronise the output of parallel inverters when used in conjunction with the Adafruit DS3502 digital potentiometer to adjust the amplitude modulation ratio.

While the output amplitude of the inverter can be effectively adjusted by varying the amplitude modulation ratio, it should be operated with an amplitude modulation ratio close to unity to reduce subharmonics [33]. The smart micro-grid testbed operation and wireless communication between devices is discussed in the next section.

C. Smart Micro-Grid Operation

Every inverter in the smart micro-grid has a local feedback that would be given by the PLL at its terminal. This local phase information would be combined with the information from the central controller to control the power output of the inverter. The inverters in this testbed did not integrate a PLL; therefore, a phase-lock is not achieved. Instead, the exchange of a reference and inverter output information over a wireless network using the Blynk server is investigated.

When operating in an islanded configuration, the central IoT controller supplies frequency and voltage profile reference to each of the inverter IoT devices using the Blynk server at regular time intervals. For each inverter, the inverter IoT device exchanges this frequency and voltage profile reference with the Arduino Nano inverter module using the I2C bus, which configures the inverter to operate at 10V 50Hz, as shown in Fig. 11a. The Arduino Nano inverter module sends the inverter output information to the inverter IoT device using the I2C bus, which is exchanged with the other devices in the smart micro-grid, including the central IoT controller using the Blynk server.

When operating in a grid-tied configuration, the grid supplies frequency and voltage references, which changes with the supply and consumption of power in the network. In the testbed, the grid reference was provided by a signal generator at 10.1V 50.1Hz. If the grid frequency or voltage changes, the inverter modules will adjust their output to achieve synchronisation, as shown in Fig. 11b.
A real-time clock is implemented with the central IoT controller to achieve a traceable common time source within the smart micro-grid testbed. A time-stamp using this common time source is sent with each packet of information for traceability and to detect missing packets. While there varying communication delays when using the Blynk server, short transmission delays will not affect load sharing control as the system would not respond instantaneously.

If any of the devices in the smart micro-grid encounter an error, this information is sent to the central IoT controller and the Blynk application. Notifications are configured to alert the application of the units affected, as shown in Fig. 11c, which is essential for fault finding.

The inverter IoT devices can interface with the Arduino Nano inverter modules using the I2C communication protocol and can be extended to integrate with any other devices or inverter modules that are capable of the I2C communication protocol. This means that the inverter IoT devices present the potential to enable wireless and smart capabilities for devices that were not capable of doing so. Therefore, older DG units and inverter modules can be integrated into a modern smart micro-grid. The flexible infrastructure configuration using centralised control can facilitate additional inverter modules with minimal change to network configuration, making it a viable configuration for a smart micro-grid.

The Blynk server can effectively bridge communication between a central IoT controller and the inverter IoT devices. The Blynk application also provides a functional user interface to control and monitor the smart micro-grid operation, which can be configured to generate error notifications. While the wireless transmission delay using the Blynk server did not affect the smart micro-grid operation, it would be desirable to establish a local server for increased stability and an increased wireless transmission rate.

D. Power Factor Measurement Simulation

The power factor measurement circuit in Fig. 5 is simulated in LTSpice to observe the operation for different load conditions. The zero-crossing detector compares the voltage waveform on the inverting input to ground on the non-inverting input; resulting in the output switching high when the voltage is positive and low when the voltage is negative. The high-side current sense circuit uses a differential amplifier to compare the voltage drop across the shunt resistor. It is configured to switch the output high when the current waveform is positive and low when the current waveform is negative. The power factor measurement for a resistive and inductive load is shown in Fig. 12.

For a purely resistive load the current and voltage waveforms are in phase; the XOR output has a duty cycle of zero per cent as shown in Fig. 12a, resulting in a power factor of one according to equations (1) and (2). The high-frequency impulses in the XOR output in result from the cross over between the zero-crossing detector output and the high-side current sense circuit output.

For a purely inductive load, the current waveform lags the voltage waveform by 90 degrees; the XOR output have a duty cycle of 50 per cent as shown in Fig. 12b, resulting in a power factor of zero according to equations (1) and (2).
The operation of the power factor measurement circuit in Fig. 5 is confirmed using LTSpice simulations and the circuit is able to determine the power factor of a supply when used in conjunction with Eq. (2). The XOR output in Fig. 12a, has high frequency impulses that needs to be accounted for when measuring the duty cycle with a microcontroller.

F. Reactive Power Compensation Unit Operation

The power factor is calculated by measuring the duty cycle of the XOR output from the power factor measurement circuit and applying Eq. (2). Power factor information is used by the Arduino Uno Rev 2 in the reactive power compensation unit to control switching of two relay modules, each with four relays and corresponding capacitors.

The power factor measurement circuit was not experimentally built, however, the switching logic of the reactive power compensation unit was confirmed by applying a control square wave signal of varying duty cycles to represent the XOR output from the power factor measurement circuit. An inductive load will consume reactive power, resulting in internal losses and a phase shift between the current and voltage waveforms as the power factor is less than one. The reactive power compensation unit will measure the power factor and has eight relays that it will switch on to connect capacitors in parallel with the load depending on the measured power factor. When the capacitors and switched in parallel with the load, it will supply a local reactance to increase the power factor and reduce the phase angle between the voltage and current waveforms.

The reactive power compensation unit is integrated with the Blynk application to provide a functional user interface to control and monitor the operation, as shown in Fig. 13. The instantaneous power factor is printed to a widget and graphed to provide a graphical representation over time. There is also a terminal window describing the mode of operation for the device.

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Figure 12. Power factor measurement simulation using LTSpice. a) Resistive load; b) Inductive load.

Figure 13. Blynk smart micro-grid application interface reactive power compensation unit. a) Device turned off; b) Device turned on and all relays connected.
The reactive power compensation unit configured with the Arduino Uno Rev 2 and integrated with Blynk poses an effective solution to supply reactive power locally to increase system efficiency. The power factor measurement circuit should be experimentally built and integrated with the rest of the unit that has been assembled and configured, as described in Appendix A.

VII. Conclusion

This project implemented low-cost Wi-Fi microcontrollers using Blynk to manage inverter modules in a smart micro-grid testbed. Testing found that a Blynk server can effectively bridge communication between the Wi-Fi microcontrollers to enable information sharing in the smart micro-grid testbed. However, to further enhance the stability and reliability of the smart micro-grid network, a local Blynk server should be integrated to replace the current Blynk cloud server used.

Wi-Fi microcontrollers can interface with and manage inverter modules capable of the I2C communication protocol in a smart micro-grid testbed. This presents the potential to enable wireless and smart capabilities for DG units not capable of doing so to integrate them into a modern smart micro-grid effectively. Therefore, additional inverter modules can be integrated with minimal change to network configuration using this flexible infrastructure configuration with centralised control, making it a viable configuration for a smart micro-grid.

VIII. Future Work

The Blynk cloud server is able to effectively bridge messages between Wi-Fi microcontrollers in the smart micro-grid and allow for information exchange, however, a local Blynk server should be created to provide better stability and zero latency as it does not rely on cloud service and thus can increase the transmission rate of messages on the network [8].

If a monitoring platform with Blynk were to be rolled out on a large scale, the project within Blynk should be published as an application to the IOS application store or the Google Play store to allow consumers to set up and manage DG in smart grids with Wi-Fi microcontrollers. The application should be published as a dynamic provisioning type to allow end-users to configure their system with dynamic authentication tokens. As a result, consumers can manage their own smart grid once the Wi-Fi microcontrollers are configured with the Arduino code presented.

The power factor measurement circuit proposed should be built and integrated to complete the implementation of the reactive power compensation unit.

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Deliverables

This project experimentally implemented low-cost Wi-Fi microcontrollers using Blynk to manage inverter modules in a smart micro-grid testbed. The additional documentation required to complete this project includes Arduino microcontroller code, the Blynk application interface and Simulink schematics. These have submitted to my supervisor A/Prof. Hemanshu Pota.

Additionally the Blynk application used to control and monitor the smart micro-grid operation, as well the reactive power compensation unit can be accessed using QR code in Fig. 14.

![QR code to access Blynk application.](image-url)
References


Appendix A – Reactive Power Compensation unit

The experimental layout of the Reactive Power Compensation unit is shown in Fig. 1. Power factor information is used by the Arduino Uno Rev 2 in the reactive power compensation unit to control switching of two relay modules, each with four relays and corresponding capacitors. The capacitor bank has a high terminal and a ground terminal to be connected in parallel with the load. There is a section reserved for the power factor measurement circuit to be implemented in the testbed, and the XOR output will be an input to the Arduino Uno Rev 2 to provide power factor information, as described by Eq. (1).

\[ \text{Power factor} = \cos \left( 180 \cdot \frac{\text{XOR duty cycle}}{180} \right) \] (1)

The Arduino Uno Rev 2 uses Eq. (1) to calculate the power factor once the duty cycle of the XOR output is obtained. The measured power factor will determine the amount of relays that are turned on. To achieve effective reactive power compensation, the capacitance of the capacitor bank will have to be modified.

An 8000mAh power bank is used to power the Arduino Uno Rev 2 and the five volt rail on the Arduino is used to power the relays. There is a low current draw from the Arduino Uno Rev 2 when the relays are not being switched and therefore the power bank is able to support sustained operation. The power bank also supports through charger, such that the device is able to be charged while powering the reactive power compensation unit. Arduino digital pins two to nine are used as inputs to control the eight relays. An Arduino IO expansion shield is used to increase the number of five volt and ground pins required for the two relay modules.

The reactive power compensation unit is controlled and monitored from the Blynk application, which can be accessed by following the QR code in Fig. 2.

Figure 1. Reactive Power Compensation unit.

Figure 2. QR code to access Blynk application.