

Exploring IEEE C37.246-2017 Guide for Protection Systems of Transmission-to-Generation Interconnections

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Abstract— This paper covers principles of transmission-to-generation interconnection protection and summarizes the IEEE C37.246-2017, Guide for Protection Systems of Transmission-to-Generation Interconnections. The scope of the guide is to document accepted protection practices for transmission-to-generation interconnections and is intended to cover the protection system applications at the interconnections between transmission systems and generation facilities. Consideration is given to technical data needed to design a reliable transmission-to-generation interconnection and data exchange between the generator and transmission owners. All types of generation are discussed such as conventional and inverter-based. Typical transmission-to-generation interconnections are presented; their adequacy, complexity, strengths and limitations with respect to a variety of bus arrangements are discussed. System studies necessary for designing reliable interconnections are described. Protection system functions that are typically applied at transmission-to-generation interconnections and their settings considerations are thoroughly presented and discussed. Specific application guidelines are provided for tapped connections as they are the most complicated relative to interconnection protection.

Index Terms— generation facility, generator owner, interconnection, interconnection protection, point of interconnection, power system, transmission owner, transmission system

I. BACKGROUND

IEEE Power System Relaying and Control Committee (PSRCC) working group C18 has developed *Guide for Protection Systems of Transmission-to-Generation Interconnections*. This summary paper introduces the new guide to the industry, now referred to as IEEE C37.246-2017 [1].

Several electric utilities have maintained over the years their internal requirements for interconnection with generation developed by independent power producers. However, a quest for an industry document was never seriously pursued until the times of power industry deregulation. This deregulation was accompanied by restructuring traditional vertically integrated electric utilities and followed by forming independent transmission companies.

A necessity to develop this industry-wide guide had become even more evident with the intervention and

penetration of inverter-based generation, which introduced serious challenges to the design and protection of the generation interconnections to transmission systems.

Finally, electric utility industry compliance with government-mandated reliability standards also necessitated the need for this guide.

This guide is intended to serve as a “one-stop shop” for power industry consultants working with various electric utilities and power producers and to help achieve consistency in the design of transmission-to-generation interconnections based on the best industry practices outlined in the guide.

II. INTRODUCTION

Reliable transmission-to-generation interconnections are essential in maintaining power system integrity. Both security and dependability of the interconnection protection is of paramount importance for power system stability and its continual reliable operation.

Design of an interconnection typically starts from the necessary technical data exchange between the generator owner and transmission owner. The success of the design greatly depends on the completeness and accuracy of the exchanged data. Therefore, the IEEE C37.246 transmission-to-generation interconnection protection guide [1] lists these data in detail for both the generator and transmission systems. It includes the main data such as generator and step-up transformer electrical parameters and transmission system protection and additional ancillary information that can help in designing a reliable interconnection. This data exchange information is presented for interconnections with either conventional or renewable energy generation sources.

The guide documents existing interconnection substation configurations and provides application guidelines for selecting and engineering interconnection protection schemes to maximize protection security, dependability, and speed of operation.

The guide discusses typical interconnection bus configurations such as straight bus or dual-terminal bus, their advantages and disadvantages, and their impact on the interconnection protection. Special attention is given to tapped connections where a generation facility is directly connected to a transmission line. This type of interconnection is more economical as compared to the other types because it has a

lower initial cost. However, it presents protection challenges to the transmission system, the generation facility, and, possibly, the distribution load the line may additionally serve.

The guide describes system studies utilized to evaluate proposed transmission-to-generation interconnections that include power flow, transient stability, short-circuit, and relay coordination.

The guide documents specific protection system guidelines that should be considered when designing a new or upgrading an existing interconnection substation. It also documents interconnection protection and control functions that are common industry practiced applications for the interconnection substation protection including synchronism check, degraded grid voltage, reverse power protection, breaker failure protection, generator step-up transformer (GSU) ground time overcurrent protection, and bus differential protection. The guide confirms the importance of protection redundancy. It addresses the issues of tripping at interconnections, autoreclosing transmission lines near generating facilities, and applying communication-based protection such as transfer trip.

The guide describes common industry concerns with tapped connections and provides detailed information for their protection. Issues such as coordination between the line relays and tapped generator relays, apparent impedance and infeed effects on line distance protection, and temporary overvoltages are covered in detail.

Finally, the guide discusses the protection challenges on the transmission interconnections with renewable energy sources such as wind and solar generation.

III. ESTABLISHING INTERCONNECTION

A. General Design Approach

Interconnection design should take into consideration the location of the generation facility and the type of generation installed. An interconnection study is typically performed that specifies the system upgrades required to accommodate the interconnection and the impact to the surrounding system and customers. Because of the importance of the general design, it is best to closely coordinate this design between the generator owners and transmission owners. Other technical details such as power system analysis are included in this guide and should be helpful for the project as it relates to the overall engineering and design approaches.

B. Information Provided by Transmission Owner

Once the point of interconnection is established, protection scheme development can begin. Specific information outlined in the guide [1] is essential to properly define the appropriate protection schemes and characteristics of the system where the interconnection is being made. Maximum and minimum fault level projections, acceptable choices for generator step-up transformer winding connections, and relay selection all have significance. Topics for additional considerations such as faults in the generator and transmission protection zones,

power system stability, synchronizing practices, autoreclosing practices, grounding coordination, and system impact studies are also presented.

C. Information Provided by Generator Owner

The preferred point of interconnection is proposed by the generator owner and then evaluated and agreed to by the transmission owner. Design drawings, generator type (synchronous, wind turbine generator (WTG), or solar photovoltaic (PV) inverter, etc.) and characteristic data, transformer configuration and characteristic data are all necessary to determine an appropriate protection system.

Other technical information influencing protection scheme development such as ride-through capability, generator voltage, reactive power, frequency response and control, and short circuit current levels are also presented.

D. Specific Considerations

In determining the final interconnection configuration, consideration should be given to the design of the interconnection and the arrangement of the transmission system. This should include ownership demarcation, evaluation of the impact of long term and momentary outages, and the impact of degraded voltage at the interconnection.

The impact of long-term high voltage or secondary systems unavailability due to maintenance or transmission system outages may determine the need for a more robust or reliable interconnection with multiple tie lines or dual GSU. Ownership demarcation should be clear and properly evaluated since individual operating and maintenance philosophies may impact the electrical system design. The protection requirements, equipment specifications, relay settings, station battery requirements, and testing procedures should be discussed and agreed upon by both parties.

The effect of voltage transients at the interconnection point should be evaluated to ensure interconnected equipment and the generator are not adversely affected. This may include schemes, which separate the interconnection from the transmission system to allow critical auxiliary systems to remain online.

IV. TRANSMISSION-TO-GENERATION INTERCONNECTION CONFIGURATIONS

A generation facility can be interconnected with the transmission system using one of the three basic interconnection configurations: tie line from the generation facility to the existing transmission substation bus; new switching station sectionalizing an existing line into two separate circuits; and tapped connection to an existing transmission line. These three configurations are illustrated as follows.

A. Tie Line

Fig. 1a and Fig.1b each depicts a tie line configuration. The generation facility is connected to the transmission

substation via a double (Fig.1a) or single (Fig. 1b) breaker arrangement. An interconnection is easily achievable using a two-terminal line protection scheme. A spare line position or space to create a new line position must be available in the existing transmission station to interconnect a new circuit from the generation facility.

B. New Switching Station Sectionalizing Existing Line

Fig. 1c shows the interconnection via a new switching station. Depending on the location of the interconnection, this interconnection substation configuration normally has a relatively low impact on the configuration of existing stations and their protection systems that typically involve two-terminal protection schemes.

A ring bus or a breaker-and-a-half bus configuration provides flexibility to the interconnection and permits taking any breakers out of service for maintenance, for example, without interruption to the generation facility. Furthermore, ring bus, breaker-and-a-half, or similar configurations such as three-breaker straight bus minimize disruptions to the transmission system for a fault in the generation facility.

C. Tapped Connection

A tapped connection is shown in Fig. 1d. It may be the most economical based on its initial cost; however, this configuration may contribute to operational problems for both the transmission system and the generation facility. The reliability of the transmission circuit that the generation facility is connected to is reduced. With the tapped connection, a more complex multi-terminal line protection is typically needed that often requires a communication-assisted protection scheme. Reliability may be decreased as the line protection becomes more complex by adding more protective elements.

Additional special configurations including tapped connection via tie line with radial transmission line to distribution load and switching station in radial configuration with distribution load are also addressed in the guide [1].

D. Ground Grid Design

When the generating station ground grid is designed, careful consideration should be taken to accommodate the total zero-sequence fault current contribution. Additional details are discussed in the guide [1].

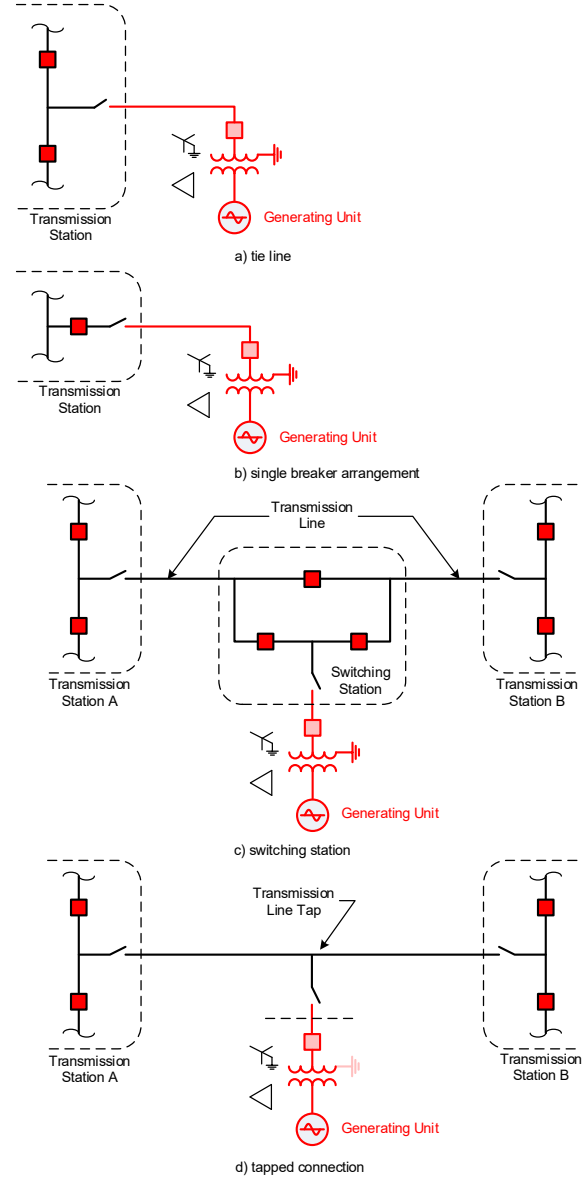


Fig. 1. Transmission-to-generation interconnection configurations

V. SYSTEM STUDIES FOR INTERCONNECTIONS

For transmission-to-generation interconnections, system impact and facilities studies are usually performed.

The system impact study generally includes an assessment of the impacts of the proposed generation interconnection; determination of adequacy of the transmission system to accommodate the requested service; and identification of required upgrades to the transmission system.

The facilities study provides a more detailed estimate of the time and cost of implementing the necessary changes to the transmission system to provide the required transmission service.

Studies specific to protection include power flow, transient stability, short-circuit, relay coordination, and subsynchronous resonance analysis.

VI. OVERVIEW OF PROTECTION SYSTEM SETTINGS FOR INTERCONNECTIONS

A. General Considerations

Generator owners should design the protection systems and install, set, and maintain all generation facility protective devices in accordance with industry standards. The generation facility protective devices should be set to properly coordinate with the transmission owner's protective equipment, both locally and remotely. The generation facility typically needs to be promptly disconnected from the transmission system whenever a fault, abnormal operating condition, or interconnection equipment failure occurs.

A transmission owner may not allow the generation facility to start producing electric energy and send it to the transmission system if, in the judgment of the transmission owner, the generation facility's protection is not adequately designed to prevent the generation facility from introducing or causing adverse impacts on the transmission system.

B. Protective and Control Functions

1) Synchronism Check Function

A generation source which can produce power without connection to the transmission system typically has a synchronism check control system to supervise the closing of the circuit breaker owned by the generator owner. The synchronism check control system should provide limits for breaker closing angle, voltage matching, and slip frequency. In cases of system restoration where reconnection between transmission and generation might occur at a location remote from the generator, a synchronism check relay may need to be installed at that location as well.

2) Degraded grid voltage protection

The magnitude of voltage being out of tolerance is an indication of unbalance between supply and demand of the reactive power. It is important to maintain voltage within specified limits to avoid damage to equipment owned by transmission, generation and utility customers. In addition, generator auxiliary systems, especially for nuclear generating plants, are sensitive to degraded voltage. Degraded grid voltage schemes are implemented to separate the generation facility from the transmission system. Since the potential for damage increases with the degree of departure from nominal value, a single overvoltage setting and a single undervoltage setting with a single time delay for each may not provide the needed protection. Relays with multiple overvoltage and undervoltage elements with different pickup and time delay values are better suited in this application. The guide discusses three different conditions that should be addressed with this protection. The time delays on voltage elements should be coordinated with generator controls, equipment capability and various protection schemes.

3) Reverse Power Protection

Reverse power protection is used to address two main issues: generator motoring and undesirable export of power. The desired directional orientation of the reverse (or directional) power relay depends on its application. For generator motoring, the relay is connected to detect power flow towards the generator. To help prevent the undesirable export of power, the relay is connected to detect power flow into the transmission system.

a) Motoring protection

During motoring conditions, combustion and diesel generators can absorb large amounts of power (up to 50% of their rated MVA). The reverse power relay should be used to protect the transmission system from a possible voltage collapse due to the generators' high-power consumption during motoring.

The motoring power of steam and hydroelectric turbines is insignificant; therefore, these turbines do not generally present a problem for the transmission system.

This is not an issue for WTGs because the inverter system is designed to motor the generator only during startup of the turbine.

For more information on the generator motoring protection, refer to IEEE Std C37.102 [2].

b) One-way power flow

Some generation facilities may not intend to export power to the transmission system. When this is the case, the reverse power flow into the system or the lack of power flow into the facility (minimum import) may be used as an indication that a local power source has become separated from the transmission system. A directional power relay (32) can be used to provide a simple, economical protection scheme to separate generation from the transmission system. The device provides an indirect detection of the loss of transmission source and operates only after the remote transmission breakers have opened. The directional power relay can be applied to this end in two different forms as further discussed in the guide [1].

In all cases, the operation is intentionally time delayed reducing the probability of misoperation due to normal fluctuations of load/generation at the interconnection. The time-delayed tripping should coordinate with any autoreclosing (see IEEE Std C37.95 [3]) to ensure that the generation is removed before it occurs.

In summary, the directional power relay provides an indirect method of fault detection by sensing loss of the transmission source. It is generally applied as a cost saving measure where there is no intent or risk of exporting power to the transmission system. This protection strategy would not be typically recommended for new installations due to the issues discussed in the guide [1].

4) Breaker Failure Protection

The generator owner should install breaker failure protection (50BF) on its generator breaker. The breaker failure protection is designed to send a signal to trip the breaker(s) at the transmission station. Remote backup functions of relays protecting adjacent transmission lines should be coordinated with the breaker failure protection of the generator breaker to allow its operation without unnecessarily removing additional lines from service.

5) Power Transformer Ground Time Overcurrent Protection

Ground overcurrent relaying (51TG or 67N) requires coordination between generation and transmission entities. Nondirectional overcurrent relaying is often used to protect GSUs and station service transformers from damaging currents caused by internal and external faults. This relaying can also provide backup protection for transmission faults.

Transformer ground overcurrent relaying protects the transformer by coordinating with the transformer's damage curve and may serve as system backup protection. This relaying must also coordinate with any transmission line ground overcurrent relays while accounting for system imbalance. When transformer relays are unable to provide backup protection for each of the lines at the station, then redundant line and breaker failure protection should be provided on the transmission system. For cases where the transformer ground overcurrent relay is used to protect for transmission system faults, settings guidance is provided in the guide regarding how to determine the relay pickup, time delay, and characteristic curve. An example of coordination for this situation is also presented in the guide [1].

6) Frequency Protection

Frequency protection, both underfrequency and overfrequency, is applied at the generation facility (IEEE Std C37.106 [4]). Frequency protection is used to protect the turbines from damage that can result from operating at off-nominal frequencies. It is also often used to detect operational islands. Island operation may result from an imbalance between generation and load, which can cause voltage and frequency within the island to quickly drift outside of acceptable levels.

Generation and load imbalance results in the generator either accelerating or decelerating depending on loading conditions with a corresponding frequency change. Frequency relays detect this change and disconnect the generation from the system preventing negative consequences to customer's equipment within the island. The islanded system should not be restored until its generation is disconnected or resynchronized with the transmission system.

Frequency protection is not always required for hydroelectric turbines since some are not subject to damage by operation at off-nominal frequency.

Caution should be exercised when using underfrequency relays for anti-islanding protection. Load shedding plans require generation to stay online long enough to give the load

shedding scheme the opportunity to arrest the frequency decline, hence preventing a premature removal of generation.

If too much generation is dropped during an overfrequency event, an underfrequency event could quickly develop.

Fig. 2 illustrates an example of generation tripping and ride-through requirements. Applicable regional requirements should be followed. Care should be taken to help ensure generation equipment manufacturer recommendations do not conflict with regional ride through requirements. For more information for off-nominal frequency protection, refer to [4].

An additional application for which frequency protection may be implemented is backup protection when the system experiences departures from nominal frequency values.

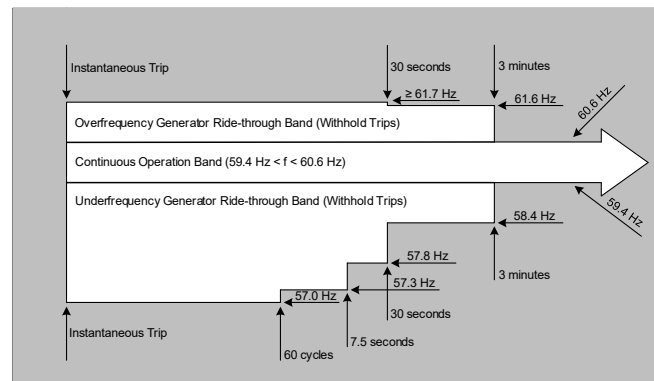


Fig. 2. Illustration of generator trip point and frequency

NOTE—Shaded areas are tripping zones with no restrictions or requirements.

7) Bus Differential Protection

If the ground grids of the generation facility and the transmission system bus are tied at the point of interconnection, then their interconnection is most commonly treated as a bus. When this is the case, the bus can be protected in accordance with the bus protection practices discussed in IEEE Std C37.234 [5]. In cases where the ground grids are not connected, or, occasionally, even when the grids are tied together but circumstances warrant otherwise, the point of interconnection may be treated as a line.

8) Tie line current differential protection

A tie line connecting the generation facility to the transmission system is typically an electrically short transmission line and is best protected by a digital communication-based current differential protective function for the following reasons:

1. Generally, the current differential function is not affected by weak infeed conditions, which may be present at interconnections with low fault MVA capacity.
2. The function only requires line current values; voltage transformers are typically not required for the scheme although they may be needed for the backup protective elements or to provide protection during a

communication issue.

3. The simplicity of settings as the current differential function is only dependent on fault current levels on the protected line.

C. Protection Performance and Redundancy

The protection schemes for interconnections should be designed to reliably isolate all faults and/or failed equipment. To accomplish this, redundant protection schemes are typically required.

When applying redundant protection at the interconnection, attributes such as dissimilar operating principles, diverse path communication channels, and different hardware platforms should be considered.

In any failure event, the generation facility should be capable of isolating itself from the interconnection to the transmission system.

D. Line Autoreclosing Function

Autoreclosing is used to restore lines after momentary faults and can increase the reliability of and provide stability to the system. However, autoreclosing of breakers on transmission lines near generation facilities can be potentially damaging to the generator owner's equipment. Transmission owners may consider the following options to mitigate negative effects of line autoreclosing on nearby generation facilities.

1. No autoreclose for three-phase faults.
2. Autoreclose at remote terminal followed by synch check reclosing at the interconnection bus.
3. Delay autoreclosing for all faults.
4. Use single-shot autoreclosing.
5. Use single-phase tripping and autoreclosing.
6. Autoreclose using voltage supervision.

High speed autoreclosing could be allowed where the generation is connected to the system via more than two lines. Autoreclosing is problematic for transmission lines with tapped generation. Potential issues and solutions are discussed in the guide [1].

E. Communication Channel Aspects

A direct transfer trip (DTT) scheme sends a trip signal via a communication channel to remote substations to trip their breakers as illustrated in Fig. 3. Direct transfer trip schemes are generally required in generation-to-transmission interconnections when the generator backup protection and/or line relays cannot detect a transmission line or bus fault.

When direct transfer trip is specified, communication device(s) and communication channel(s) are required between the generating station and each of its remote ends.

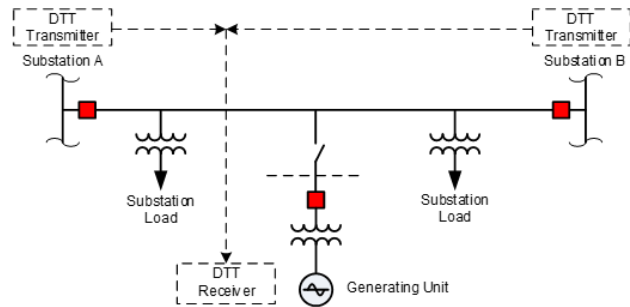


Fig. 3. DTT scheme in generation-to-transmission interconnection

F. Protection Considerations for Tapped Connections

A tapped connection adds a new terminal to an existing two-terminal transmission line and, thus, necessitates the use of multi-terminal line protection schemes. While it is the most effective multi-terminal line protection scheme, the line current differential scheme discussed above requires expensive digital or broad-band communication channels. Depending upon location and/or lack of existing communication infrastructure in the area where the new tapped generator is added, the high cost of digital communication channels can sometimes overshadow the economic benefits of using tapped interconnection configurations. In those situations, the guide [1] discusses the application of phase distance and ground overcurrent protections to achieve a successful tapped interconnection of a generating facility to a transmission system.

Phase distance and ground overcurrent schemes in multi-terminal line configurations require special considerations. Infeed current from the tapped generator on the new terminal desensitizes these protective functions at the existing transmission line terminals and thereby compromises their dependability to operate for faults. The guide [1] explains these concerns in detail. It highlights precautions that must be taken into consideration when the phase distance reach is increased to accommodate infeed from the tapped generator. The ground fault protection desensitization is often a main concern to protection application engineers because faults often involve fault resistance. The guide [1] explains recently reported methodology [6] that employs ungrounded transformer configuration at the interconnection substation to connect tapped generators. This method of tapped generator connection does not desensitize the ground protection, but it can create temporary overvoltage if the tapped generator along the transmission line to which it is connected separates from the system. A fast DTT scheme, backed-up with sacrificial surge arrestors, is discussed to address overvoltage concerns.

G. Protection System Considerations for Interconnections with Renewable Energy Sources

1) Wind Plants

Wind power plants share many similar characteristics with conventional power plants, but there are a few items that make these plants unique that have an impact on the design of the protective relaying for the interconnection. The fault current contribution from a conventional synchronous machine is

independent of the power output of the unit before the fault. For wind plants, the variability of the fault current contribution is typically much larger than from a conventional plant due to the number of smaller generators that make up the plant. The fault current contribution of a plant varies from the output of none to all generators depending on the operation of the plant before the fault. Fig. 4 is an example of a one-line diagram for a typical wind plant.

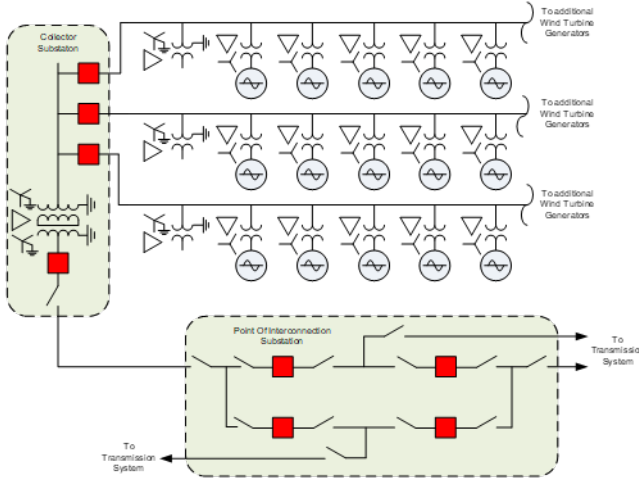


Fig. 4. Wind electric plant one-line diagram

Aside from the number of generators, the type of the generators may be different. Although responses of the different types of WTGs are different, there are some common characteristics. WTGs typically contribute fault current in the range of 3 to 5 times nominal maximum load current, dropping to 1.5 to 2 times nominal current in two cycles. For these reasons, the relaying installed to detect faults on the transmission system at the point of interconnection to the wind plants needs to be able to (1) respond to wide variations of fault current from the wind plant and (2) respond quickly due to the rapid deterioration of the fault current. Most pilot transmission line relaying systems can meet these requirements, but line current differential protection is preferred for these types of limitations.

2) Solar PV Inverters

Solar PV inverter output is controlled by a microprocessor controller. The controller typically acts to limit inverter output current under fault conditions. Depending on the manufacturer, the output current could be limited to the range of 1.1 to 1.5 per unit from 1 to 10 cycles. The filtering components of the inverter could contribute up to 2 to 3 per unit fault current for up to 1/2 cycle. Instantaneous protection elements should be set to account for the initial fault current. Time delayed elements are difficult to set due to the current limiting function of the inverter output and the variable nature of the PV source. Available fault current relies upon the solar availability at the time of the fault, which can vary from zero to maximum output depending on the time of day and weather conditions. Therefore, typical protection such as overcurrent or distance elements cannot be applied as a backup protection.

A direct transfer trip offers a viable option for tripping generation during faulted conditions.

VII. SUMMARY

Engineering a transmission-to-generation interconnection aims at designing a reliable interconnection that supports dependable system operation during either normal or abnormal system conditions. Collaboration between the transmission owners and generator owners during the design of the interconnection is crucial in achieving this goal.

The 2017 IEEE C37.246 Guide for Protection Systems of Transmission-to-Generation Interconnections has been developed to aid protection engineers representing electric utilities, independent power producers, and consulting services in designing these interconnections by documenting and explaining the protection principles and best practices and expounding on practical application issues.

VIII. REFERENCES

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