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Protection System for a Wind Generation Plant in Panama: Challenges and Solutions

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Abstract—**The Penonomé wind power plant in Panama will have a total capacity of 337.5 MW. The first two phases currently in service provide 270 MW of generation. In this power plant, wind generators belonging to different companies are connected to a 34.5 kV system. Two transformers interconnect the 34.5 kV system to Panama's 230 kV transmission system at the El Coco substation. The 34.5 kV system is grounded through zig-zag and grounded-wye/delta banks. This paper describes the 34.5 kV system protection challenges and solutions, discusses the protection coordination requirements, and provides the coordination study results. The paper also provides recommendations for future enhancements of the protection system. Finally, the paper describes an actual event involving two cross-country faults in the 34.5 kV system.**

I. INTRODUCTION

In recent years, demand for electric power in Panama has experienced some of the fastest growth among emerging economies. To meet this growing demand, the country has prioritized investments in generation projects that reduce dependence on fossil fuels. One of these projects is the wind power plant in Penonomé—located in Coclé Department, 70 miles southeast of Panama City—which started in 2012. This is the largest wind generation project in Central America, with a future generation of 337.5 MW. The project has been divided into three phases. The first two phases are currently in service, totaling 270 MW of generation. The Penonomé power plant connects with Panama's transmission system at the El Coco 230/34.5 kV substation, which is an important node of the 230 kV network.

In this power plant, wind generators belonging to different companies are connected to a 34.5 kV system. Two delta/grounded-wye step-up transformers interconnect the 34.5 kV system to Panama's 230 kV transmission system at the El Coco substation. The 34.5 kV system is grounded through zig-zag and grounded-wye/delta banks that limit the ground fault current. This type of grounding poses a challenge for ground protection coordination in the 34.5 kV system.

This paper describes the 34.5 kV system protection challenges and solutions in detail. It discusses the protection coordination requirements and the coordination study results, and it provides recommendations for future enhancements of the protection system. Finally, the paper describes an actual event involving two cross-country faults in the 34.5 kV system.

II. POWER SYSTEM DESCRIPTION

Fig. 1 shows a single-line diagram of the power system. The El Coco substation has a breaker-and-a-half arrangement on the 230 kV bus, and it connects with the Panamá II substation through 230 kV Lines 230-12A and 230-13A. It also connects with the Llano Sánchez substation through 230 kV Lines 230-12B and 230-13B. These two pairs of lines are double-circuit lines. Two 120/140 MVA, 230/34.5 kV power transformers (T91 and T92) provide the connection to the 34.5 kV distribution system. These transformers have a grounded-wye connection on the 230 kV side and a delta connection on the 34.5 kV side. Twelve circuits (made of overhead lines and underground cables) connect to the two sections of the 34.5 kV bus, which have a normally open bus-tie circuit breaker. These circuits serve as collectors for generation from the wind power plants that comprise the El Coco generation project. The system will also include seven 9 MVAR capacitor banks and a 2 MVAR reactor as determined by load flow and harmonic distortion studies. At the time of publication, the capacitor banks and the reactor were still not in service.

Proper grounding is essential to protect wind power plant equipment from sustained and transient overvoltages on the healthy phases during ground faults [1]. Typically, wind turbine generators (WTGs) and their step-up transformers are ungrounded. The system must be grounded at the substation. In addition, if a collector circuit trips for a ground fault and the WTGs remain in operation, the system becomes an islanded ungrounded system operating with a grounded phase. The phase-to-ground voltage of the healthy phases may reach the phase-to-phase rated voltage value or more. Given the recent low-voltage ride-through requirements that system operators impose on wind generation sources, WTGs may continue to feed an islanded collector circuit for several seconds, which further compounds the overvoltage problem. Grounding the wind plant collector circuits—in addition to the substation grounding—solves this problem.

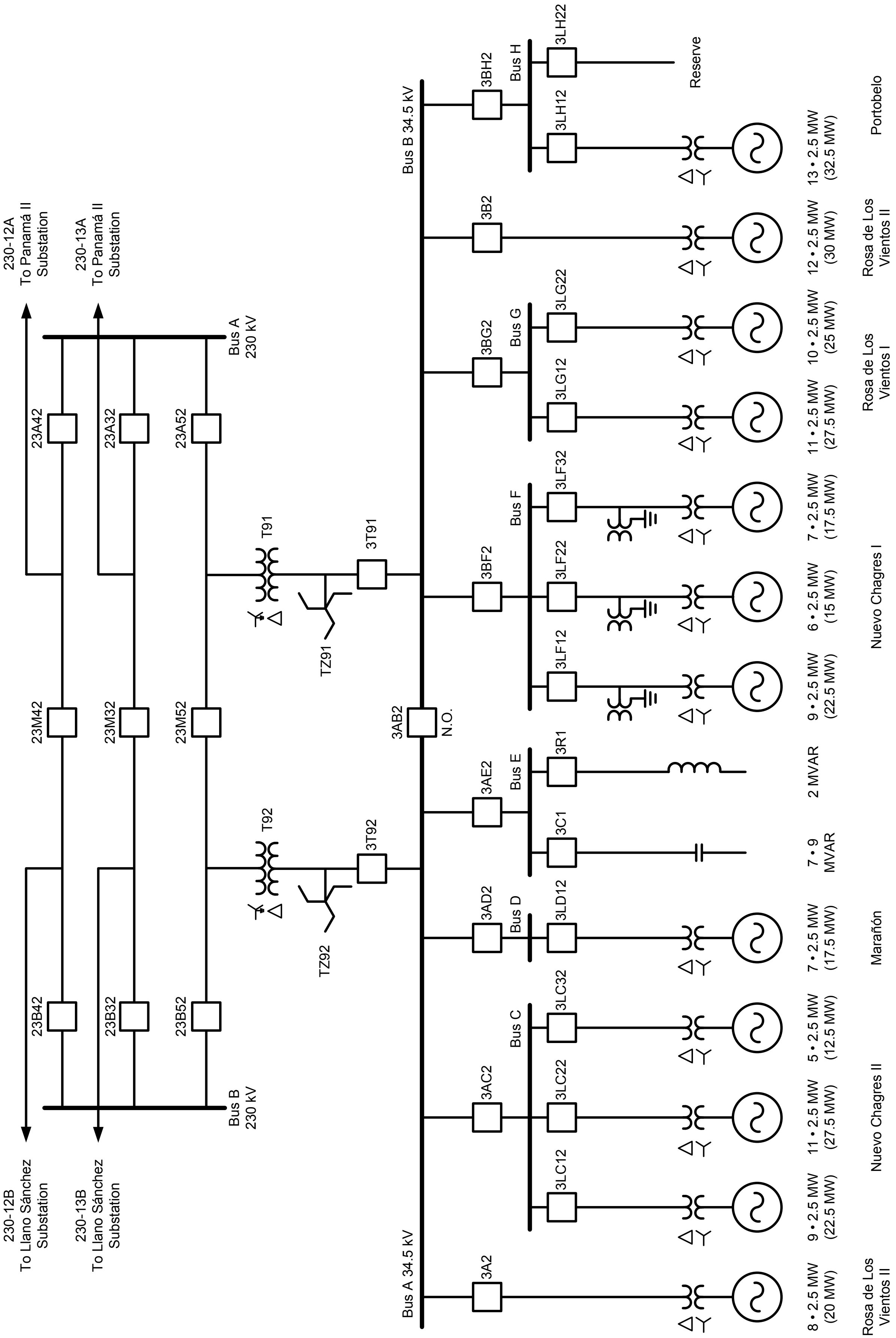

Fig. 1. System single-line diagram.

The Penonomé wind power plant 34.5 kV system is grounded through two zig-zag grounding transformers (TZ91 and TZ92) connected to the low-voltage terminals of Transformers T91 and T92. These grounding transformers limit the contribution to a bolted ground fault to approximately 1,000 A. Since the system series impedance is much smaller than the grounding transformer impedance, the ground fault current value is practically the same for any fault location on the 34.5 kV network.

In addition, three collector circuits of the Nuevo Chagres I wind power plant (Collector Circuits 3LF12, 3LF22, and 3LF32) are grounded per the wind generator manufacturer's recommendation. Three 34.5/0.48 kV grounded-wye/delta distribution transformer banks provide the circuit grounding and limit the contribution to a bolted ground fault to approximately 1,100 A. Each grounding bank is connected at equal distances from the substation and the farthest wind generator of the collector circuit. These additional grounding banks act as ground fault current sources at the collector circuits, which creates coordination problems for ground overcurrent protection.

III. PROTECTION AND CONTROL SYSTEM DESCRIPTION

The scope of the project described in this paper was as follows:

- Perform short-circuit and protection coordination studies for the 230 kV and 34.5 kV systems of the El Coco substation.
- Supply the protection and control (P&C) panels for the following:
  - Four 230 kV transmission lines with breaker-and-a-half bus arrangements at both ends (Lines 230-12A, 230-13A, 230-12B, and 230-13B).
  - Two 230/34.5 kV transformers with grounded-wye/delta connections (Transformers T91 and T92).
  - Two 34.5 kV zig-zag grounding transformers (Transformers TZ91 and TZ92).

A. Design Requirements

Meeting the wind generation plant demand for high service continuity requires dependable and fast phase fault protection, and sensitive and selective ground fault protection. The design requirements of the protection system include:

- Dual primary line protection, including current differential (87L) and directional-comparison protection schemes with the following characteristics:
  - Redundant fiber-optic communications channels.
  - Single-pole switching in the 87L scheme of Primary Protection 1.
- Line backup protection, including phase distance (21) and ground distance (21N) protection and ground directional overcurrent (67N) protection.
- Line circuit breaker automatic reclosing (79) with the following characteristics:
  - Reclosing enabled in Primary Protection 2 and available as hot standby in Primary Protection 1.
  - Master-follower reclosing scheme with the bus-side circuit breaker acting as the master and the middle circuit breaker acting as the follower. The follower replaces the master when the master is out of service.
- Breaker-failure (50BF) protection on 230 kV circuit breakers. The direct transfer trip of remote breakers must be supervised by Zone 3 fault detection.
- Dual transformer protection, including differential (87T), phase overcurrent (51), and ground overcurrent (51N) elements.
- Overcurrent protection for the zig-zag grounding banks using 51 elements.
- Overcurrent protection for the 34.5 kV collector circuits including 50/51 and 50N/51N elements.

B. P&C System Description

The P&C system uses multifunction relays with communications and programmable logic. These relays provide all the protection functions, as well as the control and monitoring functions required by the substation integrated system.

1) Transmission Line P&C System

Two multifunction relays provide fully redundant primary and backup line protection. Each relay provides the following functions:

- 87L protection that uses phase (87LP), negative-sequence (87LQ), and zero-sequence (87LG) differential elements to provide phase and ground fault protection.
- Directional-comparison permissive underreaching transfer trip (PUTT) scheme that uses 21 and 21N elements for directional discrimination.
- Distance protection that uses 21 mho elements polarized with memorized positive-sequence voltage and 21N quadrilateral elements.
- Ground directional overcurrent protection that uses a current-polarized zero-sequence directional element, and negative- and zero-sequence voltage-polarized directional elements that measure impedance.
- Automatic reclosing with synchronism checking (25) and undervoltage (27) supervision.

Because each multifunction relay provides 87L and directional-comparison protection, each line has dual 87L and dual directional-comparison protection.

The relays communicate over two fiber-optic channels that use optical power ground wire cables mounted on each 230 kV line. Each multifunction relay has two serial ports for 87L communication and two serial ports that support a proprietary peer-to-peer communications protocol. The relays can also monitor communications channels.

A bay controller provides the following functions:

- Breaker-failure protection.
- Local/remote switchgear control, interlocking, and circuit breaker supervision.

- Data collection from the substation switchyard and data forwarding to the supervisory control and data acquisition (SCADA) gateway.

2) *Transformer Protection*

Two multifunction relays provide redundant primary and backup transformer protection. Each relay provides the following functions:

- Differential protection.
- Overcurrent protection:
  - High-voltage side: 51/51N.
  - Low-voltage side: 51/51N and 51G.
- Restricted earth fault protection on the high-voltage side.
- Supervision of the sudden-pressure relay (63).

A bay controller provides the following functions:

- Breaker-failure protection.
- Local/remote switchgear control, interlocking, and circuit breaker supervision.
- Data collection from the substation switchyard and data forwarding to the SCADA gateway.

3) *Zig-Zag Grounding Transformer Protection*

A multifunction relay provides phase (51) overcurrent protection.

4) *Distribution System Protection*

One multifunction relay for each 34.5 kV collector circuit provides the following functions:

- Phase and ground overcurrent protection (50/51, 50N/51N).
- Ground directional overcurrent protection when required that uses a current-polarized zero-sequence directional element, and negative- and zero-sequence voltage-polarized directional elements that measure impedance. The relay automatically selects the best directional element for each fault.
- Underfrequency (81) alarming.
- Over- and undervoltage (59/27) alarming.

IV. POWER SYSTEM DIGITAL SIMULATION

A. *Transmission and Distribution Lines*

Fig. 2 shows the pi-circuit equivalent we used to model transmission and distribution lines.

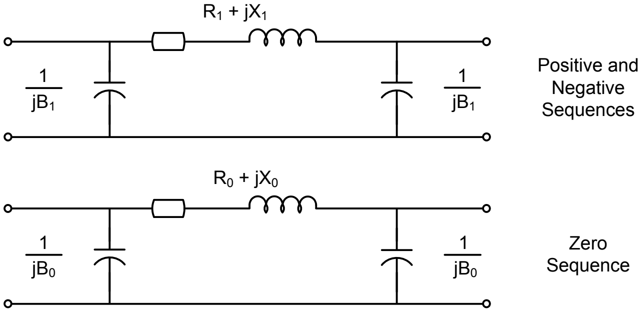

Fig. 2. Transmission line model.

In this figure, R_1+jX_1 and R_0+jX_0 are the line series impedances, and B_1 and B_0 are the shunt susceptances. Magnetic mutual coupling was included on the line models. Table III of the appendix shows the 230 kV line parameters. Table IV and Table V show the 34.5 kV overhead line and underground cable parameters respectively.

B. *Transformers*

We modeled the two-winding grounded-wye/delta transformers according to Fig. 3. Table VI of the appendix shows the transformer parameters. The short-circuit impedances are percent values based on the transformer rated apparent power and the tap rated voltage. Table VI also shows the parameters of the WTG step-up transformers and the grounding banks.

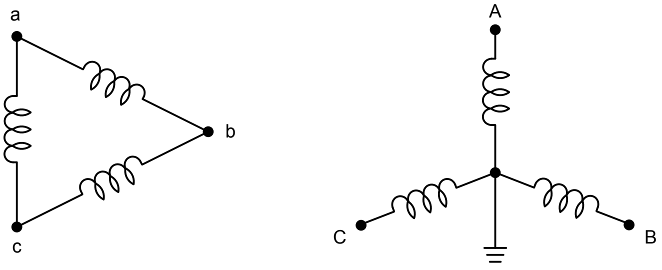

Fig. 3. Transformer winding model.

C. *Wind Generators*

The Penonomé wind power plant has 108 identical WTGs in its second stage, which are Type 4, 2,500 kW, 690 V units [2]. The third stage consists of the installation of 27 WTGs to reach the future planned capacity of 337.5 MW. Fig. 4 shows the WTG schematic diagram.

Each WTG consists of a variable-speed wind turbine coupled with bands to a multipole, three-phase, permanent magnet synchronous generator. The generator is connected to the network through a full-scale, back-to-back frequency converter based on insulated gate bipolar transistors and a 2,750 kVA, 0.69/34.5 kV, wye/delta step-up transformer. Table VII of the appendix shows the WTG parameters.

Type 4 WTGs offer design and operation flexibility. They can produce energy over a wide range of wind speeds, allow for fast and independent control of active and reactive power, limit fault current, and comply with the low-voltage ride-through requirements of industry regulatory agencies. The turbine rotates at its optimal aerodynamic speed (a slow speed), and the unit generates power at a frequency lower than the grid frequency. Inverters provide the frequency conversion and make it possible to supply reactive power to the grid [3] [4]. The WTG control system provides active power and frequency control, and reactive power and voltage control. Type 4 WTGs are typically designed to ride through a fault, as required by FERC Order 661 [5].

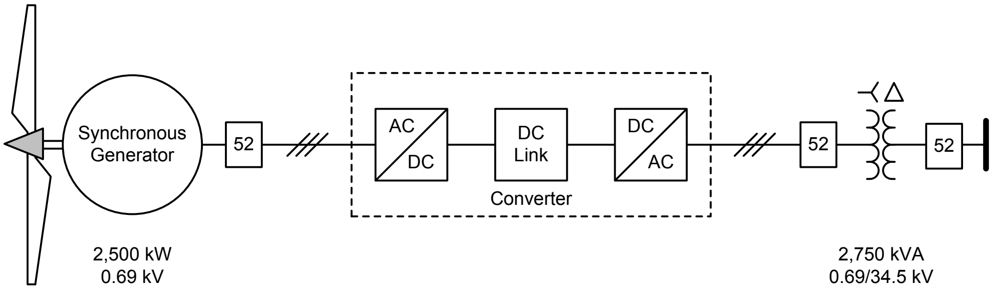

Fig. 4. WTG schematic diagram.

The behavior of Type 4 WTGs is governed entirely by the power electronics and the control algorithm. The generator response to short circuits has the following characteristics [4] [6] [7]:

- The WTG is ungrounded and contributes no zero-sequence current during a fault.
- The WTG control acts to balance the currents during unbalanced system conditions, including faults. The efficacy of this function depends on the severity of the imbalance. The WTG delivers only positive-sequence current in many cases.
- For external faults, the WTG current goes up briefly to about 2.5 times full-load current within the first half cycle. After that, the current settles back quickly to no more than 1.5 times full-load current. The WTG current response is a function of the control objective, and is not a natural generator response.

There is no consensus on whether Type 4 WTGs should be included in short-circuit studies because of their relatively low short-circuit current contributions. Some engineers recommend treating Type 4 WTGs as negative loads and ignoring them along with customer loads in short-circuit studies. In this paper, we consider WTGs as current sources for the steady-state short-circuit analysis required for overcurrent protection coordination.

V. PROTECTION COORDINATION STUDY

A. 230 kV Line Protection Coordination

In transmission systems, synchronous generators determine the phase fault current levels. The contribution from wind power plants is typically small [4]. This is true even for the El Coco wind power plant, which is connected to a weak power system: for a three-phase fault at the 230 kV bus of the El Coco substation shown in Fig. 1, Panama's power system contributes 5,374 A under maximum generation conditions, and the wind power plant contributes 717 A (less than the plant rated current). However, the delta/grounded-wye Transformers T91 and T92 significantly contribute to ground faults on the 230 kV system.

We followed the normal coordination principles for the 230 kV line protection schemes, which are phase and ground distance, ground directional overcurrent, and PUTT schemes. In particular, we considered the following problems:

- Magnetic mutual coupling between circuits in the double-circuit Lines 230-12A and 230-13A (El Coco-Panamá II), and 230-12B and 230-13B (El Coco-Llano Sánchez) [8].
- Infeed effect for ground faults from the El Coco substation, which affects protection schemes at the Panamá II and Llano Sánchez substations.

B. 34.5 kV System Protection Coordination

1) Phase Overcurrent Protection Coordination

The transmission system contribution typically determines the phase fault current levels in wind power plant medium-voltage collector circuits. The contribution from the wind power plant to collector circuit faults is normally small. For this reason, overcurrent protection is generally suitable for collector circuits. In some cases, a significant phase fault current contribution from the wind power plant makes it necessary to use directional overcurrent elements supervised by load encroachment elements [9].

Given the weak current contribution to phase faults, we use phase overcurrent protection for the El Coco collector circuits. The protection coordination study had to consider the inrush current resulting from closing the collector circuit breaker with all of the WTG step-up transformers in service. The WTG step-up transformers have fuse protection. Fig. 5 shows an example of phase overcurrent protection coordination for phase faults on Collector Circuit 3LF12. For simplicity, the fuse curves are not shown.

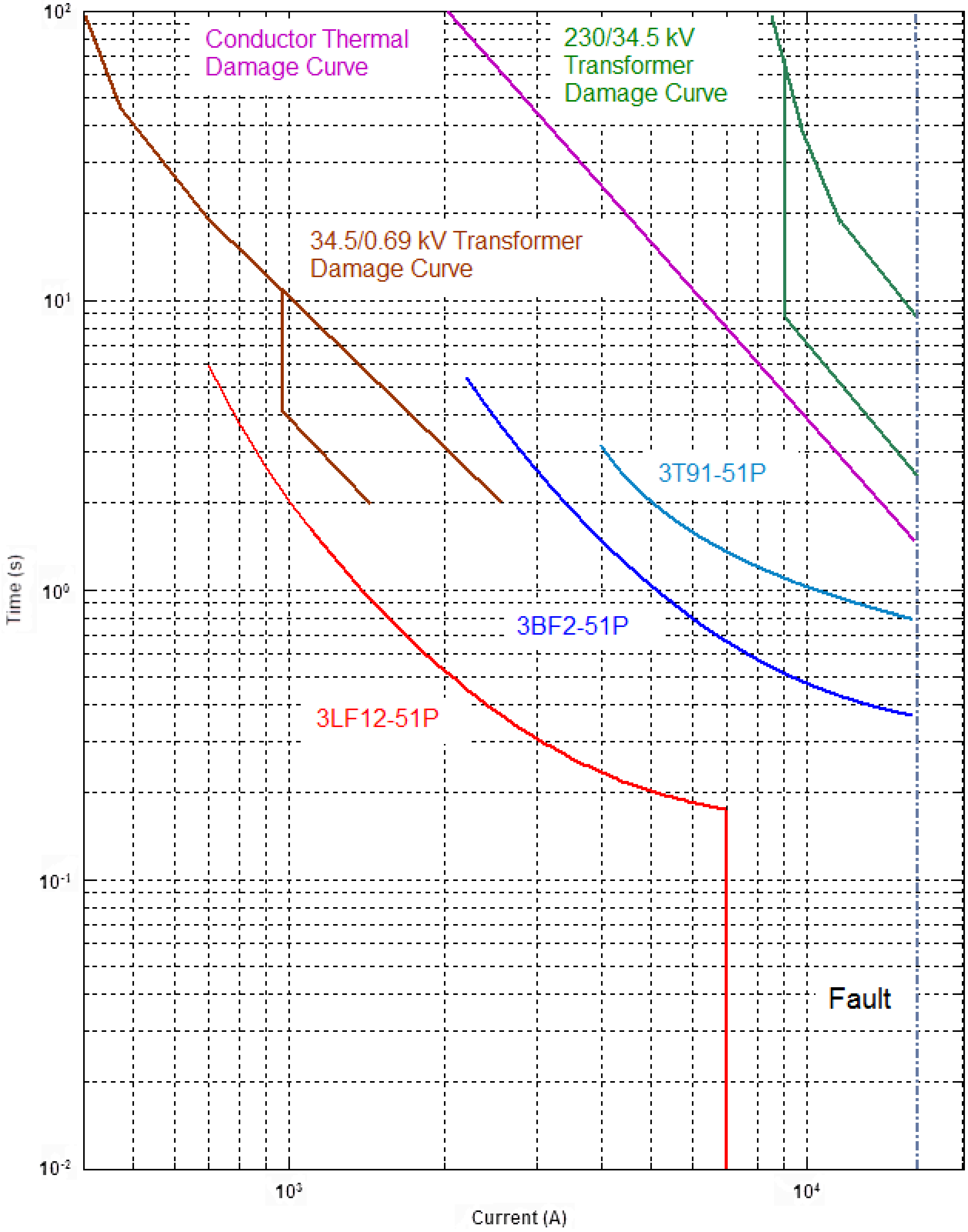

Fig. 5. Example of phase overcurrent protection coordination.

2) *Ground Overcurrent Protection Coordination*

As mentioned before, the El Coco 34.5 kV system is grounded through two zig-zag grounding transformers connected to the low-side terminals of Transformers T91 and T92. In addition, Collector Circuits 3LF12, 3LF22, and 3LF32 of the Nuevo Chagres I wind power plant are grounded through grounded-wye/delta distribution transformer banks. These five grounding transformers are the only sources of zero-sequence current for ground faults in the 34.5 kV system.

Fig. 6 shows the currents for a bolted single-phase-to-ground fault at the 34.5 kV Bus F of the El Coco substation. The grounding transformers of Collector Circuits 3LF12, 3LF22, and 3LF32 and the substation zig-zag grounding Transformer TZ91 contribute similar currents to the fault. The other collector circuits (not shown in Fig. 6) do not contribute to ground faults because the WTG step-up transformers are ungrounded.

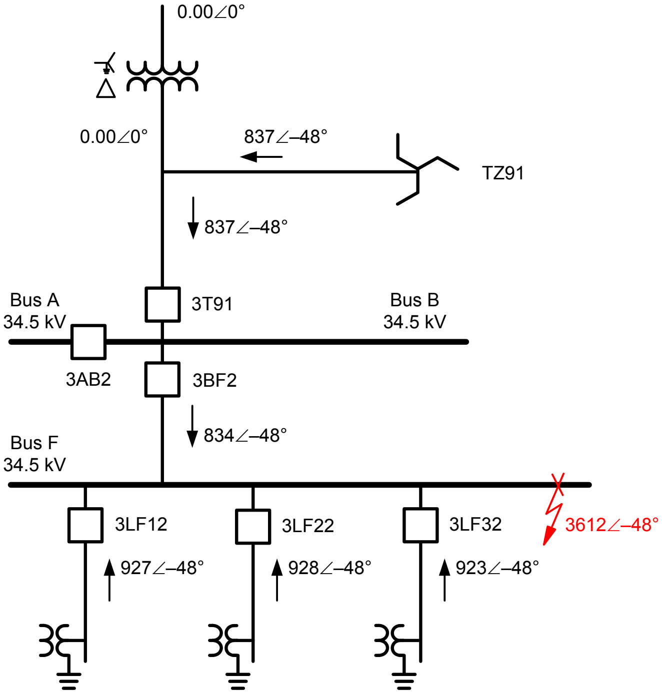

Fig. 6. Current contributions for a single-phase-to-ground fault at the 34.5 kV Bus F of the El Coco substation.

Given the ground fault current distribution, we used the following ground protection schemes for the 34.5 kV collector circuits:

- Ungrounded collector circuits have ground overcurrent protection (50N/51N).
- Collector Circuits 3LF12, 3LF22, and 3LF32 have ground directional overcurrent protection. The directional elements look into the collector circuits and supervise the 51N elements only. Our fault studies showed that the best choice for this application is a 67N element with a current-polarized zero-sequence directional element, and negative- and zero-sequence voltage-polarized directional elements that measure impedance [10]. The relay automatically selects the best directional element depending upon the fault and the system operating conditions. This 67N element provides adequate sensitivity for ground faults on the 34.5 kV system.

The 67N elements of Collector Circuits 3LF12, 3LF22, and 3LF32 provide protection for ground faults on these circuits and allow for coordination with the backup ground overcurrent elements of Circuit Breaker 3BF2. However, these 67N elements do not respond to 34.5 kV Bus B ground faults. These faults must be cleared by time-delayed operation of Relay 3BF2. We can speed-up 34.5 kV bus ground fault clearing with any of the following solutions:

- Enable a 67N element in Relay 3BF2 looking into the bus to serve as fast primary protection for bus ground faults. Enable 67N elements in Relays 3LF12, 3LF22, and 3LF32 looking into the bus to serve as time-delayed backup protection for bus ground faults.
- Add a fast bus tripping scheme at the 34.5 kV bus [11]. This scheme is currently being implemented.
- Add a bus differential protection scheme at the 34.5 kV bus.

Fig. 7 shows an example of ground overcurrent protection coordination for ground faults on Collector Circuit 3LF12.

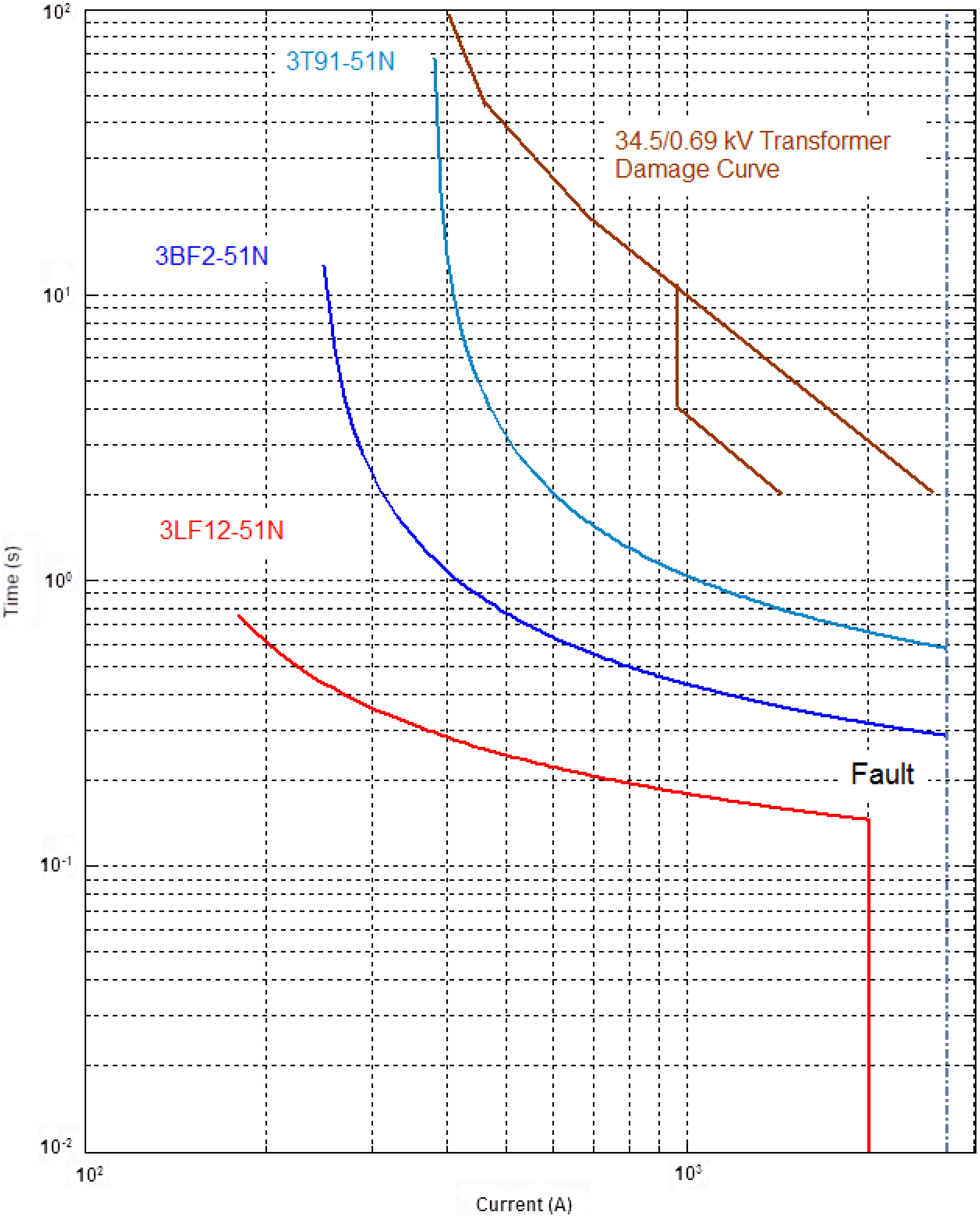

Fig. 7. Example of ground overcurrent protection coordination.

VI. Actual Fault Event

The Penonomé wind power plant protection system has operated well for almost all actual faults. This section presents a case where line insulation failures and a relay failure to operate resulted in two cross-country faults. All the other relays performed well for these complex faults.

On April 8, 2015, the section of the Penonomé wind power plant shown in Fig. 8 was operating with Collector Circuits 3LG22, 3LF12, 3LF22, and 3LF32 in service. Collector Circuit 3LG12 was out of service (Disconnect Switch 3LG11 was open and grounded). Circuit Breaker 3B2 was open and ready to be closed to energize its collector circuit for the first time.

Upon Circuit Breaker 3B2 closure, two faults occurred on two Rosa de los Vientos wind power plant collector circuits.

First, two single-phase-to-ground faults occurring on different collector circuits combined to create a phase-to-phase-to-ground cross-country fault, which evolved into a single-phase-to-ground fault and caused tripping of Circuit Breakers 3BF2 and 3T91. These circuit breaker operations caused the system to become ungrounded. With the first fault still present on one phase and the system ungrounded, a single-phase-to-ground fault on another phase of another collector circuit resulted in another phase-to-phase-to-ground cross-country fault and caused tripping of Circuit Breaker 3LG22.

Table I shows the sequence of events. Table II shows the currents measured by several relays approximately one cycle after the inception of the first fault. Because the relays are not time-synchronized, we determined these currents by manually aligning the relay time stamps.

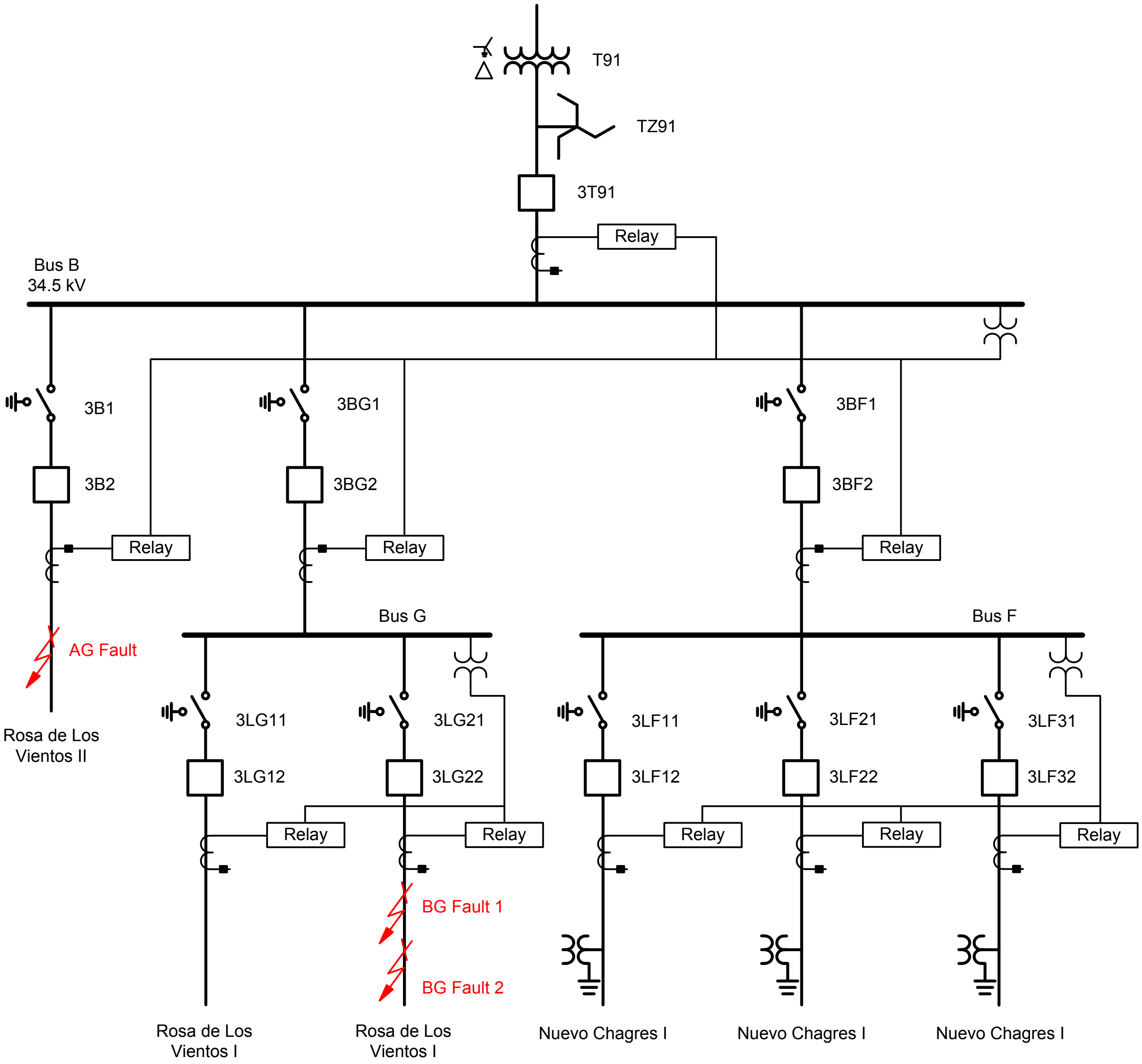

Fig. 8. Faulted power system section.

TABLE I
SEQUENCE OF EVENTS

Event	Time	Relay					
		3T91	**TZ91**	**3BF2**	**3LF12, 3LF22, 3LF32**	**3LG22**	**3BG2**
1	12:50:17:146	Pick up 2,163 A	Pick up 247 A	Pick up 1,519 A	Pick up 545 A		
2	12:50:17:359		Pick up 322 A	Trip 1,489 A T_{OP} = 0.213 s			
3	12:50:18:215	Trip 785 A T_{OP} = 1.069 s	Pick up 310 A			Pick up 457 A	Pick up 459 A
4	12:50:18:779					Trip 453 A T_{OP} = 0.564 s	

TABLE II
RELAY RECORDED CURRENTS ONE CYCLE AFTER INCEPTION OF THE FIRST FAULT

Current	Relay					
	3T91	**TZ91**	**3BF2**	**3LF12**	**3LF22**	**3LF32**
I_A	2209.2∠0°	228.7∠0°	1482.4∠0°	540.4∠0°	446.4∠0°	513.8∠0°
I_B	1819.8∠175.3°	239.4∠1.1°	1513.7∠296.8°	545.8∠291.7°	486.3∠303.7°	501.5∠301.7°
I_C	326.3∠41.2°	247.4∠–2.9°	83.1∠275.6°	28.6∠206.3°	72.2∠316.3°	26.9∠20.8°
I_1	1209.5∠327.2°	9.8∠185.1°	862.1∠30.2°	330.6∠27.4°	246.8∠34.1°	285.0∠29°
I_2	1114.9∠28.6°	3.6∠88.8°	45.9∠73.7°	22.3∠69°	13.1∠92.6°	2.9∠163.7°
I_0	245.7∠29.6°	238.4∠–0.7°	867.9∠326.6°	295.2∠324.1°	303.3∠330°	301.4∠332.5°
I_G	736.8∠29.6°	715.1∠–0.7°	2603.7∠326.6°	885.5∠324.1°	909.8∠330°	904.2∠332.5°

A. First Fault

Circuit Breaker 3B2 was manually closed at 12:50:17:146 to energize its collector circuit for the first time. Upon Circuit Breaker 3B2 closure, two single-phase-to-ground faults involving different phases occurred in two collector circuits of the Rosa de los Vientos wind power plant, which resulted in a phase-to-phase-to-ground fault condition. An insulation failure upon energization caused a permanent AG fault on an underground cable—approximately 3.2 km away from the substation—of Collector Circuit 3B2. At the same time, or immediately after the AG fault, a lightning arrester failed in an overhead section of Collector Circuit 3LG22—approximately 10.7 km away from the substation—resulting in a BG fault in that circuit. After some time, the lightning arrester exploded, which removed the BG fault. As a result, the fault evolved from a cross-country ABG fault to an AG fault on Collector Circuit 3B2.

Protection operation for this fault was as follows:

- Relay 3B2 failed to operate for the AG fault. Circuit Breaker 3B2 did not trip.
- Relay 3BF2 tripped in 0.213 seconds (the 51 and 51N elements detected the fault; the 51N element tripped). This relay operation is correct because the 67N elements of Relays 3LF12, 3LF22, and 3LF32 block tripping of their 51 elements for this fault. Circuit Breaker 3BF2 tripping removed the fault contribution from Nuevo Chagres I wind power plant and also removed the grounding provided by the grounding banks connected to Collector Circuits 3LF12, 3LF22, and 3LF32.
- Relay 3T91 tripped in 1.069 seconds (the 51N element tripped). This operation is correct. Circuit Breaker 3T91 tripping removed the fault contribution from Transformer T91 and also removed the grounding provided by the zig-zag Grounding Bank TZ91. As a result, the system became ungrounded.

Fig. 9 shows the currents and voltages recorded by Relay 3T91 at the start of the first cross-country fault. The currents are the traditional contributions from an ungrounded power transformer and a grounding bank and correspond to an ABG fault. The Relay 3T91 currents shown in Table II confirm the fault type. The voltages in Fig. 9 do not correspond to an ABG fault because the WTG inverter controls act to try to balance the voltages. The A-phase voltage remains low because of the permanent, probably low-resistance AG fault on the underground cable.

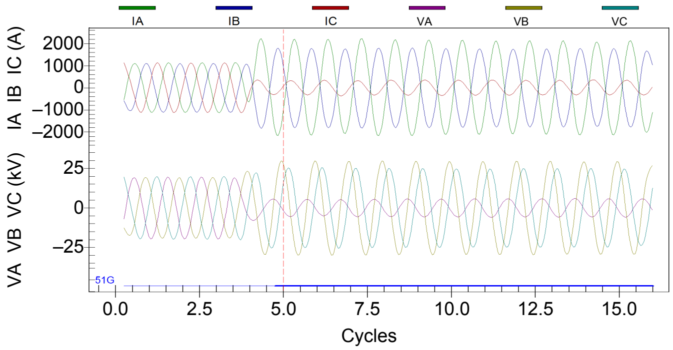

Fig. 9. Currents and voltages recorded by Relay 3T91 at the start of the first cross-country ABG fault.

Fig. 10 shows the currents recorded by Relay TZ91 (not shown in Fig. 8) at the start of the first fault. This figure and the Relay TZ91 currents shown in Table II demonstrate the typical contribution of a grounding bank to a ground fault.

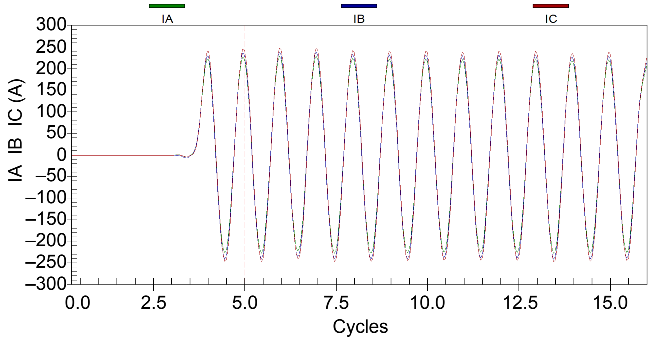

Fig. 10. Currents recorded by Relay TZ91 at the start of the first cross-country ABG fault.

Fig. 11 shows the currents recorded by Relay 3BF2 at the start of the first fault, which represent the contribution of the Nuevo Chagres I wind power plant to the cross-country fault. This figure and the Relay 3BF2 currents in Table II show that the faulted phase currents have similar magnitudes, but are less than 180° apart because of the WTG inverter controls effect. This effect and the grounding transformers connected to Collector Circuits 3LF12, 3LF22, and 3LF32 cause the zero-sequence current to be much higher than the negative-sequence current.

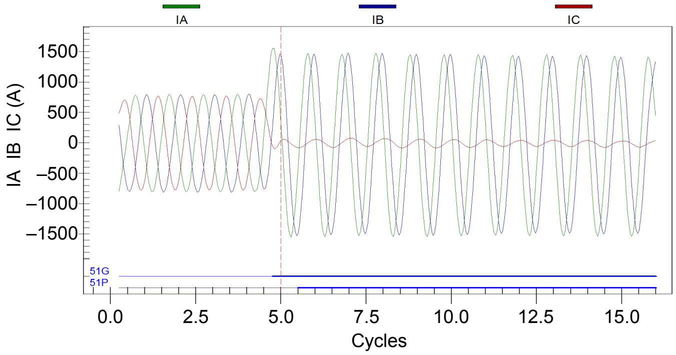

Fig. 11. Currents recorded by Relay 3BF2 at the start of the first cross-country ABG fault.

Fig. 12 shows the currents and voltages recorded by Relay 3T91 at the time of Circuit Breaker 3T91 tripping. The lightning arrester explosion removed the BG fault and the cross-country fault evolved into an AG fault on Collector Circuit 3B2. The system became ungrounded when Circuit Breaker 3T91 tripping removed the only remaining grounding source (zig-zag Grounding Transformer TZ91). With the AG fault still present, the system neutral shifted and the two healthy phase voltages took values greater than the phase-to-phase system-rated voltage, as shown in Fig. 12.

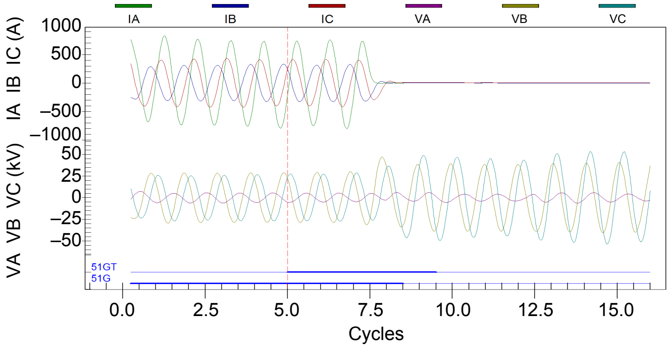

Fig. 12. Currents and voltages recorded by Relay 3T91 at the time of Circuit Breaker 3T91 tripping, when the cross-country ABG fault had evolved into an AG fault.

B. Second Fault

When the system became ungrounded, the high phase-to-ground voltages on the healthy phases shown in Fig. 12 caused the failure of another lightning arrester on the B-phase of Collector Circuit 3LG22, resulting in a new BG fault in that circuit and the evolution of the AG fault into another ABG cross-country fault in the system. Relay 3LG22 tripped in 0.564 seconds (the 51N element tripped). This relay operation is correct. Circuit Breaker 3LG22 tripping cleared the fault.

Fig. 13 depicts the currents and voltages recorded by Relay 3BG2 at the start of the second fault. The only source left in the system at this time was the Rosa de los Vientos I wind power plant. The A-phase and B-phase voltages are very low in Fig. 13, which shows the ABG type of fault. However, Relay 3BG2 measures fault current only on the A-phase. This is a result of the location of both faults. The Rosa de los Vientos I WTGs contribute to the AG fault on Collector Circuit 3B2 through Relay 3BG2, so this relay measures A-phase fault current. However, Relay 3BG2 does not measure the WTG's current contribution to the BG fault on Collector Circuit 3LG22.

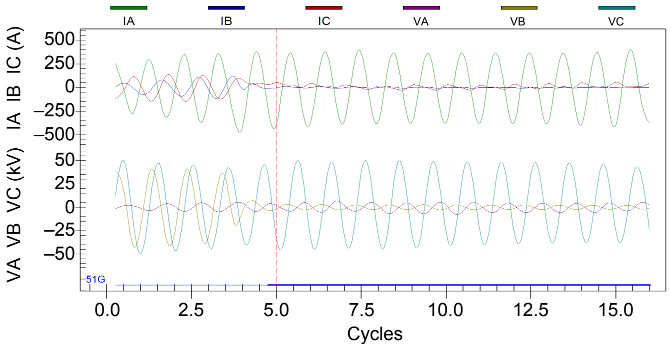

Fig. 13. Currents and voltages recorded by Relay 3BG2 at the start of the second cross-country ABG fault.

VII. CONCLUSION

From the results of the Penonomé wind power plant project, we can conclude the following:

- The Penonomé wind power plant is comprised of WTGs belonging to different companies connected to a 34.5 kV system. Two step-up transformers interconnect the 34.5 kV system to the 230 kV transmission system at the El Coco substation. The 34.5 kV system is grounded through zig-zag and grounded-wye/delta banks, which poses a challenge for ground protection coordination in the 34.5 kV system.
- The Penonomé wind power plant has 108 Type 4 WTGs. Each WTG consists of a variable-speed wind turbine coupled to a three-phase, permanent magnet synchronous generator, connected to the network through a frequency converter and a step-up transformer.
- Type 4 WTGs can produce energy over a wide range of wind speeds, allow for control of active and reactive power, limit fault current, and comply with FERC low-voltage ride-through requirements.
- The typical response of Type 4 WTGs to short circuits has the following characteristics:
  - The WTG contributes no zero-sequence current during ground faults.
  - The WTG control balances the currents during unbalanced system conditions including faults.
  - The WTG current contribution to external faults is not greater than 1.5 times full-load current.
- The P&C system uses multifunction relays with communications and programmable logic. These relays provide all the protection functions, as well as the control and monitoring functions required by the substation’s integrated system.
- We considered WTGs as current sources for the steady-state short-circuit analysis required for overcurrent protection coordination.
- We followed the normal coordination principles for the 230 kV line protection schemes. In particular, we considered magnetic mutual coupling on the double-circuit 230 kV lines and infeed effect from the El Coco substation for ground faults.
- Given the strong contribution from the 230 kV system to phase faults on the 34.5 kV system, we applied overcurrent protection for the 34.5 kV collector circuits. The WTG step-up transformers have fuse protection.
- Given the ground fault current distribution, we used ground overcurrent protection for the ungrounded collector circuits and ground directional overcurrent protection looking into the circuit for grounded collector circuits. This protection system provides time-delayed clearing on 34.5 kV bus faults.
- The following improvements can speed-up 34.5 kV bus fault clearing:
  - Enabling 67N elements looking into the bus in Relay 3BF2 and Relays 3LF12, 3LF22, and 3LF32.
  - Adding a fast bus tripping scheme at the 34.5 kV bus, which is currently being implemented.
  - Adding differential protection at the 34.5 kV bus.
- The Penonomé wind power plant protection system has operated well for almost all actual faults. The paper presents a case where line faults and a relay failure to operate resulted in two cross-country faults. All the other relays performed well for these complex faults.

VIII. APPENDIX

This section provides the power system parameters we used for the fault analysis and protection coordination studies.

TABLE III
230 KV LINE ELECTRICAL PARAMETERS

Line	**ID**	**Length (km)**	**R_1 (pu)**	**X_1 (pu)**	**B_1 (pu)**	**R_0 (pu)**	**X_0 (pu)**	**B_0 (pu)**	**R_M (pu)**	**X_M (pu)**
El Coco- Llano Sánchez	230-12B	60	0.00606	0.05400	0.11148	0.03991	0.15191	0.16072	0.03380	0.08510
El Coco- Llano Sánchez	230-13B	60	0.00606	0.05400	0.11148	0.03991	0.15191	0.16072	0.03380	0.08510
El Coco- Panamá II	230-12A	135	0.01364	0.12150	0.25082	0.08979	0.34179	0.06888	0.07620	0.19150
El Coco- Panamá II	230-13A	135	0.01364	0.12150	0.25082	0.08979	0.34179	0.06888	0.07620	0.19150

TABLE IV
34.5 KV OVERHEAD LINE ELECTRICAL PARAMETERS

Structure Type	**Circuits**	**Conductor Size**	**Ground Wire**	**R_1 (pu/ km)**	**X_1 (pu/ km)**	**B_1 (pu/ km)**	**R_0 (pu/ km)**	**X_0 (pu/ km)**	**B_0 (pu/ km)**	**R_M (pu/ km)**	**X_M (pu/ km)**
Eagle 9000	3	ACSR 477 27/6	ACS 7 No. 8	0.01032	0.03099	0.00005	0.04038	0.13812	0.00003	0.02878	0.07828
Eagle 9000	2	ACSR 477 27/6	ACS 7 No. 8	0.01032	0.03099	0.00005	0.04036	0.13813	0.00003	0.03005	0.08322

TABLE V
34.5 KV UNDERGROUND CABLE ELECTRICAL PARAMETERS

Installation Technique	**Circuits**	**Conductor Size (mm^2)**	**Ground Wire**	**R_1 (pu/ km)**	**X_1 (pu/ km)**	**B_1 (pu/ km)**	**R_0 (pu/ km)**	**X_0 (pu/ km)**	**B_0 (pu/ km)**
Direct burial	1	400	NA	0.00852	0.00988	0.00114	0.01569	0.00653	0.00114
Direct burial	1	240	NA	0.01199	0.01092	0.00097	0.02068	0.00739	0.00097
Direct burial	1	95	NA	0.02654	0.01312	0.00069	0.03784	0.00945	0.00069

TABLE VI
TRANSFORMER AND GROUNDING BANK ELECTRICAL PARAMETERS

Transformer ID	**High Voltage (kV)**	**Low Voltage (kV)**	**Rated Power (MVA)**	**Vector Group**	**Impedance (%)**	**Impedance (Ohms)**
T91	230	34.5	120/140	Ynd11	10.95	-
T92	230	34.5	120/140	Ynd11	10.95	-
TZ91	-	34.5	0.5	ZN0	-	59.47
TZ92	-	34.5	0.5	ZN0	-	60.15
TU	34.5	0.69	2.75	Dyn5	6.97	-
TDG	34.5	0.48	1.25	Ynd1	5.63	-

TABLE VII
WTG ELECTRICAL PARAMETERS

Parameter	Value	Unit
Number of phases	3	-
Nominal voltage	690	V
Rated active power	2,500	kW
Rated apparent power	2,632 (power factor = 0.95)	kVA
Rated frequency	60	Hz
Rated power factor	1.0 default; controlled: from 0.95 leading to 0.95 lagging	-
Reactive power	0.0 default; controlled: from 820 inductive to 820 capacitive	kVAR
Maximum short-circuit current	2,600	A
Positive-sequence impedance	0.7530	pu
Negative-sequence impedance	0.7530	pu

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X. BIOGRAPHIES

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