Islanding Detection Method for a Hybrid Renewable Energy System

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Abstract- The Hydrogen Research Institute (HRI) developed a hybrid renewable energy power system that uses a wind turbine, a photovoltaic array and a fuel cell. In order to fulfill utility requirements , an islanding protection device is being developed. This paper presents the passive (Under/Over Voltage, Under/Over Frequency) and active (Sandia Frequency Shift and Sandia Voltage Shift) protection methods that were chosen to be added to the system. Those four methods were combined in an innovative way in order to benefit from the strengths of each of them. This way, the islanding protection will be more efficient and the non detection zone will be reduced. This paper also presents a Matlab/Simulink model of the protection device and the simulation results that were obtained using different critical operating conditions for which the clearing times can surpass those defined by the Canadian standard C22.2 No 107.1-01. This standard is similar to the IEEE 1547 standard with a few differences. Finally, the paper presents the experimental results for a grid-connected inverter, designed by the HRI, which uses the islanding protection method presented above.

Keywords- Renewable energy system, distributed generation, islanding protection, islanding detection, modeling.

1. Introduction

Since the society becomes increasingly concerned to save energy and preserve the environment, the interest toward the “green” distributed generation systems, such as photovoltaic arrays and wind turbines, increases year after year [1], [2]. Other sources, such as micro-turbines and fuel cells, are also in development. This confirms that the opportunities to interconnect these sources with the utility grid will rise continuously in the future.

However, the interconnection of these renewable distributed generation systems with the grid introduces some technical problems. The main issue is the fact that the grid operator does not control these power sources. This can lead to islanding. This situation occurs when one or many sources continue to feed power to a part of the grid that is disconnected from the main utility [3]. Islanding can be caused by a grid failure or by an intentional disconnection of a part of the grid. Islanding situations can damage the grid itself or equipments connected to the grid and can even compromise the security of the maintenance personnel that service the grid [4]. To avoid this, an interface connecting the distributed generators to the grid must be able to detect islanding and to disconnect the sources from the grid when islanding occurs. The clearing time (disconnection time) must be below that specified in the Canadian standard C22.2 No 107.1-01 [5].

As a part of its renewable energy project, the Hydrogen Research Institute (HRI) developed a power interface that is used to tie securely to the grid its hybrid renewable energy system (RES). The HRI's RES uses a fuel cell, a photovoltaic array and a wind turbine (Fig. 1). A great interest is shown toward the islanding detection methods that are integrated to an inverter because they do not require the installation of specific equipment on the grid nor do they require the collaboration of the utility's operator. This way, these protection systems can be more flexible and they are generally cheaper than the islanding detection methods, such as the Impedance Insertion and Use of Power Line Carrier Communications methods, that require equipment located at the grid level [6].

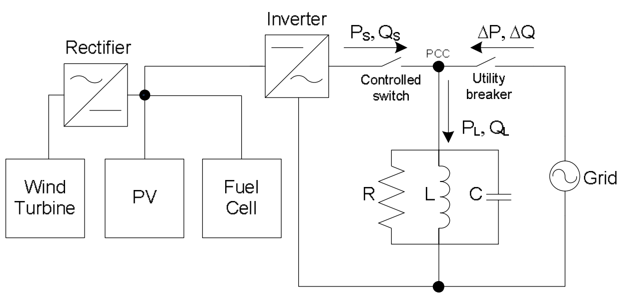

Fig. 1. Hybrid RES Connection to the Grid

This paper first presents the islanding detection and protection methods integrated to the RES inverter. The HRI improved the protection system by combining two passive islanding detection methods, Under/Over Voltage and Under/Over Frequency, and two active methods, Sandia Frequency Shift and Sandia Voltage Shift. This way, the non detection zone can be reduced. This paper then presents a model of the hybrid system with its protection methods that were developed using Matlab/Simulink. The simulation results obtained from different critical operating conditions for which the clearing times can surpass those defined by the Canadian standard C22.2 No 107.1-01 will be shown and analyzed. This standard is similar to the IEEE 1547 standard with a few differences. Finally, the paper presents the experimental results for an inverter, designed by the HRI, which uses the islanding protection method presented above. This inverter was tested for all the critical conditions identified during the simulations.

2. Islanding Protection Methods

Most of the protection methods found in the literature were developed for distributed generation systems that use photovoltaic arrays. Currently, there exist more than fifteen islanding detection methods [6-7]. These methods can be grouped into three categories: passive methods integrated to an inverter, active methods integrated to an inverter and grid-level methods.

The passive methods continuously monitor one or more parameters at the point of common coupling (PCC). When one of these parameters goes over or under a predefined threshold, the inverter operation is stopped. The parameters that are more commonly used are the voltage's amplitude, frequency or phase and the harmonics at the PCC. The passive methods thus provide a good low-level protection and they can detect islanding up to a certain point. When the grid is disconnected, the voltage often varies enough to trigger these methods. However, these methods present most of the time a fairly large non-detection zone (NDZ). In order to correct this, these methods must be coupled with other methods.

The active methods were developed to reduce the NDZ of the passive methods. The active methods force some variations of the inverter's output current to induce variation of the PCC's voltage upon islanding. These methods generally use a positive retroaction applied to the PCC voltage's amplitude or frequency. This retroaction introduces a perturbation that will destabilize the system, thus allowing a faster islanding detection. If a variation of the PCC voltage's amplitude or frequency is measured, the method will allow the system to try to amplify this variation. When the grid is still connected, its stability prevents any variation of the voltage's amplitude or frequency. On the other hand, when it is disconnected, these values tend to differ from the reference values. The active methods thus try to increase this variation by increasing or decreasing the inverter's output current amplitude or frequency. Since the grid is disconnected, this variation will again induce a voltage variation. This will be amplified again by the inverter and so on until the voltage's amplitude or frequency crosses the detection thresholds.

The grid-level methods need the installation of specific equipments at the utility level. These devices could be capacitor banks that modify the impedance seen from the PCC when the grid is disconnected. They could also be transceivers that send a signal between the utility and the consumers, thus indicating the grid status continuously. However, these methods generally require huge capital investments by the utility's operator, making this option less attractive.

Table 1 shows an overview of the advantages and disadvantages of the most popular methods found in the literature [5, 8].

3. Islanding Protection System for the HRI'S RES

An analysis of the different islanding detection methods allowed the selection of an appropriate method for the system. The chosen method is a combination of two passive methods and two active methods. This choice was made in order to increase the efficiency of the islanding detection system by reducing the non-detection zone.

The Under/Over Voltage and Under/Over Frequency methods are used as a basic protection for the system. The inverter should disconnect from the grid if the PCC voltage's amplitude or frequency crosses the defined thresholds. The Canadian standard C22.2 No 107.1-01 specifies that the PCC voltage's amplitude should stay between 88% and 110% of the nominal value and its frequency should stay between 59.5 Hz and 60.5 Hz. Table 2 compares the voltage and frequency operation limits given by the Canadian standard to those given by the IEEE 1547 standard [3,5]. Both standards apply for a grid that has a rated voltage of 120 V_{RMS} at 60 Hz. This table shows that they are very similar.

The second chosen method is an active method named Sandia Frequency Shift (SFS), which is also named Active Frequency Drift with Positive Feedback (AFDPF) [6, 9-11]. This method is known for its high efficiency [12]. It has one of the smaller non-detection zones. Moreover, it is inexpensive and simple to implement and it remains efficient even when many inverters are connected to the same PCC. However, this method lightly reduces the output current waveform's quality and it can produce instability when connected to a weak grid. Regardless, it is still a good compromise between the efficiency of the detection, the waveform quality and the effect on the transient behaviour of the system.

The SFS is an improved version of another method named Active Frequency Drift or Frequency Bias [10]. The SFS applies a positive retroaction to the PCC voltage's frequency and it tries to destabilise the grid by modifying the inverter's output current frequency in order to detect islanding faster.

The inverter's output current frequency is forced to a different value than that of the grid by adding truncations or dead times to the current's waveform (Fig. 2). This allows the increase or the decrease of the frequency. The duration of the truncations or the dead times and the current's frequency is determined by the following equations:

$$W = W_0 + K_F\,(F_{PCC} - F_{Grid}) \quad (1)$$

$$W_t = (W\,T_{Grid})/2 \quad (2)$$

$$F_{Inverter} = 1/(T_{Grid} - 2W_t) \quad (3)$$

W : Truncation or dead time duration [%]
W_0 : Initial duration of the truncation or dead time [%]
K_F : SFS gain [%/Hz]
F_{PCC} : PCC voltage's frequency [Hz]
F_{Grid} : Grid voltage's frequency (60 Hz)
W_t : Truncation or dead time duration [s]
T_{Grid} : Grid voltage's period (1/60 s)
$F_{Inverter}$: Frequency of the inverter's output current sine part [Hz]

W_0 is the duration of the waveform's dead time when the frequency error is zero, and is defined as a percentage of the grid voltage's period. The K_F gain amplifies the frequency variations by multiplying the difference between the measured PCC voltage's frequency and the nominal grid's frequency (60 Hz). $F_{Inverter}$ is the frequency of the inverter's output current sine part.

The inverter's output current waveform is set back to zero at each zero crossing of the PCC voltage in order to stay synchronized with the grid. This way, the current's waveform will be back to zero before the voltage's waveform when the inverter's frequency is higher than that of the grid. The current's waveform will thus stay at zero until the next zero crossing of the voltage occurs, and a new sinusoidal half-cycle will begin at this moment. This behaviour will produce a short dead time in the inverter's output current waveform. On the other hand, when the inverter's frequency is lower than that of the grid, the voltage's waveform will be back to zero before the current's waveform, thus forcing the current back to zero. This will produce a truncation of the current's waveform. As shown on Fig. 2, the current's waveform presents a dead time when $F_{Inverter} > F_{Grid}$ and it is truncated when $F_{Inverter} < F_{Grid}$.

Table 1. Characteristics of the most popular islanding detection methods

	NDZ	Lowers Waveform Quality	Influenced by the Number of Connected Inverters	Influenced by the Penetration Level	Characteristics
U/O Voltage U/O Frequency	Large	No	No	No	Variable and long reaction time
Voltage Phase Jump Detection	Large	No	No	No	Starting of certain loads can causes nuisance trips
Slip Mode Frequency Shift	Small	Yes	No	Yes	Difficulties with high Q load, can be inefficient in some cases
Frequency Bias	Large	Yes	No*	Yes	Inefficient with high Q load
Sandia Frequency Shift	Small	Yes	No	Yes	Inefficient with high Q load
Sandia Voltage Shift	Small	Yes	No	Yes	Not influenced by high Q load
Impedance Insertion	None	No	No	No	Very expensive, reaction time can be long
PLCC	None	No	No	No	Very expensive

* Require an agreement between the inverter's manufacturers

Table 2. Inverter's frequency and voltage operation limits for the Canadian standard and the IEEE 1547 Standard

IEEE 1547 standard		**Canadian standard C22.2 No. 107.1-01**	
Frequency at the PCC* (Hz)	**Clearing time (cycles)**	**Frequency at the PCC* (Hz)**	**Clearing time (cycles)**
f < 59.3	10	f < 59.5	6
f > 60.5	10	f > 60.5	6
Voltage at the PCC* (V_{RMS})	**Clearing time (cycles)**	**Voltage at the PCC* (V_{RMS})**	**Clearing time (cycles)**
V < 60	10	V < 60	6
60 ≤ V < 106	120	60 ≤ V ≤ 106	120
132 < V < 144	60	132 ≤ V ≤ 164	120
V ≥ 144	10	V > 164	2

* PCC: Point of Common Coupling

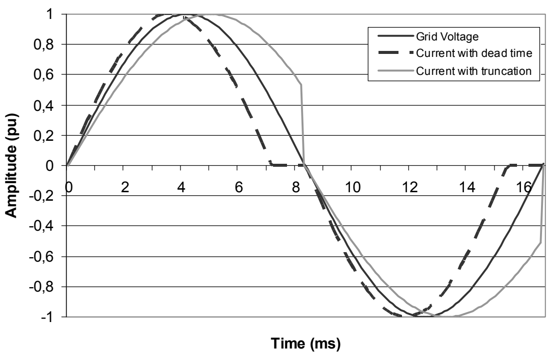

Fig. 2. Waveforms with dead times and truncations

The efficiency of the Sandia Frequency Shift method decreases significantly when the load's quality factor is high. To correct this, a fourth detection method called Sandia Voltage Shift (SVS) [6, 9, 11] will be added. The main advantage of this method is that its efficiency does not change with the load's quality factor. It will then be able to complement the Sandia Frequency Shift method. The SVS method also lightly degrades the output current's waveform quality. It has been demonstrated that the combination of the two methods is very efficient for detect islanding and it presents a very small non-detection zone [6]. The SVS method is very similar to the SFS, except that it applies a positive retroaction to the PCC voltage's amplitude instead of to its frequency. It then controls the output current according to Equation 4.

$$I_{\text{Inverter}} = K_V\,(V_{PCC} - V_{Grid}) \qquad (4)$$

Where K_V is gain expressed in A/V that multiplies the difference between the PCC voltage's amplitude and the grid voltage's nominal value (120V_{RMS}).

The implemented islanding detection system is therefore a combination of Under/Over Voltage, Under/Over Frequency, SFS and SVS methods.

4. Islanding Detection System Model

The model of the implemented islanding detection system was developed with Matlab/Simulink and its SimPowerSystems toolbox (Fig. 3). The inverter is modeled as a controlled current source. The inverter's model includes all the algorithms needed by the islanding detection system. These algorithms are based on the equations explained in section III. The inverter's output current is variable and it can present dead times or truncations. A controlled switch disconnects the inverter from the grid when islanding is detected. The local load is modeled as a parallel RLC circuit. The value of the components can be changed according to the specific case that is to be tested. The grid is modeled as a controlled voltage source that produces a harmonic content that comply with the maximum level defined by the main utility operator in Quebec (Hydro-Québec) [13]. It also includes a typical line impedance

[14] and a utility breaker used to simulate a grid disconnection.

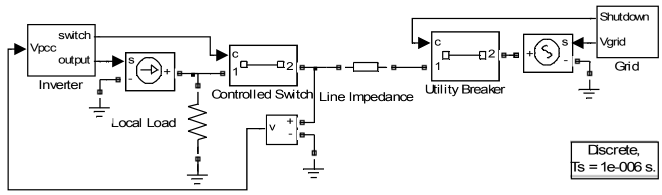

Fig. 3. System's model implemented with Matlab

The islanding detection system was tested for different operating conditions that reproduce the worst cases, which are the cases where the clearing time is the longest. These critical cases were found in the literature [8, 15] and are listed below.

1. The load's resonant frequency is close to that of the grid;
2. The power generated by the distributed source is close to that consumed by the local load ($\Delta Q = 0$ and $\Delta P = 0$);
3. The load's quality factor (Q) is near 2.5.

Under normal conditions, the inverter's output current frequency tends to drift toward the load's resonant frequency when the grid is disconnected. When there is no active control over the output current's frequency to force it outside the allowed value, the islanding situation could last too long. In a similar way, the PCC voltage's amplitude variation would be hard to measure if the active and reactive power generated by the inverter is close to that consumed by the load. In this particular case, the detection methods may not be able to detect islanding. However, an active control of the voltage's amplitude will force the voltage to go over the thresholds, thus allowing for the detection of the islanding. The load's quality factor is an important parameter that can change the detection system's ability to detect an islanding situation. An RLC load with a higher quality factor is indeed more resonant. This implies that the load's resonant frequency is more dominant, which also means that it is more difficult for the detection system to force the system's frequency outside the bounds when the grid is disconnected. Equation 5 shows that this occurs when the load presents a high capacitance C and a low inductance L, or when its resistance R is high.

$$Q = R\,(C/L)^{-1/2} \qquad (5)$$

Equation 6 defines a system where the active power P and the reactive power consumed by an inductor (Q_L) and consumed by a capacitor (Q_C) are measured at 60 Hz.

$$Q = (1/P)\,(Q_C \times Q_L)^{1/2} \qquad (6)$$

Knowing that $Q_L = Q_C = Q_{vars}$ at the load's resonant frequency, it is possible to deduce Equation 7.

$$Q = Q_{vars}/P \qquad (7)$$

A utility engineers discussion group determined that the maximal value for the quality factor of a load connected to a grid is 2.5 [15-16].

This way, the maximal value for Q_L and Q_C will be 2.5 times greater than the active power P consumed by the load.

5. Simulation Results

The hybrid RES model was simulated for the critical cases identified above. These cases occur mostly when the load's resonant frequency is near that of the grid, when the active and reactive power provided by the inverter are close to that consumed by the load and when the quality factor Q of the load is high. It was then possible to verify the efficiency of the chosen islanding detection methods and to predict their behaviour for a real system.

Case 1

The first simulated case represents a local load that has a resonant frequency near 60 Hz and a 0.5 quality factor. Since this is a low quality factor, the detection system should react quickly. In this case, the load's power factor is around 0.9, which is a realistic value.

Figure 4 shows the results for this simulation. The first two plots show the PCC voltage's amplitude and frequency. The next plot shows the state of the switch that is used to disconnect the inverter from the grid (the switch is closed when this value is 1). The switch's state drops to 0 when islanding is detected. In these simulations, the utility switch is opened at 0.4 s to reproduce a breakdown.

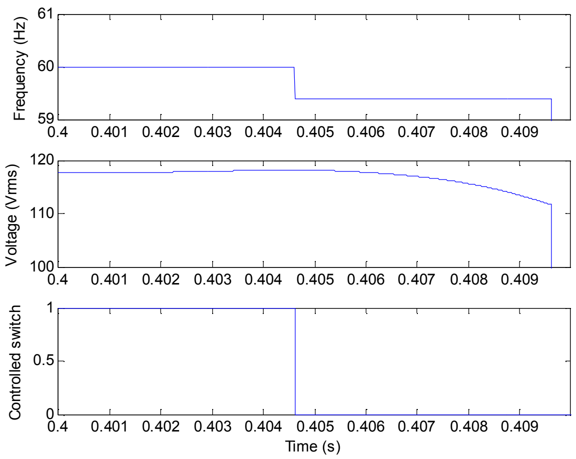

Fig. 4. PCC voltage's amplitude and frequency when the load's resonant frequency is near 60 Hz and Q = 0.5.

In this case, the frequency variation produced by the grid disconnection is sufficient to trigger the Under/Over Frequency method. Indeed, this happens the same way even when the active methods are deactivated. It is then possible to affirm that in this particular case, when the load is not too demanding of the distributed generation source, the SFS and SVS methods are not useful and they do not accelerate the disconnection. The disconnection happens in less than a half-cycle (0.007 s), which is well under the most strict disconnection time (0.1 s) required by the Canadian standard C22.2 No 107.1-01.

Case 2

This is the matched load case, which occurs when the power provided by the distributed generation source nears the power consumed by the load. Figure 5 shows the results for a resistive load that consumes the exact amount of power that is provided by the inverter (P_{load} = P_{source}). The utility switch is opened at 0.4 s to reproduce a breakdown.

The simulation shows that both the SFS and the SVS methods were able to detect the islanding situation with a clearing time approximately equal to 0.015 s (1 cycle), which is much lower than the time required by the standard. Figure 5 shows that when the SFS and SVS methods are coupled, the SVS method is faster than the SFS method and it disconnects the inverter when the voltage drops below 106 V (88% of the nominal value).

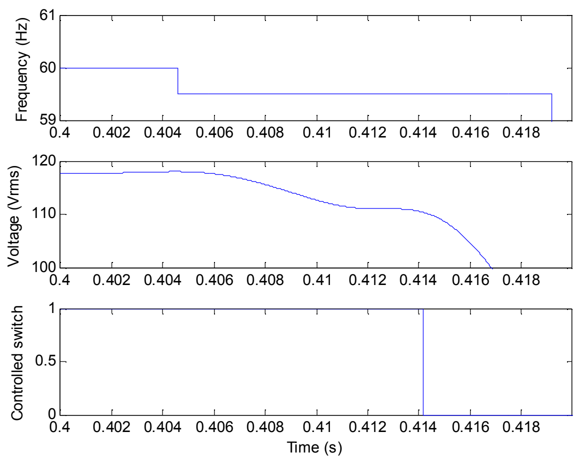

Fig. 5. PCC voltage's amplitude and frequency

Case 3

This case corresponds to a local load with a resonant frequency of 60 Hz and a quality factor of 2.5 (Fig. 6). Since the quality factor is high, the SFS alone cannot detect the islanding situation fast enough to meet the standard. On the other hand, the SVS method detects the islanding quite fast and it disconnects the inverter in 0.025 s, which is well below the required time. As for previous cases, the utility switch was opened at 0.4 s to reproduce a breakdown.

The experimental results will show disconnection times that are longer than those obtained by the simulation. Indeed, the implementation of the algorithms, the frequency of the measurements and the physical system itself will influence the disconnection times. However, the simulation results are useful to obtain an estimate of the islanding detection system's behaviour. Those results are thus used to determine the operating conditions that make the different detection methods less efficient and to find which methods are mostly used.

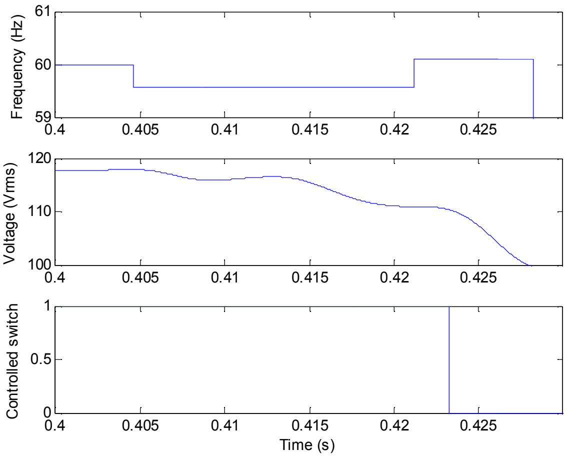

Fig. 6. PCC voltage's amplitude and frequency when the load's resonant frequency is near 60 Hz and Q = 2.5.

6. Inverter Design

The HRI used for the last few years a bidirectionnal commercial inverter. This inverter is able to power a load from one or more batteries and it can be tied to the grid in order to transfer energy to it or from it. This inverter already includes the Under/Over Voltage and Under/Over Frequency islanding protection methods, and it is protected from over-current conditions. However, this inverter does not offer sufficient protection against islanding. Moreover, it is not flexible enough to be used in the islanding protection system test bench. Indeed, a closer investigation of the inverter's behaviour shown that, when connected between the renewable energy system and the grid, there is always a minimum current of around 4.5 A flowing between the RES and the grid. The inverter avoids this way most of the critical conditions that could lead to islanding. Those cases indeed occur when the grid is connected but does not power the local load. Moreover, the power produced by the commercial inverter has a lot of undesirable harmonic components.

Given the many weaknesses of the commercial inverter, the HRI decided to design a new one. This inverter can provide up to 1000 W and is powered by the RES's batteries. It will also include an improved protection system that combines two passive islanding detection methods, Under/Over Voltage and Under/Over Frequency, and two active methods, Sandia Frequency Shift and Sandia Voltage Shift. This way, the non detection zone can be reduced. In order to implement the SFS protection, the inverter can control its output current frequency by adding dead times or truncations to the current's waveform. The current's amplitude can be controlled, thus allowing the implementation of the SVS algorithm. The inverter can also be operated in two modes, namely the stand-alone mode and the grid-connected mode. Finally, great care was provided to the output current's waveform in order to produce high-quality power.

The inverter can be divided into five main components: the DC/DC converter, the DC/DC converter's control circuit, the DC/AC converter, the DC/AC converter's control circuit and the grid-connection interface (Fig. 7).

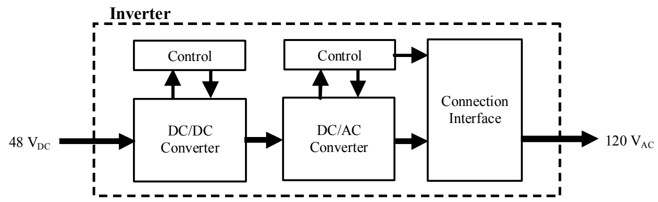

Fig. 7. Block diagram of the inverter

The DC/DC converter raises the voltage from the batteries' 48 V to the 170 V needed by the inverter stage. This is achieved by four MOSFETs used in a full bridge configuration. The converter's control circuit generates the MOSFET's gate signals in order to keep the bus voltage constant. The inverter stage also uses a full bridge. Pulse Width Modulation (PWM) control is used to convert the 170 V DC voltage produced by the DC/DC converter into a sinusoidal AC voltage. The PWM carrier's signal frequency is 14.4 kHz. A LC low-pass filter is then used to remove frequency harmonics from the AC voltage, thus producing a clean 60 Hz sinusoidal waveform. The inverter is connected to the grid through a relay and a 20 mH inductor. This inductor is mandatory to transfer power to the grid. The inverter's control is based on the measurement of the grid's voltage and current in order to create a slight phase lag between the inverter's voltage and the grid's voltage. The bridge's transistors are digitally controlled to synthesize a sinusoidal waveform that has magnitude and frequency that are compatible with the electrical grid. The DC bus voltage is adjusted by the input module so that the nominal output voltage in compatible with the grid. The sinusoidal output voltage is then controlled by the output module to compensate the variations produced by perturbations on the grid. The output module integrates all islanding detection's algorithms. According to equation 8, the active power always flows from the source that produces the leading voltage [17] :

$$P = (V_{Inverter}\, V_{Grid} \sin \delta) / X \qquad (8)$$

The equation 8 shows that the active power P flowing from the inverter depends on the grid's RMS voltage (V_{Grid}), the inverter's RMS voltage ($V_{Inverter}$), the lead angle (δ) of the inverter's voltage on the grid's voltage and the reactance between the inverter and the grid.

7. Experimental Results

When the inverter is in the stand-alone mode, it powers a load with a fixed AC voltage. This voltage must be controlled by the inverter's control circuit in order to keep it stable, independently from the load's variations. In grid-connected mode, the inverter operates in parallel with the utility grid. The local load is thus powered by both the inverter and the grid. In this mode, the islanding detection system is activated, which means that the inverter's output current waveform is slightly modified in order to include the dead times or the truncations needed to accelerate the islanding detection. Moreover, the output current is controlled so that the user can choose the power that will be fed to the grid by the inverter.

Inverter's output voltage in stand-alone mode

The figure 8 presents the inverter's output voltage waveform in the stand-alone mode.

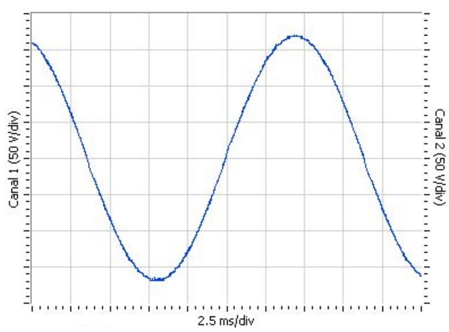

Fig. 8. Inverter's output current waveform in stand-alone mode

The total harmonic distortion is less than 1 %, which is well below the 5 % limit defined by the Canadian standard.

Inverter's output voltage in grid-connected mode

The figure 9 shows that the grid's voltage lags slightly behind the inverter's voltage. It is possible to observe that both voltages are of the same amplitude and the same frequency. This condition is mandatory to close the output relay securely.

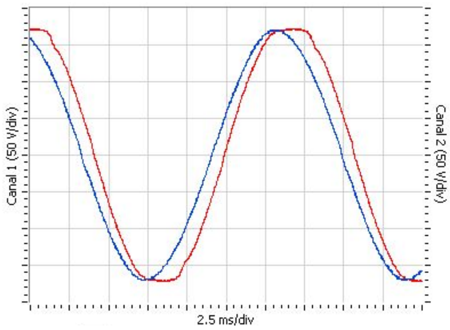

Fig. 9. Inverter's output voltage in stand-alone mode

In grid-connected mode, the inverter generates dead times and truncation in the voltage waveform to operate the islanding detection algorithm. As consequence, the inverter's output voltage is more distorted. The figure 10 shows the voltage as measured at the terminals of a resistive load. The dead times and the truncations in the voltage waveform can be seen easily. However, the total harmonic distortion is 4 % and 5 %, respectively. The standard is respected.

Inverter's functional validation

Firstly, it is important to note that in order to comply with the clearing times imposed by the Canadian standard C22.2 No. 107.1-01 while avoiding false disconnections, the islanding protection algorithms are a slightly modified version of the ones used in the simulations. As shown in Table 3, the maximum numbers of cycles before disconnection of the firmware are less than those specified by the standard C22.2 No. 107.1-01.

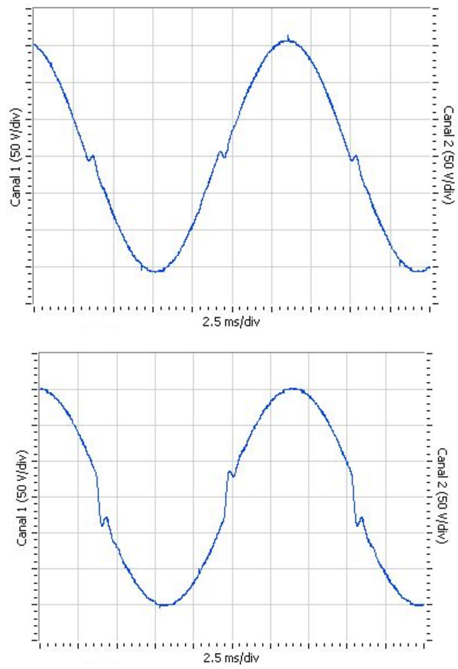

Fig. 10. Inverter's output voltage with dead times and truncations

According to the C22.2 No. 107.1-01 standard, a well-defined procedure must be used to test the inverter's compliance. The first step is to test the islanding detection system when the inverter operates at 25 %, 50 % and 100 % of its nominal power. Those tests yielded disconnection times of 5.5 cycles, 6.5 cycles and 19.5 cycles, respectively.

The next step is to test the inverter's behavior when it is connected to a grid which voltage's amplitude or frequency is out of range. The required clearing times vary with the grid voltage's frequency and amplitude. Each of the frequency and amplitude ranges specified by the standard were tested and the measured disconnection times complied with the standard in every case. Finally, the inverter was tested in each of the critical operating conditions defined in section 4.

Table 3. Inverter's frequency and voltage operation limits

Frequency at the PCC (Hz)	Clearing time (cycles)	Voltage at the PCC (V_{RMS})	Clearing time (cycles)
f > 63.0	1	V > 145	1
60.5 < f ≤ 63.5	5	132 < V ≤ 145	100
57.0 ≤ f < 59.5	5	60 ≤ V < 110	100
f < 57.0	1	30 ≤ V < 60	5
		V < 30	1

In the first case, the inverter disconnected after 6.5 cycles, which is well below the 120 cycles defined by the standard (Fig. 11).

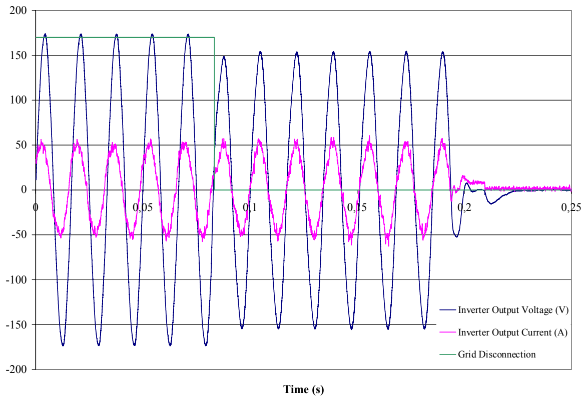

Fig. 11. Inverter's output waveform when the load's resonant frequency is close to that of the grid

This figure also shows that the output voltage's amplitude drops when the grid is disconnected. This behaviour is caused by the Sandia Voltage Shift method that tries to destabilize the voltage at the PCC. When the grid is disconnected, this perturbation appears and accelerates the detection of the islanding situation. According to the control algorithm, the system should wait 100 cycles before disconnecting when the voltage is between 60 V_{RMS} and 110 V_{RMS}. Since the system disconnects after only 6.5 cycles it is possible to determine that the Sandia Frequency Shift caused the disconnection.

The second case yielded a disconnection time of 5.5 cycles (Fig. 12). As discussed above, the output voltage's amplitude drops when the grid is disconnected because of the Sandia Voltage Shift.

Finally, the third case yielded a disconnection time of 5.5 cycles (Fig. 13).

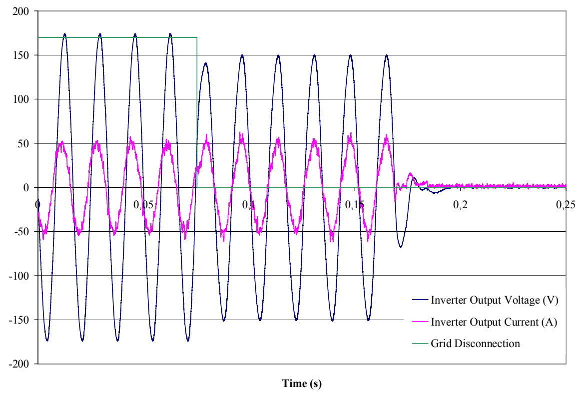

Fig. 12. Inverter's output waveform when the power generated is close to local load power (Q_L = Q_C = 350 Vars)

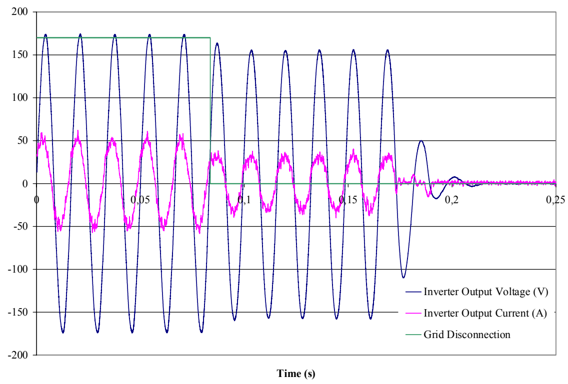

Fig. 13. Inverter's output waveform when the load's quality factor is near 2.5

8. Conclusion

The HRI developed an islanding detection system that allows the connection of its hybrid renewable energy system to the grid. The detection system used a combination of methods which are the passive methods Under/Over Frequency and Under/Over Voltage and the active methods Sandia Frequency Shift and Sandia Voltage Shift. In order to predict the hybrid RES behaviour and to identify the particular cases that make the islanding detection methods less efficient, a model of the system was developed using Matlab/Simulink and its SimPowerSystems toolbox. The simulation has shown that the critical cases that were found in the literature tend to make the detection more difficult. These cases occur mostly when the load's resonant frequency is near that of the grid, when the active and reactive power provided by the inverter are close to that consumed by the load and when the quality factor Q of the load is high. The simulation also showed that the combination of the four methods is efficient for detecting islanding situations even in critical cases. Indeed, the clearing times obtained in simulation remain below those required by the Canadian standard C22.2 No 107.1-01.

It is possible to observe that the clearing time's experimental values are generally higher than the values obtained by simulation. Many factors, as the implementation of the algorithms, the gains of the protection methods and the sample rate of the measures indeed influence the clearing times measured in the system. The simulation was still useful to determine the range of the disconnection times to be expected and the system's behaviour when used with different islanding protection methods.

A test bench was built at the HRI in order to validate the inverter's behaviour. As stated in the Canadian standard C22.2 No. 107.1-01, the islanding detection methods were tested at 25 %, 50 % and 100 % of the inverter's rated power. It was also tested for varying conditions of voltage frequency and amplitude.

The inverter's clearing times are compliant for each of the tests defined in the standard. The values measured for the three critical cases determined in the simulation are also very small, around 6 cycles. This is also well below the time of 120 cycles specified by the standard.

It is then possible to state that the chosen islanding detection system is efficient and is appropriate to protect the renewable energy system from the islanding situations.

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