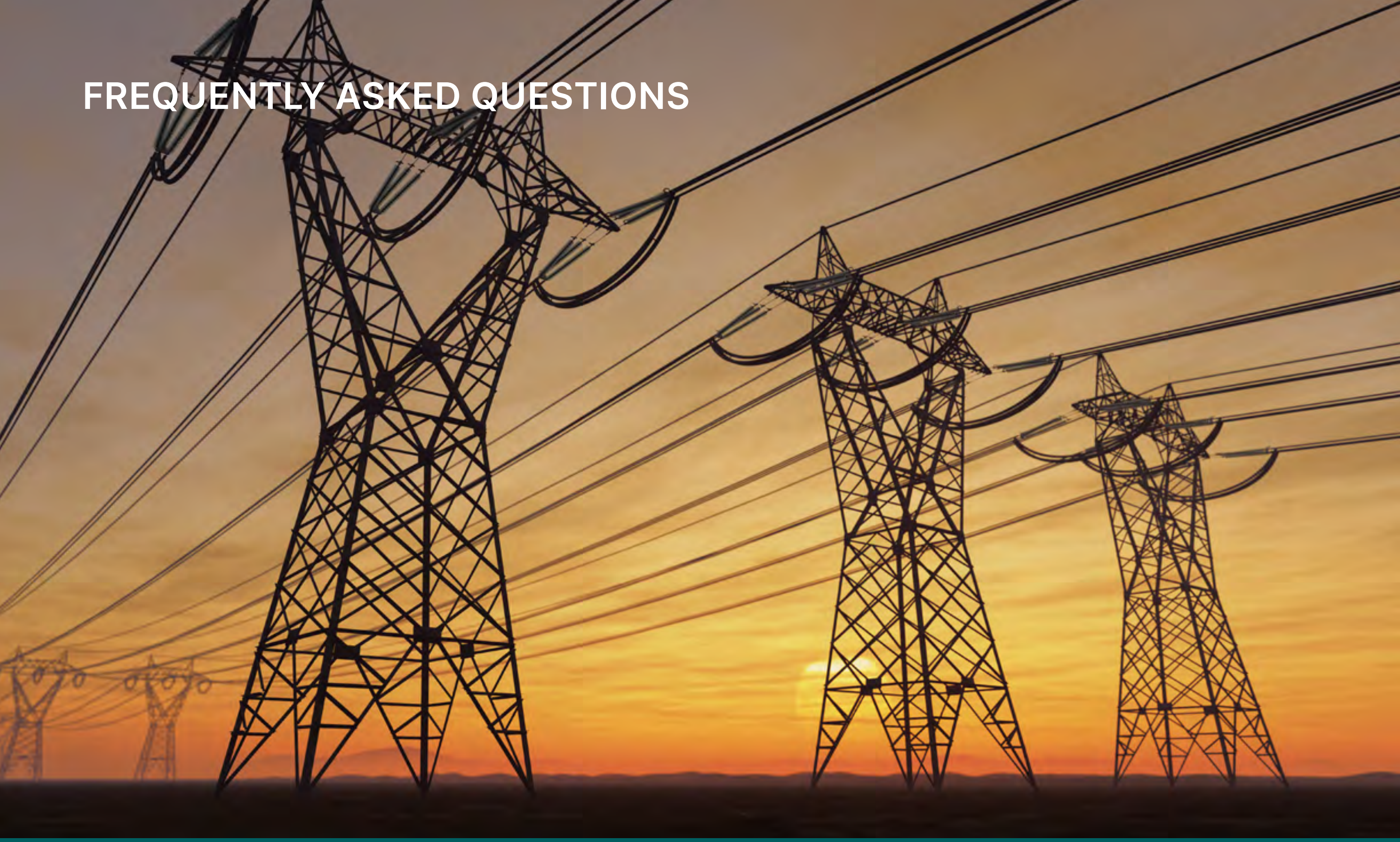

HIGH-SPEED FALLING CONDUCTOR PROTECTION (HFCP) FAQ GUIDE

GE Vernova's High-Speed Falling Conductor Protection (HFCP) provides a reliable solution in detecting, deenergizing, and isolating a broken overhead power line using secure wide-area measurements prior to the conductor touching the ground.

GE VERNOVA

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GENERAL

1. What happens when the conductor breaks?

In the typical sequence of events following the breaking of conductor, an arc begins as soon as the conductor breaks, and it extinguishes as conductors break electrically. The open phase condition results in an unbalance in the power system and asymmetrical current flows in the system. The conductor might remain hanging in the air, touch the ground or grounded through a supporting structure and may lead to a high-impedance fault that is difficult to detect by protection relays. The relay might also attempt to reclose as it is not known whether it is a temporary or permanent fault.

Failure to detect a falling conductor could cause a potential arcing ground fault and possibly an ignition point to wildfires. Furthermore, depending on the environment the falling conductor could lead to a high-impedance fault that may be difficult to detect by existing protection relays and this would pose a significant risk to any people, wildlife, or infrastructure in the vicinity.

2. What methods are available at GE Vernova for broken conductor protection?

Existing methods are explained in the following table:

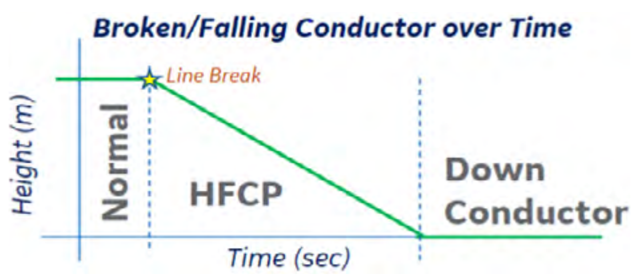
Methods	Principle	GE Vernova Solution	Limitations
I_2/I_1 ratio method	I_2/I_1 method works by calculating the ratio of negative sequence to positive sequence current ratio.	• UR Series • MiCOM Series	• Prone to fail under low-load condition. • Cannot incorporate the impact of Distributed Energy Resources (DERs). • For three-terminal or distribution lines dependability of protection is affected. • Vulnerable to mis-operateions due to remote fault conditions
Hi-Z fault detection method	Algorithm incorporating a signature-based expert pattern recognition system.	• UR F60 Series	• Performance is compromised in networks with high penetration of DERs. • It does not detect the broken conductor until it becomes a down conductor.
Impedance based method (High-Speed Falling Conductor Protection, HFCP)	Impedance change ratio (ICR) is calculated to detect an increase on load or line impedance.	• UR L90 Series for 2-terminal transmission lines • GPG platform HFCP for distribution lines • GPG platform HFCP for 2- & 3-terminal transmission lines	• Communication requirements on distribution • Time synchronization is required

3. Are there any other available methods?

Methods	Principle	Limitations
dV/dt Method	The dV/dt signatures at two Phasor Measurement Units (PMUs) on opposing sides of the break have opposite polarity. When the dV/dt value rises above the threshold value, a supervision check is performed with the help of the dV0/dt threshold.	• Voltage measurement devices are required at both ends to cover a segment of circuit. • High deployment and maintenance cost. • Communication requirements on distribution • Time synchronization is required
V0 and V2 Magnitude Method	For a falling conductor event in a given phase, occurring between PMU locations, the furthest PMU from the source has a steep increase in the V0 and/or V2 magnitude compared to the PMU closer to the source. If a break occurs, phasor sequence measurements from PMUs on the two sides of the break location show specific angular relationships that point to the falling conductor location.	
Mechanical methods	Ground wire grid: In the event of physical break in the power conductor, the guard wire grid facilitates holding the conductor and thereby preventing it from falling to the ground.	• Cost considerations make this solution less attractive. • Provides protection against down conductor related faults. • Present methods cannot detect a conductor that has fallen to the ground without breaking and this case is handled only by existing HIF protection methods.

4. What is the need of HFCP when other Hi-Z protections are already available?

Hi-Z protections only operate after the conductor touches the ground and causes a fault, whereas the HFCP operates in mid-air before the conductor reaches the ground (within 500 ms) and ultimately avoids a fault condition



High-Speed Falling Conductor Protection:	Down Conductor Protection:
Impedance based (V & I Measurements)	• Single relay/feeder based • HiZ

GENERAL

5. How much time do we have to detect and operate for the falling conductor?

The minimum height for 11kV voltage level or higher is around 5.6m or 18 feet, which results in a falling time of 1.06 seconds.

6. Can you describe the operating principle of GE Vernova's HFCP?

When a conductor breaks, the load or line impedance can change significantly as compared with the healthy, pre-fault condition. The impedance change ratio (ICR) is calculated by subtracting the pre-fault impedance from the current impedance and then normalizing it by the pre-fault impedance. Then, the ICR for phase-to-ground and phase-to-phase impedances are also calculated.

The algorithm uses the ICRs calculated from synchrophasor measurements, which are streamed from feeder protective relays, reclosers along the feeder, or dedicated PMUs. The algorithm declares a falling conductor condition when certain ICRs for a distribution feeder exceed a threshold (an adjustable setpoint, defaulted at 0.18).

7. Does the implementation change between transmission and distribution?

Yes, two different techniques are used between transmission and distribution networks. In meshed HV networks, HFCP operates by calculating the ICR of the line impedance and requires measurements on all the terminals of the line (i.e., 2 PMUs for a 2-terminal line, 3 PMUs for a 3-terminal line etc.). In MV networks the ICR of the load impedance is used for detection and a minimum of 1 PMU is required, while more PMUs can be added to improve the coverage of the solution.

SYSTEM ARCHITECTURE

8. Describe a typical system architecture.

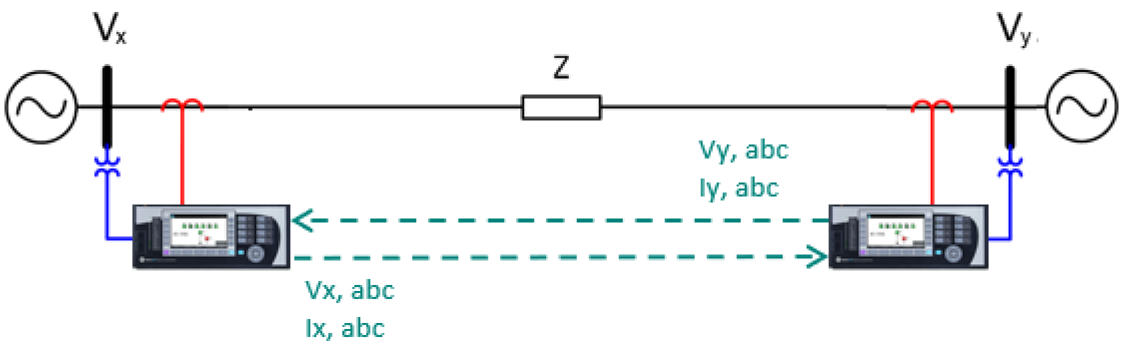
GE Vernova's High-Speed Falling Conductor Protection Solution is a scalable system that provides reliable and fast detection of broken falling conductors in the distribution or transmission systems. The solution can connect to devices inside the substation as well as along the feeder. Depending on the type of application, high-speed falling conductor has a different architecture.

There are three possible architectures:

- HFCP embedded on L90 Line different protection relays. This applies on transmission lines with 2 terminals
- HFCP implemented in GPG hardware that receives PMUs from remote ends of the transmission line for 3-terminal lines or 2-terminal lines with D60, L90, N60 or 3rd party devices with PMU functionality
- HFCP implemented in GPG hardware for distribution feeders with downstream devices of the feeder to increase sensitivity along the feeder

9. Describe a system architecture for a 2-terminal line with L90 line differential protection relay.

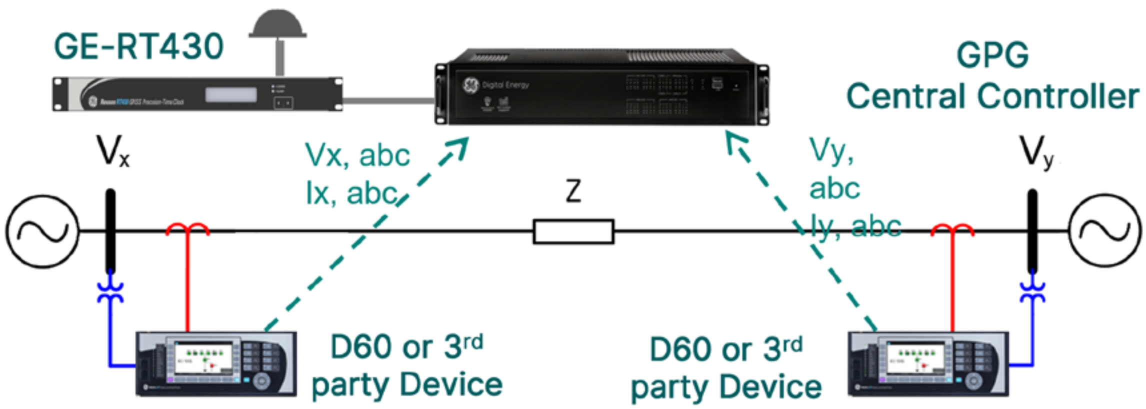
This architecture is the one that has lower hardware requirements, as HFCP is already embedded as a control element in L90 line differential protection relays. No additional hardware is required, only two L90 differential protection relays. Architecture is shown on the figure below.



SYSTEM ARCHITECTURE

10. Describe a system architecture for a 2-terminal line with D60 or 3rd party devices or for 3 terminal lines.

For transmission lines with third party devices or D60 distance protection relays, a GPG real-time controller is used to perform the calculations of high-speed falling conductor protection. This real-time controller receives the information through IEC 61850 GOOSE, IEC 61850-90-5 or IEEE C37.118 protocols from remote end devices of the line. HMI and historian capabilities can be integrated with any 3rd party devices using one of the supported protocols like Modbus, DNP3, MQTT, IEC 60870-5-101, IEC 60870-5-104 or OPC.

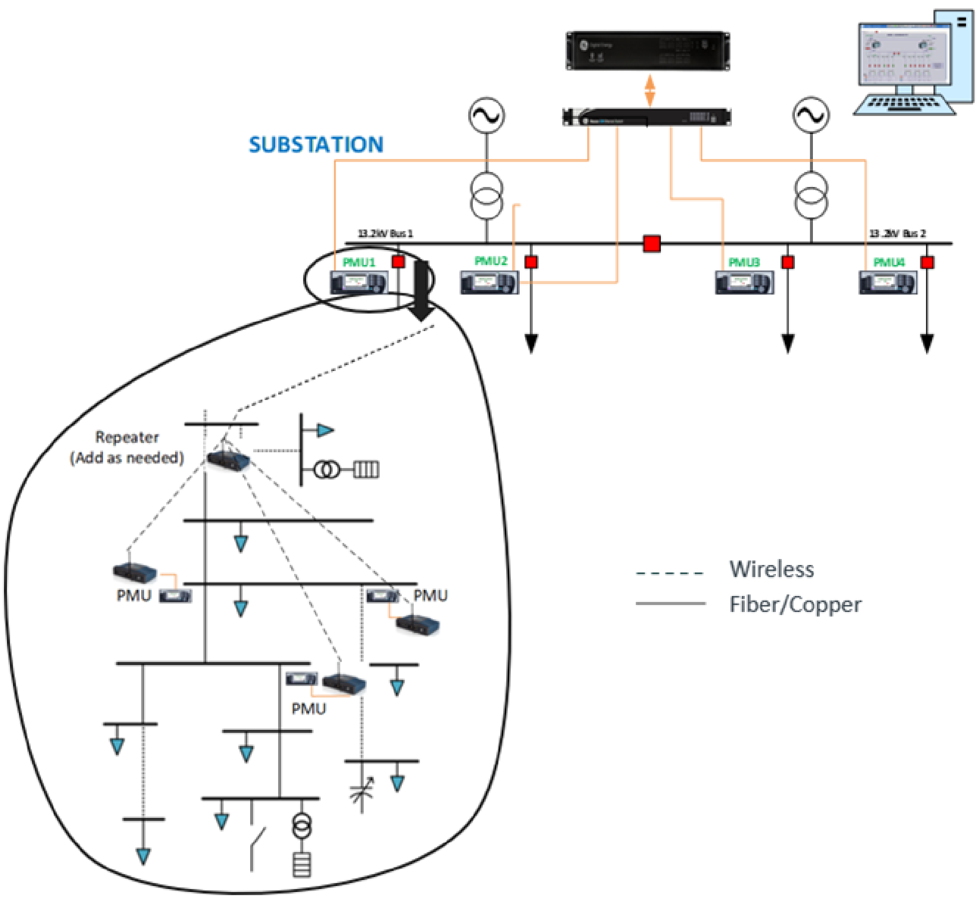


In this system architecture, the following hardware is used:

- GPG real-time controller (only GE Vernova-specific hardware required)
- Any PMU enabled IED (D60 or third party devices)
- GPS Clock (Reason RT430/434 Precision Time Clock or third party device)
- Reason S20 Switch or 3rd party device

11. Describe a system architecture for one distribution feeder.

For distribution feeders, similar architecture to the previous one shown with D60 or 3rd party devices on transmission lines must be used. A GPG real-time controller is used to perform the calculations of high-speed falling conductor protection. This real-time controller receives the information through IEC 61850 GOOSE, IEC 61850-90-5 or IEEE C37.118 protocols from remote end devices of the line. HMI and historian capabilities can be integrated with any 3rd party devices using one of the supported protocols like Modbus, DNP3, MQTT, IEC 60870-5-101, IEC 60870-5-104 or OPC.



In this system architecture, the following hardware is used:

- GPG real-time controller (only GE Vernova-specific hardware required)
- Any PMU enabled IED (F60 or 3rd party devices)
- GPS Clock (Reason RT430/434 Precision Time Clock or third party device)
- Reason S20 Switch or third party device
- MDS Orbit Radio or 3rd party device

SYSTEM ARCHITECTURE

12. Do we need a time synchronization at the GPG level?

Yes, HFCP solution requires time synchronization at GPG level and all PMUs need to be synchronized as well. IRIG-B and the IEEE 1588 Precision Time Protocol (PTP) is supported for the real-time controller while Network Time Protocol (NTP) can be used for the HMI if required.

13. Which are the communication requirements?

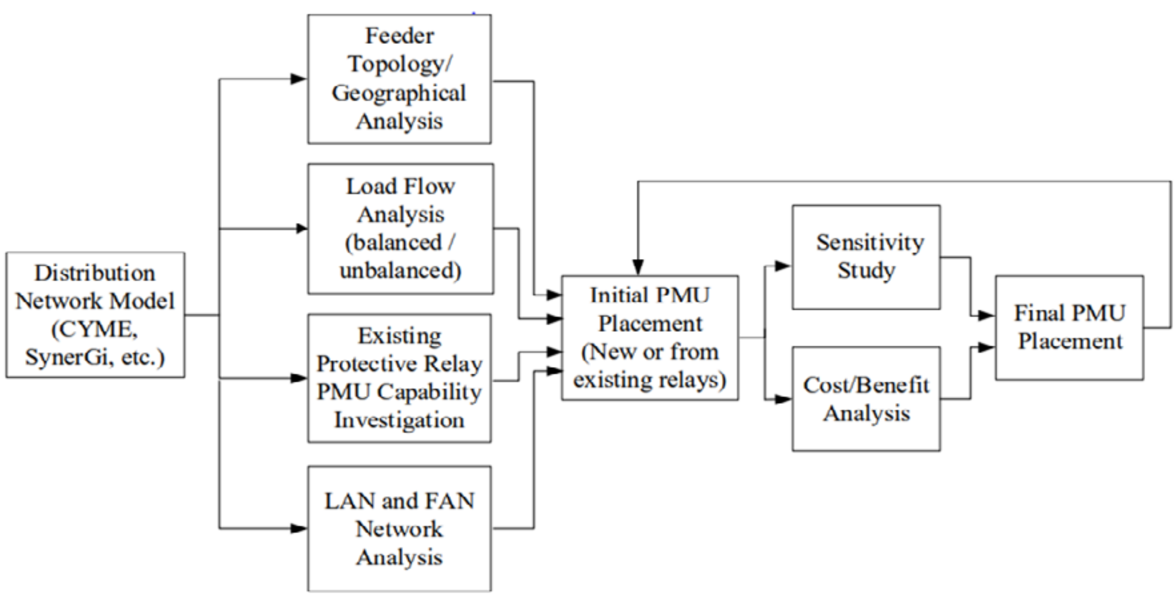
Latencies of 100 ms are acceptable in transmission systems and up to 250 ms can be accommodated in distribution systems. LTE, Radio – Private & Public, Direct Fiber, Redundancy – Radio + LTE, or Power Line Carrier can be used, as far as there is enough bandwidth at an acceptable latency to ensure that the solution can trip the breaker before the conductor reaches the ground.

14. Which are the communication protocols supported for HFCP?

IEC 61850 is used for Breaker trip commands, for voltage and current measurements, IEEE C37.118 or IEC 61850-90-5 and for SCADA purposes as per user preference from a wide range of protocols like IEC 60870-101/104, IEC 60870-103, Modbus, DNP3, OPC DA & AE or OPC UA.

15. How is the PMU quantity & location on distribution systems determined?

GE Vernova's Grid Automation provides services to study the location and optimal number of PMUS required based on the following methodology.



16. What happens when a given PMU is out of service and no synchrophasors are being received?

In transmission systems, as data from both remote ends is required for line impedance, the HFCP will be blocked, while for distribution systems, the scheme will still be in service but with reduced feeder coverage in that particular feeder section where no data is received.

17. What happens when a given trip IED/PMU fails in distribution systems?

By default, a time delay is configured for the PMU at the substation. If the downstream PMUs clear the open phase condition within this time, the PMU at the substation can be configured to trip the feeder breaker.

18. How does HFCP differ from Broken Conductor I_2/I_1?

The operating principle of the I_2/I_1 method is based on sequence currents, whereas HFCP operates based on Impedance Change ratio (ICR).

The I_2/I_1 method requires a drop of approximately 50% of the load for a successful detection, while HFCP can detect events with less than a 50% reduction in load.

The I_2/I_1 method has also been shown to be insecure for radial networks, as upstream faults could lead to a significant reduction in phase current on a given phase and lead to mis-operation.

HFCP also provides considerable advantages in terms of security and sensitivity based on its adaptive setpoint and the ability to improve coverage by adding additional PMUs and coordinating between these devices without affecting security, which is not possible with the I_2/I_1 method. HFCP is also able to discriminate between fuse blown events and broken conductor events and provide an alarm when a fuse blown event was detected.

19. How does HFCP differ from Hi-Z?

The Hi-Z approach incorporates a signature-based expert pattern recognition system. Harmonic energy levels in the arcing current and a sophisticated expert system assures security and dependability for detection of Hi-Z faults.

Hi-Z protection can detect events only after a fault condition has occurred, whereas HFCP can detect events prior to theconductor reaching the ground and avoid a fault condition from developing. Hi-Z protection and HFCP are complementary technologies.

PROTECTION

20. How does HFCP differ from Sensitive Earth Fault (SEF)?

SEF protection works by measuring the residual current across the three phases in a system. This is done by using CBCT. In ideal conditions the residual current is zero, however in the event of a fault the residual current will not be zero as the current from the faulted phase flows through the earth.

SEF can detect events only after a fault condition has occurred, whereas HFCP can detect events prior to the conductor reaching the ground and avoid a fault condition from developing. SEF and HFCP are complementary technologies.

21. How does HFCP differ from REFCL (Rapid Earth Fault Current Limiter)?

REFCL is one of the fire mitigation methods that limit the electrical energy released during the earth fault by connecting arc suppression coils and fault current limiters operate for phase to earth fault. It operates after a fault condition has occurred, whereas HFCP operates before the conductor reaches the ground.

REFCL and HFCP are complementary technologies.

22. Could we choose one or the other method, e.g. either Hi-Z or HFCP?

Hi-Z protection work for detecting down conductor fault once the conductor has already reached the ground and resulted in a fault, whereas HFCP operates before the conductor reaches the ground. The two technologies are complementary with the HFCP objective of preventing a fault from developing and Hi-Z protection providing additional protection to detect faults that may not have been detected by HFCP (e.g., if loading conditions were too low for detection). Some events may be detected by HFCP that Hi-Z may not be able to detect and vice versa, but HFCP provides the added feature of de-energizing the line before it reaches the ground and causes a fault.

23. Can HFCP be applied to different grounded/ ungrounded systems?

HFCP operates by calculating impedance change ratio from load current and voltage measurements, and as a result the system grounding has no effect on the HFCP solution.

24. How do DERs affect the HFCP?

HFCP is designed to work on networks with a high penetration of DERs as their effect is considered in the impedance change ratio. High penetration of DERs may reduce the sensitivity of the solution in some cases, however this can be mitigated by adding additional PMUs to the feeder to improve the coverage.

25. How does load current affect HFCP?

HFCP operated based on both voltage and current measurements, there is a minimum load current required for operation of HFCP, and it can operate effectively in low-load condition.

The setpoint/threshold for the ICR in the HFCP logic is adaptively adjusted based on the feeder loading (current). As the feeder load reduces, a higher ICR is utilized to correctly detect a broken conductor condition.

26. How does topology of the system affect HFCP?

HFCP is designed to work in a variety of different system topologies, and it does not adversely affect the solution. However, the topology of the system would be a major consideration in terms of how many PMUs would be required and where they should be placed on the feeder to optimize the HFCP coverage. HFCP is also designed to function on networks with a high penetration of DER.

27. How does the HFCP behave during lightning strikes?

Transient phenomena like lightning strikes would not impact HFCP operation. PMUs send out the phasor measurements and filters out of the high-frequency components of the voltage and current. Moreover, the operating time of the solution is long enough for any lightning-induced currents and voltage to dissipate.

28. Can the system detect contact with tree branches?

HFCP is designed to detect open phase conditions, so is not suited to detect this type of event and Hi-Z Protection would be more suitable in this case.

29. Would HFCP work for the "covered" overhead conductors?

Yes, HFCP works for covered overhead conductors. There is no effect on the HFCP solution based on the type of conductor or its line parameters if an open phase condition occurs and a significant impedance change can be observed. The performance of HFCP is adversely affected for feeders with bundled conductors where only one conductor breaks.

30. Does HFCP work for bundle conductors?

The performance of HFCP is adversely affected for feeders with bundled conductors where only one strand breaks as there would not be a significant impedance change in this specific case.

PROTECTION

31. If the conductor falls without any considerable arcing will the protection be able to detect the fault. Also, can this be used in MV feeders specifically 11 kV?

The presence of arcing does not adversely affect the HFCP solution, and a falling conductor can still be detected within the required time.

HFCP can be implemented for HV and MV networks with two different techniques. In meshed HV networks, HFCP operates by calculating the ICR of the line impedance and requires measurements on all the terminals of the line (i.e., 2 PMUs for a 2-terminal line, 3 PMUs for a 3-terminal line etc.). In MV networks the ICR of the load impedance is used for detection and a minimum of 1 PMU is required, while more PMUs can be added to improve the coverage of the solution.

32. How will harmonic content affect the algorithm? Will higher THD make the HFCP less effective or less accurate?

Harmonic content does not affect the HFCP operation as harmonic components are filtered by PMUs, and the calculation of the ICR (Impedance Change Ratio) depends on fundamental components.

33. Does HFCP depend on circuit breaker performance?

The total operating time of HFCP depends on the network latency, the time to detect the falling conductor and the breaker operating time. Total clearing time must be lower than 1 second to allow tripping before broken conductor becomes a down conductor.

34. How does HFCP coordinate with downstream devices?

On distribution, if multiple PMUs are installed on a feeder, an adjustable time delay, by default at 300 ms, can be configured for the PMU at the substation. The downstream PMUs can be configured to trip their own respective breakers or the breaker at the substation. If a falling conductor is detected by the downstream PMUs and cleared within that configured time, the PMU at the substation will not trip the breaker. Furthermore, if the downstream devices detect a loss of voltage condition on one phase the upstream PMU will trip the breaker immediately.

On transmission, HFCP solution calculates line impedance and there is no need for coordination with any downstream devices.

35. For what conditions would HFCP be blocked? Could a single pole trip be falsely considered a HFCP? Also, will a three-pole trip cause a misoperation?

For a fault condition the HFCP operation is blocked, and a single pole trip due to a fault would not cause a mis-operation.

To avoid mis-operation for a manual operated single pole trip, a blocking signal should be considered. HFCP is not vulnerable to three-pole reclosing operation.

36. Are there any limitations of HFCP?

The coverage of the HFCP solution is dependent on system topology, load distribution and profile, and the number of PMUs. There is no method available currently that can cover 100% of branches, but a significant coverage can be achieved.

HFCP requires a blocking signal for a single pole operation if no fault preceded the trip signal.

HFCP may not be able to detect falling conductors during low load conditions, and the sensitivity of the solution may be reduced in networks with a high penetration of DERs. This can be mitigated by installing additional PMUs on the feeder to increase coverage.

37. In the event of a fuse blowing on overload rather than fault, would the algorithm treat that as a broken conductor and open the recloser?

No. The algorithm detects that an unusual current event occurred and blocks operation.

38. Is there a threshold on CT accuracy that will be required?

No, this is not a problem for HFCP. PMUs are placed throughout the distribution network for optimal coverage. If sensitivity decreases because of large-ratio CTs, another PMU can be added to increase the coverage of the required area.

39. Are single or three phase switching scenarios a concern? Does HFCP need to be disabled during switching?

No. HFCP is automatically blocked in case of single pole tripping through fault overcurrent detectors, which block HFCP. For three phase switching, HFCP does not operate, as it detects only single-phase broken conductors, and it is blocked in case high impedance is detected in all phases.

TESTING & COMMISSIONING

40. How could this system be tested?

Hardware in the loop (HIL) testing is recommended to determine and validate the performance of HFCP on the target line/feeder. It is offered as a value-added service, and it is up to the customer to decide it would be worthwhile.

HFCP can also be commissioned without HIL testing. HFCP functionality can be tested using PMU emulation software to simulate predefined scenarios. Moreover, a test set that injects currents and voltages to a relay with PMU capability can be used for testing HFCP.

41. Do we need an outage of the entire system to commission the HFCP?

The commissioning procedure is similar to a relay installation, the feeder under commission of HFCP needs to be taken outage.

TRAINING

42. How would you describe the learning curve for HFCP?

Trainings are offered to operators and engineering customer teams. The core concepts are easy to understand, and typical training duration is usually from one day to two days, depending on the level of detailed to be covered.

DEPLOYMENT COST

43. What other services are provided by GE Vernova for HFCP implementation?

GE Vernova's Grid Automation services cover from initial and design steps up to testing and installation.

Initial steps include PMU placement assessment and deployment strategy, network and communications system design and hardware specification Design steps include system configuration and settings development.

Testing and installation include Hardware-in-the-Loop (HIL) tests, field and site integration services, as well as maintenance and training.

44. Typical cost of deploying a HFCP system.

Please contact our sales team specifying your needs on the following link Sales Contact.

For more information
visit **gevernova.com/grid-solutions**

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English
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