Distributed Generation Grid Connection Experiences Minimizing High Voltage Equipments

Aidan Foss, *Senior Member, IEEE*, and Kalle Leppik, *Member, IEEE*

Abstract— Since 2007, farm-based biogas utilizing small synchronous generation has emerged in Ontario. Initial attempts at grid connection revealed several costly barriers.

First, a requirement for proponents to pay for consequential upgrades to distribution infrastructure was mitigated through an amendment to the Ontario Distribution Code. Second, a requirement for transfer-trip to protect against feeder islanding was removed through the evolution of a low-cost alternative involving passive protections. Third, high-voltage equipments, contained in the standard grid connection designs, were considered disproportionately expensive. To minimize the use of such equipments:

- **For connections to three-wire feeders, fast imbalance protection was employed to avoid using high-voltage potential transformers.**
- **For connections to feeders employing single-phase reclosers, the effective grounding requirement was relaxed, enabling high-voltage equipments associated with wye-delta transformation to be avoided.**
- **For connections to feeders with ganged three-phase reclosers, high-voltage equipments were avoided through utilizing a low-voltage wye-delta transformer for grounding.**

***Index Terms*—Distributed power generation, Power system interconnection, Power system protection, Grounding.**

I. Introduction

Ontario has had an aggressive program for the advancement of renewable energy generation. In the fall of 2006, the Ontario Power Authority (OPA) launched the Renewable Energy Standard Offer Program (RESOP), which was superseded in 2009 by the Green Energy Act, which led to the launch of the Feed-In Tariff (FIT) program [1]. In 2007, the Ontario Ministry of Agriculture, Fisheries and Rural Affairs (OMAFRA) launched an incentive scheme for the establishment of a biogas industry in Ontario. The farm-based projects were generally in the 100-500kW size range, connecting to rural distribution feeders with voltages ranging from 4.8kV to 44kV.

Initial attempts at grid connection revealed several costly barriers. First, proponents were required to pay for any consequential upgrades to the distribution network. An amendment to the Ontario Distribution Code was passed in 2008 [2] that transferred many such costs to the utility to be socialized across their customer base. Second, proponents were often required to install expensive communications-assisted transfer trip for anti-islanding protection. Arising from the connection of the Terryland Farms 180kW (2007) and Fepro Farms 499kW (2009) biogas systems, a low-cost alternative involving passive protections evolved [3-7]. A third barrier was generator-owned high-voltage equipments contained in the standard grid connection designs. For small generation, these can be disproportionately expensive, have long lead times for replacement, and require more expensive services for installation and maintenance. Discussions with farmers indicated that they were prepared to accept some additional nuisance tripping if these disadvantages could be avoided. This paper describes three developments that have allowed the connection of biogas generation with minimal high-voltage equipments.

II. Connecting to the Ontario Distribution Grid

The most common voltages on Ontario distribution feeders are:

Voltage	Conductors
44kV	3-wire (3P)
27.6kV 16.0kV	4-wire (3P+N) 2-wire lateral (P+N)
12.5kV 7.2kV	4-wire (3P+N) 2-wire lateral (P+N)
8.3kV 4.8kV	4-wire (3P+N) 2-wire lateral (P+N)

44kV feeders comprise 3 phase conductors and no neutral conductor. This configuration is similar to most European distribution feeders. The Ontario lower voltage feeders include a neutral wire, and extensively employ single-phase laterals containing a single phase conductor and a neutral.

For generation sizes above 1MW, wye-delta or delta-wye transformation is generally required for connection, whilst for smaller generation wye-wye transformation can be used.

Two particular items of the utility generator connection technical requirements [8] that can lead to a requirement for farm-owned high-voltage (HV) equipments are:

Manuscript submitted March 2013, revised June 2013. Aidan Foss and Kalle Leppik are with ANF Energy Solutions Inc., PO Box 1111, Richmond (Ottawa), Ontario K0A 2Z0, Canada, www.anfenergy.ca (Email: amfoss@ieee.org, & kleppik@ieee.org.)

First: to be able to detect and respond to remote feeder ground faults. For delta-wye transformation, HV potential transformers (PTs) are generally required, whilst for wye-delta transformation an HV neutral current transformer (CT) is usual. In contrast, wye-wye transformation offers good detection using only low voltage (e.g. 600V) measurements as there is no phase shifting or loss of zero sequence components across the transformer.

Second: for effective grounding [9] on 4-wire feeders to avoid unacceptable over-voltage on the unfaulted phases during feeder ground faults, combined with the need to disconnect all ground sources following a fault. Delta-wye transformation typically requires the installation of HV grounding transformers and related HV switchgear and protection, whilst wye-delta transformation requires HV switchgear and protection. Wye-wye transformation offers the possibility to avoid HV equipment, but requires the generator to be solidly grounded. However, this can also lead to undesirable high levels of neutral current (3I0) through the alternator, during either ground faults or from feeder voltage imbalance. In summary:

Impact of Transformer Configuration on HV Equipment Requirement		
	Requirement to Detect Remote Feeder Faults	Effective Grounding and Ground Source disconnection (Not for 44kV 3-wire)
wye-wye	HV equipments not generally required.	None if solidly grounded generator, but high neutral current risk
delta-wye	HV PTs and protection	HV grounding transformer, switchgear, PTs & protection
wye-delta	HV neutral CT	HV switchgear, PTs, & protection

III. Detecting 3-wire Feeder Faults

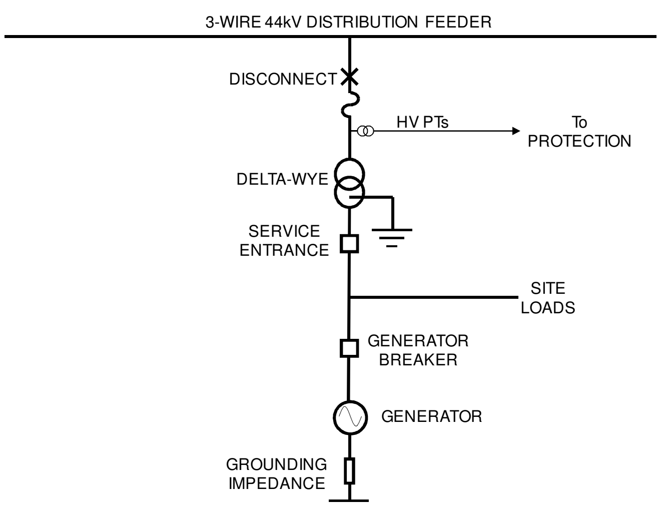


Fig. 1. Typical connection to 44kV 3-wire feeder.

For connecting to 44kV 3-wire feeders, delta-wye transformation is invariably used, see Fig. 1. The conventional method for detecting remote feeder faults is through the use of primary-side PTs, which at 44kV are not inexpensive for small farm-based generation. 44kV feeders are generally grounded at the supply substation, where they are protected using ganged 3-phase reclosers. Once the recloser opens, the feeder can become ungrounded, so that a feeder ground fault becomes undetectable at LV.

Since the feeder is generally well-grounded prior to opening of the substation breaker, a ground fault will initially exhibit significant negative sequence voltage, causing a large negative sequence current to be drawn from the biogas alternator. On two biogas projects, Maryland Farms and Kirchmeier Farms, it was proposed to utilize this characteristic to detect feeder ground faults using fast negative sequence current protection instead of installing HV PTs. As this needed to operate in advance of substation recloser opening, and a 3 cycle delay time was agreed with the utility. In comparison, the use of primary-side PTs would have allowed a time delay of some 5-6 cycles. Analysis of monitoring results showed that for trips in response to a utility-side disturbance:

Kirchmeier Farm Biogas (August 2012-June 2013)	
4	Instantaneous over-current trips
3	Negative Sequence current trips after which feeder voltage collapsed (e.g. due to feeder recloser opening)
10	Negative sequence current trips with no loss of feeder voltage (e.g. due to fault on an adjacent feeder)

Maryland Farm Biogas (June 2012-June 2013)	
2	Instantaneous over-current trip
2	Negative Sequence current trips after which feeder voltage collapsed (e.g. due to feeder recloser opening)
13	Negative sequence current trips with no loss of feeder voltage (e.g. due to fault on an adjacent feeder)

Thus Kirchmeier and Maryland farms experienced 17 trips each, instead of 7 and 4 trips respectively had HV PTs been installed. Analysis of the oscillographs confirmed that negative sequence current is an extremely sensitive protection. As the inter-tie protection relays were programmed for auto-reclose following a feeder fault, the net generation loss was some five minutes per trip. Discussions with farmers indicated that this was preferable to the costs associated with HV PTs.

IV. Imbalance

Imbalance is generally regarded as electrical pollution, as it does not convey useful power. Three-phase generators can act as a sink for feeder imbalance by providing a low impedance path. Relatively small amounts of voltage imbalance can thus lead to high current imbalance through transformers and alternators. This causes heating and other stresses, and reduces the capacity available for useful balanced currents, often leading to equipments being intentionally over-sized.

Ontario's four-wire rural feeders extensively employ single-phase laterals in which a large number of consumers are connected to the same phase. This creates imbalance, and is considered to be the major source of imbalance on the Ontario rural distribution network. Studies show that single-phase laterals contribute similar levels of negative-sequence and zero-sequence imbalance. European distribution feeders, on the other hand, are generally 3-wire with few cross-phase laterals, and thus have much lower levels of imbalance with no zero sequence imbalance impacting on generation. The table below compares voltage imbalance standards:

Voltage Imbalance Design Standards		
	3-wire (Europe)	4-wire (Ontario)
Negative Sequence	2-3% [10]	3-5% [11]
Zero Sequence	no impact due to delta-wye transformer	

Since biogas is typically composed of around 60% methane and 40% carbon dioxide, special lean-burn combustion engines are required. With the biogas industry being well established in Europe, there has been a significant influx of European biogas generation sets into Ontario. Many of these have been found to have alternators with lowish impedances making them more vulnerable to the higher levels of imbalance on 4-wire feeders.

The magnitude of the imbalance current is a direct consequence of Ohm's law. Since the star-point of a generator is a point of zero negative sequence voltage, the negative sequence current (I2) due to feeder voltage imbalance for a single generator installation is (excluding imbalance due to site single-phase loads):

$$I2 = V2 / (Z2+ZT) \qquad (1)$$

where V2 is the feeder negative sequence voltage imbalance, ZT is the transformer impedance (typically 2%-6%) and Z2 is the alternator negative sequence impedance (typically 5%-25%). As there are no low-cost remedies post-installation, it is important that negative sequence imbalance is verified at the design stage.

Ohm's law can also be applied to zero sequence imbalance. For wye-wye transformation with the generator solidly grounded, the neutral current (IN) and zero sequence current (I0) are given by:

$$IN = 3I0 = 3V0 / (Z0+ZT) \qquad (2)$$

where V0 is the feeder zero sequence voltage imbalance, ZT is the transformer impedance (typically 2%-6%) and Z0 is the alternator zero sequence impedance (typically 0.5%-12%). Since alternator zero sequence impedances can be very low, such equipment can be susceptible to high neutral currents if solidly grounded via a wye-wye transformer. Preliminary discussions with alternator manufacturers provided little guidance on safe levels of neutral current.

V. Transient Over-voltage and Grounding

In order to limit transient over-voltage on 4-wire feeders, a utility requirement is that generation sites be effectively grounded with an X0/X1 ratio of less than 2.5 [8].

For wye-wye transformation this can be achieved by solidly grounding of the alternator neutral, but can result in high neutral currents. In 2007, two biogas facilities at Terryland Farms (180kW) and Pinehedge Farms (100kW) were connected using this approach. The alternators had relatively high zero sequence impedances (8-11%), and the supplier had over-sized the alternators by some 40% to allow for zero sequence imbalance.

The following year, at Fepro Farms (499kW) and Ledgecroft Farms (499kW), it was intended to connect European biogas generators, each with a much lower zero sequence impedance (1-2%). Studies showed that the resulting levels of neutral current would be unacceptable, and the conventional design option, based on large generation, would be to connect via wye-delta transformation, requiring high voltage switchgear and protection. Concerns were raised by the farmers relating to higher equipment costs, longer lead times for equipment replacement, higher installation and maintenance costs, and greater disruption to farm loads.

Following detailed technical discussions with the utility, it was agreed that for feeders where only single-phase reclosers were employed (see Fig. 2), there was no risk of over-voltage on the unfaulted phases in response to a feeder ground fault as the two remaining reclosers would stay closed. This generally applied to 8.3kV and 12.5kV feeders, where it thus allowed the requirement for effective grounding to be relaxed.


Fig. 2. Single-phase (left) and three-phase (right) pole-mounted reclosers.

Subsequently, impedance grounded generators with wye-wye transformation became the standard design for connection to 8.3kV and 12.5kV feeders as shown in Fig. 3.

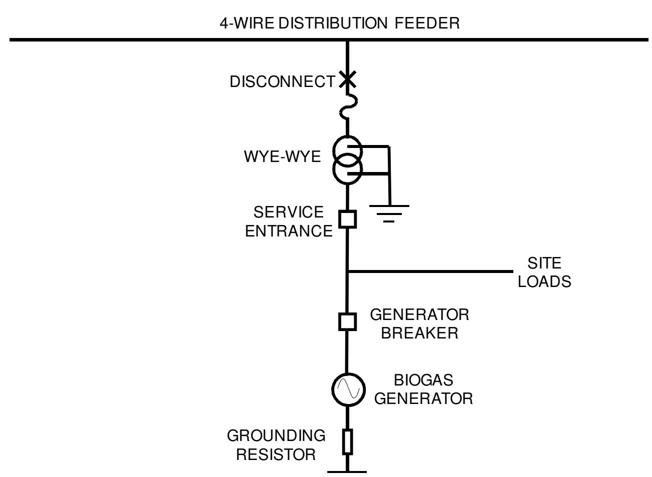


Fig. 3. Wye-wye transformation with impedance grounding.

A. *Wye-delta Connection*

The effective grounding relaxation did not apply to 4-wire feeders employing ganged 3-phase reclosers, which is typically the case at 27.6kV. Accordingly, it was decided to grid connect the Petro Corn 499kW biogas facility, containing a low zero impedance alternator, using wye-delta transformation, thus requiring High Voltage switchgear, PTs, neutral CT, neutral reactor and protection (Fig. 4). The incremental cost of the additional HV equipment and associated engineering was estimated at some $50K.

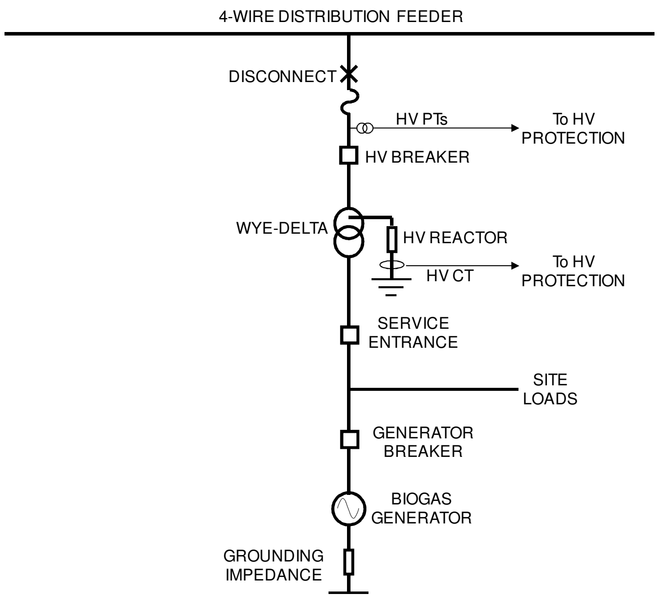


Fig. 4. Typical wye-delta transformer connection.

B. *Connection with LV Grounding Transformer*

Carleton Corner Farms and Jockvalley Farms were proceeding with the connection of 498kW biogas solidly-grounded generation via wye-wye transformation to 27.6kV feeders equipped with ganged three-phase reclosers. In 2011, a situation developed which forced a change of generator, and the replacement generators for both sites had a low zero sequence impedance. Neutral current calculations showed that this alternator was not suitable for solid grounding via wye-wye transformation. The conventional solution would have been to switch to wye-delta transformation, but at an unacceptable project cost and delay.

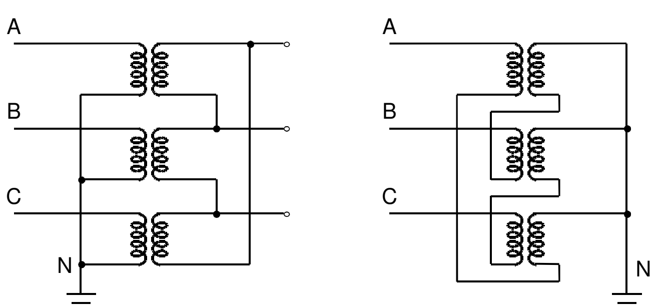


Fig. 5. Wye-delta (left) and Zig-Zag (right) grounding transformers

To avoid this, it was proposed to install a 600V grounding transformer to give the required X0/X1 ratio, which combined with impedance grounding of the generator, would divert neutral current away from the generator and into the grounding transformer. Two types of grounding transformer were considered, either a zig-zag or a wye-delta with no secondary connections (see Fig. 5).

Procuring a certified zig-zag transformer of the appropriate impedance, short-term and long-term neutral current ratings in the available time-frame proved problematic, whereas suitable wye-delta transformers were readily available. The solution adopted was to utilize a 150kVA 600V/240V wye-delta transformer as a grounding transformer through grounding of its primary neutral (See Fig. 6).

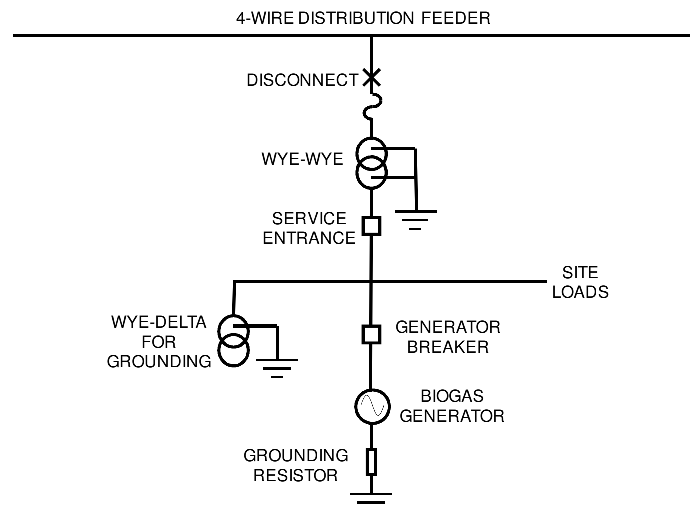


Fig. 6. Wye-wye transformation with LV grounding transformer

Analysis showed that the impedance of the transformer would meet the X0/X1 grounding requirement, and allowed operation up to 2% continuous feeder zero-sequence voltage.

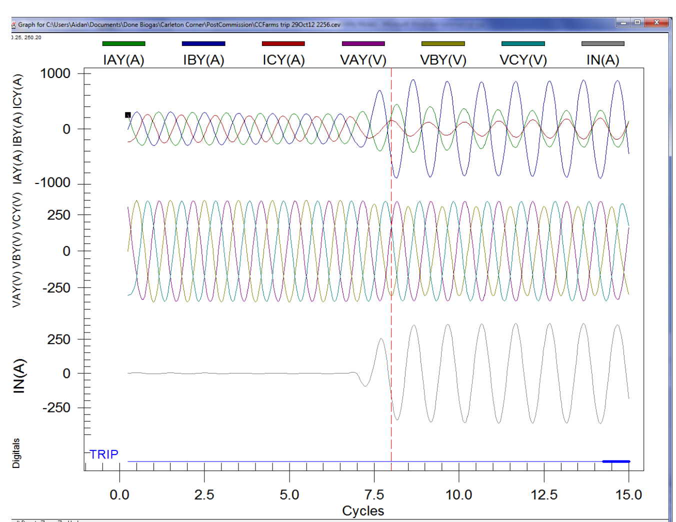


Fig. 7. Feeder ground fault (showing generator currents and voltages, and neutral current through the grounding transformer)

The systems were commissioned in 2012. Fig. 7 shows the inter-tie protection operating in response to a feeder ground fault, ahead of recloser operation and whilst maintaining effective grounding. Another advantage of this design is that it allowed digester load to remain in service whilst generation was tripped.

VI. Summary and Conclusions

Much progress has been made over the past five years to reduce the cost of connecting farm-based biogas generation to Ontario rural distribution feeders. In particular:

- Socializing of certain distribution system infrastructure costs
- Low-cost passive anti-islanding protection instead of fast transfer-trip
- Alternative connection designs that avoid the need for high voltage equipments. For small generation, these can be disproportionately expensive, have long lead times for replacement, and more expensive services for installation and maintenance. In summary:

First, for two projects connecting to 44kV feeders involving delta-wye transformation, fast imbalance protection was used to avoid the need for primary-side PTs. Although some additional tripping was experienced, feedback from farmers was that this was preferable to the costs associated with high-voltage PTs.

Second, for connections to 8.3kV and 12.5kV feeders employing only single-phase reclosers, the requirement for effective grounding was relaxed, allowing wye-wye transformation with impedance grounded generation to become the standard design option, and avoided the high voltage equipments associated with wye-delta transformation.

Third, for two projects connecting to 27.6kV feeders with ganged three-phase reclosers, high-voltage equipments were avoided through utilizing a low-voltage 600V wye-delta transformer for grounding in combination with existing wye-wye step-up transformation.

VII. Acknowledgments

The authors wish to acknowledge the many biogas farmers that have facilitated these developments, in particular George Heinzle (Terryland Farms), Josef Heinzle (Pinehedge Farms), Paul Klaesi (Fepro Farms), Ben Green (Ledgecroft Farms), Michael Henrard (Petro Corn), Jim Callaghan (Maryland Farms), Thomas Kirchmeier (Kirchmeier Farms), Brian Burnett (Carleton Corner Farms), and Shane Mowat (Jockvalley Farms). To Dale Williston (Williston and Associates) for his contribution to the grounding requirement relaxation, to Martin Hutchings for his work on the LV grounding transformer design, and to the many Hydro One engineers involved in the evolution of their Distributed Generation Technical Interconnection Requirements.

VIII. References

[1] Feed-in Tariff Program, Program Overview, Version 1.1, Ontario Power Authority, 30 Sept 2009.

[2] Distribution Code Amendment, OEB Board File No: EB-2009-0077, 21 Oct 2009.

[3] Aidan Foss, "Grid Connection Commissioning of 180-kw Biogas Generator at Terryland Farm", Natural Resources Canada, CETC Number 2007-161 / 2007-10-05 http://canmetenergy-canmetenergie.nrcan-rncan.gc.ca/eng/renewables/integration_der/publications.html?2007-161

[4] Katiraei, Foss, Abbey & Strehler, "Dynamic Analysis and Field Verification of an Innovative Anti-islanding Protection Scheme based on Directional Reactive Power Detection", IEEE Electrical Power Conference, Montreal, October 2007.

[5] Aidan Foss, "Anti-Islanding Protection Strategy and Commissioning of 499kW Biogas Generator at Fepro Farms on a 12.47kV Hydro-one Rural Feeder in Ontario", Natural Resources Canada, CETC Number 2009-198 / 2009-12-15. http://canmetenergy.nrcan.gc.ca/renewables/smart-grid/publications/2732

[6] Aidan Foss & Kalle Leppik, "Design and Implementation of an Anti-Islanding Protection Strategy for Distributed Generation involving Multiple Passive Protections", IEEE Electrical Power and Energy Conference, Montreal, October 2009.

[7] Aidan Foss & Kalle Leppik, "Protection Challenges facing Distributed Generation on Rural Feeders", IEEE Electrical Power and Energy Conference, Halifax, August 2010.

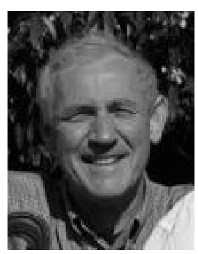
[8] Distributed Generation Technical Interconnection Requirements – Interconnections at Voltages 50kV and Below, Hydro One, Rev 2, June 2011.

[9] IEEE Std 142-1991 (Green Book), IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems.

[10] EUROPEAN STANDARD– EN50160. Voltage characteristics of electricity supplied by public distribution systems. Brussels, CENELEC, 1994.

[11] Conditions of Service, HONI Distribution Customers, Section 2.3.2, October 2011.

IX. Biographies



Aidan Foss PhD, P.Eng, SMIEEE, has over 35 years of professional engineering experience covering power, control, software and simulation. A graduate in mathematics from Cambridge University with a doctorate in turbine control from Imperial College, Aidan initially specialized in computer control and simulation for industrial, aerospace and off-shore applications. In 1990, Aidan joined the National Grid Company, focusing on generator-grid interconnection, frequency and voltage control, and power quality. In 2001, Aidan moved to Ottawa, and co-founded ANF Energy Solutions. As the Principal Engineer, Aidan provides distributed generation technical services specializing in automation, protection and grid connections for biogas, solar, small hydro, wind, and waste-to-energy generation systems.

Kalle Leppik P.Eng. MIEEE, obtained a Bachelors degree in electrical engineering from Carleton University in Ottawa in 1981. For over 25 years, he was been extensively involved in instrumentation and control projects, in particular automated tooling of the CANDU nuclear reactors, and control system design of the Whole Body Calorimeter at the University of Ottawa. Since 2007, Kalle has worked with ANF Energy Solutions Inc. on grid inter-connections, specializing in detailed design, equipment procurement and ESA approvals.