NERC

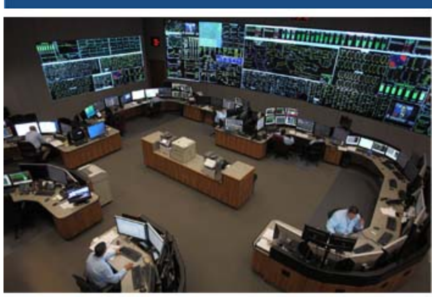
NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Short-Circuit Modeling and System Strength

White Paper

February 2018

RELIABILITY | ACCOUNTABILITY

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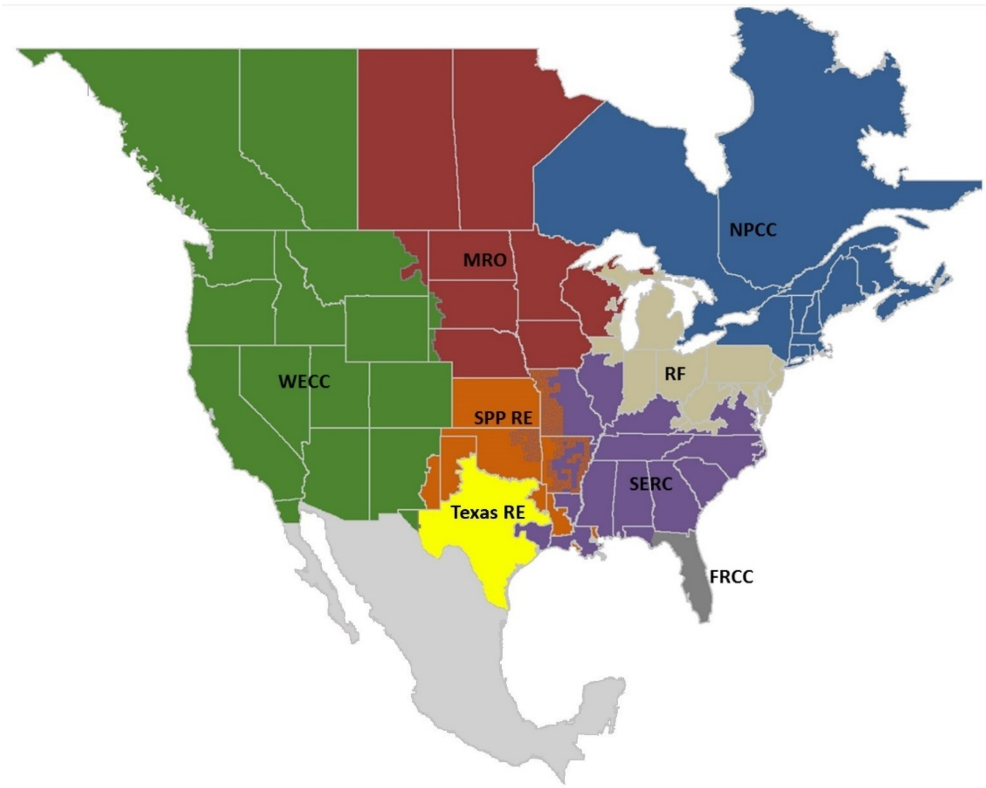
Preface

The North American Electric Reliability Corporation (NERC) is a not-for-profit international regulatory authority whose mission is to assure the reliability and security of the bulk power system (BPS) in North America. NERC develops and enforces Reliability Standards; annually assesses seasonal and long-term reliability; monitors the BPS through system awareness; and educates, trains, and certifies industry personnel. NERC's area of responsibility spans the continental United States, Canada, and the northern portion of Baja California, Mexico. NERC is the Electric Reliability Organization (ERO) for North America, subject to oversight by the Federal Energy Regulatory Commission (FERC) and governmental authorities in Canada. NERC's jurisdiction includes users, owners, and operators of the BPS, which serves more than 334 million people.

The North American BPS is divided into eight Regional Entity (RE) boundaries as shown in the map and corresponding table below.



The North American BPS is divided into eight RE boundaries. The highlighted areas denote overlap as some load-serving entities participate in one Region while associated transmission owners/operators participate in another.

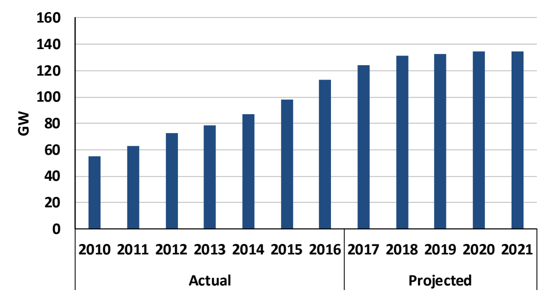
FRCC	Florida Reliability Coordinating Council
MRO	Midwest Reliability Organization
NPCC	Northeast Power Coordinating Council
RF	ReliabilityFirst
SERC	SERC Reliability Corporation
SPP RE	Southwest Power Pool Regional Entity
Texas RE	Texas Reliability Entity
WECC	Western Electricity Coordinating Council

Introduction

In 2015, the Essential Reliability Services Task Force (ERSTF)[1] recognized that North America's electric power system generation resource mix is changing from large traditional sources (e.g., coal, nuclear) to a fleet of smaller-sized resources with varying generation characteristics. The graph in figure 1.0 shows the cumulative installations of utility scale wind and solar generation within the NERC footprint from 2010 -2016 and additional installations forecasted up to 2021. As this transformation continues, there is a fundamental shift in the operational characteristics of the power system as a whole and potential reliability implications.[2] The ERSTF Measures Framework Report provides directional measures to help quantify the challenges faced by the industry with respect to changing generation characteristics. This effort is to understand the on-going transition and to help guide policy makers to prepare for it. The report provides insight into key technical considerations that may not have represented challenges with a synchronous generation fleet but may pose risks to BPS reliability under a changing generation fleet.[3]

This paper focuses on the background to support Measure 10 of the *Essential Reliability Services Task Force Report*.[4] Measure 10 is titled "System Strength" and is based on short-circuit contribution considerations. ERSTF Measure 10 is used to identify the impact of inverter-based sources on grid stability. Traditional large generating facilities provided the grid with large sources of system inertia and stored energy to strengthen areas during system events. New forms of distributed generation reduce the local system inertia and (if not managed correctly) the ability to buffer system events. The ERSTF's goal in evaluating Measure 10 is to screen areas to determine if low system strength poses a potential risk to wide-area bulk power system (BPS) reliability.

NERC-Wide Utility Scale Wind and Solar Actual and Projected Nameplate Capacity Doubled within the Past 5 Years



Source: 2016 LTRA Reference Case—Tier 1 Additions
Fig 1.0

Short-Circuit ratio

In order to measure the strength of an area, the short-circuit ratio (SCR) is calculated. SCR is a metric that has traditionally represented the voltage stiffness of a grid. Areas identified with a low short-circuit ratio may require monitoring or additional studies because they indicate low system strength conditions that can exacerbate system perturbations and disturbances and potentially impact protection system coordination relay settings. The Essential Reliability Service Working Group (ERSWG) and NERC have concluded that the generation resource mix transition has a profound impact on the transmission reliability and will require energy policy, system planning, and system operation considerations as the resource mix evolves. Some specific concerns are voltage performance, frequency response, and system stability (i.e., fault induced delayed voltage recovery in addition to voltage stability).

System short-circuit strength is measured by calculating the short-circuit ratio at a resource's point of interconnection (POI). The short-circuit ratio (SCR) is used in order to develop an understanding of the reliability implications and to quantify the risks associated with high-level integration and penetration of inverters into the BES. The strength of a system (the measure of voltage stiffness) with inverter based technologies differs from conventional generation system strength. The SCR is a screening measure to identify weak areas of the grid within the BPS at a specified point (i.e. bus); therefore, a system consisting of numerous generators and transmission lines will have a different SCR at each bus.

[1] Essential Reliability Services Working Group (ERSWG) and Distributed Energy Resources Task Force (DERTF).
[2] NERC Essential Reliability Services Abstract Report, December 2015.
[3] Essential Reliability Services Task Force Framework 2015 Report: Measure 10, November 2015.
[4] ibid

Modeling Accuracy

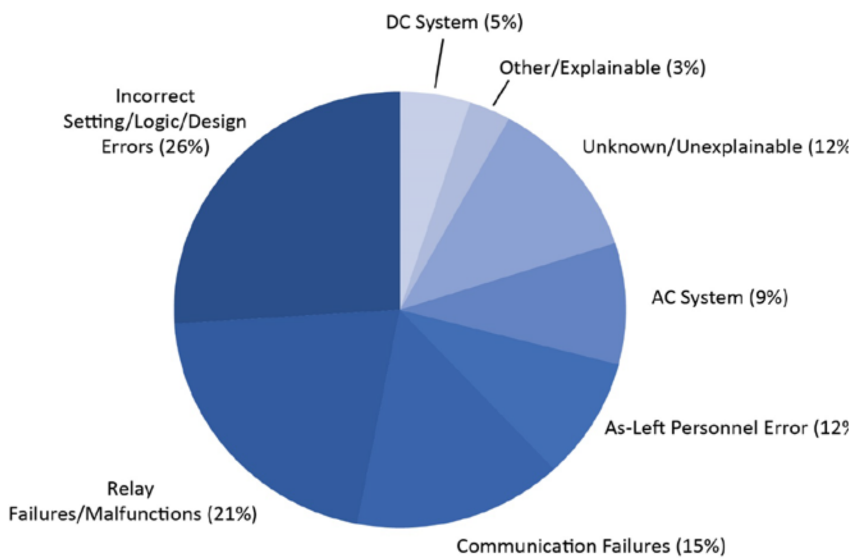
Power system models form the foundation of calculating operating limits, performing event analysis, setting protection systems (relay setting) evaluation and coordination, performing planning studies, and completing performance assessments. A primary aspect of power systems analysis is accurate modeling of the quantity of components that form complex interconnected systems within operational planning, short and long-term planning, and protection models.

The accuracy of power system models are vital in determining the settings of protection devices. Inaccuracies in power system models can lead to misoperations caused by inaccurate settings of protection devices that often directly result in loss of load. In 2013, NERC's System Protection and Control Subcommittee researched the causes of misoperations and published the findings in the 2013 Misoperations Report.[5] Investigation into the regional short-circuit cases showed incorrect short-circuit values and coordination errors. Incorrect short-circuit values were a result of outdated or incorrect data used to calculate relay settings. The coordination errors in these cases all involved pilot protection either of insufficient carrier blocking trip delays or of improper choice of ground pickup values used in a blocking scheme[6].

Misoperations due to coordination errors are only one of the contributors that can lead to severe outages. NERC's 2016 State of Reliability (SOR) report[7] identified that, while protection system operations improved in 2015, misoperations continue to be one of the largest contributors to transmission outage severity and remains an area of focus. The key findings section of the SOR cited settings/logic/design inaccuracies as the principal cause of misoperations in 2015. The other two predominant misoperation causes were relay failure/malfunctions and communication failures.

The 2016 SOR results indicated that targeting the top three causes of misoperations should remain an effective mitigation strategy. As indicated in the 2016 SOR, it is important to perform periodic reviews of a system's previously modeled protection settings/logic/design when there has been considerable changes to the network's topology, its components (e.g., lines, transformers, breakers, relays), or to its generation resources that supply the network and respective loads. In order to accomplish these tasks, power system engineers need to be equipped with tools and models that accurately reflect the power system under study. Then there can be an increased reliance on the validity of power system study results for current operations, short- and long-term planning, and protection of the BPS.

NERC 2016 State of Reliability Report: NERC Misoperations by Cause Code (2Q 2011-3Q 2015)



[5] NERC System Protection and Control Subcommittee's Misoperations Report, April 1, 2013.

[6] *ibid*

[7] NERC State of Reliability Report, May 2016.

Overview

The following chapters of this white paper will provide information on short-circuit analysis fundamentals. Short-circuit sources and modeling are discussed in the first chapter followed by an overview of the short-circuit ratio calculation method in chapter two. Chapter three lists details on short-circuit model verification and the fourth chapter provides a review of NERC's Essential Reliability Services Working Group's Measure 10 – System Strength. Lastly, recommendations for short-circuit case development and maintenance are presented. The appendix provides a summary of NERC reliability standards which are applicable to short-circuit studies

Chapter 1: Short-Circuit Sources and Modeling

Safe and reliable operation of electrical power systems requires the ability to predict and simulate sources of fault current. Accurate modeling of power system facilities is essential for the appropriate selection of equipment ratings as well as the setting of protective system parameters for various operating conditions. Nonsynchronous powered generating resources and synchronous generation are sources of fault current and are considered in short-circuit calculations.

In a balanced three-phase system, the currents flowing in the three phases under normal operating conditions constitute a symmetrical positive-sequence set. Cases that include sequence network parameter data can be used to calculate the current flow paths of each phase of the system. These positive-sequence currents cause voltage drops of the same sequence only. Individual sequence (positive, negative, and zero) circuit characteristics are essential for obtaining the values of the sequence impedances of elements of a power system in order to construct the sequence networks for unbalanced fault calculations. The neutral points of a symmetrical three-phase system are at the same potential when balanced three-phase currents are flowing.

Synchronous machine fault current and short-circuit behavior has been established and is well understood in comparison to nonsynchronous plants. Nonsynchronous resources have unique short-circuit characteristics. The uniqueness emanates from two different physical grid connections:

- The first type of connection is when an induction generator is directly connected to the grid; this generator produces short-circuit current that is similar to synchronous machines. This topic is discussed in section 0 of this white paper.
- The second type of connection is when the nonsynchronous machine is decoupled from the grid through power electronic devices (e.g., inverters). There are various types of nonsynchronous generators and each type has unique short-circuit fault current associated with its respective type. Types of nonsynchronous generators are discussed in sections 0 through 0.

Alternating current synchronous resources, induction motors, generators, and utility ties are the predominant sources of short-circuit currents. In this chapter, the primary sources of fault current in the BPS are presented (i.e., synchronous generators and condensers, nonsynchronous generators, and secondary sources of fault current, including passive elements like reactors and transformers). The level of fault contribution provided by primary sources is greater than the fault current provided by the secondary sources. Hence, the primary fault current sources are presented first in this white paper.

Synchronous Generators and Condensers

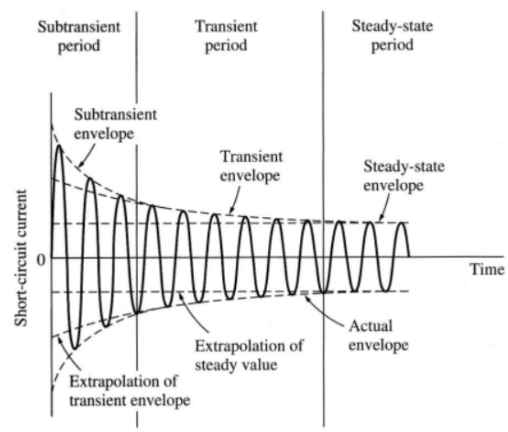
Synchronous generators are a major source of short-circuit contribution. For positive and negative sequence representation, the generator saturated-subtransient impedance ($X^{"}_{dv}$) is used for tripping delay, opening time, and arcing time calculations.[8] Generator zero-sequence reactance generally is not required in short-circuit studies because the generator step-up transformer high-voltage to low-voltage windings are normally specified with Wye-grounded to delta (Δ) connections, blocking the flow of generator zero-sequence currents during system faults.

At the time of a fault, synchronous and induction motor convertors will act as current sources and will supply short-circuit current to the fault corresponding to the amount of their impedances. The current contributed to a short circuit by distribution induction motors and small synchronous motors are usually ignored on utility systems because of the low penetration of these components. Nonsynchronous (Inverter-Based) Generators

[8] IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis, IEEE Std C37.010-1999 (R2005), 2005.

Nonsynchronous and a conventional generating resources differ in the total number of machines/units connected to the transmission substation. A typical conventional generating facility (i.e., combustion, hydro, or steam) consists of a single unit or a few large units and step-up transformer(s). In contrast, a nonsynchronous generating resource of similar capacity consists of many smaller machines/units (wind turbines/photovoltaic systems), individual step-up transformers, a medium voltage collector system, and a substation transformer. Hence, each of the components of a nonsynchronous generating facility needs to be modeled to calculate balanced and unbalanced fault current contribution.

Sub-transient period: first cycle or so after the fault (AC current is very large and falls rapidly).
Transient period: current falls at a slower rate.
Steady-state period: current reaches its steady value.



In order to model wind turbines and photovoltaic systems accurately, their grouping must be identified. Utility-scale wind turbines can be divided into five main groups (according to International Electrotechnical Commission - IEC 61400-27)[9] based on machine type, speed control capabilities, and operational characteristics:[10]

- Type I: squirrel-cage induction generator
- Type II: squirrel-cage wound rotor induction generator with external rotor resistance
- Type III: doubly-fed asynchronous generator
- Type IV: full power converter generator
- Type V: synchronous generator mechanically connected through a torque converter

As a wind plant may have any number of turbines operating at any given time, the short-circuit contribution will vary from zero to the maximum current with all turbines operating. This is true even with addition of a Type III crowbar function.

Photovoltaic systems generally use a full power dc–ac converter and are typically modeled as a Type IV wind machine. Fault contributions of nonsynchronous plants can vary depending on turbine design; turbine manufacturer must provide accurate information on balanced and unbalanced fault performance for the particular turbines.

[9] International Electrotechnical Commission Standard on Wind Turbines - Part 27-1: Electrical simulation models - Wind turbines, IEC 61400-27-1:2015, Feb. 13, 2015.
[10] IEEE PSCR C17 2013 Report on Fault Current Contributions from Wind Plants, 2013.

Type I: Squirrel Cage Induction Generator

In a synchronous machine, the excitation is provided from an independent dc source that is unaffected by a fault on the ac system and will continue to supply high transient currents throughout the duration of a fault. The induction generator fault current is dominated by the transient reactance of the machine. In contrast to synchronous machines whose fault current is dominated by the machine's subtransient reactance. The duration of the fault of an induction generator will be much longer in comparison to a synchronous machine.

Type I wind turbines use an induction generator directly connected to the grid without a power converter. The drop in line voltage in an induction machine following a three-phase fault to ground causes loss of excitation, resulting in supply of substantial transient current into the fault during the subtransient period (first few cycles), eventually leading the ac component to decay to zero. A phase to ground fault will result in a lower, but not negligible, transient phase to ground fault current; however, the remaining phases remain connected to the network and maintain excitation, and current oscillations do not decay to zero. Figure 1.1 shows a network diagram model of a type I squirrel cage induction generator, its capacitor, transformer and collector line is connected to a collector bus which is directly connected to the power grid.

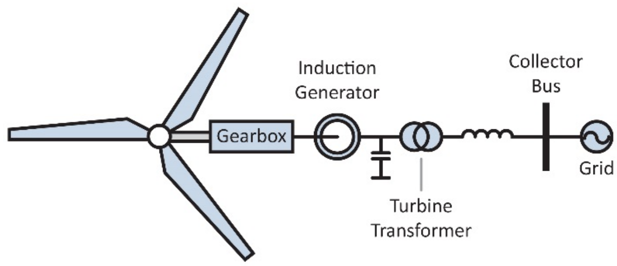


Figure 1.1: Type I Squirrel Cage Induction Generator Model

Type II: Squirrel Cage Wound Rotor Induction Generator with External Rotor Resistance

Type II wind turbines are similar to Type I wind turbines, but Type II turbines are equipped with variable rotor resistance and therefore use a variable rotor resistance nonsynchronous machine. The reason for this is to provide a more steady power output from the wind turbines during wind speed variations.

External rotor resistance adds impedance in short-circuit equivalent calculations, lowering the maximum available fault current of the induction machine. However, Type II wind turbine external rotor resistor control is inactive below rated speed and active above rated speed where the resistor control allows the slip to vary, resulting in variable speed operation. The short-circuit behavior of Type II machines is similar to Type I machines with different impedances. Figure 1.2 shows a network diagram model of a type II squirrel cage wound rotor induction generator with its external rotor resistance modeled as a variable resistor. The generator's capacitor, transformer, and collector line are connected to a collector bus that is directly connected to the power grid.

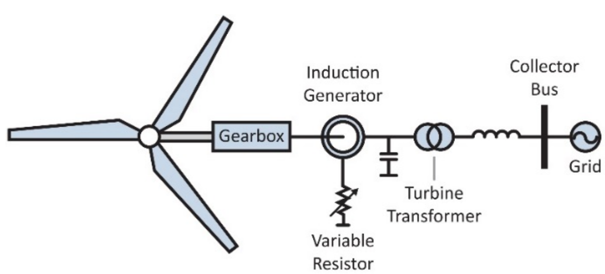


Figure 1.2 Type II Squirrel Cage Wound Rotor Induction Generator with External Rotor Resistance Model

Type III: Doubly Fed Nonsynchronous Generator

Type III wind turbines use double-fed induction machines where the stator is directly connected to the grid and the rotor is connected through a back-to-back power converter. A crowbar system is used for power electronics converter protection (used to divert the induced rotor current protecting the rotor-side converter against over currents and the dc capacitors against over voltages) during faults. The effects of the crowbar resistance can dictate the ac fault contribution. Electromagnetic transient type simulations are only necessary where detailed assessments are performed. Figure 1.3 shows a network diagram model of a Type III doubly fed nonsynchronous generator. The power electronic components (power converter, thyristors) are modeled in addition to the generator's transformer and collector system (the line is connected to a collector bus that is directly connected to the power grid).

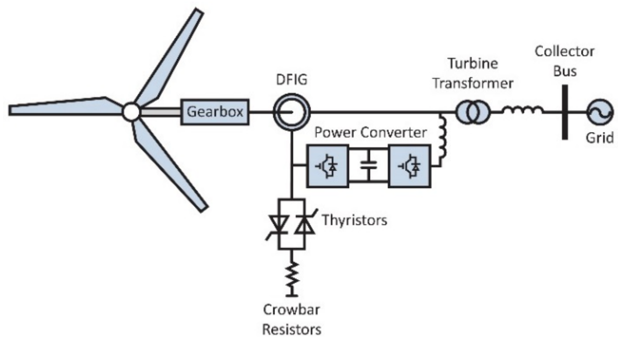


Figure 1.3 Type III Double-Fed Nonsynchronous Generator Model

Type IV Wind and Solar: Full Power Converter Generator (Wind or Photovoltaic)

For Type I's and Type II's, the short-circuit behavior is dominated by the individual generator characteristics in contrast to Type III and Type IV generators. For Type IV's, a power converter drives the electrical behavior during a fault as the generator is connected to the grid through a full-scale power convertor that is sensitive to excessive currents. In order to protect the power electronics devices during a fault close to the plant, a current limiter is designed into the power converter. Rather than the common voltage source behind an impedance short-circuit equivalent used to model most generators, the Type IV design is represented as a simple current source for maximum short-circuit contribution. Type IV machines use different control modes (reactive power control, voltage control, reactive power control with fault-ride-through) that affect the fault current contribution during a disturbance. Figure 1.4 shows a network diagram model of a type IV full power converter generator for wind and photovoltaic (PV) resources. The power electronic power converter is modeled in addition to the generator's transformer and collector system (the line is connected to a collector bus that is directly connected to the power grid).

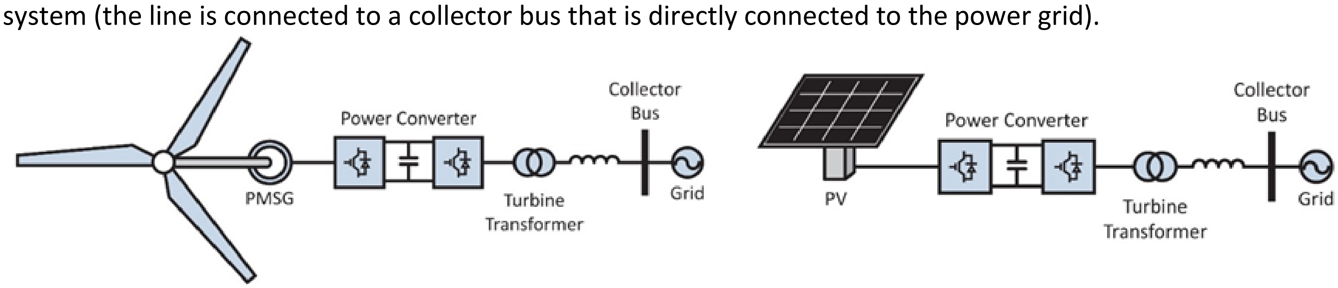


Figure 1.4 Type IV Full Power Converter Generator Model for Wind and photovoltaic (PV) System

Type V: Synchronous Generator Mechanically Connected Through a Torque Converter

The Type V turbine exhibits typical synchronous generator behavior during faults and can be modeled similarly to synchronous generators. Figure 1.5 shows a network diagram model of a type V synchronous generator mechanically connected through a torque converter. This synchronous generator model, is connected to a line and collector bus that ultimately connects to the power grid.

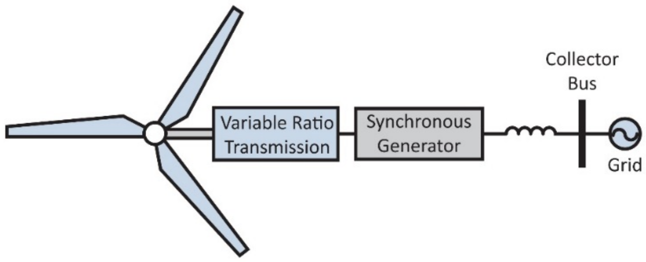


Figure 1.5 Type V Synchronous Generator Model

Flexible Alternating Current Transmission System Devices (Static VAR Compensator and Static Synchronous Compensator)

Flexible alternating current transmission system devices and other power-electronic devices are generally not considered in short-circuit calculations. However, the transformers integrating these facilities into the bulk power system are included.

HVDC (Classical and Voltage Source)

Static power converters (both classical and voltage source) are frequently used in high-voltage dc transmission systems. It is important to note that the static power converters are not a source of short-circuit current and are considered to be similar to flexible alternating current transmission system devices. However, the transformers that integrate the static power converters are sources of fault current and are included in short-circuit calculations. Therefore, the transformers connecting to HVDC facilities are modeled explicitly in the short-circuit cases.

Motors

Induction motors can also be a source of short-circuit current. Large induction motors can have a slow fault current decay despite the lack of a dc rotor winding. The ANSI C37.010 provides three groups of motors depending on the motor output horse power (i.e., small, medium, and large) with different impedance modifiers for subtransient and interrupting time calculations approximated from the transient impedances[11].

Variable frequency drives are generally considered in three-phase short-circuit calculations. Specifically, reversible converter fed drives can contribute to fault current when the rotational mass of the motor and the static equipment operate as a transient inverter. In transient inverter mode, a reverse transfer of energy is produced for deceleration, and current from the inverter will contribute to the fault during the first few fault cycles. After the motor reaches a steady-state speed, the short-circuit contribution will then be limited to the power electronic protection (e.g., fuses, internal circuit breakers).

Passive Elements

Passive elements in transmission systems that are considered for short-circuit analysis include transformers, lines and series reactors.

Transformers

Each transformer's nameplate impedance data and its respective configuration (delta-wye or wye-delta during unbalanced faults) provides the required information for short-circuit calculations. Furthermore, the type of

[11] IEEE Application Guide for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis, IEEE Std C37.010-1999 (R2005), 2005.

transformer (i.e., auto, two-winding, or three-winding) is required to be modeled accurately because the fault contribution varies by the individual transformers characteristics (i.e., type/ configuration and impedance).

Lines, Switchable and Fixed Capacitors, and Reactors

The configuration and length of a transmission line are needed to calculate line impedances. Reactors are treated as equivalent impedance of a transmission line.

As a capacitor’s current angle always leads the system voltage by 90 degrees, the short-circuit contribution from capacitors is neglected. For instance, if the sinusoidal system voltage during a fault is at its minimum (i.e., zero), the capacitor’s initial current will be at its maximum with the current 180 degrees out of phase. The fault current contribution from the capacitors decay rapidly. Similarly, if the system voltage is at its maximum, the capacitors current contribution is zero.

Chapter 2: Short-Circuit Ratio Calculation Methods

As inverter-based resources replace synchronous resources, an operating point will be reached where the grid is no longer strong enough to support stable operation of the power electronic converters connected by the wind and photovoltaic generating resources. Short-circuit ratio (SCR) is a calculation used to screen weak grids close to power electronic converters. This method has been borrowed from the screening of weak grid conditions near high-voltage dc converters and is currently being applied to nonsynchronous plants.[12]

SCR is a metric traditionally described as the voltage stiffness of the grid. The voltage stiffness of the grid is determined in a two-step process. The initial process is to perform classical three-phase fault analysis at the interconnection/collector bus where a source under study is connected to the grid. The second process calculates the ratio of the short-circuit capacity, at the interconnection bus where the source of fault current is located, to the megawatt rating of the source of fault current. Based on this definition, SCR is given by the following:

$$\mathrm{SCR} = \frac{S_{SCMVA}}{P_{RMW}} \tag{1}$$

S_{SCMVA} is the short-circuit MVA capacity at the bus in the existing network before the connection of the new generation source, and P_{RMW} is the rated megawatt value of the new connected source. A low SCR[13,14] is of significant concern because internal plant controls will not function in a stable manner (i.e., the positive sequence stability representation of the plant may not represent the true behavior of the plant or be mathematically stable), increasing the chance of sub-synchronous behavior and control interactions among neighboring devices employing power electronics. When plants are electrically close to each other, they may interact with each other and oscillate against one another. In such cases, the SCR calculation using Equation 1 can result in an overly optimistic result.

There is currently no industry-standard approach to calculate an SCR index of a weak system with high penetrations of wind and solar power plants or other inverter-based resources, such as battery storage. To take into account interaction effects between generating resources and to provide a more accurate system strength index calculation, a better indicator is needed to assess the potential risk of complex instabilities. Several approaches, such as GE's composite SCR[15] and ERCOT's weighted SCR methods, have been proposed for calculations of SCR of a weak system with high penetrations of inverter-based resources.[16]

ERCOT's Weighted Short-Circuit Ratio

$$WSCR = \frac{Weighted \quad S_{SCMVA}}{\sum_{i}^{N} P_{RMWi}} = \frac{\left(\sum_{i}^{N} S_{SCMVAi} * P_{RMWi}\right) / \sum_{i}^{N} P_{RMWi}}{\sum_{i}^{N} P_{RMWi}} = \frac{\sum_{i}^{N} S_{SCMVAi} * P_{RMWi}}{\left(\sum_{i}^{N} P_{RMWi}\right)^2}$$

Where S_{SCMVAi} is the short-circuit capacity at bus i before the connection of wind plant i and P_{RMWi} is the MW rating of wind plant i to be connected. N is the number of wind plants and i is the wind plant index.

The low SCR is typically identified and addressed during nonsynchronous generation interconnection studies. The low SCR can be remedied with system upgrades, such as employment of synchronous condensers; however, synchronous

12 SCR is the ratio of the available system strength (measured in short-circuit MVA) to the MVA rating of the wind or PV plant.

13 Cigré Brochure 370. "Integration of Large Scale Wind Generation using HVDC and Power Electronics". WG-B4.39. ISBN: 978-2-85873-057-5. pg. 157, 2009.

14 W. Lovelace, Minnkota Power Cooperative Inc., "Low SCR Wind Integration and Mitigation," Presented at Minnesota Power Systems Conference 2015, Nov. 11, 2015

15 S. Achilles, N. Miller, E. Larsen, J. MacDowell, GE Energy Consulting, "Stable Renewable Plant Voltage and Reactive Power Control," Presented to NERC ERSTF, June 11-12, 2014

16 Essential Reliability Services Task Force Measures Framework Report, November 2015.

generator retirements, network topology changes, and the addition of invertor-based technologies can manifest into weaker local areas within the bulk power system.

Transmission and generation maintenance outages are an example of temporal network modifications. These planned outages may weaken the interconnection point SCR. Compounded changes in the same geographic area (i.e., same buses) may weaken the grid. A study on these types of network modifications should be addressed during the interconnection study phase of a project or may be studied and in subsequent planning studies when a network experiences multiple system changes (i.e., configuration, equipment modifications) over a period of time. Since analytical methods and currently available tools are not well suited for studying large-scale risks of many plants over wide geographic areas, the detailed analytical results of a few plants should be extended across larger areas using more practical methods.

Figure 2.1 is a diagram depicting SCR results for three networks with their respective tie areas shown as the overlapped regions in the diagram. The SCR categories for each section in a network appear in the trapezoid or decagon region. The inner SCR score is the interior network score. Network A's areas have high SCR with the exception of one section. Network B has as a mixture of low and high SCR scores. Network C's areas all have high SCR.

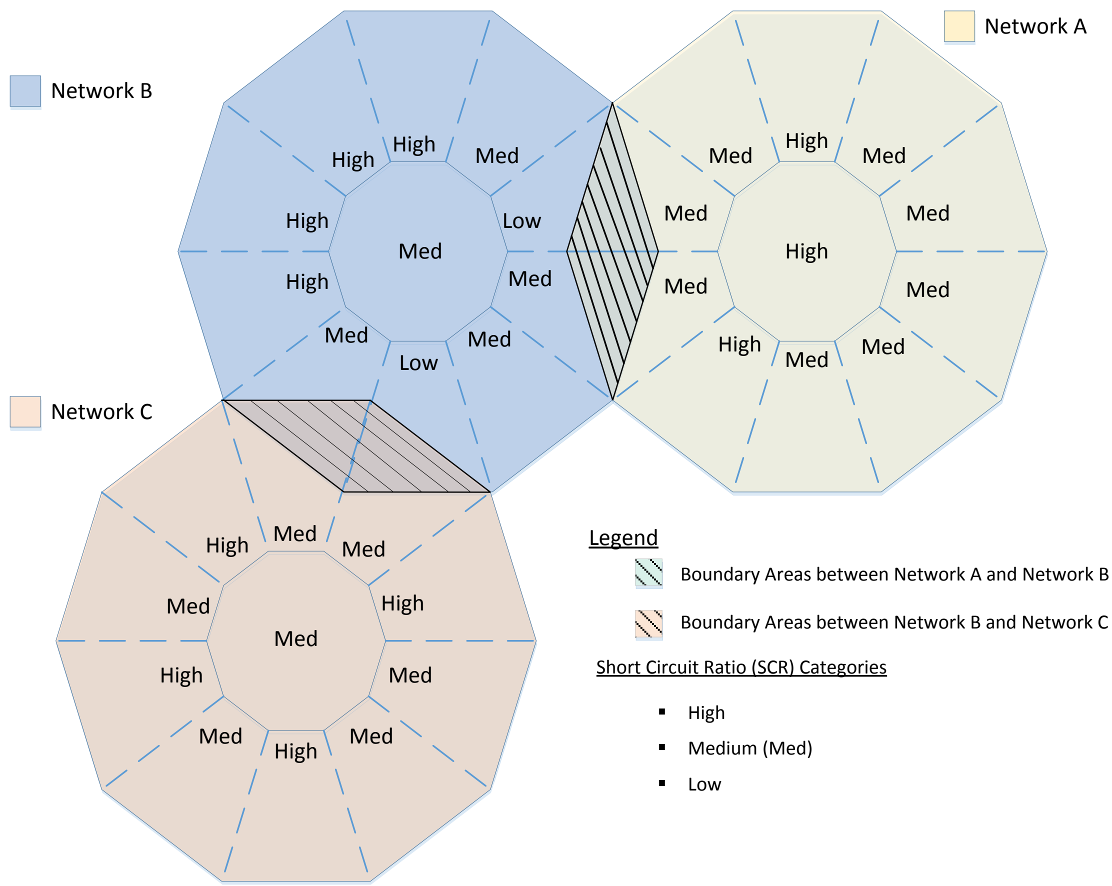


Figure 2.1 Example of Short-Circuit Ratio Results on a Multi-Network Area – Potential Unstudied Stability or Modeling Coordination Issues at Boundary Areas

Network B's low SCR scores do not match the scores at the tie section with Network A. The SCR score mismatch may be the result of an unstudied stability problem or it may be a result of an area to area coordination and modeling problem. Likewise, the same statement can be made when comparing Network B's tie area to Network C.

The SCR screening of weak grid conditions facilitates multiple network areas to be compared for possible wide-area issues. Once the weak areas are identified, further analysis or coordination can be performed to determine stability issues.

Chapter 3: Short-Circuit Model Verification

Short-circuit sequence data (i.e., zero, positive, and negative) is necessary to perform several types of planning studies, such as breaker duty evaluation and relay coordination. The data includes the following:

- Generator reactance and characteristics (e.g., saturated subtransient reactance)
- Transmission lines and associated Mutual Coupling of Line Impedances
- Transformer winding connections and transformer impedance data

Figure 3.2 is an example of a nine bus system that is used to illustrate the importance of accurate modeling practices. In Figure 3.2, the upper network diagram (a), shows the system without errors. The lower network diagram (b), is the same system with errors. The errors are indicated by dashed red lines and circles. The list of errors depicted in Figure 3.2 (b) in comparison to (a) are as follows:

- Bus 3 to Bus 6 has an additional tie line
- Bus 6 to Bus 9 has a three winding transformer incorrectly modeled as a two winding (Wye-Delta) transformer
- Bus 6 to Bus 10 also has a three winding transformer incorrectly modeled as a two winding (Wye-Delta) transformer
- Bus 4 contains a generator
- Bus 9 is modeled as a load bus

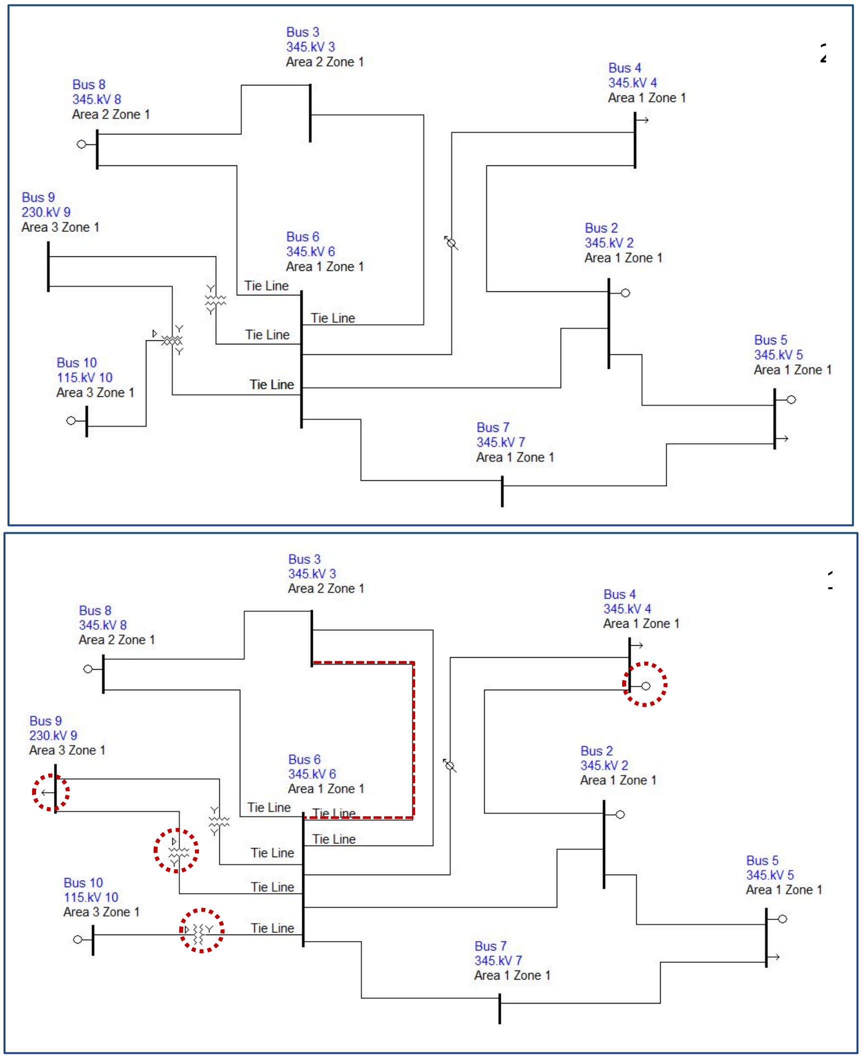


Figure 3.1 Network Diagram Example of a Nine Bus System (a) No Errors (b) Errors

The tie line in Figure 3.1 requires further investigation because the aggregated impedance from Bus 3 to Bus 6 may be identical to the impedance of the single line provided in (a). Therefore, the impedance data must be examined for both networks.

In Figure 3.2, the per unit line impedance data, the complex power (active and reactive power) at load buses and generator reactance for the network diagrams (a and b) are provided. In Figure 3.2, the upper network diagram (a) shows the system without errors. The lower network diagram (b) is the same system with errors. The errors are indicated by dashed red lines and circles. The line impedance data shows that Bus 3 to Bus 6 tie line connections are modeled incorrectly. This example illustrates the basic errors that may occur when modeling short-circuit cases.

Other errors may occur due to network equivalents. Creating a network equivalent requires engineering judgment concerning the size, accuracy, and complexity of the neighboring system. To create an equivalent network is to replace a portion of the network with an equivalent circuit that contains boundary buses with equivalent lines, generators, loads, and shunts from the external system which has been eliminated. The equivalent circuit is created such that the current-voltage relationship at the load of the original network is unchanged. Therefore, the fault current at the boundary buses between the two systems should remain unchanged.
An equivalent network is used when a system is to be partitioned from its neighboring study area or when a system is to be partitioned from its distribution network. In practice, partitioning is best accomplished when the

network equivalent is created three buses away from the boundary buses. Different software platforms use different algorithms to create network equivalents, hence having a buffer of three buses away from the desired partition will minimize differences in the fault current observed at the boundary buses.

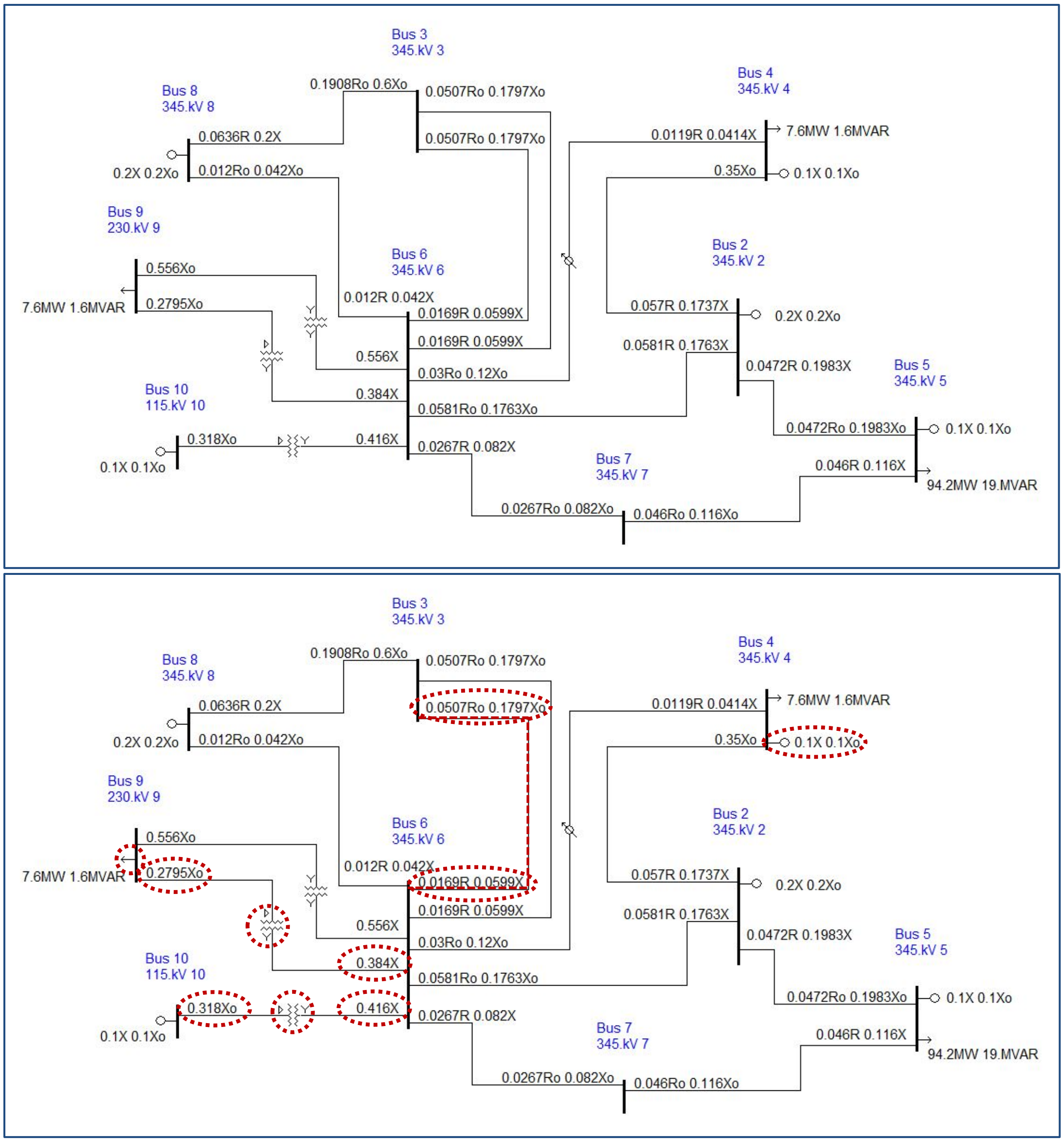


Figure 3.2 Detailed Network Diagram Example of a Nine Bus System with Complex Power, Reactance and Impedance Data Labeled (a) No Errors (b) Errors

In the next chapter, NERC's Essential Reliability Service's (ERS) Measure 10 System Strength will be presented

Chapter 4: NERC's ERS Measure 10 – System Strength

The *2015 ERS Task Force Measures Framework Report*[17] recommended that the industry monitor events related to voltage performance, periodically review the short-circuit current at each transmission bus in the network, and do further analysis of SCR when the penetration of nonsynchronous generation is high or anticipated to increase.

The purpose of performing Measure 10 is to address system strength. The calculation of SCR can be used for identifying areas that may potentially have reliability risks associated with fault-induced delayed voltage recovery (FIDVR) type events and other related voltage stability phenomena. Weak grids can reduce voltage stability and thereby become a contributing factor to delayed voltage recovery. In areas where FIDVR may already be a concern, the weak grid will exacerbate the problem.

Fault-Induced Delayed Voltage Recovery (FIDVR)

Fault-Induced Delayed Voltage Recovery (FIDVR) events were identified by NERC Reliability Assessment Subcommittee (RAS) as an emerging issue in 2012. The FIDVR events are characterized by a depressed voltage for 5 to 30 seconds following a fault. The RAS lists FIDVR events as a concern because they show a temporary loss of voltage control in an area, and they pose a risk of cascading to a larger area, especially if another unexpected event occurs while the voltage is depressed. FIDVR events have been studied and are believed to be initiated by the stall of low- inertia induction motors during the fault. Motors at risk of stalling include compressor-driving loads such as air conditioners. The subject of FIDVR events, their causes, and solutions is covered in a 2008 NERC white paper on this topic.

Source: 2012 RAS—Assessment of Fault-Induced Delayed Voltage Recovery (FIDVR) Simulations

NERC Transmission Issues Subcommittee 2008 White Paper on Fault-Induced Delayed Voltage Recovery

ERS Measure 10 is applicable in areas where there is a significant amount of inverter-based resources or other nonsynchronous resources where an additional study process beyond the traditional short-circuit calculation is recommended. Measure 10 is a valuable screening tool used to identify system areas that would be prone to detrimental inverter based control interactions.

The three-phase (3Φ) short-circuit calculations at the point of interconnection of an inverter based resource (from transmission planning studies) can be used to calculate the SCR. The system strength analysis would also examine the SCR for the 500 kV and above transmission buses on the BPS. The SCR used in the Measure 10 study is defined in IEEE Standard 519-2014.[18] Once low-SCR areas are identified (typically resulting in an SCR value less than three[19,20]), entities can use traditional study techniques (e.g., sub-synchronous control interaction studies) to further analyze the potential for FIDVR, voltage stability and subsynchronous control issues.

The initial step to performing the Measure 10 study requires validation of the interconnection-wide short-circuit case. The case quality check is performed by comparing the 3Φ short-circuit fault currents at the interconnection-wide planning case boundary buses with the 3Φ short-circuit fault currents at the boundary buses of the Regional Entities cases. In performing this preliminary evaluation, NERC found that the 3Φ symmetrical fault current values at boundary buses where inconsistent across the interconnection-wide and regional short-circuit cases. Further investigation into these short-circuit cases revealed modeling discrepancies that include, but are not limited to, unequal numbers of electrical network components (i.e., total impedances and total generator MVA) in the system, network topology differences, and inaccurate network component models (e.g., transformer windings, line mutual coupling data). In addition to disproportionate 3Φ fault current values, the modeling errors between the interconnection-wide and regional cases could result in relay setting misoperations because the relays may not be studied in a coordinated effort.

[17] NERC Essential Reliability Services Task Force Framework: Measure 10, November 2015.

[18] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE Std. 519-2014, 2014.

[19] Cigré Brochure 370. "Integration of Large Scale Wind Generation using HVDC and Power Electronics". WG-B4.39. ISBN: 978-2-85873-057-5. pg. 157 2009.

[20] M. Bassini, M. Horita, J. Jardini, and M. Davies, "Assessment of enabling technologies for the connection of wind farms to weak AC networks, "Cigré Science and Engineering, No. 6, Oct. 2016.

NERC and the Regional Entities will verify that adequate coordination of boundary data between entities during the assembly and maintenance of short-circuit, steady-state and dynamic models occurs. This verification can help remediate previously discovered discrepancies and foster data coordination. The coordination will facilitate the calculation of ERS Measure 10 and identify the potential relay settings issues that could cause relay misoperations.

Recommendations from NERC on short-circuit modeling and coordination are provided in the next chapter.

Chapter 5: Recommendations and Summary

In this white paper, the importance of model accuracy as a first step for determining SCR was presented. The recommendations in this section of the paper refer to the significance of model accuracy and best practices for improving planning models. Creation and maintenance of steady-state, dynamic, short-circuit, operations planning, and real-time cases should consider the following practices:

- A database that serves as a common source for operating horizon and planning horizon models used by the appropriate entities involved in model construction is needed.
- Whenever system changes occur, the updated data should be entered into the database as soon as possible and notices should be sent to the end user.
- The database should include a mechanism for tracking of all data changes and the entity making the change.
- Benchmark planning cases against operations dynamic events or steady-state operating conditions.
- Where possible, create criteria to compare common characteristics between various cases, such as:
  - total current at faulted tie-lines buses between neighboring cases,
  - number of tie-lines modeled and their respective impedances,
  - generating resources availability (lengthy maintenance outages, mothballed, retirements and planned additions),
  - total number of generators and total MVA of generation,
  - transformer type, configuration (winding representation) and impedances.
- When partitioning an area, the network equivalent should be done three buses away from the short-circuit bus under investigation.
  - If the study bus is a tie bus, then the network equivalent will be performed three buses away from the tie and will include all neighboring area data for the three buses away from the tie bus.
  - If the study bus is a sub-transmission bus (230 kV> bus kV > 100 kV), then the network equivalent will be performed three buses downstream (into the distribution network) from the study bus and will include all distribution data for the three downstream buses.

In summary, coordination and validation of short-circuit planning cases and the production of comparable fault currents at boundary buses between neighboring areas are needed for the continued reliability of the BPS. If a large difference exists in short-circuit values between neighboring entities boundary buses, then there is a potential risk of relay misoperation as the coordination of relay settings may rely on the short-circuit characteristics of the system. Therefore, it is necessary to correct the inaccuracies in power system models to minimize the number of misoperations. Misoperations often result in a direct loss of load and generation in the BPS. The 2016 SOR cites incorrect settings/logic/design errors as the largest cause of misoperations in 2015. In order to ensure misoperations are minimized, it is necessary to perform a periodic review of a system's previously modeled protection settings/logic/design. When there have been considerable changes to the network's topology, its components (e.g., lines, transformers, breakers, relays) or to its generation resources that supply the network and respective loads then a review of the protection system is warranted. After the short-circuit cases are verified, the ERS Measure 10 system strength can be used to identify weak areas in the grid. The identified weak areas may have reliability risks associated with FIDVR and other related voltage stability phenomena. Furthermore, this measure will assist in identifying system areas that would be prone to sub-synchronous behavior and control interactions among neighboring devices that employ power electronics.

NERC Next Steps

NERC will continue to work towards ensuring the reliability of the BPS by collaborating with the industry to provide guidance on the characteristics of weak areas where further investigation is needed and to develop necessary feedback and validation processes as reported in this white paper.

Appendix A: NERC Standards

Coordination between real-time contingency analyses, short-circuit, steady-state, dynamic, operation planning, and resource adequacy cases are paramount in effective, and optimum planning and operation of the bulk power system. Despite the fundamental differences in the use of various cases, coordination should be performed between the cases to account for availability of resources and result sharing between registered entities.

The **MOD-032-1** — Data for Power System Modeling and Analysis[21] standard requires each Balancing Authority, Generator Owner, Load-Serving Entity, Resource Planner, Transmission Owner, and Transmission Service Provider to provide steady-state, dynamics, and short-circuit modeling data to its Transmission Planner(s) and Planning Coordinator(s) according to the data requirements and reporting procedures developed by its Planning Coordinator(s) and Transmission Planner(s). The Planning Coordinator is then required to provide the modeling data for its footprint to the appropriate party responsible for building interconnection-wide cases.

Coordination of neighboring data is essential for accurate short-circuit studies required under **TPL-001-4** — Transmission System Planning Performance Requirements[22] to sufficiently check circuit breaker duties and to accurately set protection equipment.

FAC-001-2[23] requires each transmission owner to document facility interconnection requirements and update them as needed, including generation, transmission, and end-user facilities. In addition, the transmission owners' procedures should incorporate coordinated studies of new or materially modified existing interconnections and their impacts on affected system(s).

IRO-010-1a[24] requires each transmission owner and generator owner to provide the modeling information to reliability coordinators for the models that support real-time monitoring, operational planning analyses, and real-time assessments of their reliability coordinator's area to prevent instability, uncontrolled separation, and cascading outages.

The **TPL-001-4** standard encourages each Planning Coordinator and Transmission Planner to share planning assessment results with adjacent Planning Coordinators and Transmission Planners. As a side benefit of a coordination study, the interrupting ratings of all protective devices and short-circuit withstand ratings of conductors and switches are all checked for adequacy. Inadequate equipment ratings can result in extensive damage to the equipment during faults, and system operation may introduce hazards to plant operating personnel and increase the protection misoperation events.

[21] NERC Standard MOD-032-1 — Data for Power System Modeling and Analysis

[22] NERC Standard TPL-001-4 — Transmission System Planning Performance Requirements

[23] NERC Standard FAC-001-2 — Facility Interconnection Requirements

[24] NERC Standard IRO-010-1a — Reliability Coordinator Data Specification and Collection

Appendix B: Contributors

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