Abstract—Intentional islanding describes the condition in which a microgrid, which consists of a load and a distributed generation (DG) system, is isolated from the remainder of the utility system. In this situation, it is important for the microgrid to continue to provide adequate power to the load. Under normal operation, each DG inverter system in the microgrid usually works in constant current (or constant power) control mode in order to provide a pre-set power to the main grid. When the microgrid is cut off from the main grid, each DG inverter system must detect this islanding situation and switch to a voltage control mode. In this mode, the microgrid will provide a constant voltage to the local load. This paper describes a control strategy to implement intentional islanding operation of microgrids. The described method proposes two control algorithms, one for grid-connected operation and the other for intentional islanding operation.

I. INTRODUCTION

Islanding is a condition in which a microgrid or a portion of the power grid, which contains both load and distributed generation (DG), is isolated from the remainder of the utility system and continues to operate [1]. Some distinctions of islanding are [2]:

- **Non-intentional** islanding occurs if after the fault it is not possible to disconnect the DG; non-intentional islands must then be detected and eliminated as fast as possible;
- **Intentional** islanding refers to the formation of islands of predetermined or variable extension; these islands have to be supplied from suitable sources able to guarantee acceptable voltage support and frequency, controllability and quality of the supply, and may play a significant role in assisting the service restoration process;
- microgrids, as particular types of intentional islands, basically operated in autonomous mode, not connected to the supply system; the whole microgrid can be seen from the distribution system as a single load and has to be designed to satisfy the local reliability requirements, in addition to other technical characteristics concerning frequency, voltage control and quality of supply.

The disconnection of the DG once it is islanded is required by the IEEE Std. 929-2000 [3]. With the increasing competition amongst the power companies to secure more and more customers, pressure to maintain a high degree of uninterrupted power service quality and reliability are made by the utility companies [4]. Thus, in a deregulated market environment, current practices of disconnecting the DG following a disturbance will no longer be a practical or reliable solution. As a result, the IEEE Std. 1547-2003 states, as one of its tasks for future consideration, the implementation of intentional islanding of DGs [5].

During the normal grid connected operation, each DG inverter system in a microgrid is usually operated to provide or inject pre-set power to the grid, which is the current control mode in stiff synchronization with the grid [6]. When the microgrid is cut off from the main grid, intentional islanding operation, each DG inverter system has to detect this islanding situation and has to be switched to a voltage control mode to provide constant voltage to the local sensitive loads [7]. This paper describes a control strategy to implement intentional islanding operation of microgrids. The described method proposes two control algorithms, one for grid-connected operation and the other for intentional islanding operation. Fig. 1 shows the main circuit topology.

![Fig. 1. Schematic diagram of the grid-connected inverter system](image-url)
II. SYSTEM DESCRIPTION

A. Worst case load: Parallel RLC load

The ability of an inverter to detect islanding is largely dependent on the electrical load present in the island [8]. Some loads do not interfere with islanding detection, whereas others make islanding detection extremely difficult. Studies have shown that the worst-case load that could be expected to cause the most difficulty islanding detection is a parallel RLC load [9] – [11]. Such loads may be conveniently described using quality factor $Q_f$. This $Q_f$ is defined as follows:

$$Q_f = \frac{\text{Energy stored} - \text{during} - a - \text{acycle}}{\text{Energy dissipated} - \text{per} - \text{cycle}}$$

(1)

The value of $R$ can be determined by using the inverter active power (equation 2) and the values for $L$ and $C$ can be determined by using the $Q_f$ (equations 3 and 4).

$$R = \frac{v_a^2}{P_{DG}}$$

(2)

$$L = \frac{v_a^2}{\omega Q_f}$$

(3)

$$C = \frac{Q_f}{V_a^2 \omega}$$

(4)

B. LCL filter

To attenuate the current ripple produced at the output of the inverter, a LCL filter is placed in between inverter and grid [12]. In LCL filter, inductor on inverter side is used to limit current ripple generated by inverter and capacitor is used to attenuate the current ripple. Also, the LCL-filter offers the possibility to reduce the harmonics caused by the switching of the converter with reduced values of the inductance, compared to the L-filter case.

The LCL filter can be designed using the following step-by-step procedure [12]:

- Select the required current ripple on the converter side → design the inner inductor $L$. The outer inductor value can then be determined as a function of $L$, using the index $r$ for the relation between the two inductances

$$L_g = rL$$

(5)

- Select the reactive power absorbed at rated conditions → determine the capacitor value. Take $x$ as a percentage of the reactive power absorbed under rated conditions

$$C_f = xC_h$$

(6)

- Select the desired current ripple reduction → knowledge of $r$ and then design the outer inductor $L_f$. The ripple attenuation, calculated neglecting losses and damping of the filter can be rewritten as

$$\frac{i_g(h_{nw})}{i(h_{sw})} = \frac{1}{|1 + r(1 - ax)|}$$

(7)

where $h_{nw}$ is the order of the switching frequency harmonic, $i_g(h_{nw})$ are currents harmonic at the switching frequency, and $a = LC_f \omega^2_{SW}$ is a constant.

- Verify the resonant frequency obtained

$$\omega_{res} = \frac{L_T}{LL_T C_f}$$

(8)

where $L_T = L + L_f + L_{TT}$, $L$ is the inductance on the converter side, and $L_T$ is the transformer inductance.

- Set the value of the passive damping. This damping must be sufficient to avoid oscillation. At the resonant frequency the impedance of the filter is zero. The aim of the damping is to insert impedance at this frequency to avoid oscillation. Hence, the damping value is set to a similar order of magnitude as the series capacitor impedance at the resonant frequency.

- Verify the filter attenuation under other load conditions and with other switching frequencies.

C. Controller

Under normal operation, each DG inverter system in the microgrid usually works in constant current (or constant power) control mode in order to provide a pre-set power to the main grid. When the microgrid is cut off from the main grid, each DG inverter system must detect this islanding situation and switch to a voltage control mode. In this mode, the microgrid will provide a constant voltage to the local load.

The controller presented in this work (sections III and IV) provides constant DG output and maintains the voltage at the PCC before and after the grid is disconnected.

III. GRID CONNECTED OPERATION MODE

For grid-connected operation, the controller shown in Fig. 1 is designed to supply constant current output. A phase locked loop is used to determine the frequency and angle reference of the Point of Common Coupling (PCC) voltage. To simplify the design and operation of the controller, the control of the system is designed in a synchronous reference frame (SRF) [13]. Fig. 2 shows this control topology employing synchronous frame current control.
The inverter currents are transformed into a synchronous frame by Park’s transformation and regulated in dc-quantity corresponding to the current references $I_{dref}$. In the following stage, the voltage references in dc-quantities $V_{dq}$ which being processed by PI controllers are transformed into a stationary frame by the inverse of Park’s transformation and utilized as command voltages for generating high frequency pulse width modulated (PWM) voltage.

When using the current control, the output current from the filter is fed back and compared with reference current $I_{ref}$ and the error is passed to the PWM to generate voltage reference for the inverter. In order to get a good dynamic response $V_{dq}$ is fed forward. Fig. 3 shows the block diagram of the DG interface control for grid-connected operation. For unity power factor operation, $i_{qref}$ is set to zero.

### Islanding Detection

The instant at which the intentional islanding occurs must be detected in order to the inverter changes between grid-connected to intentional island modes. The detection is achieved using a SRF phase-locked loop (SRF-PLL) [14]. The schematic of the SRF–PLL is illustrated in Fig. 4.

This structure uses the coordinate transformation form abc $\rightarrow$ dq and the lock is realized by setting the $V_d$ to zero. A regulator, usually PI, can be used to control this variable and the output of this regulator is the grid frequency. Additionally to the frequency, the SRF-PLL is capable to track the magnitude of its input signals, e.g. the grid voltages. These two parameters, frequency and voltage magnitude, are used in the islanding detection algorithm to detect the grid condition. Then, the algorithm sends a signal that switches the inverter to the suitable interface control. The algorithm is shown in Fig. 5.

### Load Shedding

Load shedding is defined as the process in which a part of the system loads is disconnected according to certain priority in order to steer the power system from potential dangers with the least probability of disconnecting the important loads [15]. To determine the amount of load to be disconnected the following algorithm is proposed:

1. get the voltage amplitude expression before load shedding

   
   
   \[
   V_d(t) = V_d + \Delta V_d(t) = V_d + i_{dqp}Z_{gmp}R_p + \frac{e^{2i\omega t}(1 + e^{i\omega t} - 2e^{i\omega t}\cos(\omega t))}{R_p^2 + Z_{gmp}^2}
   \]

   \(9\)

2. derive the slope of the voltage amplitude

   
   
   \[
   s = \frac{d\Delta V_d(t)}{dt} = \frac{e^{2i\omega t}i_{dqp}Z_{gmp}(e^{i\omega t}\sin(\omega t)R_p + (-1 + e^{i\omega t}\cos(\omega t))Z_{gmp})}{(1 + e^{i\omega t} - 2e^{i\omega t}\cos(\omega t))(R_p^2 + Z_{gmp}^2)}
   \]

   \(10\)

3. derive $I_{dqp}$ at a fixed time $t_0$

   
   
   \[
   i_{dqp} = \frac{1}{\omega Z_{gmp}(e^{i\omega t}\sin(\omega t)R_p^2 + (-1 + e^{i\omega t}\cos(\omega t))Z_{gmp})}
   \]

   \(11\)

4. Obtain the value of load to be shed

   
   
   \[
   R_{gmp} = \frac{1}{\sqrt{\frac{I_{dqp}^2}{Z_{gmp}^2} - 1}}
   \]

### IV. INTENTIONAL ISLANDING OPERATION MODE

#### A. Controller

The voltage closed loop control for intentional islanding operation is shown in Fig. 6.
The control works as voltage regulation through current compensation. This controller uses voltage compensators to generate current references for the current regulation.

As shown, the load voltage, $V_d$, is forced to track its reference by using a PI compensator. The output of this compensator, $I_{ref}$, is compared with the load current, $I_d$, and the error is fed to a current compensator (PI). The output of the current compensator acts as the voltage reference signal that is fed to the sinusoidal pulse-width modulator (SPWM) to generate the high frequency gating signals for driving the three-phase voltage source inverter.

The current loop is included to stabilize the system and to improve the system dynamic response by rapidly compensating for near-future variations in the load voltages [16].

### B. Synchronization for grid reconnection

When the grid-disconnection cause disappears, the transition from islanded to grid-connected mode can be started. To avoid hard transients in the reconnection, the DG has to be synchronized with the grid voltage [17]. The DG is operated in synchronous island mode until both systems are synchronized. Once the voltage in the DG is synchronized with the utility voltage, the DG is reconnected to the grid and the controller will pass from voltage control mode to current control mode. This synchronization is achieved by implementing the following algorithm:

- Assume that the phase difference between grid voltage and inverter voltage is given by:
  \[ \phi = \angle V_G - \angle V_i \]  

- In order to get information of $\phi$, two sets of voltage values are used:
  \[ k = V_{sa}V_{ga} + V_{sb}V_{gb} + V_{sg}V_{gc} = \frac{3}{2} \cos(\phi) \]  
  \[ g = V_{sg}V_{gb} + V_{sb}V_{gc} + V_{sa}V_{ga} = \frac{3}{4} [- \cos(\phi) + \sqrt{3} \sin(\phi)] \]  

Using the variables $k$ and $g$, $\sin(\phi)$ can be found as:
  \[ \sin(\phi) = \frac{\frac{3}{4} - \frac{2}{\sqrt{3}} k}{\sqrt{3}} \]  

The implementation of this synchronization algorithm is shown in Fig. 7.

V. Simulation Results

The performance of the proposed control strategies was evaluated by computer simulation using SABER. The RLC load was adjusted to be resonance at 60 Hz and consumes 10 KW. The DG system was design to supply 10 KW and zero reactive power. The system was operated initially as grid-connected operation. The grid was disconnected at 0.3 seconds, and this event was detected at 0.30155 seconds. After 0.30155 seconds the control mode was changed from current controlled to voltage controlled operation. Fig. 8 shows the voltages and currents at the PCC before and after grid disconnection.

The grid was re-connected at 0.6 seconds. The DG was operated in synchronous island mode until both systems were re-synchronized.

Fig. 9 shows the synchronization of voltages at both ends of the PCC when the synchronization algorithm start to work at $t = 0.6$ seconds in the intentional islanding mode. The proposed algorithm successfully forces the voltage at the DG to track the voltage at the grid. As can be seen, both systems are synchronized after 0.18 seconds.

Once the synchronization was completed, the DG was reconnected to the grid and the controller was passed from voltage control mode to current control mode (Fig. 10).
Fig. 11 shows the phase voltage, $V_a$, without and with the synchronization algorithm implemented. As can be seen, the algorithm avoids a hard transient in the reconnection from intentional islanding operation to grid-connected operation.

![Fig. 11. Phase voltage without and with synchronization](image)

When there is a power mismatch between the DG supplied power and the load consumed power, the magnitude of the voltage will be out of its normal range ($0.88 < V < 1.1 \, \text{pu}$). Fig. 12 shows the theoretical voltage transients for the worst case load under various power differences (from 50% to +50%) after main power outage.

![Fig. 12. Voltage Transients of Worst Case Load at Main Power Outage](image)

For both cases (mismatch of -25% and -50%) when the voltage is out of the normal operating point, the load shedding algorithm cut off the power difference from the load and the voltage was brought back to the normal range ($0.88 – 1.1 \, \text{pu}$) for intentional islanding operation.

### VI. CONCLUSION

Through this paper, control, islanding detection, load shedding, and re-closure algorithms were proposed for the operation of grid-connected DG. A controller was designed with two interface controls, one for grid-connected operation and the other for intentional-islanding operation. An islanding detection algorithm, which was responsible for switching between the two controls, was designed.

The simulations results showed that the detection algorithm can distinguish between islanding events and changes in the loads and apply a load shedding algorithms when needed. The reclosure algorithm causes the DG to resynchronize itself with the grid. Also, it is shown that the response of the proposed control schemes is capable of maintaining both voltage and frequency within the standard permissible levels during grid-connected and islanding operation modes.

### ONGOING WORK

A hardware prototype of Fig. 1 will be implemented for experimental verification. The control, PLL, detection, and re-closure algorithms will be programmed using a universal DSP control board developed at the Power Electronics and Motor Drives Laboratory in Michigan State University. The system will be connected to a 3Φ, 208 V grid interconnect to experimentally verify the simulation results. Shown in Fig. 14 are the inverter, the DSP board, the filter, and the load.

![Fig. 14. Implementation of load shedding](image)

### REFERENCES


