Dynamic analysis and field verification of an innovative anti-islanding protection scheme based on directional reactive power detection

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Abstract*— Based on current utility practice, anti-islanding protection is one of the main protection requirements for interconnection of a distribution generation (DG) to the medium and low voltage grids. For connecting a small synchronous generator to the utility grid, DG interconnection guidelines require the use of a transfer-trip scheme when the minimum load of a connecting feeder is less than twice the rated capacity of the total DG units. Some standards (e.g. IEEE Std. 1547) suggest a more aggressive generation to load ratio of one-third. Implementation of a fast communication based transfer-trip scheme with a detection time of less than a second is very expensive and not economically feasible for small DG projects. The fast islanding detection is mainly required to comply with the feeder protection coordination, especially the first reclosing time of the feeder automatic reclosure (in this case 1.5 seconds). This paper presents the computer modelling, simulation, and field verification of a proposed passive, local anti-islanding protection scheme based on directional reactive power measurement. The protection scheme was tested on a farm-based biogas DG to demonstrate compliance with the utility requirements. The detailed simulation studies and field tests consistently yielded detection times of less than 0.25 seconds. Based on these results the solution and the DG interconnection were approved by the utility. The proposed protection scheme can effectively be utilized for anti-islanding protection of synchronous generator based DG units on feeders with inductive load.

***Index Terms*— Distributed Generation, anti-islanding, protection, interconnection standards, directional reactive power relay, biogas engine.**

I. Introduction

For distributed synchronous generation, one of the key utility concerns is the detection of loss of the grid leading to unintentional islanding of the generator on the feeder, [1]. In such situations, it is important that the distributed generation (DG) is rapidly disconnected from the utility feeder for reasons of:

- De-energizing the feeder for the safety of the utility linemen,
- Preventing poor power quality electricity supply,
- Preventing out-of-phase reclosing leading to equipment damage from voltage wave and/or torque shock.

The grid interconnection guidelines such as IEEE Std. 1547, [1], or the draft CSA C22.3 No. 9, [2], require equipping a rotating machine-based DG unit with a Transfer-Trip (TT) scheme for anti-islanding protection if the minimum load on connecting feeder is less than twice the generator capacity (2 to 1 rule of thumb). Although an islanding detection time of less than 2 seconds is specified by IEEE Std. 1547, some utilities require a fast detection and DG disconnection time of less than one second, depending on the protection coordination and reclosing time of the automatic reclosure of the feeder. However, a fast TT scheme is very expensive and normally the economy of a small DG project (below 500-kW) does not allow such expenses. As discussed in the DG connection guidelines, alternative anti-islanding methods can potentially be investigated; however, utility acceptance of any proposed method requires a field test or a third party certification, [3].

Many islanding detection schemes have been proposed and investigated in the literature, [4], either categorized as a passive or an active protection technique. The aim of extensive research applied in this area is to suggest precise anti-islanding schemes which can distinguish normal disturbances in the system, due to faults or load switching, from a loss of the main-grid condition. A reliable scheme should also have no or negligible Non Detection Zone (NDZ), [5]. That means the scheme should detect unintentional islanding of a DG under any load and generation condition.

This paper presents the results of simulation investigations and field tests of a proposed anti-islanding protection technique for a case of a farm-based biogas synchronous generator. The absence of a low-cost alternative to TT had been delaying the grid connection of this generator. The turnkey cost of an utility-approved TT with a safe disconnection time of less than 0.5 seconds is in the range of $120k to $250k CAD. However, an alternative method (passive scheme) based on utilizing a directional reactive power relay (40Q), [6], to detect reactive power flow direction of the generator, while operating in an importing VAr condition, was adapted and successfully field tested. The alternative method employs an inexpensive off-the-shelf protection relay equipment. The field investigations and relay protection testing were mainly supported by a federal government fund for technology and innovation (T&I) through CANMET Energy Technology Center-Varennes and

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performed by the Electrical Consultant (ANF Energy Solutions Inc.) and the DG developer (Genesys Biogas Inc.).

Computer-based modelling and dynamic simulation studies are used to investigate dynamic behaviour of the biogas engine-generator during and subsequent to disconnection from the main grid (unintentional islanding) to gain confidence in the method and also capture operating scenarios that were not covered during field tests. The modelling and simulation studies were particularly focused on analyses of frequency/voltage transients, and active/reactive power variations in the first two-second interval following the disconnection from the grid. The reported field tests and computer analyses examine the engine-generator responses to various levels of the power mismatch between load and generation.

The rest of the paper is structured as follows. Section 2 explains the anti-islanding concept employed for this case. Section 3 provides a brief description of the study system. The DG modelling is discussed in Section 4. The computer simulation studies and field test results are represented in Sections 5 and 6, respectively. The paper summary and conclusions are stated in the last section.

II. Proposed anti-islanding control concept

Conventionally, voltage limits, frequency limits and directional active power are used for unplanned islanding protection of distributed generation when the generation on the feeder is significantly below the feeder load. Typical transient phenomena expected subsequent to DG islanding are described as follow:

- Following the loss of feeder supplied active power, there may be a sudden increase in DG output in order to meet the feeder loads. Detection of this increase can indicate islanding.
- Following the loss of feeder supplied active power, there may be a rapid decrease in frequency. Detection of this can indicate islanding.
- Typically, automatic voltage regulation (AVR) controls of DG units are in power factor or VAr regulation mode so that they rely on the grid support for voltage regulation. Loss of the main grid can therefore lead to rapid voltage variations, whose detection can indicate islanding.

When the generation on the feeder is more closely matched to the feeder load, the loss of active power import can be relatively small, limiting the effectiveness of directional active power and under-frequency protections. However, if it can be ensured that there will be a significant change in reactive power, this can be used to provide a basis for the detection of islanding.

Rural feeders generally have resistive and inductive load, with little capacitive load. If a DG is set-up so that it is always a sink for reactive power when the grid is present, the loss of the grid will force the synchronous generator to begin supplying reactive power, which can then be used to detect an islanding condition.

Setting the generator AVR to regulate about a VAr import setting can be used to achieve the pre-fault reactive power absorption condition. Setting the directional reactive power

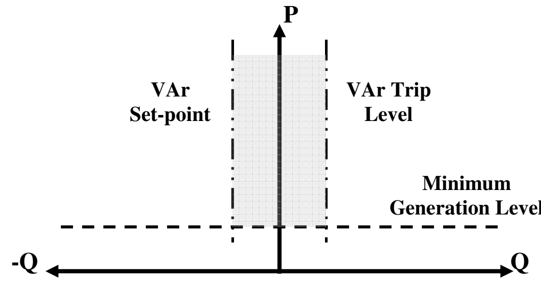

Fig. 1. Generator Operating and Trip Characteristic

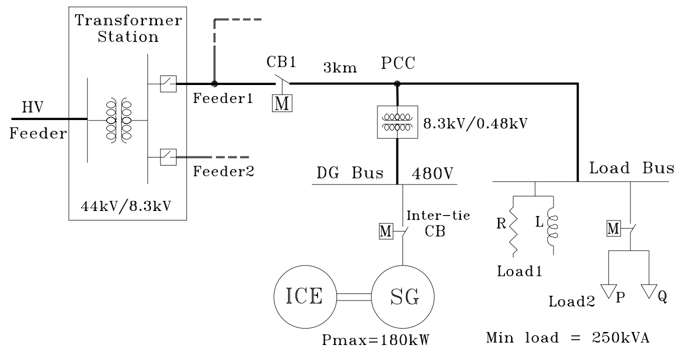

Fig. 2. One-line diagram of the rural feeder under study

relay to trip for a particular reactive power export level can therefore be the islanding detection trip criterion. In order to ensure that the reactive power load on the utility feeder is not unduly high in the pre-fault situation, a VAr import setting corresponding to 0.97 leading power factor at half-rated power is proposed as shown in Fig. 1.

III. System Description

The DG unit under investigation consists of a 313-kW, 480-V synchronous generator with a 200-kW biogas internal combustion (reciprocating) engine (ICE) prime mover. The DG unit is connected to a three-phase radial feeder at 8.3-kV level. The radial feeder is connected to a distribution substation at about 3-km distance from the point of common coupling (PCC) of the DG. The radial feeder mainly supplies several farm facilities (single-phase and three-phase loads) and some dispersed residential customers. The minimum load of the feeder is about 18-A at 8.3-kV which is the equivalent of 258-kVA or 245-kW at power factor of 0.95 lagging. The maximum generation capacity of the DG unit with biogas fuel is 180-kW.

Fig. 2 shows one-line diagram of the study network including the distribution substation, the distribution feeders, the DG unit connection, and the equivalent load of the study feeder (fixed and variable loads). The circuit breaker CB1 represents the automatic reclosure of the feeder. CB1 is used to disconnect the feeder to simulate an unintentional islanding situation and/or a loss of the grid condition. The grid and the distribution substation are modelled as an equivalent representation of a voltage source in series with a RL impedance based on the scope of the study. The distribution feeder is also

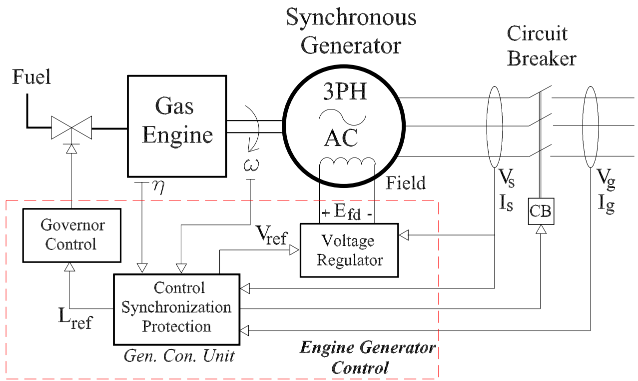

Fig. 3. Engine and Generator control systems

represented by an equivalent Π (pi) model with line parameters based on a 3/0 kcmil conductor size. The distribution load of the feeder is lumped together and modelled as either constant impedance or constant power load with lagging power factor of 0.95 or higher.

It is assumed that the DG unit operates in a constant active power generation mode, whereby the power generation of the unit can only be adjusted externally by changing a load reference set-point provided by an operator. The terminal voltage of the DG unit is also controlled to operate in a grid-following mode while adjusting the reactive power and power factor of the unit as required. A reactive power set-point based on a leading power factor of 0.97 is applied to the generator that ensures reactive power import for the DG plant despite the variations in the on-site load.

The system model is developed in the PSCAD/EMTDC software environment.

IV. Distributed Generation Model

The DG for this study is comprised of a round-rotor synchronous generator as the grid interface medium and a four-stroke, dual-fuel reciprocating gas engine. Both the gas engine and the synchronous generator are equipped with several controllers and protection devices to perform various tasks of engine start-up, generator voltage/speed adjustment, automatic synchronization with the grid, and active/reactive power generation controls for sound and proper operation during the grid connected or the stand-alone operation. An overall block diagram representation of the DG unit including controls and interconnection equipment are shown in Fig. 3. Detailed study and modelling of each control block are described in [7].

Two main control units that have a major impact on the dynamics of the DG during transients are the generator voltage regulation and engine governor controls. The former controller adjusts the field excitation current of the generator and the latter controls the speed of the gas engine. Although decoupled control strategies may be adopted to adjust the generator voltage and the rotating speed of the engine, the active and reactive power generation of the DG unit is ultimately dependent on both actions. Appropriate governor and voltage regulator control models are adapted for this study based on manufacturers' specifications.

V. Islanding transition study

The principal objective of this study is to investigate the dynamic behaviour of a reciprocating engine based distributed generation unit during and subsequent to disconnection from the main grid that represents an unintentional islanding of the radial feeder with the corresponding load. The study is particularly focused on analysis of frequency and voltage transients in the first two-second interval following the disconnection from the grid. Then the engine-generator response characteristics for various levels of the power mismatch between load and generation are examined and ranges of voltage and frequency excursions, rate of change of the frequency are determined.

The study system of Fig. 2 is used to investigate the dynamic behaviour of the DG unit and voltage/frequency transients after CB1 disconnection, while the DG unit operates in a constant power generation mode. The DG unit is equipped with an excitation and governor control system as discussed in Section IV.

The distribution feeder in Fig. 2 is equipped with an automatic reclosure (represented by CB1) that employs a first reclosing time of 1.5 seconds following a fault downstream of the feeder and the CB1 tripping. The corresponding utility company requires disconnection of the DG unit before restoration of the grid supply to avoid an out-of-step reclosing and damage to the line equipment. That means islanding detection and disconnection of the DG inter-tie breaker should happen in less than one second considering a time discrimination of 0.5 s. The following case studies based on changing the power mismatch level of the generator and minimum load of the feeder are performed:

- **Case IS-1:** +50% and +25% power mismatch levels (under generation),
- **Case IS-2:** 0% power mismatch for resistive/inductive load (close match between load and generation),
- **Case IS-3:** 0% power mismatch for resistive load,
- **Case IS-4:** -15% power mismatch (over generation).

Although the protective relays equipment for the line or the DG source are not modelled, analyzing the range of variations in DG voltage and power frequency obtained from the simulation cases can help determine behaviour and effectiveness of typical DG interconnection protection. The simulation results for two marginal cases of +25% and 0% mismatches are presented in the following subsections. Details of dynamic simulation studies for rest of the cases are reported in [7].

A. (Case IS-1) +25% power mismatch

For this study, a power mismatch levels of +25% between the load and the DG output power prior to disconnection of the CB1 is analyzed. Considering the feeder load at the minimum level, 245-kW with a lagging power factor of 0.95, the DG output power is adjusted to 180-kW for +25% mismatch. The reactive power of the DG unit is controlled through the excitation system to import -31.00-KVAr from the grid.

Fig. 4 shows the frequency, voltage and power variations of the load and DG subsequent to disconnection of the CB1 at t = 20 s. Within a two-second interval after disconnection, the frequency excursions in the range of ± 1 Hz are

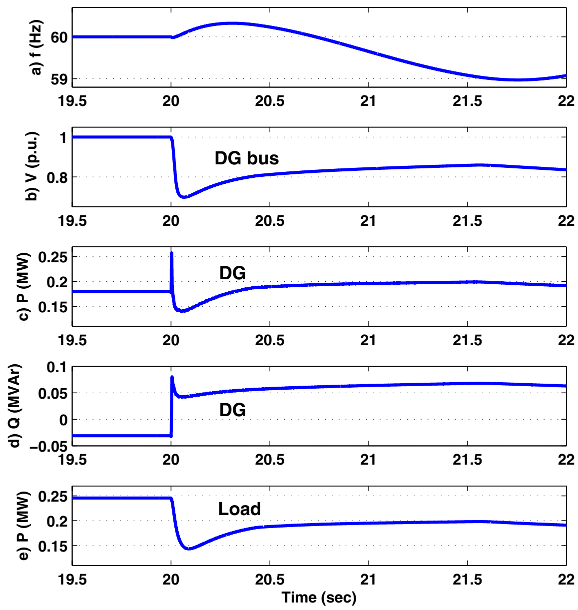

Fig. 4. Islanding at t=20 s. for +25% power mismatch

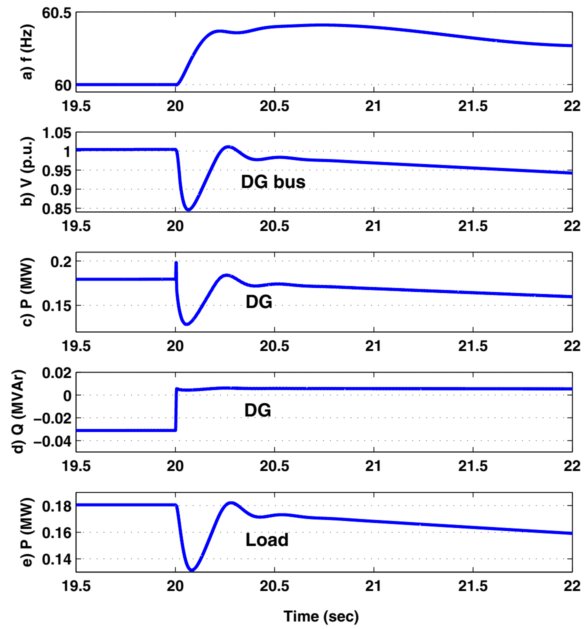

Fig. 5. Islanding at t=20 s., zero load/generation imbalance (resistive load)

experienced, Fig. 4-a. The bus voltage at the PCC drops below 0.8 p.u., Fig. 4-b, and the reactive power of the DG unit shows a sudden change in the direction, from -31.00-kVAr to +80-kVAr, Fig. 4-d. It should be noted that after disconnection from the grid the electrical output power of the DG unit is determined by the load current in the isolated system, Figs. 4-c and d. The difference between the electrical load and mechanical power accelerates and/or decelerates the synchronous generator which causes frequency deviations. The voltage is dominantly affected by the changes in the reactive power balance and mainly follows the variations in the internal voltage of the synchronous generator which is in turn controlled by the excitation system. On the other hand, changes in the bus voltage vary the active power of the load, which affects the power balance and subsequently affects frequency deviations.

It can be observed in Fig. 4-d that disconnection of the grid causes a sudden drop in the line voltage, which affects the reactive power output of the DG and reverses the flow direction toward the grid.

B. (Case IS-3) 0% power mismatch, resistive load

Fig. 5 shows the system response to an accidental switching event that leads to disconnection of the main grid and islanding of the distribution feeder which is modelled by opening CB1 at t=20 s. Prior to disconnection of the grid, the feeder load and generation is closely matched to represent an unintentional islanding case with 0% power mismatch. The DG unit supplies 180-kW of active power at 0.97 leading power factor. The feeder load is also 180-kW and assumed to be purely resistive (pf=1.0). Although the frequency deviations obtained under this condition may not exceed the under/over frequency protection thresholds of the frequency protective devices (typically 0.5 Hz), the voltage variations are large enough to be detected by under/over voltage protection of the generator, Fig. 5-b. Voltage variations have also caused a sudden change in the reactive power direction of the generator, Fig. 5-d, which is detectible by a directional reactive power relay.

This case may be considered as the worse case islanding scenario based on the transient behaviour observed in the simulation results and limited range of variations in the power frequency. However, by applying appropriate settings, a protection method based on changes in the reactive power direction can be suggested as an effective detection measure. This provides the basis for the protection strategy proposed and field verified.

VI. Field verification

Following computer-based simulation studies, a series of off-line field test were planned to demonstrate performance of an anti-islanding protection based on directional reactive power detection approach and to determine detection times under various power mismatch levels. An overview of the electrical configuration of the test set-up is shown in Fig. 6. A 480-V, 350-kW 3-phase rental diesel generator unit was used to simulate the area electric power system. A disconnect switch on the engine was used to initiate the islanding condition. A 180-kW biogas generator is the machine under test. The generator protections and control settings were kept almost identical to those of the original grid interconnection setup. Only the Exhaust Heat Recovery Unit of the generator was temporarily bypassed, since there was no thermal load use. The engine was also supplied by "propane" for part-load tests (up to 90-kW) and "bottled methane" for half to full-load tests. Several resistive load banks and existing motor loads (with or

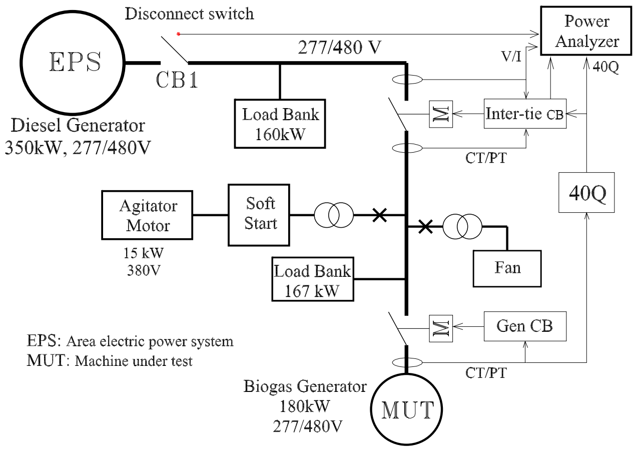

Fig. 6. Overview of electrical configuration of the field verification setup

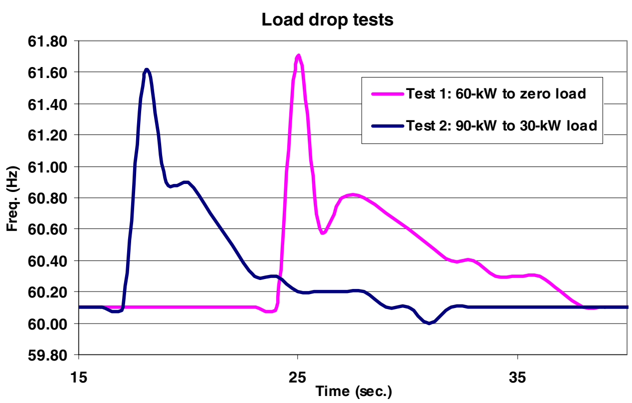

Fig. 7. Load drop tests at two different operating points

without soft-starter) as part of the farm load were used during the test to achieve various power mismatch levels.

A. Isolated operation and load-drop tests

In a stand-alone mode, the synchronous generator operates as a grid forming source employing direct voltage regulation control and load following strategy to supply the load at nominal voltage and fix frequency. A load drop test is normally used to calibrate the frequency/voltage regulation controllers of an engine-generator during the commissioning phase. A similar test can be performed to analyze dynamic performance of the DG unit and to determine inertia constant and generator control parameters.

Fig. 7 shows the power frequency variations of the engine-generator under study based on the field test results for two cases of load-drop tests. In each case, the generator was first loaded using a resistive load bank, then the load was suddenly dropped by 60-kW. The frequency curves for two initial operating points of 60-kW and 90-kW are overlaid on a same graph for comparison.

In Fig. 7, the response time of the generator and the speed control loop for frequency adjustment is about 12 seconds. A 60-kW load drop has also caused a frequency deviation in the range of 1.6 to 1.7 Hz. The frequency of slow oscillations (electromechanical mode of the generator) based on the first swing is about 1.7 rad/sec. The information extracted from test results of Fig. 7 is then used to tune the gain factors of the speed/load controllers of the generator to achieve similar dynamic performance.

B. Anti-islanding protection tests

Thirteen different load/generation mismatch conditions were tested. The test procedure for an islanding test is described as follow:

1) The biogas generator was synchronized with the diesel generator,
2) Using the load banks, fan and agitator motor, the total required load was set. Using the DG load reference set-point, the active power output of the biogas generator was set to a pre-specified value,
3) The generator reactive-power set-point and/or AVR reference voltage was changed manually to operate at unity power factor or to achieve the required VAr import,
4) Pre-test data was recorded including voltages, load currents and active/reactive power import/export,
5) The disconnect switch of the diesel generator was opened while trip signals from the diesel generator breaker, the DG inter-tie breaker, and the 40Q relay were logged using a digital power analyzer (Yokogawa PZ4000).

Several nuisance tripping tests were also performed, involving switching of resistive load (load test) or of agitator motor (motor test), to ensure reliable operation of the directional relay during normal conditions.

A summary of test results from six islanding tests is given in Table 1. Figs. 8 and 9 also show variations in voltage and current of the generator, and trip signals for two islanding test cases, FT-1 and FT-6, obtained from the field measurement. The first trip signal shows the disconnection of CB1 and is used as a reference point for an islanding initiation measure. The second trip signal illustrates islanding detection by the directional reactive power relay (40Q). The inter-tie CB tripping time is also determined by the time at which the generator currents drops to zero. Comparing the islanding detection times of two relays in Figs. 8 and 9 and also to the rest of the reported cases in Table 1, it can be concluded that the 40Q relay has an islanding detection time of less than 0.25 s. However, the inter-tie relay with an over/under (O/U) frequency threshold of ± 1-Hz (case FT-1, Fig. 8) may detect islanding after the 40Q relay tripping. An O/U threshold of ± 0.5-Hz (case FT-6, Fig. 9) may result in a faster islanding detection by the inter-tie relay than the 40Q relay.

The test results specifies that:

- The directional reactive power protection relay (40Q) consistently tripped in less than 0.25 seconds for all test conditions, including when the generator was at a unity power factor, covering the range of loading levels. The 13 islanding tests covered a range of 30 to 168-kW (17-93%) of generator loading, and 39-100% of feeder loading.
- The directional reactive power protection (40Q) did not trip in response to resistive load step changes or switching of the 12-kW agitator motor.

TABLE I
SUMMARY OF THE TEST RESULTS FOR SIX ISLANDING TEST CASES

Test	Load ratio	DG (kW)	DG (kVAr)	Power factor	Load banks (kW)	Other loads (kW)	Relay trip time (sec.)	
							40Q relay	Inter-tie
O/U freq. protection set to +/- 1.0 Hz								
FT-1	71%	168	0	1	217	20	0.14	0.21
FT-2	80%	88	0	1	90	20	0.11	0.53
FT-3	86%	123	-37	-0.96	123	20	0.15	No trip*
FT-4	92%	161	0	1	155	20	0.17	No trip*
FT-5	100%	133	0	1	125	8	0.11	No trip*
O/U freq. protection set to +/- 0.5 Hz								
FT-6	91%	130	-37	-0.96	123	20	0.23	0.17

* : No trip means within a 2-second interval subsequent to islanding

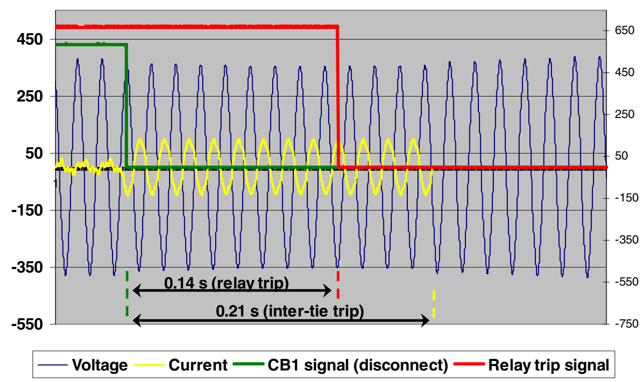

Fig. 8. Islanding case FT-1: 40Q relay tripped before the inter-tie CB tripping

- The generator under-frequency protection also operated for all conditions when set to a limit of 0.5 Hz deviation, but not consistently when set for 1.0 Hz deviation.

VII. Scope of Application

The main requirement for reliable anti-islanding protection based on a directional reactive power detection scheme is the significant shortage of reactive power for the islanded area upon disconnection of the grid. Loss of the grid supplying reactive power will then force reactive power export by a DG unit, reversing the direction, provided that the DG technology has the capability to import/export a certain amount of reactive power. Hence, the method is recommended for anti-islanding protection of synchronous generator based DG units connected to rural feeders with inductive load with large equivalent X/R ratio for the feeder and load. The following special conditions may limit the application of the scheme and require further investigations:

- Presence of large capacitive loads and/or capacitor banks,
- Utilization of any active method of voltage regulation support for a feeder either through DG voltage regulation controls or a dedicated static VAr compensator,
- Occurrence of fast, on-site, reactive power transients such as dynamics caused by frequent starting of a large motor load.

VIII. Conclusions

This paper investigated a directional reactive power protection relay methodology for anti-islanding protection of a small biogas synchronous generator. The method was applied as part

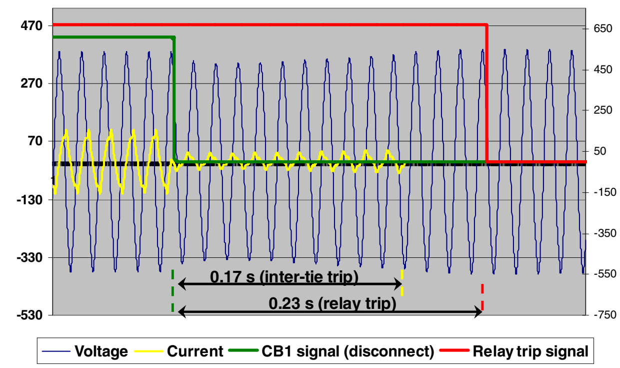

Fig. 9. Islanding case FT-6: 40Q relay tripped after the inter-tie CB tripping

of the interconnection protection requirements of a 180-kW farm-based biogas synchronous generator. The results from several field tests successfully demonstrated the feasibility of the concept for high generation to load ratios. All tests showed relay trip times of less than 0.25 seconds with no nuisance tripping. The simulation studies of the method and complimentary field tests also proved that alternative passive islanding detection methods can be used to provide fast and reliable solutions at extremely low cost compared to a transfer-trip scheme. The proposed solution was reviewed and accepted by the corresponding utility company as an alternative anti-islanding protection solution for this interconnection. Although this protection scheme has outstanding merits, its application is mainly recommended for anti-islanding protection of small synchronous generator DG units on rural feeders with inductive load, where few or no capacitor banks are installed.

IX. Acknowledgement

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