STRAY VOLTAGE MITIGATION

Kinectrics Inc. Report No.: K-014283-001-RA-0001-R00
Client Contract Number: 9297

April 9, 2008

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1.0 EXECUTIVE SUMMARY

This report has been produced by Kinectrics Inc. in response to a request of the Ontario Energy Board (OEB) staff. The objective of the report is to discuss the farm stray voltage issue and evaluate mitigation techniques that could limit this voltage. Relative costs for each mitigation technique are provided and discussed.

Before the 1930s, a thee-phase, three-wire system with no neutral was widely used in North America. In this system, transformers were connected phase to phase on the primary side and there was no electrical connection between the primary and secondary sides of the transformers. In 1930, for public safety purposes and to increase the load capability of the feeders, several changes were made to the distribution system configuration.

- Distribution voltage level increased to 4 160 V phase to phase.
- Multi-grounded neutral wire was added (four wire concept).
- Transformers were connected between phase and neutral.
- Primary and secondary neutrals were electrically connected together.

Now, the earth forms parallel return path for the neutral current allowing part of the neutral current to continuously flow through the earth. This arrangement causes neutral to earth voltage and is partially responsible for the phenomena which have been termed as “stray voltage” or “tingle voltage”.

The symptoms of stray voltage with dairy farms have been identified since the 1970s. Other reports address symptoms such as uneven milk production, increasing mastitis, reluctance to drink water that may occur when stray voltages are present. OEB has commissioned a separate literature review regarding the impact of farm stray voltage on farm operations.

Stray voltage can be caused by either on-the-farm or off-the-farm sources. Off-the-farm sources include: phase unbalance, inadequate number of ground rods, undersized neutral wire and high resistance splices on the neutral wire. On-the-farm sources include: insulation failure, electrical fence operation and neutral wire and ground wire connection in more than one location.

There are several techniques to mitigate stray voltage caused by off-the-farm sources. Section 3.0 briefly describes the techniques and explains effectiveness of each technique. While it is clear that the mitigation techniques would vary in cost and effectiveness for different feeder configurations, the following table attempts to give some relative comparison between various mitigation techniques.

This table is based on some examples that were considered representative but should not be considered applicable to all situations. It can be used as a guide and to indicate where detailed analysis of a particular case may be warranted.

Technique	Effectiveness	Cost
Phase balancing	<80% , >30%	<$10,000
Conversion from single to three phases	< 80% , > 30%	< $ 160,000
Increasing number of ground rods	<80% , >30%	<$200,000
Increasing distribution voltage level	<80% , >30%	>$500,000
Increasing neutral wire size	<30%	>$50,000
Changing pole configuration	<30%	>$50,000
Use of five wire distribution system	<100% , >80%	>$500,000
Use of Variable Threshold Neutral Isolator	<100%[1] , >80%	<$5,000
Use of Saturable Reactor Filter	<80%[1] , >30%	<$2,000

1 The effectiveness of this technique is based on stray voltages of about 10 V. For stray voltages higher than 10 V, this technique has "Low" effectiveness

2.0 BACKGROUND

This paper has been produced by Kinectrics Inc. in response to a request of the Ontario Energy Board (OEB) staff. The objective of the paper is to discuss the stray voltage issue and evaluate mitigation techniques to limit this voltage. The relative cost of each mitigation technique is described and discussed.

As guidance for the scope and contents of the report, Kinectrics Inc. addresses a number of questions posed by OEB staff.

2.1 Terminology

Several terms have been used to describe an electrical voltage that affects animals. Important terms are:

- Neutral to Earth Voltage (NEV): is a voltage measured between the neutral conductor and remote earth.

- Stray or Tingle Voltage: is the difference in voltage which appears between the two contact points of an animal.

2.2 Identifying the Problem

Before the 1930s, a thee-phase, three-wire system was widely used in North America. The reason that this system is called "three-wire" is because it does not have a neutral wire. In this system, as shown in Figure 1, transformers were connected phase to phase (φB and φC) on the primary side and there was no electrical connection between the primary and secondary sides of the transformers.

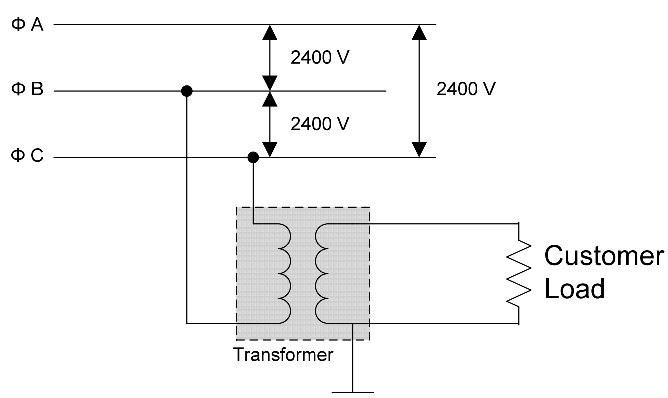

Figure 1 - Distribution System Configuration Before 1930

After the 1930s, for public safety purposes and to increase the load capability of the feeders, several changes were made to distribution system configuration. Figure 2 shows some of these changes which include:

- Distribution voltage level increased to 4 160 V phase to phase. (d)
- Multi-grounded neutral wire was added (4 wire concept). (e)
- Transformers were connected between phase and neutral. (f)
- Primary and secondary neutrals were electrically connected together. (g)

Now as shown in
Figure 2, the earth forms parallel return path for the neutral current allowing part of the neutral current to continuously flow through the earth. This arrangement causes neutral to earth voltage and is partially responsible for the phenomena which have been termed as “stray voltage” or “tingle voltage”.

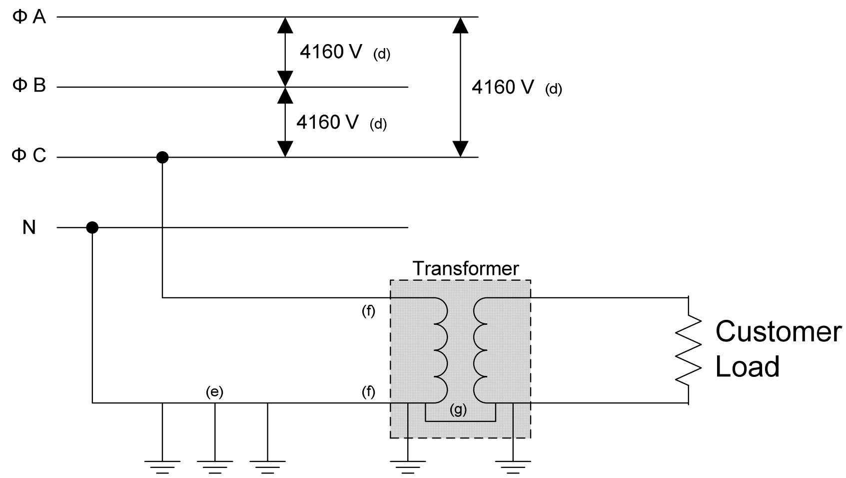

Figure 2 - Distribution Configuration after the 1930s

As an example, Figure 3 shows a dairy cow standing on the ground and leashed to an electrically grounded stanchion pipe. If the volt-meter, shown in the figure, indicates a potential difference between the animal’s legs where they touch the floor and the animal’s neck where it touches the stanchion, it is possible that this voltage can lead to a number of problems for the livestock, which may be sensitive to such low voltage levels.

2.3 Voltage Levels that Affect Animals

The following guide line is applicable when considering stray voltage problems [1]. However, it is Kinectrics’ understanding that additional information on this subject is being obtained by OEB from a consultant in this area. Kinectrics makes no claims to be an expert in this issue and the voltages below are directly extracted from reference 1 with no expert judgment.

- 0.1 to 1.0 V: has not been determined to affect animals at the present time.
- 1.0 V and above: may affect some animals under wet conditions.
- 50 to 110 V: probably fatal

The Ontario Electrical Safety Code Rule 75-414 establishes the maximum neutral to earth voltage as 10 volts. Stray voltages and problems caused by neutral to earth voltage above 10 V are expected to be mitigated by utilities. Problems caused with the voltages below 10 V are expected to be mitigated by the customer.

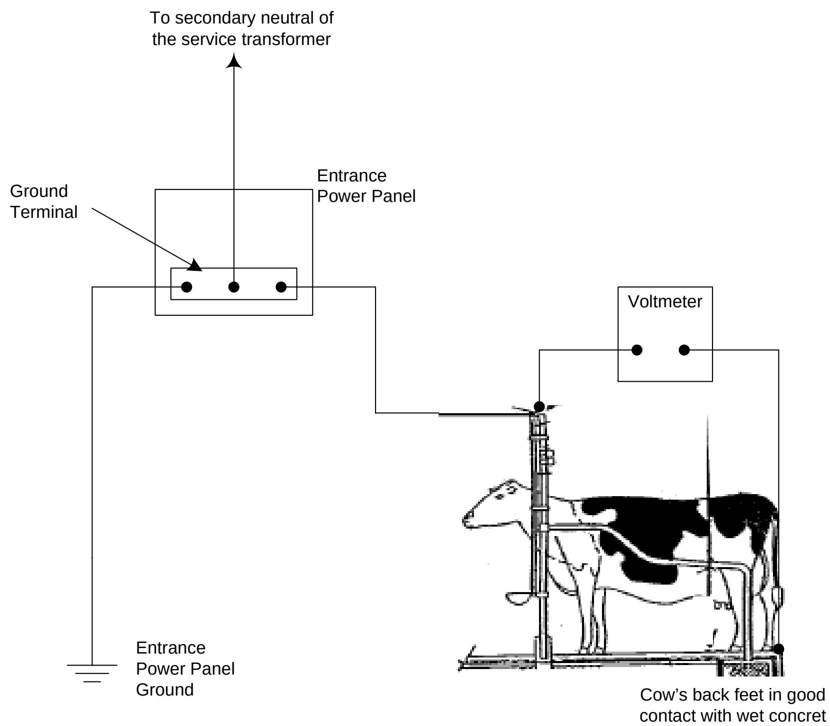

Figure 3 – Stray Voltage Measurement

2.4 Stray Voltage Symptoms with Dairy Farms

The impacts of stray voltage on dairy farms have been identified since the 1970s. Studies have identified the symptoms that may occur when stray voltages are present. Below are some of the symptoms addressed by others [2].

- Uneven milk production. The mechanism is not fully understood. However, when milk out is uneven, more machine stripping is required and longer milking time may become necessary.
- Cows are extremely nervous while in the parlor. Often this is characterized by cows moving or stepping around almost continuously while in the parlor stall.
- Increasing mastitis. When milk-out in incomplete, more mastitis (inflammation of the udder) is likely to occur. As white blood cells rush to fight the infection and are discarded in the milk, an increased somatic cell count may result.
- Reduced feed intake in the parlor. If cows detect stray voltage while eating from the grain feeders, they become reluctant to eat and reduced feed intake occurs.
- Reluctance to drink water. Stray voltage may reach the cows through the water supply or metal drinking bowls. Thus, cows become reluctant to drink.
- Lowered milk production. Each of the symptoms described previously is associated with stress, reduced nutrient intake, or disease. In any case, a drop in daily milk protection can occur.

In must be noted that there are other factors such as milking machine problems, sanitation and nutrition disorders that could cause similar problems to those described above.

2.5 European and North American Distribution Network Differences

The usual North American configuration of a common primary and secondary multi-grounded neutral has evolved rather differently from European distribution systems. Before the 1930s, the grounding practices were similar. Primary feeders supplied delta or phase-to-phase connected transformers, requiring only three conductors [8]. The system was grounded at the source transformer neutral through an impedance. The impedance value was chosen as a tradeoff between limiting the fault current, and thus the ground potential rise, and the ability to detect which of several feeders had faulted.

Secondary systems have always required a multi-grounded neutral in Europe, as in North America for systems rated below 150 V to ground [9]. This limits the voltage rise in the event of a primary to secondary fault due to transformer failure or clashing of conductors in a storm. Multiple connections provide redundancy and reduce the overall resistance to ground. Grounding also makes it easier to detect faulted branch circuits through the operation of protection.

On the other hand, many commercial and industrial 480 or 600-V systems operate without neutral grounding because conduits and equipment frames are otherwise bonded to maintain safe potentials. These systems serve typically a single jurisdiction, with branch circuit disconnects and a voltage unbalance indicator. Such devices make fault location possible, where this would not be practical when serving a number of private residences from a pole transformer.

North American practices diverged significantly from those in Europe during the 1930s [8]. This continent always had lower secondary voltages with a higher load per house, usually at single phase. These factors increase the number of distribution transformers needed here per customer by about a factor of ten relative to Europe, making this a much more cost-sensitive item.

During this period, many North American utilities found the primary phase-to-phase voltage of 2 400 V too low for serving increasing loads. It became apparent that adding a fourth neutral conductor and reconfiguring the system at 4 160 V phase-to-phase provided a number of benefits beyond increased load capacity. The existing single-phase transformers could be reused with one side grounded, also eliminating one fusible cutout and arrester. New transformers operated at this higher voltage actually had reduced insulation requirements on the neutral end, lowering the cost, but only if the primary neutral was multi-grounded. Multi-grounded neutrals also provided redundancy to limit the neutral rise for the contingency of a broken neutral conductor.

The resulting increased primary fault levels due to this multi-grounding had two other consequences. It became possible to cascade and coordinate multiple fuses and reclosers in order to minimize the area affected by a primary fault. Secondly, it became more difficult to limit residential neutral potential rise caused by a primary to secondary fault. This forced North American utilities to interconnect the primary and secondary neutrals, thus providing a metallic path for such fault current back to the source.

In turn, interconnection of the primary and secondary neutrals had several other ramifications. It was found that water systems contributed significantly in reducing neutral potentials on the primary system. Secondly customer ground systems gained reliability. Thirdly, some neutral current on the primary system began to flow through customer grounds creating the farm "stray" voltage issue [10, 11]. Steady stray potentials normally range from 1 to 10 V. Fourthly, it was found that phase-to-neutral faults could cause significant neutral to earth potentials to appear on the secondary neutral [12-18].

Both stray and fault-related voltages were exacerbated by a related development in the 1950s. It became the norm in North American to bond portable appliance cases using grounded receptacles. This conductor had to be interconnected to the secondary neutral at the service entrance in order to provide enough current on faults to operate customer fuses or breakers. As a result, stray and fault-related voltages appeared in many more touchable locations in customer premises than had occurred previously. Examples include:

- Touching a TV set while holding an externally grounded coaxial cable in the other hand.
- Adjusting the thermostat of an outdoor hot tub while standing on earth.
- Vacuuming the car on a wet driveway.
- Using a case grounded electric drill in the backyard.
- Pushing the button of a traffic signal while standing in salty slush.

Pressured water pipes had always been bonded to the service neutral and often provided the service panel ground. Examples of stray and fault-related voltages impresses across the body from this connection include:

- Attaching a hose to an outdoor faucet while barefoot.
- Touching shower faucet while standing on a drain connected to soil under the building.
- Barn animals drinking out of a pipe-connected water bowl.

Later editions of safety codes mitigated some of these potentials across the body by calling for bonds between the secondary neutral and touchable objects such as:

- Metallic drains
- Telephone and cable TV service wiring
- Gas service pipes to the gas meter
- Gradient control grids under animal stalls

3.0 SOURCES OF STRAY VOLTAGE

Stray voltage can be caused by off-the-farm or on-the-farm sources. This section will briefly describe both sources.

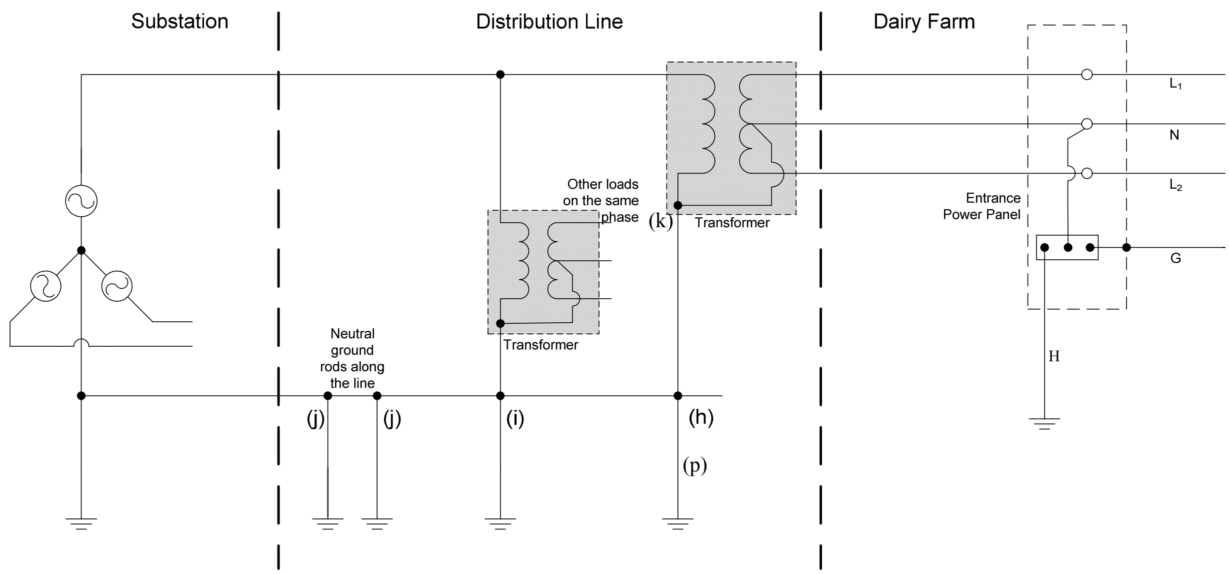

Figure 4 - Electrical Diagram of a Power Distribution Network

3.1 Off-the-farm Sources

Figure 4 shows the electrical connections of a distribution system in North America. As mentioned in Section 2.5, the secondary (N) and primary neutral (h) of the pole transformer feeding the farm are bonded together (k) and connected to a ground rod via a down lead (p). This rod is provided to reduce neutral to earth potentials and to protect the pole transformer in case of a lightning strike.

As shown, there are usually several transformers connected to the same phase of the distribution feeder, sharing the same neutral wire. Neutral current of each one of these transformers, supplying neighborhood farm loads, can return to the substation through several paths:

- Primary (h) and secondary neutral (N) wire
- Local grounding (h, p)
- Neighboring grounding (i)
- Pole Grounds (j)

In addition to the neutral current created by the transformers that are connected phase to ground, neutral current can also be created by induction from high currents in parallel power lines. This source of neutral current is rare and is treated in more detail in Section 5.

The portion of the current passing through the farm grounding electrode (H) can cause steady current which circulates in the farm and produces stray voltage. Since the power panel disconnect switch breaks the phase but not the neutral, the stray voltage is present even when the disconnect switch is open.

The Canadian Standard Association (CSA) overhead line standards enforce neutral bonding for pole-mounted telephone and TV cables. These slightly reduce neutral impedance and thus stray voltage. On the other hand, if the customer plans to use a Variable Threshold Neutral Isolator or Saturable Reactor Filter to isolate neutral wire and ground (will be discussed later), these service drops may need special attention since they bring the neutral into the buildings. In this case, the source of the disturbance is still the power system, not the telephone or TV companies which are a passive carrier of the current.

Steel gas customer service pipes are not usually a source for stray voltage because gas utilities install insulating flanges at the customer meter in order to apply upstream cathodic protection to prevent corrosion.

Gas companies also employ cathodic protection on gas transmission pipe lines which can cause stray voltages up to 1 V. This voltage is not expected to significantly contribute to the overall stray voltage, seen at a farm. When transmission lines run parallel to gas pipe lines, a detailed study should be carried out to find out if inducted voltage on the gas pipelines is significant.

3.2 On-the-farm Sources

Although stray voltage is associated with the use of electricity, stray voltage is not only caused by the arrangement on the utility side of the customer transformer. In order to identify these sources, stray voltage caused by on-the-farm sources can be measured after temporary disconnection of the primary to secondary neutral bond ((g) in
Figure 2) at the pole.

Possible on-the-farm sources of stray voltage are summarized below [5]:

- Insulation failure: any condition which results in a high resistance contact between a live wire and earth may cause current flow in the ground. Insulation failure may be a result of poor installation, incorrect use of equipment or breakdown of insulation on buried cable.

- The operation of an electric fence: many farms have an electrical fence to keep the animals within the farm's perimeter. Any connection between the electrical fence and the ground can be an origin for the stray voltage. For example weeds can make the fence to ground connection.

- Neutral wire and ground wire connection in more than one location: per the Ontario Electrical Safety Code, the neutral and ground wire should be bonded only in the customer's entrance electrical panel. A second attempt to connect these wires inside a farm can cause portion of the neutral current to circulate in the earth.

4.0 STRAY AND NEUTRAL TO EARTH VOLTAGE MITIGATION TECHNIQUES

There are several techniques to mitigate stray voltage caused by off-the-farm sources by reducing the neutral to earth (NEV) voltage. There are also techniques to reduce stray voltage by separating the farm neutral from the distribution system neutral. This section briefly describes the techniques and explains effectiveness and relative cost of each technique.

4.1 Distribution Load Balancing

Load balancing is one of the most effective methods to limit the neutral to earth voltage. Single phase transformers and single phase lines connected to one phase of a three phase line should be balanced lengthwise among the phases (connected to appropriate phase). Achieving balanced current only at the head end substation is not sufficient.

In order to show the effectiveness of the technique a model has been constructed assuming an overhead three phase line with 100 kVA, single phase, loads on poles 5, 10, 15, 20, 25, 30, 35, 40 and 45. These loads can represent dairy farms along a line at the pole locations. Table 4.1 shows phase balancing of the loads along the line, neutral to earth voltage seen by the farm, as well as other parameters of the utility distribution system. For example in case A, the customer at Pole # 5 who is connected to phase "A" of the distribution feeder experiences 2.2 V of neutral to earth voltage whereas the customer at Pole # 10 who is connected to phase "B" of the distribution feeder will see 2.4 V of neutral to earth voltage

Figure 5 shows neutral to earth voltage along the line for each series, using a custom made simulation software which was previously validated [19]. As shown, neutral to earth voltage is reduced if the line is longitudinally balanced. This is a method to lower the neutral to earth voltage considerably but there still would be some neutral to earth voltage left on the feeder because of unbalance between customers. The higher neutral to earth voltage may occur at the middle or end of a line depending on the phasing of the loads.

In Table 4.1, the ideal situation is Case A with all the loads perfectly balanced. The worst case is Case B with all the loads connected to phase A. Loads on Case C and D are connected to arbitrary phases. These are simplified ideal situations to illustrate the significance of the phase balancing. Rebalancing single phase transformers and laterals should require only brief outages as the transformer or lateral is reconnected to a different phase. The Kinectrics spreadsheet used to generate these results could help utility engineers to achieve the most effective balance for the distribution system.

The cost of load balancing was estimated by Hydro One and reported to the OEB in a report on energy loss and loss reduction cost benefits [21]. To balance one circuit the estimate is based on one day for a bucket truck, crew and a technologist at a cost of $ 4,000. This estimate is based on balancing many circuits as part of an overall loss reduction project. The cost to balance a single circuit may be slightly higher, estimated by Kinectrics to range from $ 2,000 for a short circuit with 4 km of three phase line to $ 10,000 for a long circuit with 80 km of three phase line. A distribution circuit is also known as a distribution feeder.

Table 4.1 – Load Arrangement Along a Three Phase Overhead Line

Customers Connected to Pole Numbers	Case A		Case B		Case C		Case D	
	Customers Connected to Phase	NEV (V)	Customers Connected to Phase	NEV (V)	Customers Connected to Phase	NEV (V)	Customers Connected to Phase	NEV (V)
5	a	2.2	a	5.2	a	5.65	a	6.2
10	b	2.4	a	7.2	a	7.14	b	6.9
15	c	1.1	a	13.1	a	6.37	b	3.9
20	a	1.6	a	17.0	b	7.08	c	3.6
25	b	1.1	a	19.2	b	6.66	a	8.8
30	c	2.2	a	20.2	b	4.89	c	12.3
35	a	2.4	a	20.2	c	9.35	c	14.8
40	b	1.3	a	19.5	c	13.2	c	15.8
45	c	4.9	a	18.5	c	14.6	c	15.7

Other parameters used in the simulation:
System voltage: 12.5 kV, Soil resistivity: 500 Ωm, Number of ground rods per kilometer: 5, including one customer service ground, Ground rod resistance: 8 Ω, pole span: 100 m, Neutral wire size: 85 mm^2 (3/0[1]), Customer Load: 100 kVA, Distance neutral to phase: 3 m

4.2 Converting Laterals from Single to Three Phases

Distribution circuits typically follow a tree-like topology. A three-phase main feeder or "backbone" runs through the centre of the serviced area and may extend 10 to 20 km. Single or three-phase branches or "laterals" leave in a transverse direction along township roads, typically at intervals of 1.6 km and usually extend less than 10 km. A 4.5-km long single-phase lateral with a relatively heavy load (900 kVA) can produce a significant neutral to earth voltages (18.5 V as shown for Case B in Table 4.1). Conversion of this line to three phases would reduce the stress to 4.9 V (as shown by Case A in the table). Here loads must be well balanced among phases as described in the previous section.

The cost of three-phase conversion will as a minimum require two new conductors ($ 4 000 / km if 85 mm^2 (AWG 3/0) - see Table 4.4 for other sizes), two new insulators per pole ($ 2 000 / km) and labour costs (estimated as $ 7 000 / km, the amount a crew can upgrade in one day). More typically, the existing line will require rebuilding adding the cost of poles ($ 12 000 / km) and labour (estimated as $ 7 000 / km). Thus conversion of a 5 km lateral may cost from $ 65 000 to $ 160 000.

[1] American Wire Gage 000 (AWG 3/0)

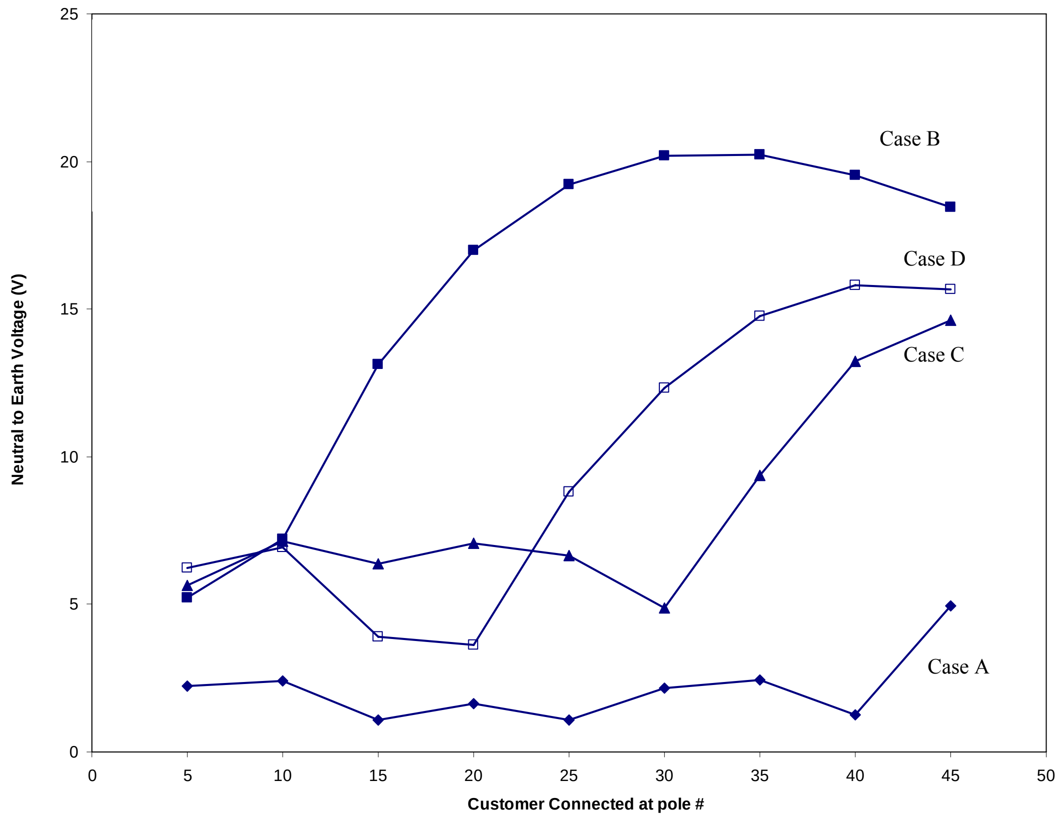

Figure 5 – Neutral to Earth Voltage along the Line

4.3 Increasing Number of Ground Rods

As mentioned, the neutral wire is multi-grounded in North American distribution systems. This includes pole grounds at fixed span intervals, pole transformer grounds and customer service grounds. The resistance of the ground electrodes must be lower then 25 Ω to satisfy standard requirement [3]. If the neutral to earth potential is still excessive, the following improvements should be considered:

- Increasing the number of poles with ground rods.
- Increasing the ground rod length to 9 m.
- Installing a buried conductor (counterpoise) along the line.

Some times adding a remote grounding grid may be helpful in achieving lower ground rod resistance in rock country. Note that adding a remote grounding grid is the most expensive way of reducing the ground rod resistance.

The Ontario Hydro Grounding Guide [4] lists the allowable single phase or three phase unbalanced line loadings for various neutral conductor size, system voltage ratings, and ground rods to keep the neutral to earth voltage under 10 V. This table is reproduced as Table 4.2 in this report. As an example, if we increase the number of 25 Ω ground rods from two to six per kilometer on a 4.16 kV distribution feeder, the single phase or phase unbalance power can be increased from 3 to 10 kVA while maintaining the same NEV voltage level of 10 V.

Table 4.2 - Neutral Loading Limits (kVA/km) over System Voltage, Neutral Size and Grounding Density to Maintain NEV <10V

System Voltage (kV)	Neutral Size mm^2 (AWG[1])	Number of 25 Ω ground rods per km		
		2	4	6
4.16 / 2.4	85 (3/0)	3	7	10
	53 (1/0)	3	6	9
8.32 / 4.8	85 (3/0)	7	14	20
	53 (1/0)	6	12	18
12.5 / 7.2	85 (3/0)	10	20	30
	53 (1/0)	9	18	26
25 / 14.4	85 (3/0)	20	41	61
	53 (1/0)	18	36	53
27.6 / 16	85 (3/0)	N/A	N/A	78
	53 (1/0)	N/A	N/A	68

Figure 6 based on the Kinectrics spreadsheet shows the benefit of increasing the number of ground rods as well as increasing the distribution system voltage. This graph assumes a neutral wire size of 85 mm^2 (AWG 3/0) and single phase or phase to phase unbalanced power of 20 kVA per kilometer. As shown, the neutral to earth potential varies inversely with the number of ground rods. For example, in distribution voltage level of 12.5 kV, increasing number of 25 Ω ground rods from two to six and ten per kilometer, lowers the neutral to earth voltage by 65% (20.13→7.09 V) and 74% (20.13→5.14 V) respectively.

Based on suppliers' web pages in January 2008, a single ground rod costs \$ 12-\$ 20 (use \$ 15), the connectors cost \$ 15, and the 3 m of 13 mm^2 (AWG #6) copper ground lead \$ 10. The installation cost has been estimated based on the cost to replace a single insulator on a one phase line which is known to Kinectrics from previous work with utilities and would take a similar time for a crew. The installation cost has been estimated as \$ 170. The total cost estimate is therefore \$ 210 per additional ground rod. Assuming an additional four ground rods are installed per km, the total cost for a circuit could range from \$ 33,600 for a short circuit with 40 km of line to \$ 168,000 for a long circuit with 200 km of line.

[1] AWG is American Wire Gage, AWG 3/0 represents a wire with cross sectional area of 85 mm^2 and AWG 1/0 represents a wire with cross sectional area of 53 mm^2

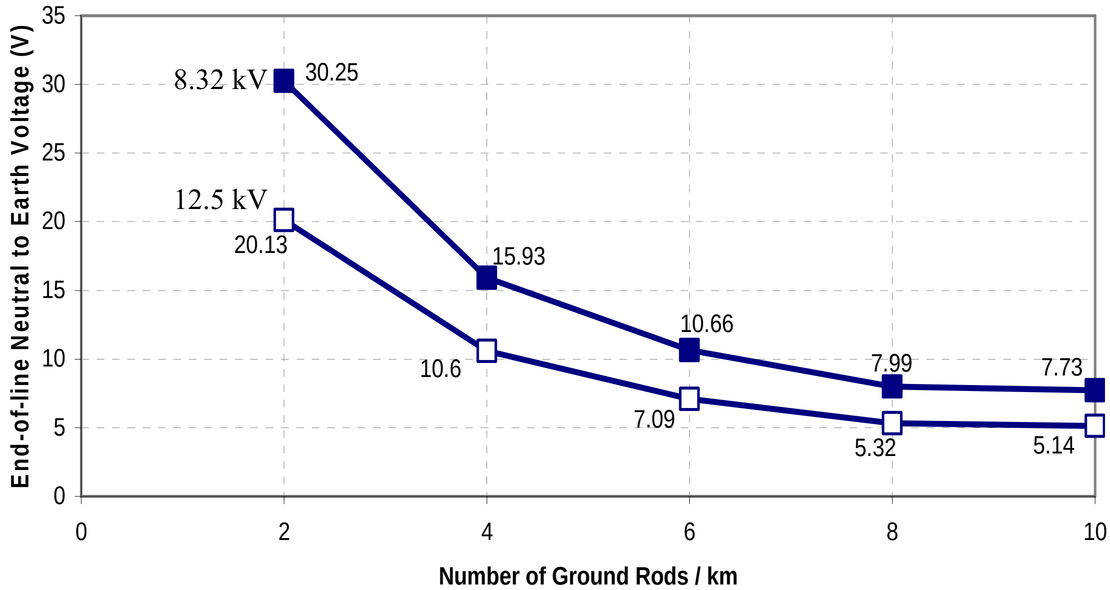

Figure 6 – NEV by system voltage and grounds per km
Neutral Wire Size = 85 mm^2 (3/0)

4.4 Increasing Distribution Voltage Level

Neutral to earth voltage is also inversely proportion to voltage level. As shown in Figure **6**, increasing voltage level by 50% from 8.32 kV to 12.5 kV in a four ground rod per kilometer system, can reduce the neutral to earth voltage to 34% (15.93 to 10.66 V).

The cost of increasing the distribution line voltage depends on the amount of increase and the design of the original line. Generally higher voltages require taller poles to provide more ground clearance and more spacing between the phase and neutral wires. However, often a utility will use a single line design for all voltages, in which case the higher voltage design is used at all voltages and the poles in this case would not need to be replaced during a voltage upgrade. Poles that do need to be made taller can sometimes be extended, especially for single phase lines, at considerably less cost than replacing the pole. The cost of increasing the voltage on a circuit has been estimated from typical replacement costs for poles, insulators, distribution transformers and substation transformers. It was assumed that the conductor could be left in place. Table 4.3 lists the assumptions used.

The total cost estimate for a voltage upgrade on a single rural circuit is $ 2,034,000 with pole replacement and $ 809,000 without pole replacement. The actual cost may vary ±25% from this estimate based the actual voltages being used and details of the individual circuit.

Table 4.3 - Component Costs for Voltage Increase

	Replacement Cost	Population on Typical Circuit[1]	Cost ($)
Pole (1 phase)[2]	$ 1,500	250	375,000
Pole (3 phase)[2]	$ 2,000	425	850,000
Insulator (1phase)	$ 170	250	42,500
Insulator (3 phase)	$ 170	1275	216,750
Distribution Transformer	$ 1,500	300	450,000
Step-up Transformer	$ 100,000	1	100,000

4.5 Increasing Neutral Wire Size

The impedance of a wire consists of resistive and reactive components. Increasing the wire size reduces resistance but has a small effect on the reactance. In wire size ranges that are normally used, only the reactance is dominant. Thus, increasing neutral wire size will have a modest effect on neutral to earth voltage. This is shown in Figure 7. Increasing neutral wire size by 60 % (from 53 mm^2 or AWG 1/0 to 85 mm^2 or AWG 3/0), lowers the NEV voltage by about 12% (from 12.0 to 10.6 V). This assumes four 25 Ω ground rods per kilometer on a 12.5 kV system.

In addition, by reducing the distance between the neutral wire and phase wire, mutual impedance between the mentioned wires will be reduced. Reducing the mutual impedance is a virtual way of increasing neutral wire size. However this distance can not be reduced beyond a minimum as allowed by safety standards according to each voltage level.

It has been estimated that a line stringing crew costing $ 7,000 per day can replace 2 km of neutral per day. The conductor cost depends on the size of the neutral as shown in the following table. A typical single phase line has 34 mm^2 (AWG #2) conductors for both phase wire and neutral. A typical three phase line has 85 mm^2 (AWG 3/0) phase wires and a 34 mm^2 (AWG #2) neutral.

[1] 17 km of three phase and 25 km of single phase
[2] 1 phase has 10 poles/km, three phase has 25

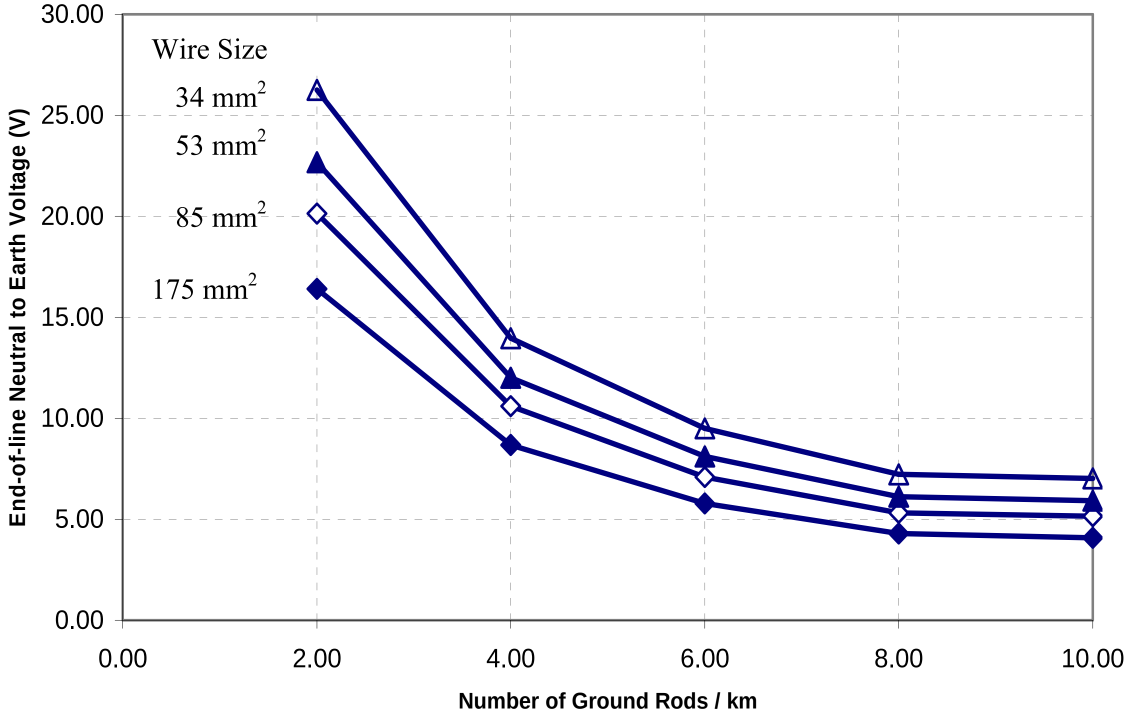

Figure 7 – NEV for Various Number of Ground Rods - System Voltage = 12.5 kV

Table 4.4 - Neutral Wire Increase Cost

Wire Size and Type[1]	Wire Area (mm^2)	$/km
#2 ACSR	34	900
1/0 ASC	53	1200
3/0 ASC	85	2000
336 ASC	175	3700
556 ASC	289	5700

A typical rural circuit has a maximum of 12 km of line distance to the substation in southern Ontario. This can vary from 4 km to 80 km over the whole province. Since not all of the neutral will need to be replaced to mitigate the NEV at one farm, the cost for replacement of 10 km with 85 mm^2 (AWG 3/0) conductor can be estimated as $35,000 labour and $20,000 materials for a total of $ 55,000. If there were several farms on the circuit and all the neutral wires required upgrading to 85 mm^2 (AWG 3/0) conductor the cost could be as high as $1,100,000 for a 200 km circuit.

[1] ACSR is Aluminum Conductor Steel Reinforced. ASC is Aluminum Stranded Conductor.

4.6 Changing Pole Configuration

Even when loads are perfectly balanced, neutral to earth voltages may result from induction due to unequal spacing between the phases and neutral. There are three typical distribution pole constructions in Ontario. These are shown in Figure 8. Typical phase to phase and phase to neutral distances for a 12.5 kV feeder are listed in Table 4.5.

Table 4.5 – Typical Phase to Phase and Phase to Neutral Distances for a 12.5 kV Feeder

	Armless Vertical Construction	Armless Triangle Construction	Crossarm Construction
Phase to phase distance (cm)	150	75	100
Lowest Phase to neutral distance (cm)	180	150	150

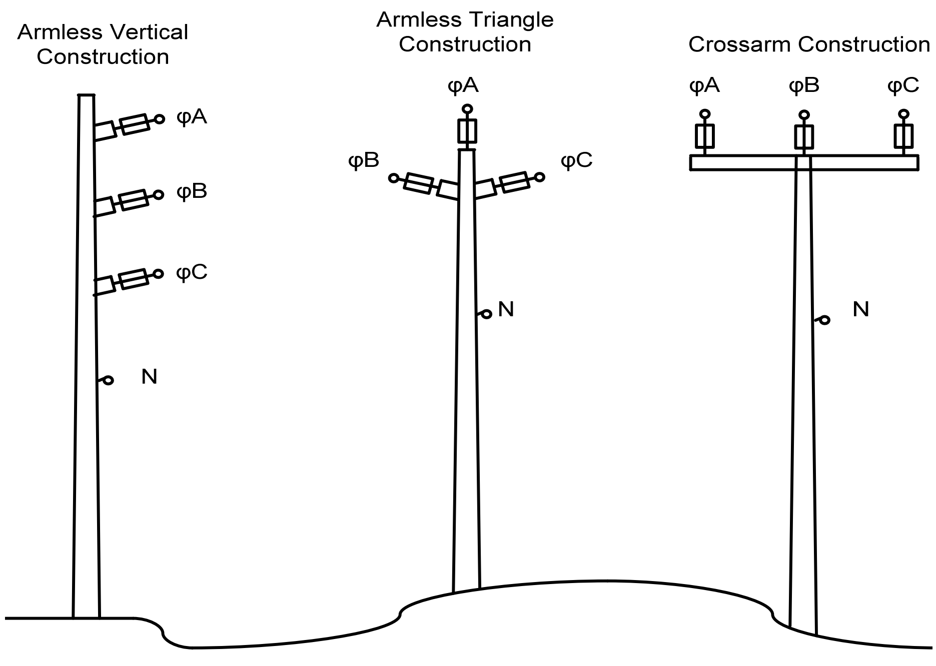

Figure 8 - Typical Pole Configurations

For armless triangle and crossarm construction, the phase to neutral distances are close to equal, causing little neutral to earth voltage. However, in armless vertical construction, distances between each phase and neutral are quite different. These distances are 180 cm, 330 cm and 480 cm for phases A, B and C respectively.

The Kinectrics spreadsheet reviewed the neutral to earth voltage for a 5 km distribution line with armless vertical pole configuration and a balanced load of 600 kVA at the far end. Other parameters for this study are:

- System Voltage: 12.5 kV
- Soil Resistivity: 500 Ωm
- Number of 25 Ω per kilometer: 6
- Neutral size: ACSR[1] 85 mm^2 (AWG 3/0)

As shown in Figure 9, the neutral to earth voltage reaches 20 V at the far end of the line. This study describes the worst case scenario to show the significance of induction voltages. In typical cases with line length of 0.5 km and balanced load of 300 kVA at the end of the line, the neutral to earth voltage caused by induction reaches values of about 2 V. This voltage is not expected to significantly contribute to the overall NEV voltage.

The potential can be mitigated by changing the pole configuration to armless triangle or crossarm construction.

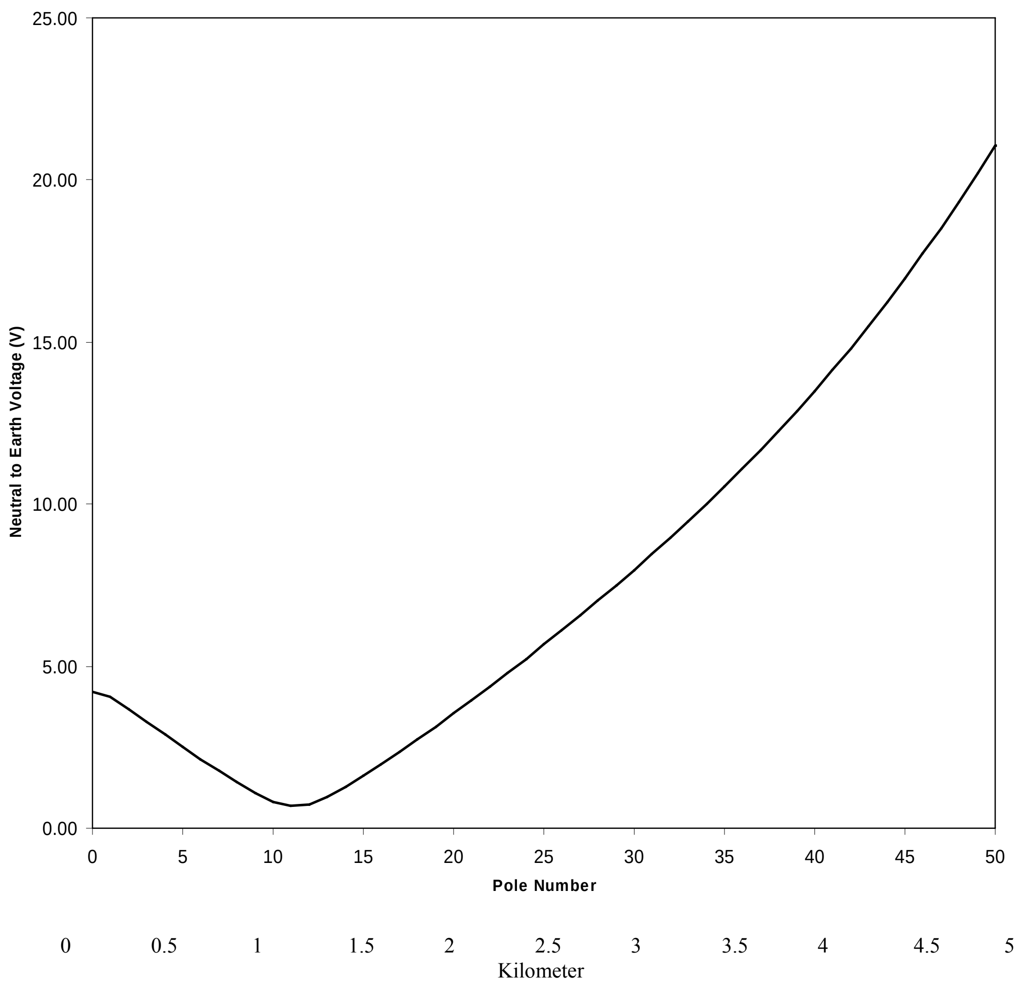

Figure 9 – Neutral to Earth Voltage for a Balanced Load With Armless Pole Configuration

[1] ACSR is Aluminum Conductor Steel Reinforced

The cost of changing the pole configuration from armless vertical construction depends on the number of circuits. If there is only one circuit then the vertical configuration could be changed to armless delta for a relatively low cost, estimated by Kinectrics to be about $ 4,000/km or $ 70,000 for a typical circuit. However the vast majority of single circuit lines will already be armless delta or crossarm. The armless vertical configuration may have been used for a single circuit line to allow for future expansion to two circuits with the second circuit mounted on the other side of the pole, precluding the use of armless delta. If there is more than one circuit then changing the pole configuration to horizontal crossarm construction is more costly, however the pole height should be sufficient to allow for the conversion without replacing the poles. The estimated cost, based on the component costs in Table 4.3 and using six insulators per pole (two circuits), is $ 620,000 per circuit.

4.7 Five Wire Distribution System

The five wire system includes a uni-grounded neutral wire in parallel with multi-grounded ground conductor, as shown in Figure 10 [6]. The transformer secondary neutral is connected to the ground wire but is isolated from the distribution system neutral.

In this configuration, unbalanced primary current will return to the substation through the neutral current and the earth carries very little current. Since the primary and secondary neutrals are not bonded together, neutral current does not flow to the customer's farm and eliminates of-the-farm NEV voltage issue. This is very similar to the system configuration which was used before 1930.

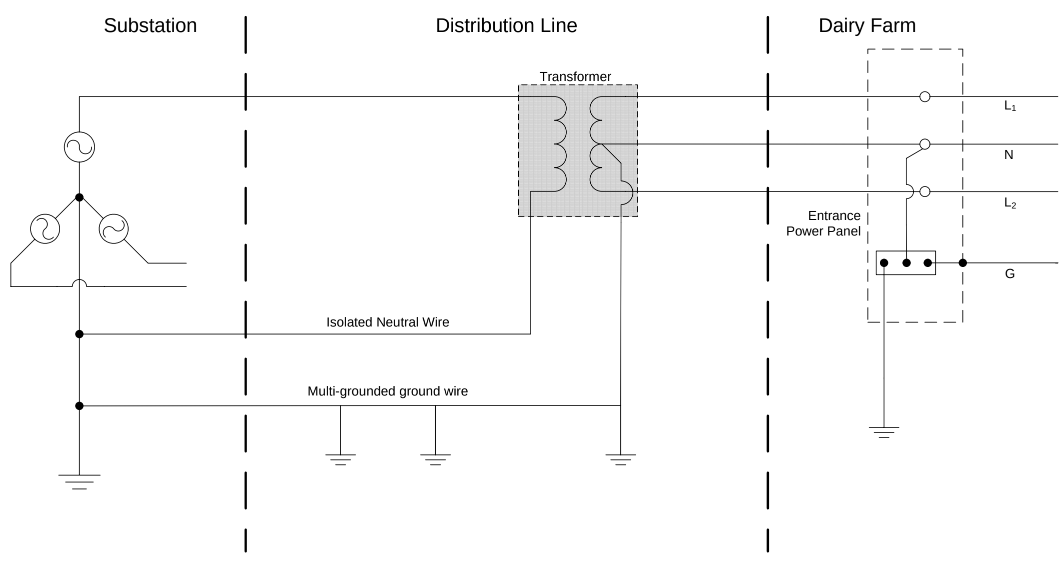

Figure 10 - Five-wire Distribution System

Although the five wire distribution system mitigation technique has an advantage of eliminating the NEV voltage, it is a costly solution. The higher cost results from the following: an additional conductor, an isolated neutral, adding neutral arresters at equipment, requiring two bushing for transformers and capacitors, adding neutral switches for reconfiguration and the need for taller and higher strength poles. As a result the five wire system is a design that is not in use on any distribution system.

The cost of changing to a five wire has been estimated by Kinectrics to be similar to the cost of a voltage increase which was estimated in Section 4.5 as $ 2,034,000 per circuit.

4.8 Isolation Transformer

This mitigation technique consists of using an isolation transformer at the entrance power panel between the distribution transformer of the utility and the farm's electrical panel. The isolation transformer permanently disconnects any bond between utility and the farm's neutral system. By breaking this connection, primary neutral current cannot flow to earth through the dairy farm and stray voltage issue will be eliminated.

However, isolation transformers are expensive and a winding to winding fault could produce hazardous touch potentials. Use of an isolation transformer is not a practical solution for stray voltage mitigation. Since it is not recommended, no cost estimate has been made.

4.9 Variable Threshold Neutral Isolator (VT/NI)

Companies producing this type of devices include Dairyland Electric Industries (www.dairyland.com), Nuvolt Corporation Inc. (www.agrivolt.com) and L&B Stray Voltage Services (www.lbstrayvoltage.ca)

As shown in Figure 11 the isolator consists of a voltage limiting device, typically a Metal Oxide Varistor (MOV), installed between primary and secondary neutrals at the pole transformer.

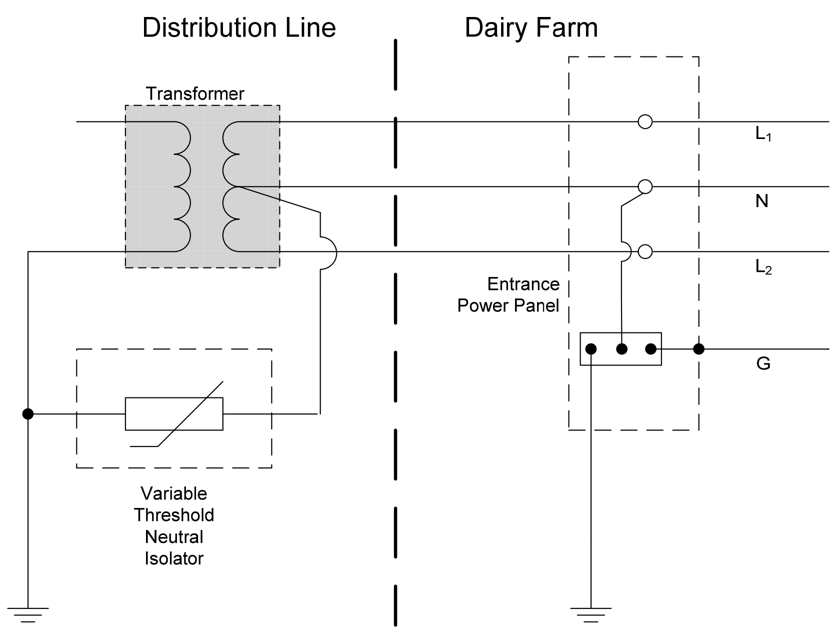

Figure 11 – Variable Threshold Neutral Isolator Installed on Utility Pole

Its function is to isolate the primary and secondary neutrals with a high impedance voltage limiting device. In case of a fault from a primary phase to the secondary wiring, the Isolator conducts heavily, causing the operation of primary feeder protection.

Telephone and cable TV serving the location where the Variable Threshold Neutral Isolator is to be installed may have a parallel interconnection between the utility primary neutral and the customer secondary neutral since the communication lines are bonded to the primary neutral to increase electrical safety for communications company staff. The communications cables can therefore provide a parallel path bypassing the isolator. Therefore, all utilities should be consulted when installing the filter to assure the desired isolation between the neutrals is obtained.

Although the use of Variable Threshold Neutral Isolator is a good technique to eliminate off-the-farm stray voltage issue, there are some safety concerns with regards to its usage:

- Fault duty: voltage limiting device has limited thermal capacity. In case of a severe ground fault, it is possible that the voltage limiting device burns open and permanently isolate primary and secondary. This can cause serious touch potential hazard. The fault duty of the voltage limiting device should be specified based on utility's short circuit data prior to installation. Moreover, this device should indicate if it has failed.

- Transferring the stray voltage further down the distribution line: By installing an isolation transformer, driving point impedance of the neutral system will be increased for other electricity users on the same feeder. This will raise the NEV voltage at the nearest neighbor as well as further down the distribution line. The increase may not be significant in many instances because the neutral is multi grounded.

The cost of these devices ranges from $ 900 to $ 1,700 plus installation, which requires a power utility crew, an electrician, and possibly communication utility crews [20].

4.10 Saturable Reactor Filter

The Saturable Reactor Filter has a winding mounted on nonlinear iron core. This filter should be installed between the neutral and the ground connection at the customer's entrance power panel in order to limit the stray voltage, as seen in Figure 12.

As discussed before, the stray voltage is produced by the customer's ground grid resistance when part of the primary neutral current passes through the mentioned resistance.

The filter has a high impedance for neutral to earth voltage of up to 25 V. As a result, potentials below this value are not transferred to the farm ground. However, if a fault develops on the farm, the filter voltage will attempt to rise to 120 V and the iron core will saturate, causing the flow of sufficient fault current to trip branch circuit breakers.

The filters are no longer manufactured bus refurbished units may be available at a cost of approximately $500 plus installation. [20].

4.11 Summary of Mitigation Costs and Effectiveness

While it is clear that the mitigation techniques would vary in cost and effectiveness for different feeder configurations, Table 4.6 attempts to give some relative comparison between various mitigation techniques.

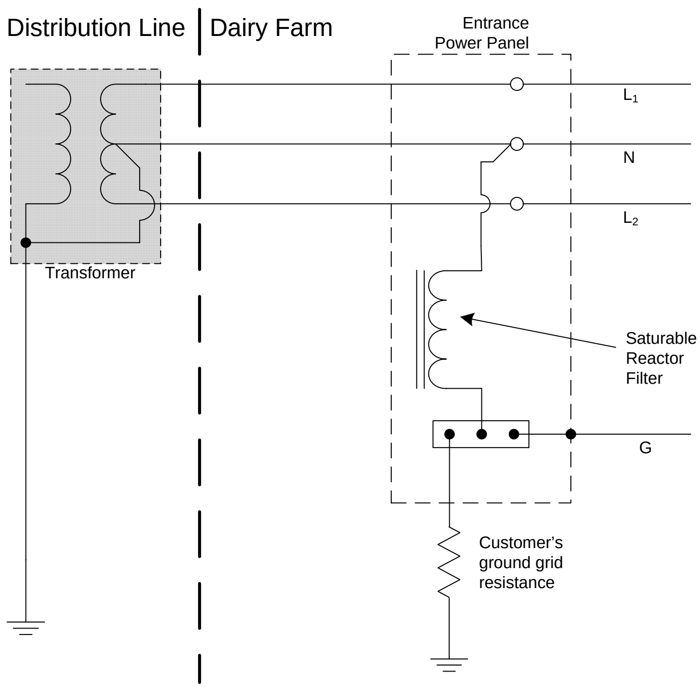

Figure 12 – Saturable Reactor Filter Installed at the Entrance Power Panel

Table 4.6 – Cost and Effectiveness of Mitigation Techniques

Technique	Effectiveness	Cost
Phase balancing	< 80% , > 30%	< $10,000
Conversion from single to three phases	< 80% , > 30%	< $ 160,000
Increasing number of ground rods	< 80% , > 30%	< $200,000
Increasing distribution voltage level	< 80% , > 30%	> $500,000
Increasing neutral wire size	<30%	> $50,000
Changing pole configuration	<30%	> $50,000
Use of 5 wire distribution system	<100% , >80%	> $500,000
Use of Variable Threshold Neutral Isolator	<100%[1] , >80%	< $5,000
Use of Saturable Reactor Filter	<80%[1] , >30%	< $2,000

This table is based on some examples situations and cannot be used for specific applications. It can be used as a guide only and detailed analysis is necessary for each particular case.

1 Effectiveness of this technique is based on stray voltages of about 10 V. For stray voltages higher than 10 V, this technique has "Low" effectiveness

5.0 DISTRIBUTED GENERATION AND NEV VOLTAGE

Small scale distributed generation connected to existing rural lines is usually single phase and rated less than 100 kW. The in feed should tend to cancel load current along a distribution line, thus reducing NEV voltage. Medium scale distributed generation for example co-generation in a greenhouse, may be rated 100 kW to 10 MW. This usually has a dedicated three-phase step up transformer connected to the distribution line through a delta winding. Since there is no connection to the neutral, this injects no unbalanced current and thus does not contribute to NEV voltage.

Large scale distributed generation connected to the HV transmission system may gather the energy from 50 or more wind turbines and achieve a total of 100 MW. The collection line may contain three feeders at 34.5 kV and carry a current approaching 600 A per phase. It is common for the three feeders to be mounted on a single pole in the vicinity of the main substation connected to the HV system. Inductive coupling from these collection lines to existing rural lines may cause significant NEV voltage.

As shown in Figure 13, Circuit 1 is usually mounted at the top of the pole with phases (1A, 1B, 1C) in a triangular configuration. Circuits 2 (2A, 2B, 2C) and 3 (3A,3B,3C) may have the phases configured vertically on either side of the pole using armless construction. Note that the phasing may be reversed on either side. The collection system often has no need for a neutral because the transformers are all delta connected. In some cases, a ground wire running under the phases has been used to bond together the grounding systems of individual turbines. This reduces their ground potential rise on faults where grounding is difficult due to high resistivity soil conditions.

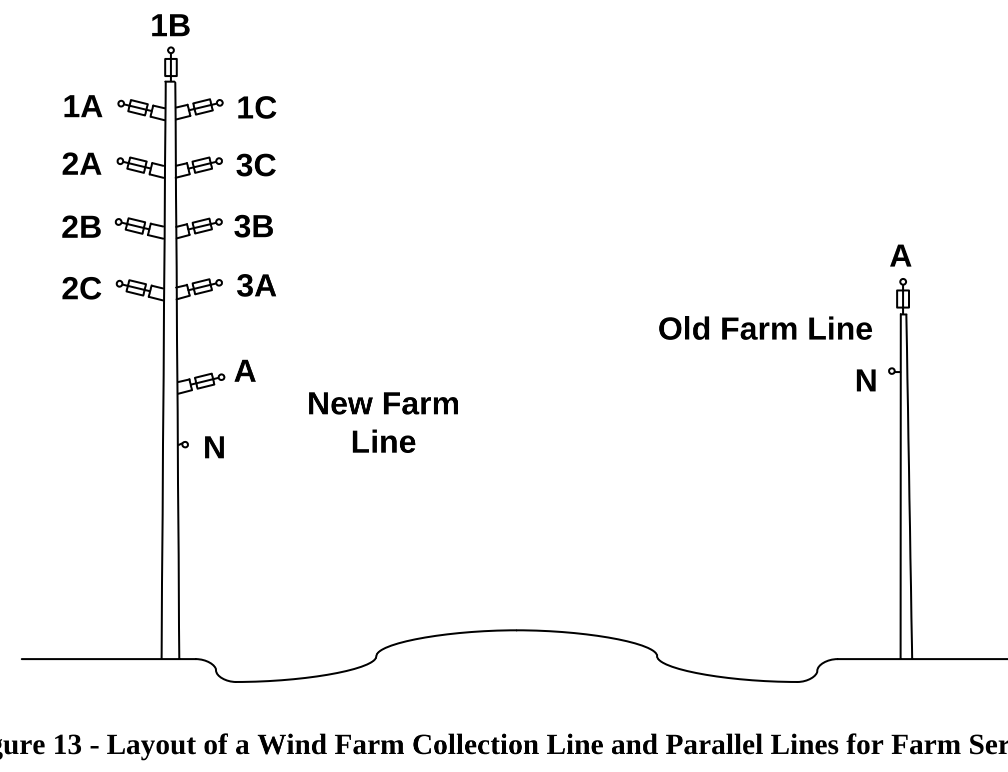

Figure 13 - Layout of a Wind Farm Collection Line and Parallel Lines for Farm Services

Questions may arise whether the same poles should be used for rural farm distribution, here shown as a single Phase A with Neutral N. NEV voltages may arise from inductive coupling between the rural neutral and the collection phases. Since these collection conductors are stacked vertically on the pole, one of the phases will be closer to the neutral. As a result, unbalanced eddy currents may be induced in the neutral and lead to NEV voltage.

Kinectrics has investigated this coupling using a spreadsheet modeling tool [19] and found the effect to be significant for certain constructions of collection lines. The base case considers three collection circuits rated 34.5 kV, on one pole. Each circuit carries the output of 24 turbines rated 1.5 MVA, or about 600 A per phase. The first circuit is at the top of the pole. The second and third circuits are configured vertically with phasing A above B above C on one side and C above B above A on the other (ABC, CBA). This reversal of phases tends to reduce the eddy currents induced in the neutral. As a variation, the second circuit is considered out of service, leaving only ABC on one side. A third variation has each collection circuit mounted on a horizontal crossarm (a horizontal crossarm is illustrated in Figure 8) which tends to cancel the induced potential in the neutral.

The rural multi-grounded neutral is 53 / 9 mm^2 ACSR (aluminum conductor / steel reinforced) (AWG 1/0) mounted on the same pole 3 m below the lowest phase. The vertical spacing between phases is 1.8 m. Three grounding scenarios include the equivalent of 2, 5 and 10 grounds per kilometer, each 25 Ω. This includes pole, transformer and customer service grounds. The collection line and rural neutral run parallel for 0.5 km. The soil resistivity is 500 Ωm. Table 5.1 displays the sensitivity of the maximum NEV voltage to changes in these parameters.

Table 5.1 – Sensitivity of NEV (V) to Collection Line Parameters

Phasing of Circuits ->	**ABC, CBA**			**ABC**			**Crossarm**		
Number of 25 Ω grounds per km ->	**2**	**5**	**10**	**2**	**5**	**10**	**2**	**5**	**10**
0.5 km parallel exposure (base case)	**3.33**	3.16	2.92	15.1	14.3	13.2	1.20	1.14	1.05
1.0 km parallel exposure	**6.22**	5.37	**4.35**	28.2	24.3	19.7	**2.24**	1.94	**1.57**
2.5 km parallel exposure	**10.6**	**6.81**	**4.79**	**47.8**	30.9	21.7	3.81	2.46	1.73
5.0 km parallel exposure	**10.9**	**6.91**	4.92	49.3	31.3	22.3	**3.93**	2.49	**1.78**
Neutral 1.8 m below phase	**6.31**	6.01	5.54	**21.1**	20.1	18.5	2.82	2.68	2.47
Neutral 5.0 m below phase	**1.59**	1.52	1.40	**10.3**	9.83	9.08	0.46	0.43	0.40
Larger Neut 85 / 14 mm^2 (AWG 3/0)	3.34	3.20	2.99	15.2	14.5	13.5	1.21	1.16	1.08
Reduced soil resistivity of 50 Ωm	3.33	3.17	2.93	15.1	14.4	13.2	1.20	1.14	1.06

The results show that crossarm construction for the collector line is by far the best strategy. For a 5.0 km parallel exposure, increasing the equivalent number of 25 Ω grounds per kilometer from 2 to 10 leads to a modest 55 % reduction in the NEV (3.93→1.78 V). For a 1.0 km parallel exposure this benefit diminishes to just a 30% reduction in NEV (2.24→1.57 V). Removing one of the vertically-phased circuits from service (say due to a line fault) increases the NEV voltage by almost a factor five (10.6→47.8 V). If the wind farm developer has installed both vertically-phased circuits with the same orientation (ABC, ABC), the NEV voltage further doubles to 95.6 V (nine times the ABC, CBA scenario).

For short parallel exposure distances (0.5→1.0 km), the NEV voltage scales almost linearly with the parallel length (3.33→6.22 V). The voltage increases only slightly beyond a critical length (2.5, 2.5 and 1 km for 2, 5 and 10 grounds / km respectively). For ABC, CBA phasing, the NEV voltage diminishes rapidly for larger spacing between lowest phase conductor and neutral (6.31→1.59 V). For ABC phasing, the reduction is more modest (21.1→10.3 V).

Contrary to first expectation, increasing the neutral size actually increases the NEV voltage slightly (3.33→3.34 V). Here the longitudinal impedance of the neutral is reduced more than its driving point impedance (the impedance of this conductor combined with its distributed grounds). NEV voltage results from the driving point impedance times the neutral current.

Soil resistivity changes the depth with which eddy currents flow in the earth under the line. This has a negligible effect on the mutual and self inductances of the phase and neutral conductors and thus the NEV voltage (3.33→3.33 V). Here the change in soil resistivity was assumed not to affect the resistance of the pole, transformer and customer service grounds.

The above NEV voltages due to distributed generation are in addition to those resulting from the normal operation of the rural distribution system. The values are high enough to warrant more detailed studies on the part of wind turbine developers. Collection lines may need to use crossarms or be located on the opposite side of roads relative to existing distribution lines in order to limit this impact.

Inductive coupling between the phases of a heavily-loaded High Voltage (HV) line and a parallel distribution line may also contribute to neutral earth voltage [22]. A preliminary study showed that a 500-kV line, carrying 1 000 A with phases horizontally aligned, can cause a neutral potential of 14 V for a 1.6 km length of parallel exposure. In this study, the HV phases were separated by 10 m with an offset of 100 m from the distribution line. Fortunately most HV lines in Ontario have a vertical phase arrangement, which leads to negligible neutral potential for this separation since the phases are about equally distant. Distribution lines running parallel to, and under, a heavily loaded HV line may need further study if the neutral to earth voltage is elevated. The mitigation techniques discussed previously are applicable to this kind of inductive coupling.

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7.0 REPORT DISTRIBUTION

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