Fast Wind Farm Restoration Using Wireless Fault Sensors to Identify Faulted Segments

Afonso César Tavares
CPFL Renováveis

Andrei Coelho and Mauro Magalhães
Schweitzer Engineering Laboratories, Inc.

Original edition released April 2020

Fast Wind Farm Restoration Using Wireless Fault Sensors to Identify Faulted Segments

Afonso César Tavares, *CPFL Renováveis*
Andrei Coelho and Mauro Magalhães, *Schweitzer Engineering Laboratories, Inc.*

***Abstract*—New wind energy sources are coming online every day. As demand for renewable energy sources increases, so does development related to the particularities of wind generation. Depending on the project and application, wind farms usually cover a large geographic area consisting of overhead and underground medium-voltage systems that interconnect various wind turbines to their respective bays in the primary step-up substation. Due to the large size, it can be time-consuming to travel across an entire wind farm in search of faults on the system. For this reason, intelligent solutions are being developed to minimize search and repair resources. This paper presents improvements in wind farm fault identification systems based on innovative fault sensor systems with wireless communications.**

I. Introduction

In Brazil, large wind farms have several branches of collector circuits, which interconnect wind turbines with the National Interconnected System (Sistema Interligado Nacional [SIN]). When a short circuit occurs on the medium-voltage system of one of the collectors, the respective collector circuit breaker is expected to open. All machines connected to the collector are disconnected, and there is no possible selectivity using switches. More machines being shut down results in lower generation on the wind farm, which in turn reduces operator revenue. After the collector circuit breaker opens, maintenance teams locate the fault to isolate the area to the smallest extent possible and resume generation quickly. There is a strong correlation between the fault locating time and the loss of revenue from the wind farm. For this reason, there is great demand for solutions that can shorten the fault locating time on wind farms.

Fig. 1 shows a simplified one-line diagram of a wind farm and highlights one of several collectors. In this collector (Collector 1), a circuit breaker (BK1) is in the substation where the collector connects to the bus. This circuit breaker is triggered by a relay responsible for clearing the collector's downstream faults. If there is a fault, the circuit breaker opens, interrupting the short-circuit current and disconnecting the collector's entire generation capacity.

The maintenance team then locates the fault and isolates it using disconnect switches. After the fault is isolated, BK1 can be closed again. The other wind turbines are able to continue generating energy and, in turn, revenue.

This paper is an English translation of [1] and includes updates to the installation point locations.

II. Fault Identification System

At a wind farm in Morro dos Ventos, Brazil, to minimize the time spent searching for faults, a fault identification system based on innovative fault sensor systems with wireless communications [2] [3] was installed at each collector fork. The system has fault sensors installed at the forks [4] [5] and is configured to detect faults downstream of the installation point. The fault sensors are robust, single-phase devices that include a high-speed fault detector element. A sensor is installed on each phase conductor at the fork of each branch.

If any fault sensor installed detects a short circuit downstream of the installation point, it sends a high-speed wireless message using a proprietary protocol to a receiver installed near the substation relay. The receiver transmits status signals to the protective relay to indicate on which of the forks the short circuit has occurred. The protective relay logic is configured to capture the received fault status, and after the breaker trips, communicate the faulted branch information to the control center using a standard communications protocol.

An important differentiating feature of the equipment used in this solution is its high data transfer speed. The fault sensors are powered by current from the conductor and have no batteries. In conditions where medium-voltage cables conduct enough current to power the sensor (approximately 15 A), the fault message transfer time from sensor to relay is on the order of 1 cycle (16.6 ms for a 60 Hz system).

Fig. 2 shows a system one-line diagram that includes installation points of the previously mentioned equipment. The fault sensors are represented by gray circles at each collector fork and the receiver is positioned close to the collector relay.

III. Installation

The first application of this solution was in Brazil on a 145.2 MW wind farm. In this wind farm, nine sensors were installed on three forks of the same collector on the medium-voltage 34.5 kV system. Each fork has rated power of 14.4 MW, 4.8 MW, and 9.6 MW, totaling rated currents of 241 A, 80 A, and 161 A, respectively. Because installations are composed of three fault sensors (one per phase), the nomenclature "trio" is common, where a trio is the combined indicators for Phases A, B, and C of the same branch.

To ensure that the fault sensors effectively communicate with the receiver, a connectivity study is required. This study aims to determine the height of the receiver antenna so that the line-of-sight between receiver and fault sensor antennas is sufficient to overcome the topographical interference of the installation. To perform this study, it is necessary to provide the geographic coordinates of the fault sensors as well as the geographic coordinates of the receiver antenna. After analysis of the geographical characteristics of the region, it is possible to determine the minimum antenna height. Fig. 3 is a drawing representing an overhead view of the wind farm equipment.

The bottom of Fig. 3 shows the location of the substation, including the relay, receiver, and antenna installation points. The top of Fig. 3 shows the installation points of the three fault sensor trios. For this application, the furthest trio is 1.82 km from the substation in a straight line. With these data points, the required antenna height was calculated at 4.2 m.

Fig. 4 shows sensors installed on medium-voltage lines (left) and the receiver antenna in the substation (right).

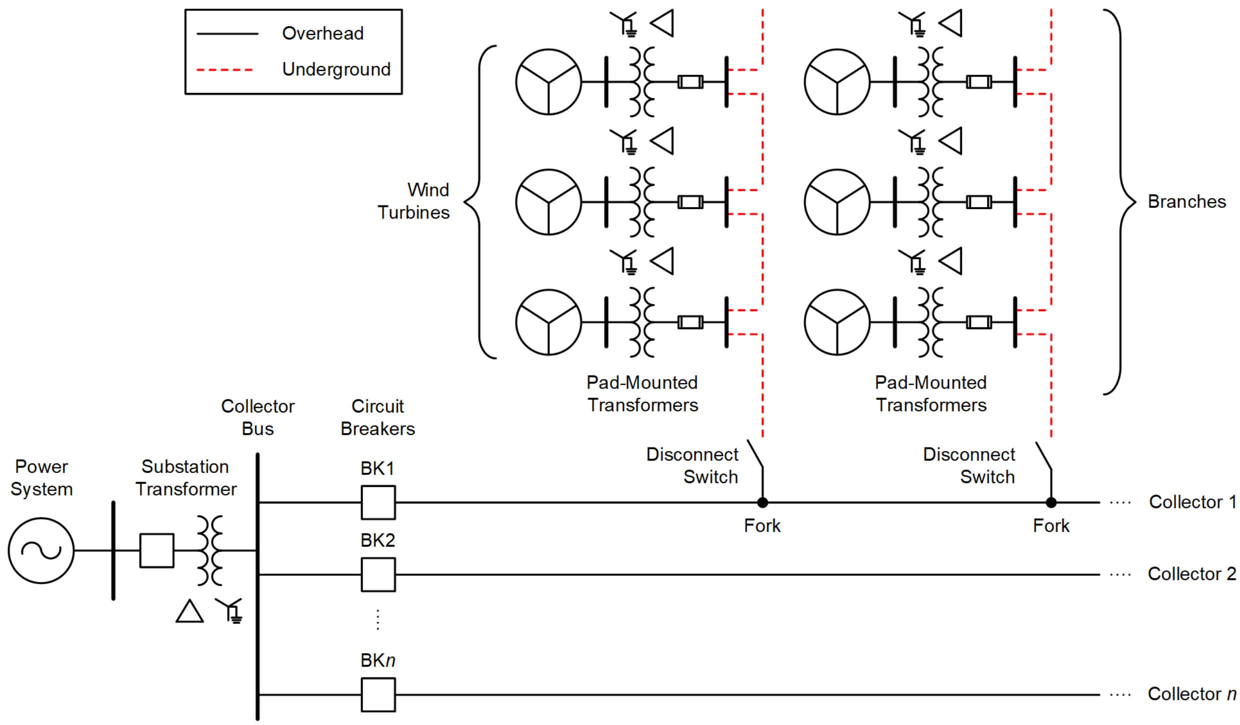

Fig. 1. One-line diagram of a wind farm

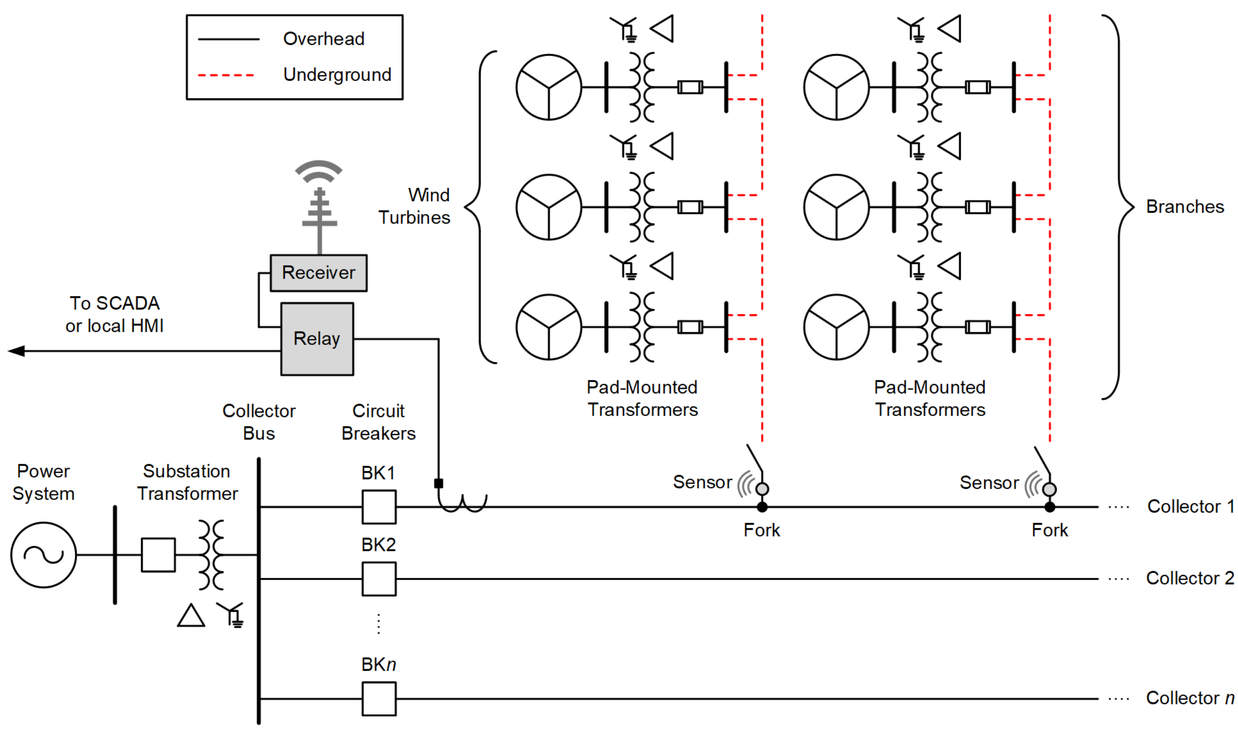

Fig. 2. One-line diagram including equipment for the solution

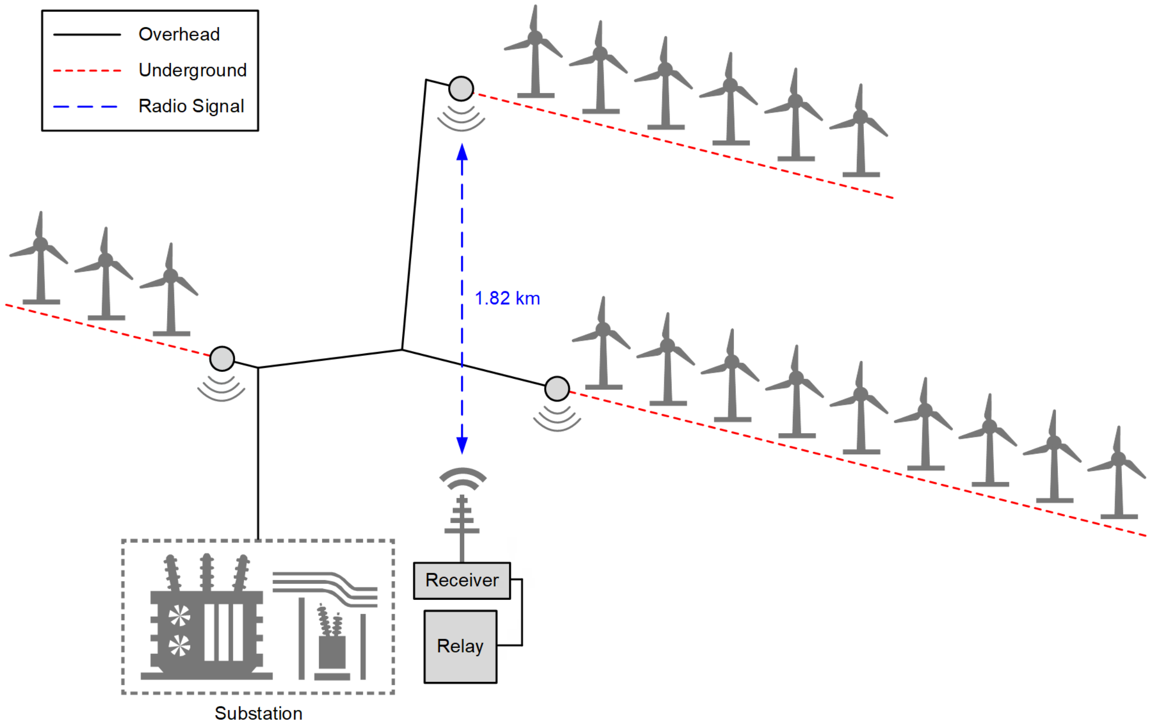

Fig. 3. Drawing of an overhead view of the equipment installation

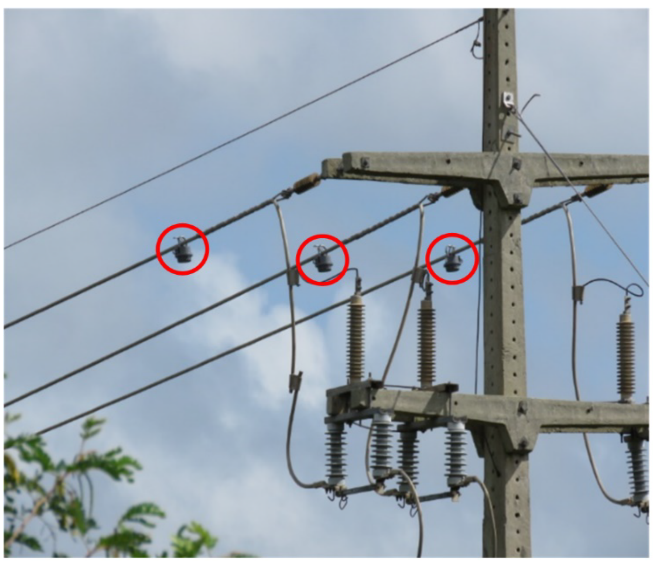

Fig. 4. Sensor installations on medium-voltage lines (left) and receiver antenna in the Brazil substation (right)

IV. Settings

A. Sensor Settings

The fault sensor devices have eight setting levels for the overcurrent function, which allows for operational selectivity. It is noteworthy that there are various generators on the system, one of which is represented by the interconnection point with the power system (a high-inertia generator) and several wind turbines inside the farm, which are connected to the ac system using frequency inverters. Wind turbines do not contribute to short circuits in the same way as a conventional power system generator. It is important to select a pickup value that prevents the sensors from responding to fault currents in neighboring branches.

Each type of wind turbine contributes differently for faults in the power system. Type IV wind turbines normally have short-circuit contributions limited to between 1.1 and 1.2 times the rated current of the equipment [6], while Type III have short-circuit contributions limited by generator subtransient reactance in the worst-case scenario crowbarred state. This application uses Type III wind turbines, and a maximum possible short-circuit contribution is 2.63 times the branch nominal current, considering the generator subtransient reactance and transformer impedance. A conservative assumption is that all wind turbines are able to contribute maximum short-circuit current at the same time for a fault in a parallel branch.

Considering the rated currents of the branches described previously, it is estimated that the maximum contributing currents for short circuit would be 634 A, 210 A, and 423 A, respectively. It is also necessary to consider the tolerance ranges of the fault sensors, which vary according to the pickup, as shown in Table I.

TABLE I
SENSOR RANGE TOLERANCE

Fault Sensor Pickup	Tolerance
≤50 A	50%
>50 A and <400 A	30%
≥400 A	20%

Table I provides the tolerances for the fault sensors applied in this specific installation. More accurate sensors may be available for future projects.

Considering the margin of error, this application uses pickup settings of 800 A, 400 A, and 600 A for each of the monitored branches. These values are sensitive enough to detect system faults and also safe enough to avoid false indications.

Other necessary monitoring is implemented to provide security during system inrush conditions. When one of the circuit breakers is closed, several downstream transformers are energized and drain a high magnetizing current. Fault sensors may be sensitive to these currents, and this sensitivity is undesirable. Inrush currents are rich in harmonics [7], and it is possible to use specific relay elements to correctly block operation when they are detected. This inrush security strategy was not used in the installation.

B. Protective Relay Settings

The protective relay receives data from the receiver, which receives information from the fault sensors. Fast communication between devices is performed using a high-speed protocol, which sends eight bits both directions, or full duplex. The eight bits of data transmitted in the protocol are labeled TMB1-8, and the corresponding received bits are labeled RMB1-8.

It is important to realize that the relay receives data from twelve fault sensors, but the protocol provides eight messages at a time. Data can be transmitted to the protective relay in an alternating fashion.

The relay, in addition to receiving eight messages from the receiver, can also transmit eight messages to the receiver. By alternating a specific bit on the protective relay, it is possible to change the composition of messages that the receiver transmits to the relay, as shown in Table II and Table III.

The protective relay is configured with logic that alternates the state of TMB4. When TMB4 = 0, the eight messages the relay receives correspond to the first six fault sensors (i.e., the first two trios). Messages 1 and 2 indicate whether any trio detected a fault, and Messages 3 through 8 represent individually and by phase which fault sensor detected a fault.

When the relay executes the alternating logic, the variable TMB4 = 1 causes the eight messages to correspond to the last two trios. Messages 1 and 2 are related to the presence of faults, and Messages 3 through 8 indicate the individual per-phase information of the last six fault sensors. Therefore, the relay receives information from the 12 fault sensors through simple logic that periodically alternates the state of the digital variable TMB4.

TABLE II
INFORMATION RECEIVED WHEN TMB3 = 1 AND TMB4 = 0

Relay Commands							
TMB1	**TMB2**	**TMB3**	**TMB4**	**TMB5**	**TMB6**	**TMB7**	**TMB8**
0	0	1	0	0	0	Reset Link Status	Target Reset
Data Transmitted by the Concentrator							
RMB1	**RMB2**	**RMB3**	**RMB4**	**RMB5**	**RMB6**	**RMB7**	**RMB8**
Trio 1 Fault	Trio 2 Fault	Fault 1	Fault 2	Fault 3	Fault 4	Fault 5	Fault 6

TABLE III
INFORMATION RECEIVED WHEN TMB3 =1 AND TMB4 = 1

Relay Commands							
TMB1	**TMB2**	**TMB3**	**TMB4**	**TMB5**	**TMB6**	**TMB7**	**TMB8**
0	0	1	1	0	0	Reset Link Status	Target Reset
Data Transmitted by the Concentrator							
RMB1	**RMB2**	**RMB3**	**RMB4**	**RMB5**	**RMB6**	**RMB7**	**RMB8**
Trio 3 Fault	Trio 4 Fault	Fault 7	Fault 8	Fault 9	Fault 10	Fault 11	Fault 12

V. Indicators

Based on the information the receiver receives from the fault sensors, the relay can indicate the faulted circuit as well as the phases. The protective relay contains logic with variables that the user can easily query. Table IV shows the variables used to represent the faulted trio.

TABLE IV
FAULTED TRIO

Latch (LT_{nn})	Fault on Trio
01	1
02	2
03	3
04	4

Upon detecting the breaker opening, the wind farm operator can see which of the variables (LT01, LT02, LT03, and LT04) are active. These variables indicate which trio and thus which fork presented a fault. Additionally, the system displays the variables described in Table V indicating the faulted phase.

TABLE V
FAULTED PHASE

Latch (LT_{nn})	Phase
05	A
06	B
07	C

Another set of indicators is provided so that each sensor has an individual indicator, as shown in Table VI.

TABLE VI
SENSOR INDICATORS

Latch (LT_{nn})	Indicator
08	1
09	2
10	3
11	4
12	5
13	6
14	7
15	8
16	9
17	10
18	11
19	12

In addition to the wind farm operator's local interface, these variables are available on the SCADA system, where there is an automatic remote query of the defect point. Based on this indication, the operator can open the corresponding disconnects and re-energize the circuit breaker and wind turbines not affected by the short circuit.

VI. Next Steps of the Project

This system was installed in 2019 and is monitoring for future faults. Considerable operational gains and cost savings are expected from this solution. The expected cost savings may fuel further system improvements in the future, such as installation of motorized disconnect switches.

Currently, switches are operated manually, which requires operators to be physically close to the switches to operate them. When the current switches are replaced with motorized switches, the entire operation can be performed remotely via SCADA. It is also possible to consider opening switches automatically using the protective relay that executes fault identification logic.

VII. Conclusion

Demand for renewable energy encourages the installation of more wind farms. These farms operate over a large geographic area, which makes it difficult to locate internal faults. During the fault locating process, generators are offline, which negatively impacts project revenues.

In a Brazilian wind farm, an innovative solution was used based on sensor devices installed in the medium-voltage network. Upon detecting a fault, the sensors send signals to a concentrator and relay to indicate the branch where the event occurred. This allows rapid isolation of the fault and mitigates revenue loss. The cost savings from this process could make it possible to implement motorized switches in the future, which will make the system even more effective at isolating faults.

VIII. References

[1] A. Tavares, A. Coelho, and M. Magalhães, "Rápido Restabelecimento de Parque Eólico com Utilização de Sensores de Falta para Identificação do Trecho sob Defeito," proceedings of the XIII SIMPASE (Simpósio de Automação de Sistemas Elétricos), Recife, Brazil, September 2019.

[2] S. V. Achanta, B. MacLeod, E. Sagen, and H. Loehner, "Apply Radios to Improve the Operation of Electrical Protection," proceedings of the 37th Annual Western Protective Relay Conference, Spokane, WA, October 2010.

[3] J. Fowler, S. V. Achanta, K. Hao, and D. Keckalo, "Apply a Wireless Line Sensor System to Enhance Distribution Protection Schemes," proceedings of the 43rd Annual Western Protective Relay Conference, Spokane, WA, October 2016.

[4] *SEL-FT50/SEL-FR12 Fault Transmitter and Receiver System Instruction Manual*. Available: selinc.com.

[5] *SEL-FT50/SEL-FR12 System Installation Sheet*. Available: selinc.com.

[6] B. Kasztenny, M. V. Mynam, and N. Fisher, "Sequence Component Applications in Protective Relays – Advantages, Limitations, and Solutions," proceedings of the 72nd Annual Conference for Protective Relay Engineers, College Station, TX, March 2019.

[7] *SEL-751 Feeder Protection Relay Instruction Manual*. Available: selinc.com.

IX. Biographies

Afonso César Tavares has a degree in electrical engineering from Universidade Federal de Itajubá (UNIFEI) and 27 years of electrical engineering experience. He completed a specialization in protection/JICA and electric power systems from UNIFEI, and the management development program from Fundação Getúlio Vargas (FGV). He also completed a specialization in small hydroelectric plants from UNIFEI. He worked as an asset management and protection studies coordinator for power distributor Energisa Minas Gerais. He currently works for CPFL Renováveis as a Specialist II in line and substation maintenance and protection for wind farm and small hydroelectric generation assets. He has extensive experience in asset management and protection studies in the energy sector.

Andrei Coelho received a degree in electrical engineering with an emphasis in electric power systems from Universidade Federal de Itajubá (UNIFEI) in 2014, and a specialization in electrical systems automation from Instituto Nacional de Telecomunicações (INATEL) in 2019. He has worked in application engineering and technical support at Schweitzer Engineering Laboratories, Inc. (SEL) since 2014, focusing on power transmission and distribution applications in addition to supporting various industrial sectors in areas of protection, control, and automation. He contributes to the development of articles and technical presentations at industry seminars and is an SEL University course instructor.

Mauro Magalhães received a degree in production engineering with an emphasis in management in 2008 from Faculdade de Ciência e Tecnologia—Area1. He worked at Companhia de Eletricidade do Estado da Bahia (COELBA) from August 1983 to February 2009 as an electrical system maintenance analyst. Since 2009, he has held the position of protection application specialist at Schweitzer Engineering Laboratories, Inc.

20200424 • TP6971-01