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Widespread Loss of Communications in Grid Systems: Impacts and Response Strategies

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Abstract

This report explores the reliance on communication systems for bulk grid operations and considers selected options as a supplement to cyber security. The extreme scenario of a complete loss of communications for power grid operation is assessed, presenting a bounded, worst-case perspective. The paper explores grid communications failures and how a system modifications can, at an increased cost, retain a moderate level of preparedness for a loss of communications and control when used in partnership with cyber security protocols. Doing so allows the increased economic and secure operation that communication based controls affords, but also ensures a level of resilient operation if they are lost. The motivation of this paper is due to the proliferation of photovoltaic (PV) resources, and more generally, smart-grid resources within the US grid, which are requiring more and more active and wide-area controls. Though the loss of communication and control can affect nearly any grid control system, the risk of losing load at large scales requires a broad view of system interconnectivity, so it has been evaluated from a transmission perspective in this report.

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EXECUTIVE SUMMARY

Operating the electric power grid without communications systems is possible, but doing so would require significant and costly modifications to existing infrastructure and significant changes to operating procedures. *A prudent approach to address the risk of losing communication during system operation is to focus on implementing the technologies and procedures necessary to transition to operation without communication, only when needed.* Doing so preserves the significant economies and reliability afforded by communication systems during its availability but establishes resilient operation when it is not.

The use of control systems has substantially evolved over the last century. The use of physical systems such as flywheel governors in the early 20th century have largely been replaced by increasingly complex, wide-area digital control and communications systems. Modern systems afford higher performance and economy by utilizing SCADA and other communication systems, can cover greater distances and have increased the reliability of our grid.

These systems allow higher resource utilization of our grid infrastructure, which not only lowers costs, but also defers the need to expand transmission and distribution infrastructure which has public opposition. Regulatory effects [1], environmental issues and the *Not In My Backyard* public attitudes have greatly minimized the expansion of transmission infrastructure in recent decades [2]. Communication system have largely been used to mitigate the impact of the lack of new transmission infrastructure, which has resulted in increased efficiencies and higher transfer capacities but with lower stability margins and sharper edges to instability which must be actively controlled. Although these margins are well managed, a loss of communications requires immediate actions by system operators to maintain reliable power grid operations. While system impacts were evaluated, the feasibility of specific threats, such as an EMP event, were not considered in this paper.

Although these control systems lower electricity costs, our dependence on them also increases our vulnerability to communication failures, an unquantified risk which emerges in many places across the grid. In this report, two simulations were conducted to demonstrate these effects. The first focused on the inability to maintain secure dispatches across the interconnection, resulting in line and path overloads, increasing the risk of cascading failure. The second analyzed the effect of losing a Remedial Action Scheme, with consequences that were compounded by the first.

The results of this analysis show that:

- The use of communications in power systems operations reduces the cost of operations.
- The use of communications in power systems operations increases system reliability.
- A reduction in power delivery is required to preserve system reliability when communication is lost.
- A prudent and economical approach to mitigate the impacts of a complete loss of communications is possible. There are numerous solution variants that can be employed, but generally, they include the elements identified in 6.1, summarized as:

- The need to develop a grid-wide system that identifies the pervasiveness of any communication loss for each Balancing Authority, generation station, major substation, and control center.
    - The continuous creation and dissemination of emergency dispatch schedules to be used if communications is lost.
    - The development of emergency operating procedures which coordinate interconnection-wide operation. As a minimum, such procedures must include a means to ensure system balance, load management and tripping priorities, maintain operation within transfer limits, secure dispatching and redispatching (e.g. TLRs), operation without RAS, and the management of local protection such as transfer trip schemes.
    - Procedure to coordinate the system-wide transition from normal operation to operation without communications.
    - Ubiquitous under frequency loads shedding systems (UFLS), which discriminates priorities of load tripping based on criticality.
    - Generation reserve allocations which ensures that sufficient locational capacity exists in the event of a loss of communications.
    - All connected generators capable of speed governing should be transitioned to droop control mode.
    - All offline generators capable of synchronizing, should synchronize to the grid.
    - Staff all major substations. Replace all lines back into service that tripped on Zone 3. Consider disabling Zone 3 relay trip settings. Consider restoring lines to service that are suspected of having tripped on impedance, due to line sag.
    - SOCs establish telephone and/or radio communications with powerplants as first priority and major manned substations as a second priority.
    - Establish a method to conduct a security constrained dispatch without the use of SCADA, Phasor Data, State Estimators, EMS, ICCP systems, or voice communications.
- There are ways to provide secure operation of the grid without any communications, but they are unfeasible. Such operation implies a significant reduction in power transfer capacity, increase in operating cost, and a significant increase in infrastructure buildout.
- We have not analyzed the effects of a partial loss of communications, but doing so would require
    - A significant model development endeavor which combines power system models with communications models.
    - Identifying and collection communication system models which interact with the grid, major control systems, and RAS Systems.
- There is a need to develop strategies and procedures and apply technologies which can make a loss of communications to our power grid less costly financially and socially.

These strategies should be incorporated into ongoing infrastructure planning and operating processes. This approach should be used to reinforce cyber security solutions, not as an alternative to them.

There are several research areas that would provide significant benefit, identified in 7.1, and are summarized as follows:

- Develop planning and operating procedures to coordinate and manage system operation without communication systems in place.
- Develop resilient communication systems using multiple modes of communication.
- Design and implement advanced UFLS and demand response.
- Integrate communications into system planning models and studies.

NOMENCLATURE

Term or Abbreviation	Definition
Adequacy	*Adequacy and Security* are two components of grid reliability. Adequacy is a measure of the duration (in hours per year) which dispatched generation is expected to serve the system load, given uncertainties in the demand and unplanned generator contingencies.
Capacity	A measured quantity of service that a system component can provide. Transfer capacity refers to the quantity of power that the transmission system can move between two points.
Communications	The deliberate transfer of information between two or more locations (e.g. EMS data between control centers using inter-control center communications protocol, ICCP).
Control	The use of information (supplied locally or remotely) to affect the operation of a system (e.g. Automatic Generation Control).
Decision Support	A human grid operator's use of electronically derived information (e.g. real time analysis using state estimation data) to make operational decisions.
Dispatch	A list of all generators and their outputs at any given time. The dispatch differs from a dispatch schedule. The dispatch is realized, but the dispatch schedule is an instruction and expectation that may not be realized.
Dispatch Schedule	The selection of specific generators and their associated output values for a 24 hour period typically calculated using a SCED and formalized in a dispatch schedule. This is given to all grid operators. Also called generation schedule, dispatch schedule.
EMS	Energy Management System. This system stores and presents system telemetry to system operators and transmits their control actions to selected field equipment such as transmission line breakers.
GW	Gigawatts of electric power
Local Controls	The control of an electronic device using either no communication system, or a communication system and/or protocols that are restricted to a LAN or field bus (e.g. generator voltage regulator and governor). These controls are considered to remain in service during a pervasive loss of communications for the purpose of this report.
RAS	Remedial Action Schemes, also called Special Protection Schemes (SPS) and Wide Area Protection. Automated wide-area control and communications systems that, when armed, remain on standby, ready to perform a predetermined operation should a critical contingency occur. These systems are typically 'armed' and 'disarmed' by system operators as they deem necessary for the given operating condition.
SCED	Security Constrained Economic Dispatch (SCED) is a software optimization tool used to determine the most cost effective dispatch of generation, given a system topology and demand. SCED security constraints ensure that cost optimal dispatch solutions do not result in a violation of system reliability.

Term or Abbreviation	Definition
Security	Security and Adequacy are two components of grid reliability. Security is the ability of a system to deliver electrical power during a contingency event. The term is sometimes used loosely, without defining a specific type of contingency, but it typically refers to the preservation of thermal line overloads, voltage stability margins, and transient stability margins during a contingency such as the loss of one or more generators, transmission lines, or non-load-serving power transformers.
Servo control	The control of an electrical device using communications embedded within the controller (e.g. Flexible AC Transmission System unit). These controls are considered to remain in service during a pervasive loss of communications for the purpose of this report.
Small Signal Instability	Negatively damped electro-mechanical power oscillations below 1Hz occurring between groups of generators. These oscillations typically occur across very wide geographic distances, such as several hundred miles.
Stability Margin	An quantifiable change in system state that would lead to a higher probability of significant load loss. (This is a simplified definition).
State Estimation	The use of a system model to complete an incomplete set of telemetered data using computational algorithms and known system topology.
Telemetry	The use of communications to retrieve remote sensor data (e.g. SCADA).
Transient Instability	The loss of a generator synchronization due to an instantaneous change in system input impedance at the generator (typically fault induced), and often perpetuated by lower sending and receiving end voltages.
Transmission Loading Relief (TLR)	A sequence of actions taken during real-time operation to avoid or remedy security violations associated with the transmission system. TLR Levels indicate the criticality of the request. The highest, TLR Level 6, is an emergency procedure which can include any of: the redispatch of generation, reconfiguration of transmission, or disconnection of load.
Voltage Instability	The injection of capacitive reactance decreases the voltage at that node. The Voltage Stability (VS) margin is typically identified in terms of increased transmission line power flow resulting in a voltage drop and (eventually) collapse.
Wide Area Protection	The use of electronic devices to enact control action across large distances, and often using more than a single WAN (e.g. Remedial Action Scheme). Such systems are typically feed-forward control systems but can be implemented as continuous feedback control systems.
Zone 3 Impedance Relay	Zone 1 and 2 transmission relays are designed to measure line voltage and current, identify a fault and trip on a low impedance considering direction and distance. Zone 3 relays, although they do not trip on overcurrent, have their impedance trip settings established to trip at an equivalent current of 1.5 pu at $0.85\angle 30^{o}$ pu Voltage sustained for 2 to 3 seconds. Therefore, they effectively act as an overcurrent relay, and can perpetuate a cascading outage [3].

1. INTRODUCTION

The term *grid* is very broad, applying to transmission, distribution and generation. Within these three areas, transmission and centralized generation incur the greatest risk associated with a loss of communication and control. Risks associated with distribution systems are lower due to their lack of broad interconnectivity and their limited load service for a given communications infrastructure. This assumption, however, may be changing due to the widespread use of common communications and control platforms for large numbers of distributed PV [4]. Planning and operations are also important to consider for each type of grid infrastructure, and both will be addressed without distinction since operational strategies imply prior planning. For example, an operating strategy that relies on a process or procedure will have assumed to have been vetted through a planning process. Therefore, the discussions will focus more on operations than planning.

The degree of risk to system stability[1] that is encountered during a loss of communications depends greatly on the type, extensiveness, quality reduction and location of the loss. Understanding the incremental risk associated with various degrees of communications lost is a large research endeavor and has not been evaluated in detail to the understanding of the authors, nor will this report attempt to do so. However, the report will attempt to bound the consequences of a pervasive loss of communication in order to provide insight regarding potential risks, but not expected risks.

The remainder of the paper is structured in the following way: Chapter 2 describes the evolution of the US power system into the communication-heavy system of today. Chapter 3 identifies the typical uses of communications systems in today bulk power system. Chapter 4 discusses the impacts that communication systems have on the generation and transmission of bulk power. Chapter 5 provides two analyses which help to explain the process and impact by which a pervasive loss of communication can affect the bulk power system. Chapter 6 lists some means by which risk can be reduced in the power grid due to a loss of communications. Chapter 7 identifies conclusions and further study.

[1] This paper applies a liberal definition of the term stability. The term has specific meanings in power system literature, including voltage stability, transient stability, and small signal stability, each of which can cause or aggravate a system collapse. Management of frequency nadir, for example, is sometimes loosely referred to as frequency stability as well. Although no relation to control theory, a mis-management of system frequency can cause wide-scale load loss via relay action. In that manner, other critical system effects which can trigger a blackout, such as a lack of droop regulation and Zone 3 thermal overloads on lines will be discussed generally under the term stability.

2. EVOLUTION OF THE U.S. POWER GRID

The US power grid has evolved for more than a century. The first high voltage power line (15kV, AC) was established in 1890, and by 1914, fifty-five transmission systems operating at more than 70kV were in service [5]. The use of centralized generation and high voltage transmission provided the economies of scale for electric power, but in the late 1960's and beyond, financial pressures to reduce the number of new transmission lines was growing. The reduction in new transmission assets was further perpetuated in 1992 as deregulation of wholesale electric power was enacted via Federal Energy Regulatory Commission (FERC) Orders 888 and 889 [6]. An increase in the transfer capacity of existing transmission infrastructure was required to serve a growing population, and was made possible by using advanced control and communication systems. Such systems provide essential operations data via Supervisory Control and Data Acquisition (SCADA) and Energy Management Systems (EMS), state estimation systems, Security Constrained Economic Dispatch (SCED), and wide-area controls and Remedial Action Schemes (RAS). These systems largely rely on communications and are required to preserve high reliability at adequate costs.

2.1. The Early 20th Century

The grid of the early 20th century functioned well, but had limited communications. Alexander Graham Bell invented the telephone in 1876. Long distance telephone service was expanding greatly by 1880 with an estimated ten million Bell telephones in service by 1918 [7]. Telephone communications has always been an integral part of centralized generation and transmission of electricity. Some of the earliest SCADA systems were in place in the 1920s, relaying messaging and controls between co-located substations and generator power houses. At that time, the telephone was used to relay generator dispatch orders from a remote system control center [8] to the generator power houses. By the 1930's utilities started coordinating calculations to determine generator dispatches.

Early in the 20th century there were few electrical control systems, with the exception of mechanical control systems such as local governor droop regulation. There was very little power transmission over long distances, as loads were mostly served by local generation and distribution. For those tightly coupled electrical systems, stability was limited to balancing supply and demand with little effort spent on power quality issues such as frequency and voltage.

For the few transmission lines that existed, stability relied on the low impedance of transmission lines, the use of large transmission margins, and the use of governor droop regulation. Voltage was controlled on early generators using rotating dc exciters, which were slow responding but highly reliable.

2.2. The Expansion of the Grid

In the early to mid-20th century, the transmission grid expanded significantly. As this occurred, the emergence of transient stability issues arose, which placed generators at risk of separation during system transients. These stability issues were primarily managed by lowering system impedance through additional transmission infrastructure. In the mid-20th century, transient stability problems were addressed using fast generator excitation systems as opposed to an increase in transmission infrastructure. This offered an inexpensive solution to ensuring system reliability against transient stability issues.

The 1970s through the 1990s saw the introduction of Flexible AC Transmission Systems (FACTS) power electronics based voltage control devices. Static VAR Compensators (SVCs) improved the voltage management of the transmission grid, but created a sharper edge to voltage instability, requiring faster and more accurate control systems. High initial response excitation systems were implemented to increase transient stability margin, however, doing so also resulted in lower damping for post fault oscillations. And the emergence of nuclear power, which is a base load resource, lowered the system governor droop response. This was compensated by increasing the droop gain on all remaining generators. But as droop gain increased, small signal stability decreased. Notable problems in the WECC surfaced regarding small signal stability, which led to the Western blackout of 1996, resulting in 30,000MW of load lost, affecting 7.5 million customers [9].

Circa 1980, tap changing transformers were introduced to help manage the voltages at the loads (distribution systems). These transformers made automatic adjustments in response to load changes throughout the day, changing their reactive power consumption. The use of these tap changing transformers made loads appear to be constant power loads as opposed to the constant impedance loads they were, which triggered an emergence of voltage stability problems. Voltage controlled capacitor banks were introduced using automatic controls to help mitigate this problem. Both of these voltage management issues perpetuated line overloads. All of these issues resulted in a greater increase in the use of control systems and associated communications.

As the demands for transfer capacity on the grid increased, Remedial Action Schemes became more frequently used. These wide-area control systems offered a means to increase transfer capacity, keeping reliability high, and costs low.

2.3. The Modern Grid

Reliance on communication systems allows increased reliability, reduced staffing and greater economic benefits. As the US generation fleet transitions to a higher degree of inverter-based energy resources, such as storage, photovoltaic solar generation, wind generation, and new types of automatic generation control systems, reliance on wide area communications will be increased. An early example of this includes fast regulation signals, which are responsive to FERC order 755 [10].

Energy Market systems also utilize communications for bids and offers. Although these systems are not used for system control, they are relied upon to provide an economic mechanism to ensure real time energy (e.g. energy imbalance markets), next day energy (e.g. day ahead markets) and future capacity needs (e.g. capacity markets) are met. Note that the dispatch of generation, whether in real-time, hourly, or other, is not dependent on the operation of a market system.

3. THE USE OF COMMUNICATIONS IN ELECTRIC POWER SYSTEMS

The use of communications systems in the electric power industry is very broad [11-13], spanning many different types of infrastructures. For the bulk electric power system, these rely on a hybrid mix of technologies such as fiber optic, copper wire lines, wireless and microwave communications with backbones.

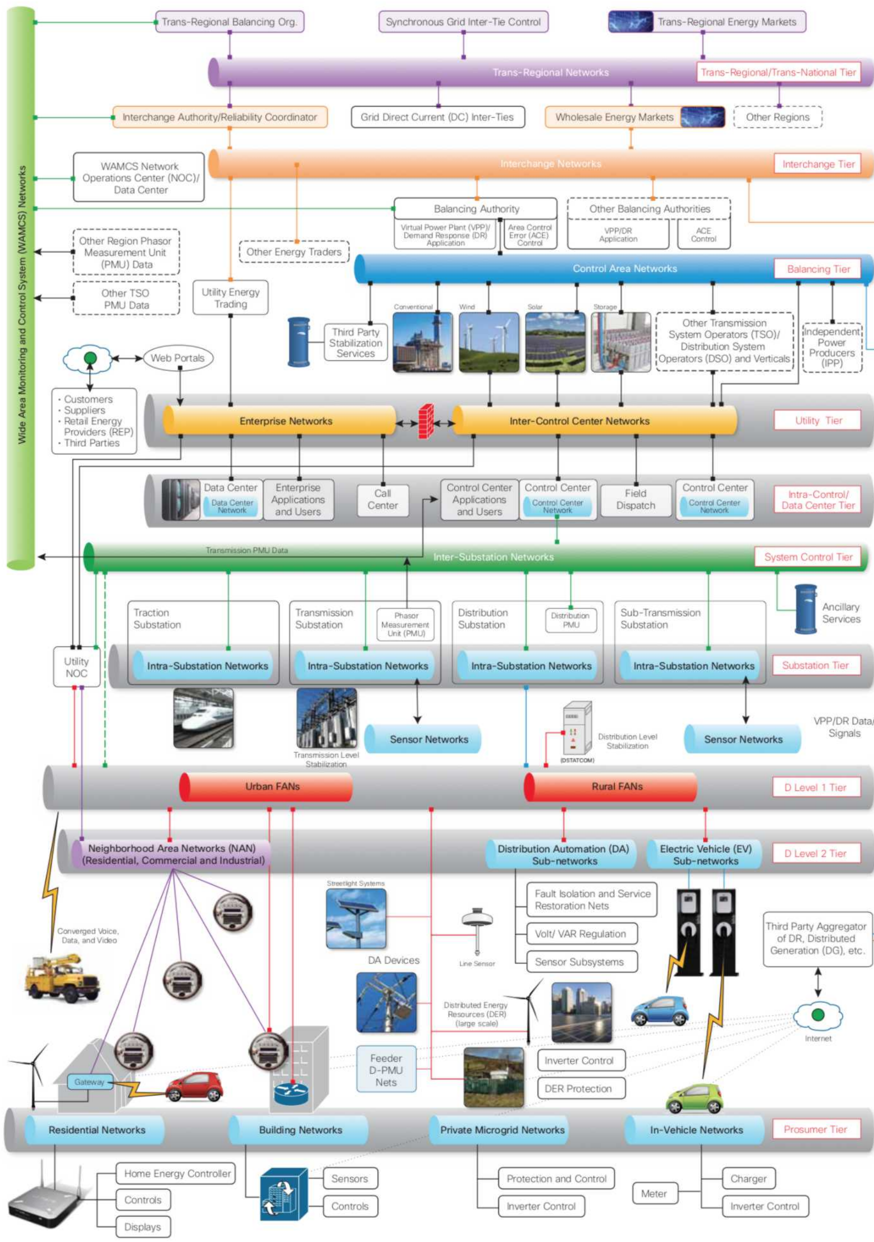

Figure 1 GridBlocks Reference Model by Cisco Systems [14]

Cisco Systems, GridBlocks Reference Model, shown in Figure 1, provides a communication model for the electric power grid. Although the specific architecture offered is proprietary to

Cisco, the model enumerates many of the communication components that are currently engaged in the delivery of power systems. Even given the complexity of this diagram, there are a significant number of important details absent from the diagram. For example, the Wide Area Monitoring and Control System Network is shown as a single block, but includes many distinct networks, owned and operated by different parties, interfacing across multiple Balancing Authorities.

Trends in the use of communications in power systems [15] include faster system dynamics, hidden feedbacks and cross-coupling, increased penetration of variable renewable energy resources, and an evolving control system structure, which is increasingly affected by latency and quality of service [16-18]

4. IMPACTS OF COMMUNICATION ON GRID STABILITY

The majority of reportable grid disturbances arise from a loss of monitoring and control, however, these disturbances do not correlate to a widespread communications outage, but represent the spectrum of typical disturbances.

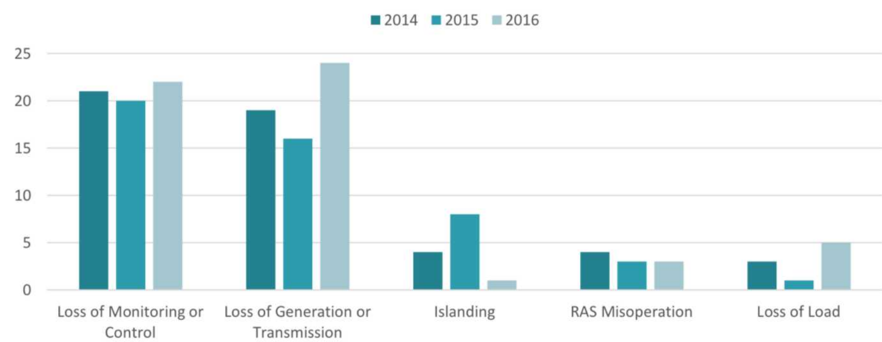

Figure 2 US Reportable Grid Disturbances by Category [19]

For the North American grid, a pervasive loss in communications would necessitate an immediate reduction in power transfers to preserve system stability, implying the selective tripping of loads and/or the redispatch of generation. Alternatives to this scenario would require significant changes to the grid system architecture, planning and procedural development at a sizeable increase in cost, as there are also many subsystems that require communications. The following discussion explains how system stability and reliability at the bulk power system level are dependent upon communication systems.

4.1. Stability Margins and How They are Affected by Communication Systems

Stability margin refers to the additional amount of a capability that can be provided by the grid, a subsystem, or component, without risking the reliability of the system. As communication systems and control systems deteriorate, stability margins decrease. If these systems did not exist, stability margins would need to be preserved through a reduction in transfer capacity and/or a buildout of transmission, generation and related infrastructure.

4.1.1. Generation Adequacy

Generation adequacy is a term used to identify the sufficiency of available power generation sources. It measures the adequacy power supply in terms of the amount and variability of loads and the probability of any given generator undergoing unforeseen problems that would prevent it from delivering its scheduled power. In preparation for each operating day, a Security Constrained Economic Dispatch (SCED) schedule is created which ensures sufficient generation and reserve capacity for the expected demand. Risk associated with a lack of adequate generation is typically mitigated by increasing the allocation of system reserves by the SCED. During operation per a SCED schedule, if problems occur such as an unexpected load increase or unforeseen generator outages, the system operator manages system balance using this reserve generation. Dispatching reserve generation is accomplished using communications systems, including SCADA, EMS, AGC, and even the telephone. In extreme cases, such as several operating hours without communications, generation schedules change and the inability to update forecasts will likely increase uncertainty of having sufficient generation.

4.1.2. Frequency Stability

Frequency stability refers to the ability of the system to maintain 60 Hz within tight tolerances. Significant deviation from the nominal 60 Hz operating point can irreparably damage generation equipment, transformers, and loads, therefore, it must be managed closely. The use of communications to maintain system frequency is essentially limited to droop response, with the exception of telemetry that is required for the situational awareness of operators who may intervene. The remaining items below are autonomous systems that are do not rely on communication, but are described for context. The order of the items listed is based on their speed of response from fastest, to slowest.

4.1.2.1. Inertial Response.

The power grid is primarily supplied by synchronous generation and these units store a small amount of kinetic energy in proportion to their inertia (mass) as their rotors spin. When system frequency changes, so does the physical rotation of the turbine generators. Thus a decrease in the grid's frequency results in the slowing of all connected synchronous generator rotors, releasing their kinetic energy into the grid in the form of electric power. This process slows the change in frequency, buying the time (a few seconds) needed to increase (or decrease) the mechanical power output of the prime movers. This inertial storage is accessed without a control system or communication—it is a property of the synchronous generator physics, accessed according to the law of conservation of energy: energy supplied into the grid (generation) equals energy consumed (loads) plus energy losses (transmission resistive losses) plus energy stored (inertial storage)[2].

4.1.2.2. Droop Response

A turbine governor is a device connected to the prime mover of each generator's throttle, similar to a cruise control on a vehicle, adjusting the fuel into the prime mover to control its speed of rotation (which is proportional to system electrical frequency). Droop response is a feature of a governor that automatically adjusts output if system frequency deviates from 60 Hz. This feature is found on most (but not all) generators and significantly aids the frequency stability of the grid without requiring external communication.

In Figure 3, a turbine-generator is initially operating at point 1., supplying 100MW at a system frequency of 60 Hz. The system frequency declines due to an increase in system load and the turbine-generator responds by increasing its power output in accordance with its droop curve from point 1. to point 2., restoring system balance. This occurs automatically, without operator intervention, and without the need for communications.

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[2] Since the electric grid is a closed system, physics requires that the supply of electric power to be equal to electrical consumption (loads and losses) plus any changes in stored electrical energy. Thus, for an operating grid, there cannot be a system imbalance between the electrical power supply and the electrical power demand. Common vernacular, however, uses the term 'imbalance' to compare the total system mechanical input power to the total system electrical power demand and losses. Differences are automatically corrected by the mechanical rotational kinetic energy of turbine-generators, and are observed as a change in rotational speed and system frequency. Due to the unique electro-mechanical design of a synchronous generator, its rotational speed and its electrical frequency are equal (by a constant factor), and the energy conversion between rotational energy and electrical energy occurs instantly and automatically, without the need of a control system.

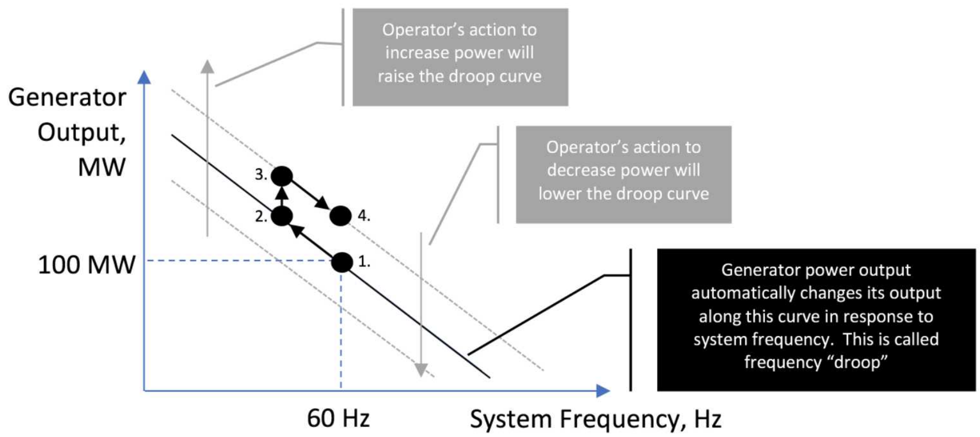


Figure 3 Frequency Droop Control and Plant Operator Initiated Power Changes. This Control Does Not Depend on Communication Systems.

The operator observes the decrease in system frequency and raises the prime mover's output, raising the droop curve[3] to a higher level, resulting in point 3., operating along a higher droop curve. The increase in power creates a surplus of power in the grid. The governor acts to balance power by lowering output along the droop curve, resulting in an increase in frequency from 3. to 4. Without operator intervention to manually increase the power output (by raising the droop curve), the system would have remained balanced, but at the lower frequency of point 2. Manual intervention of the generator output is typically reserved for large, scheduled power changes. Smaller adjustment to power output are typically applied to select generators only and use an AGC system, replacing the need for continuous operator adjustments.

4.1.2.3. Automatic Generation Control (AGC)

AGC is a wide-area control system that relies on communication systems and which is important to maintain the system frequency within established tolerances. This system automatically and continuously adjusts the output of key reserve generation units to ensure the grid is properly balanced and system frequency is managed at 60Hz. This task could be accomplished manually with additional staffing if needed and as described in the preceding paragraph. Such operation would result in the continuous manual adjustments of generator output in response to random changes in system load.

The AGC system is assumed to be unavailable if a pervasive loss of communication occurs. In that situation, system balance must be managed using a combination of generator inertia, droop control and generator plant operator intervention using dispatched and reserve generation. As a last resort, UFLS will automatically deploy if system frequency falls below critical setpoints.

4.1.2.4. Under Frequency Load Shedding (UFLS)

If more load exists than generation capacity, frequency will fall and continue to fall until a balance between power generated and power consumed is achieved. As a last line of defense, substations implement UFLS to trip up to 25% of system load off line, typically starting at

[3] When an operator changes the output of a generator, s/he raises or lowers the droop curve using an adjustment on the speed governor control panel. Doing so does not change the slope of the droop curve, which is a fixed parameter.

59.1Hz, continuing until 58.3Hz or until system balance is achieved- otherwise a blackout would occur. This feature does not require communications since it is activated by sensing the system frequency at each substation where the relays and breakers are located. There are no operator interventions or activations required for this to occur. Load is tripped off over a small band of frequency so that the smallest amount of load will be impacted in order to preserve the system. Unfortunately, this UFLS acts at the substation level and is unable to make a distinctions between critical and non-critical loads which are connected to the grid by a common distribution feeder breaker.

4.1.3. Transmission Capacity

Transmission capacity margins refer to the additional amount of power flow that a transmission line or group of lines can maintain. This flow is not directly controllable, since the power flows in accordance with system physics properties. Therefore, the means of adjusting power flow over a transmission line relies on the re-dispatch (adjustment of the output power) of generators serving the grid. When necessary to preserve or restore reliability, the transmission operator will initiate a Transmission Loading Relief (TLR) communication, which will be used as a formal means of signaling the need for line flow reduction, and which is implemented using a generator curtailment or redispatch. A redispatch will using a real-time view of system wide information, calculating new dispatch values for generators that supply the existing demand and act to relieve the congested transmission lines, all at the lowest cost feasible. The lack of communications, therefore puts transmission security at risk. As load patterns change through the day, transmission line loading levels change. The manner in which the system can be put at increased risk if a transmission line overload occurs are explained in the following four items. Although each of these items is highly affected by transmission line flows, they can also be affected by other factors.

4.1.3.1. Thermal Trips

If transmission capacity margins are significantly exceeded and TLR efforts have not been successfully remedied the overloads, line flows may reach up to 150% of their rated capacity. If this occurs, transmission line expansion (line sag) is assumed to be significant enough to potentially cause conductor electrical contact with vegetation, buildings, or other structures. To avoid this, Zone 3 backup relays will deploy. These impedance relays act like overcurrent relays, as they have their setpoints based on 1.5 pu current (at $V=0.85\angle 30^{o}$ pu). Since transmission lines are networked, tripping a line out of service does not reduce the connected load, therefore power seeks alternate paths and increases the power flow on other lines. During conditions when many transmission lines are already over their capacity, tripping an additional transmission line has the potential to effect a cascade. These conditions, however, are readily avoided by standard operating procedures such as the use of TLRs. The case where there is no communication systems operable, thus no means to effect a TLR or secure redispatch merits significant attention.

4.1.3.2. Transient Stability

Transient stability enables a synchronous generator to stay synchronized to the grid during and through a significant electrical transient. Typically, transient stability is maintained by having sufficient physical inertia in a synchronous machine, but sometimes this cannot be accomplished. In those cases, High Initial Response (HIR) excitation units help to mitigate the problem. In other cases, inertia is added to the grid in proximity to the generator using synchronous condensers, and in some cases control systems are used to dump power and or modify reactive power during the transient to maintain stability. As synchronous machines are being displaced by inverter based systems (wind, solar, storage) transient stability issues will re-emerge with the most cost effective solution likely relying on fast acting, semi-local controls, reliant upon communications.

4.1.3.3. Voltage Stability

Voltage stability is primarily managed by ensuring that line flows remain constrained below predetermined limits. These extreme conditions, however, are readily avoided by standard operating procedures which adheres to operation within secure operating criteria. In the case where there was no means of communications, thus no means of system observation or a secure redispatch, this situation merits attention.

4.1.3.4. Small Signal Stability

This problem is not normally managed using active control systems, although some new wide-area controllers have been developed and are emerging. Instead, these issues are typically managed by ensuring operating conditions remain within predetermined planning boundaries. In some instances, such as the Southern California Import Transmission Nomogram, these boundaries are affected by the type and location of the generation dispatch. In other cases, power flows across specific transmission paths are maintained within specific limits. Operationally, it is standard procedure to manage these situations. However in the case where there is no means of communications, thus no means of a secure redispatch, this situation merits attention.

4.1.4. Remedial Action Schemes

A Remedial Action Scheme (RAS) is a wide-area control system designed to monitor system conditions and automatically implement predetermined corrective actions if and when a specific grid contingency is detected [20-26]. The use of an automated control system allows remedial actions to be enacted quickly and precisely, but the actions are triggered only by a narrowly defined grid condition.

In nearly all cases, a RAS scheme is a less expensive means of increasing or preserving system reliability when compared to alternatives. There are over one hundred RAS schemes in operation within the Western Interconnection today, and many more in the Eastern Interconnection. Some of these system are contained within a single Balancing Authority’s domain, and some of them cross Balancing Authority boundaries, requiring coordination among different system operators and communication systems within the same interconnection.

4.1.4.1. RAS Scheme Example

A utility transmission owner wishes to increase the transfer capacity of a transmission line that is voltage stability limited. Although stable at higher flow rates, planning studies show that the occurrence of a critical fault during a high flow condition may cause voltage instability, resulting in the risk of system collapse. Although the critical fault is expected very infrequently, the risk is deemed unacceptable and the system operator is faced with three choices 1) a very costly physical transmission system upgrade, 2) the use of more expensive and less environmentally friendly generation that is nearer to the loads, preventing the needs for imported electricity using the line, or 3) the design and implementation of a RAS scheme. The RAS scheme is designed to immediately trip specific load offline if the fault occurs. Although the RAS scheme itself places a small amount of load at risk by design, it preserves overall system integrity by doing so. Since the automated control actions occur within a fraction of a second of the critical contingency, the RAS scheme ensures that the risk of system collapse is never allowed to materialize. Thus the transfer capacity of this path has been safely increased.

5. ANALYTIC EXAMPLES

The following two scenarios provides analytic examples related to a system-wide loss of communications. The scenarios exhibit different grid problems, but are related in that the first scenario compounds the effects of the second. Such compounding effects are difficult to predict and result in increased uncertainty with respect to harmful consequences. The following analyses provides insight into the potential (not expected) consequences to the grid for a widespread communications outage.

5.1. Example: Dispatch Drift

This scenario evaluates the effects of increasing load across the interconnection without any communication systems in place. This means that generators will be adjusting their output to control observed system frequency rather than following a dispatch schedule. The latter guarantees system security, but the former does not. The scenario provides insight regarding how lines and paths may become overloaded, over time, during a loss of communications. We use the term dispatch drift to indicate how an initially secure dispatch can drift into an unsecure dispatch when there is no communications.

In the WECC system there are about 4000 industrial generators, 75% of which are in service and dispatched at a given time, depending on the season, time of day, and maintenance schedules. A SCED algorithm selects which generators should be used to supply the system load, hour-by-hour for a 24 hour period. This algorithm ensures sufficient generation is dispatched to meet demand while ensuring that transmission and path limits are not violated.

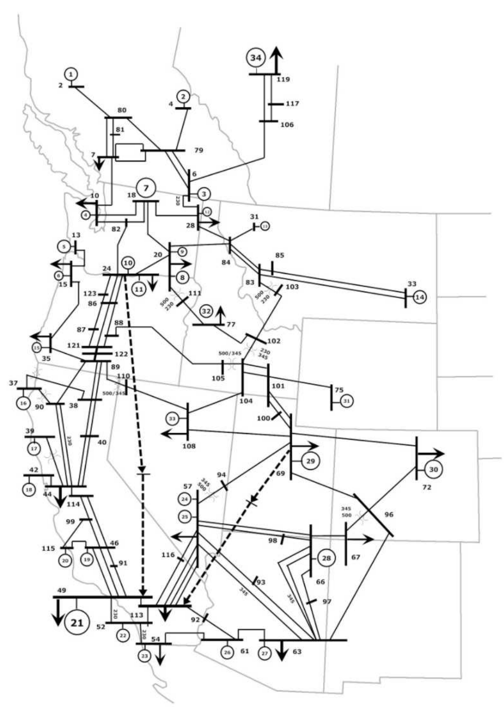


Figure 4 Reduced Model of the Western Interconnection (mini-WECC model)

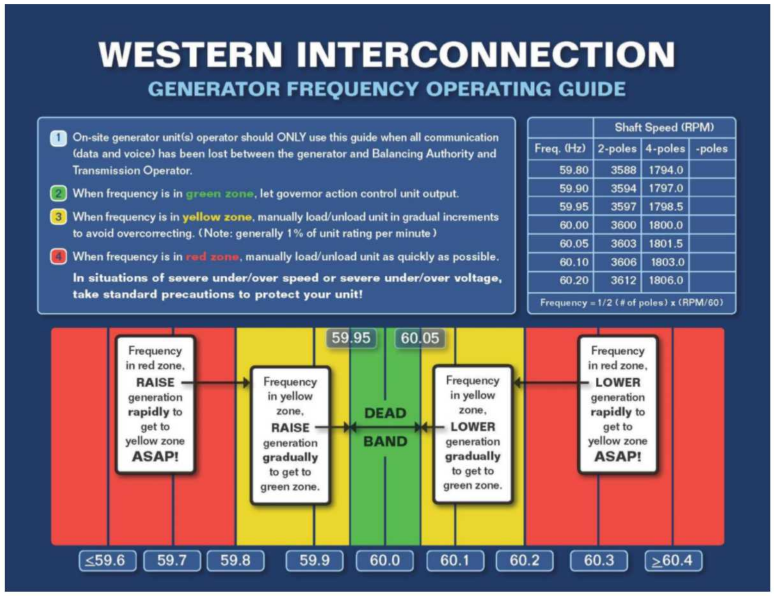


Figure 5 Western Interconnection Generator Frequency Operating Guide During a Loss of Complete Communications [27]

5.1.1. Scenario

The system was operating securely (per schedule) assumed to have lost communications at about 0400 hours, the lowest daily load as shown in Figure 6. As the day progresses, system load increases, and the generator plant operators are assumed to follow the guidelines of Figure 5, increasing plant output in response to frequency decline.

As the day progresses, system load increases and the generation schedule will dictate adjustments to power plant outputs, with some plants going off line and others coming on line. Due to the emergency, plants that are scheduled to decrease their output or go offline will instead follow [27] and remain online, adjusting output to maintain system frequency.

Generators that are scheduled to come online, will likely do so. Normally, when a new generator comes on line, its increase in power output is time synchronized with the decrease in power output of another. In this manner, generation and load remain balanced during changes to dispatch. However, for the loss of communications scenario, the generating plants are not expected to decrease their output per [27]. So generators that are scheduled to come online may attempt to increase their power output to their scheduled amount, but will find system frequency increasing as a result, and will back off their power to prevent causing an over frequency condition. These generators will likely stay online, providing capacity if a drop in system frequency indicates that it is needed, but increases in generator power outputs will not be according to schedule, thus they will not be proven to be secure dispatches.

At about 1700 hours Figure 1 indicates that the maximum system load will have been reached--nearly double its value from when communications was lost. Although a generation schedule exists, it was not possible to follow due to the emergency procedure of [27]. The likely result is that all generators scheduled to be connected at any time during the day will be connected. Their outputs however, will be random, not in accordance with the schedule. This occurs since some plant operators will be quick to respond to frequency deviations per Figure 5, resolving the system frequency problem before other plants have a chance to increase the plant output. Over time, plant outputs are not equally increased[4], nor will they be following a schedule that ensures system security constraints are met. This randomness in generator output results in uncertain line and path flows and is basis for the scenario.

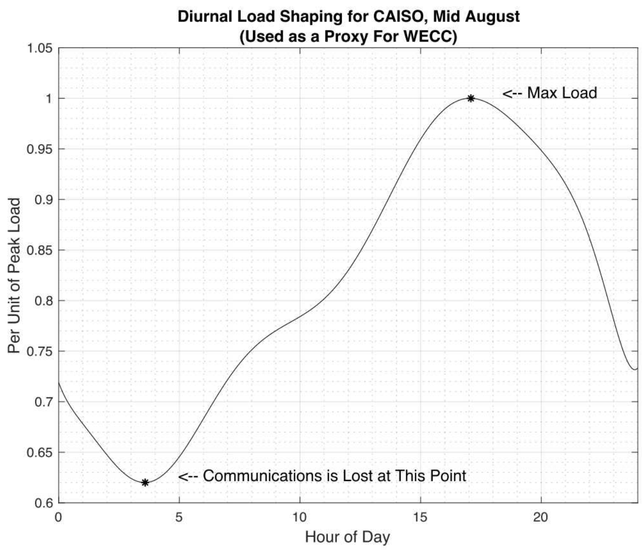


Figure 6 Diurnal Load Shape, Taken from CAISO [28]

It is difficult to make assumptions regarding how each generator's output might deviate from a day ahead schedule, because the procedure for maintaining system balance is not tightly synchronized or coordinated. Additional elements would also be a factor in those deviations, each of which would provide a random effect regarding the loading of transmission lines. These additional factors may include:

- The preparedness of unscheduled generation to provide power, including fuel supplies and manpower availability.
- Preparedness of scheduled generation to provide power. If a large-scale loss of communications affects the general population, there may be secondary effects that prevent operation. These may span from insufficient manpower at a generating station or substation (due to the emergency) and/or due to a lack of sufficient fuel supply (noting that other infrastructures such as natural gas and rail may also be affected by the loss of communications).

[4] If each generator in the power grid were to increase its output in a coordinated manner, proportional to the system load increase, this condition would still be insufficient to manage system security. As system load increases, it may be necessary to change the power flow patterns across transmission lines to prevent lower capacity transmission lines from overloading. This can only be done by adjusting injection points of power (changing the dispatch), or as an undesirable alternative, adjusting the transmission loading patterns by selectively dropping customer loads.

- Uncertainty associated with system abnormalities such as knowledge of voltage levels or line trips, but without knowledge of a specific location or cause.

- Reluctance to provide power resources if not previously scheduled due to concern with financial recovery.

- Significantly abnormal load conditions. Given the general population may also be experiencing a loss of communications, this may lead to abnormal load conditions significantly deviating from the forecast. These could be problematic if net system load increased, or unexpected load deviations across geographic areas.

- Unknown operating reserve margins, especially those utilizing droop control.

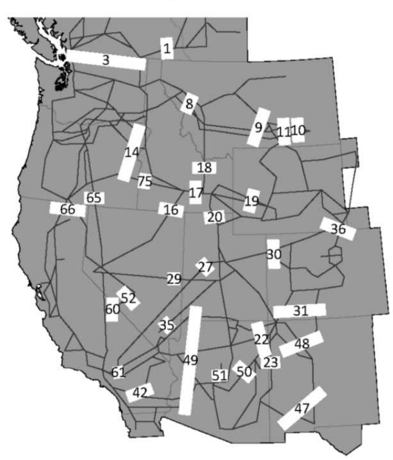
- The ability to operate the Pacific DC Intertie and the Intermountain DC lines without communications.

5.1.2. Simulation

Using the mini-WECC model, power flows were determined (in percent, normalized to the day's peak load condition) for select WECC paths. Generally, paths provide a means of observing system power flows at a higher level than individual transmission lines. Each path identifies power flow over a specific set of power lines.

Relating the mini-WECC model (Figure 4) to the WECC path catalog (abbreviated via Figure 7), we observe the major WECC paths. These paths are simulated on the mini-WECC model, and although the mini-WECC model omits some of the specific transmission lines used to define WECC paths, the existing lines are sufficient to provide a good indication of WECC path flows.

Major WECC Paths



2015 Path Flow[2]

Path	U75	Path	U75
Path 1	3%	Path 35	7%
Path 3	16%	Path 36	36%
Path 8	9%	Path 42	4%
Path 9	6%	Path 47	11%
Path 10	35%	Path 48	27%
Path 11	25%	Path 49	0%
Path 14	1%	Path 50	0%
Path 16	0%	Path 51	0%
Path 17	0%	Path 52	1%
Path 18	22%	Path 60	0%
Path 19	38%	Path 61	0%
Path 20	1%	Path 65	24%
Path 22	0%	Path 66	41%
Path 23	0%	Path 75	0%
Path 27	27%	Path 76	0%
Path 29	0%	Path 78	1%
Path 30	6%	Path 79	2%
Path 31	2%	Path 83	3%

Figure 7 Major Paths of the WECC [29].

The paths of greatest interest are those which represent the highest consistent flows. The UL75 metric shown in Figure 7 identify the percentage of time each path is loaded beyond 75%. For this assessment, we've selected paths 19, 36, 48, 49 and 66. Although some of these paths are typically less than 75% loaded, some of them have a large impact on overall system stability.

Others, such as Path 10 are essentially radial, largely unaffected by the system dispatch, except for the Colstrip units supplying them, thus they provide little interest to this analysis. Note that paths 27 and 65 are DC transmission lines, which are not subject to flow variations as a function of system dispatch. Instead, their flows are established by operators at their terminals.

A Monte Carlo analysis was conducted. One thousand random dispatches were evaluated, with each generator's power output uniformly distributed between ±15% of its nominal output power for the system peak load. For each dispatch, a load flow was conducted and the path flows were calculated and stored. Approximately 13% of these cases did not converge, although each had system generation properly balanced against total system load plus system losses. The non-convergence does not imply instability, although these cases were clearly stressed in terms of system voltage. A deeper inspection of the non-converging cases would likely reveal the need for system capacitor bank switching, which would be accomplished by staff located at major substations during the event. The authors verified that the percentage of non-converging cases decreased if the randomness of dispatches was narrowed, as was expected. This implies that the cases which did not converge are those that would have shown up on the histogram tails.

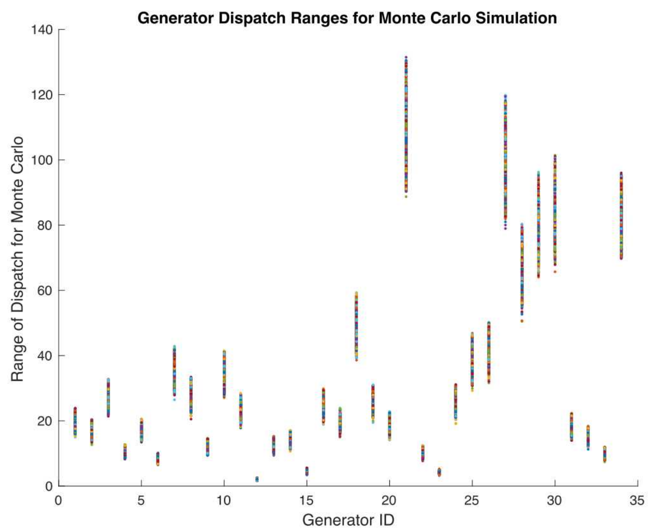


Figure 8 Generator Plant Dispatch Ranges Analyzed. Plant Output (per-unit on a 100 MVA Base), Corresponds to a Generation Dispatch of 110.6 GW, and Max Load of 106 GW.

Results[5] of the analysis are shown as histograms in Figure 9, providing insight into the possible transmission path loads during a severe loss of communications. The most interesting result is the effects of Path 66, the California-Oregon Intertie, COI. This particular path is critically relied upon during heavy loads, transferring excess hydro generation into California from the Pacific Northwest. There are several Remedial Action Schemes, which rely upon wide-area communication systems, and which permit the reliable transfer of power along this path. As can

[5] This analysis does not offer a conclusive result, but an indication of how lines and paths may become overloaded during a loss of communications. A more detailed analysis is necessary to draw conclusions, either specific or general. Such an analysis would include diurnal changes to the generator schedule, a complete system security analysis, use of properly vetted base cases, use of detailed planning software such as pslf, a complete evaluation of bi-directional line and path limits, and the proper selection of reactive resources for each condition.

be seen from Figure 9a, there are conditions in which Path 66 has more than doubled its flow. Sustaining an extreme condition like this is not possible, and would result in Zone 3 line trips (typically set to trip individual lines at 1.5pu) to interrupt flow, very likely before achieving the high flows shown. The consequences of unanticipated line trips could range from tens of thousands of MW of load dropped in California, to generation overspeed and subsequent trip in the Pacific Northwest, any of which could lead to a cascading outage.

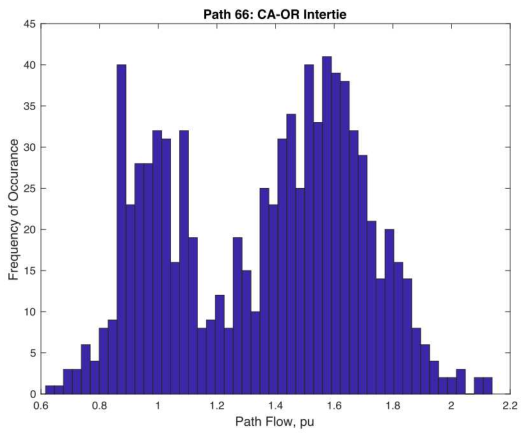


Figure 9a: Path 66

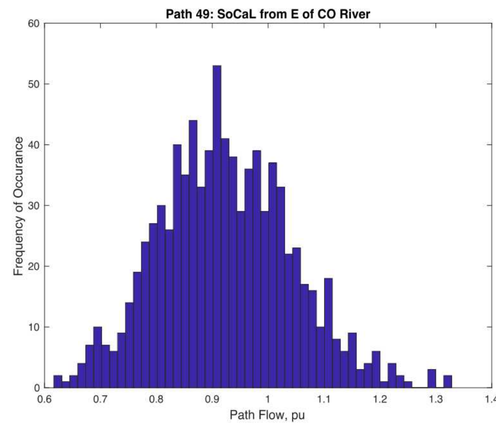


Figure 9b Path 49

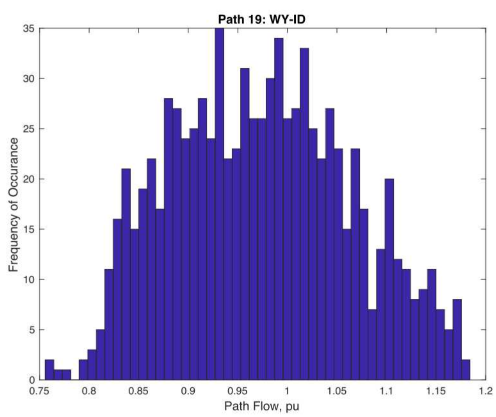


Figure 9c: Path 19

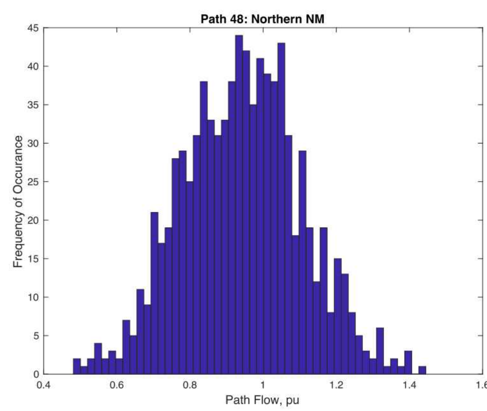


Figure 9d: Path 48

Figure 9 Histograms of Select Path Flows in the WECC When the System Dispatch is Randomly (Uniformly) Adjusted Within ± 15% From its Dispatch During Peak Load Conditions (106 GW). Simulation Was Conducted Using a Reduced Order Model. Total System Load and Generation Remain Constant for Each Dispatch.

This example has served to explain one aspect of our dependency on communications systems for grid operations. The example assumed very extreme conditions regarding a complete and comprehensive loss of communication. Although these results provide a bounding of what could happen, they do not reflect what is expected to happen, since the pervasive loss of communications is an extremely unlikely scenario. But the results do provide some insights for even a more limited loss of communications. As seen in Figure 9a, a complete loss of communications results in path flows far exceeding system capability, implying that local protections relays would likely trip, such as Zone 3 impedance relays (which emulate overcurrent protection) well before the condition shown was reached. Once a transmission line trips due to overloading, other transmission lines in the network are forced to carry the power using a different path to the load, thus increasing their load, placing them at risk of tripping and a potential cascading scenario.

5.2. Example: Loss of RAS for California-Oregon Intertie Imports

WECC classifies RAS schemes according to the consequences of their failure to operate, with "Wide Area Protection Scheme (WAPS)" defined as a RAS intended to mitigate reliability criteria violations outside the owner's operating area [30]. WAPS schemes inherently rely upon communications for both sensor data acquisition and actuator commands. Figure 10 shows an overview of a network architecture for a typical WAPS RAS. Communications paths from substations recording measurements, to redundant central controllers at geographically diverse sites, and communications paths back to the substations initiating a control action are evident. The measurement and/or action substations can span multiple operating entities and substantial geographic distance. Initial and periodic reviews of all WAPS RAS are conducted by the WECC RAS Reliability Subcommittee where communications redundancy, availability and security are all vetted. The "Telecommunications" section of the RASRS document "Procedure and Information Required for RAS Assessment" describes information required by WECC reviewers [30].

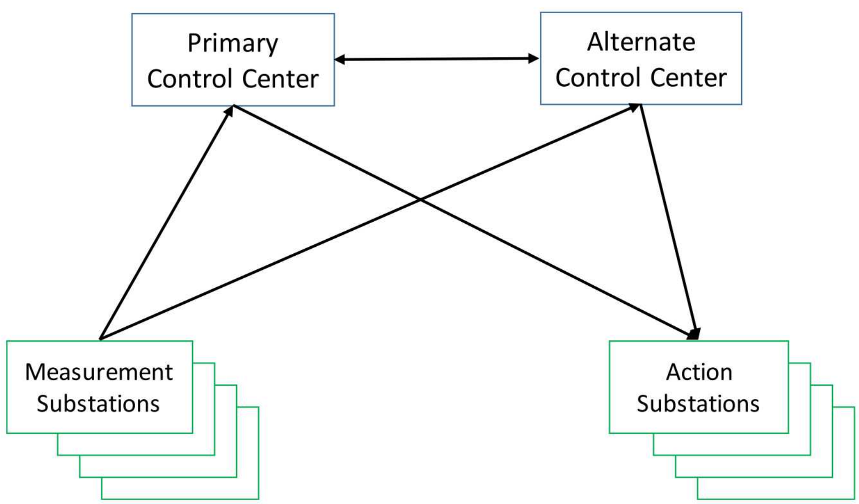


Figure 10. Typical network data flow for WAPS RAS.

Where the previous example illustrated gradual "drift" effects associated with a loss of communications, and therefore loss of SCED algorithms, this example focusses on how a loss of communications may impact RAS. Figure 2, noted in the previous example, shows the frequency of Reportable Grid Disturbances over a period of time. A "Reportable Grid Disturbance" is defined in NERC's Glossary of Terms [20]. Reportable disturbances are events that reach a threshold of severity such that they merit further investigation by reliability organizations. RAS misoperation is reportable, as noted in Figure 2, because of the importance of RAS schemes in maintaining overall reliability. Whereas unintended RAS operation constitutes a greater number of reportable incidents, failure of a RAS to operate when needed can have a much more significant reliability impact. For example, a RAS action may trip a generator in the event of a line outage. The underlying purpose of the RAS may be to allow for power transfer limits on the line in excess of what would be possible without the RAS. In this case, failure of the RAS to operate may cause catastrophic damage to the generating equipment. Such may be the case in a loss of communication scenario.

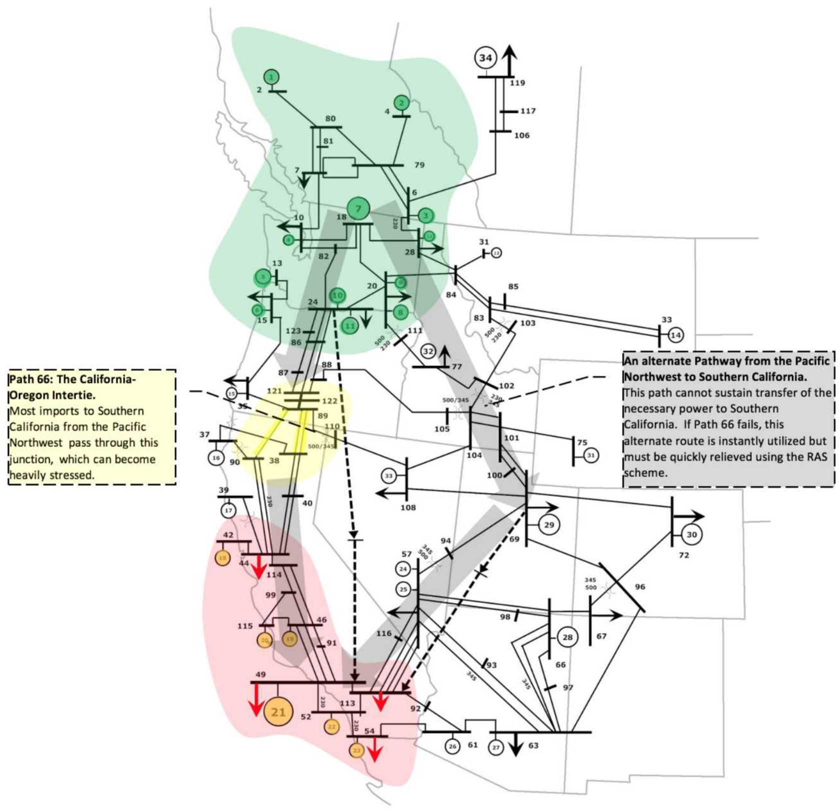


Figure 11 California-Oregon Intertie (Path 66) Northwest Generator Tripping RAS

The California-Oregon Intertie (COI, also called Path 66) northwest generator tripping RAS is a wide area protection scheme. The COI is defined as a set of transmission lines as measured at an imaginary “cut plane” at the California-Oregon border, defined in Figure 7 and Figure 11 as Path 66. COI flow, in units of Mega Watts (MW), is an important operating parameter for the Western Interconnection. A 2008 Bonneville Power Administration (BPA) planning document states, “The main purpose of [the northwest generator tripping] RAS for contingencies is to maintain the Operating Transfer Capability (OTC) of the transmission system” [31].

5.2.1. Scenario

To illustrate the effect of loss of communication on this RAS scheme, a simulation demonstrating the impact of a loss of generation contingency with/without RAS was conducted. The base case begins with a detailed model of the western interconnection incorporating over

3000 generators and 130 GW of load. A dispatch was developed for the base case to reflect realistic conditions in which the COI northwest generator tripping RAS would be armed, and a loss of generation contingency was initiated in the south region of the simulated power system. Figure 12 shows flows on the COI with an example SOL/IROL at 4300 MW for this condition.

5.2.2. Simulation

General Electric's Positive Sequence Load Flow (PSLF®) simulation environment was used to simulate the scenarios *"with RAS action"* and "no RAS". The simulation begins with a quiescent period of 2 seconds to ensure that the more than 200,000 state variables were properly initialized, then at t = 2 seconds 1,400 MW of generation in central Arizona were instantaneously tripped to simulate a loss of generation event in the southern part of the western system. When the generator tripping RAS is armed, i.e. in the "with RAS action" case, 1,000 MW of generation on the Columbia River are tripped in response to the Arizona event, thus preventing excessive flows on the COI. Figure 12 shows flows on the COI with a hypothetical SOL/IROL at 4300 MW for this condition.

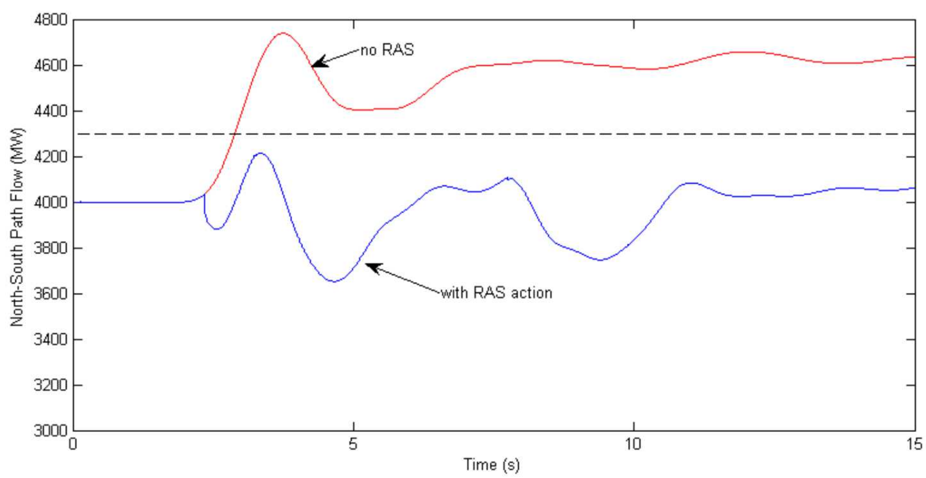


Figure 12. Path 66 (COI) Flow for Hypothetical Dispatch Showing Impact of RAS.

System Operating Limits (SOLs) and Interconnection Reliability Operating Limits (IROLs) are metrics developed through extensive system planning studies and used to provide objective guidelines for systems operations personnel [32]. Operations personnel can, with a high degree of confidence, be assured that a given generation dispatch does not pose a serious reliability risk by adhering to the SOLs and IROLs unless the SOL or IROL assumptions are violated.

In normal operation, loss of any single channel of communication would not cause the RAS scheme to fail to operate because RAS schemes are required by the reliability governing bodies to be fully redundant, including redundancy of communications channels. However, a total loss of communication on redundant channels would render a RAS scheme inoperable. With knowledge that the RAS scheme was inoperable, and with the benefit of other unrelated operations communications unaffected, operations personnel across the region would normally move the system to a safer dispatch. In the case of this example, operators would move the system to a dispatch that would result in COI flows 300-400 MW lower than originally scheduled. Specifically, to reduce flows on a transmission path, i.e. a “safer” dispatch, operations personnel across the interconnection would work together (requiring some degree of communications) to bring idle generation resources located near load centers online and delivering energy, and to simultaneously reduce the output of generators located in geographically remote locations. In the western US, for example, reducing flows on the COI would involve increasing generation in southern California while simultaneously reducing generation from the powerplants in the pacific northwest.

If, on the other hand, the loss of RAS communication channels were associated with a more widespread loss of multiple communications channels, then operations personnel would not only deduce that RAS was inoperable, but operations would also have no means to coordinate shifting the system to a safer dispatch. System operators would find themselves in the same situation studied previously in this paper, i.e. the “schedule drift” case study.

6. MANAGING THE RISK ASSOCIATED WITH A LOSS OF COMMUNICATIONS

Utility operations personnel make use of various communications channels in the normal course of business. These systems include wide area networks, local area networks, point-to-point radios, satellite radios, telephones, and numerous additional legacy systems. To frame the discussion of risk management, it is important to establish a general vocabulary related to common uses of each of the predominant channels.

- Wide area networks are commonly used for communications between the system operations center (SOC) and the substation, and for communications from the SOC to the powerplant operations personnel. SCADA infrastructure is predominantly based upon WAN technology, as is the Inter-Control Center Protocol (ICCP) which is used to deliver operational information between the control centers of the various actors in an interconnected grid.
- Local area networks carry traffic, measurements and control commands, within the substation, within the powerplant, and within the SOC.
- Point-to-point radios are still used in many legacy systems for SCADA traffic, however this use is declining with the increasing availability of fiber to the substation and powerplant. Radios are still widely used within the powerplant and within the substation for voice communication.
- Satellite radios are used for voice communication. Most large utilities incorporate the use of satellite radios in their emergency restoration plans and for voice communication with extremely remote substations.
- Plain old telephone service (POTS) and wireless telephony are widely used for voice communication between the SOC and powerplant operations, and between the SOC and substation operations personnel tasked with performing switching actions.

A risk assessment positing a complete loss of communications assumes that all of the aforementioned communications channels are disabled. The likelihood of this scenario is very small, but nevertheless provides a baseline for discussion.

The grid is generally robust around any stable operating point defined by a valid dispatch. Should a complete loss of communications occur while the grid is already at a quiescent operating point there is no reason to assume that the loss of communication would, in and of itself, change the existing stability of the grid. However, the loss of RAS, and situational awareness does place the grid at a higher risk of instability should a contingency occur. As illustrated in the "dispatch drift" example, the most likely near-term outcome would be a gradual drift to an unknown, and less reliable, dispatch. The "dispatch drift" example did not require a contingency to realize this risk. The longer the duration of the communication outage, the greater this risk becomes.

The scenario involving a total loss of all communications is presumed, for the purpose of risk assessment, to have little impact on "local" controllers, i.e. controllers using only local sensing and measurement values to make control decisions[6]. A ubiquitous example is the "protective relay", which is a controller intended to protect a particular piece of equipment installed as part of the BES. A relay, for example, might sense the magnitude of the electric current flowing through a transformer. If current were to exceed a pre-configured setpoint, then the relay would act to isolate the affected transformer. Another important example of a local controller is a "governor" used to control the amount of mechanical energy generated by a prime mover (e.g turbine) and which subsequently drives an electric generator. Governors, when acting in "droop" configuration, act to increase or decrease energy from the BES based upon variations in grid frequency. When system frequency declines, speed governors cause the prime mover to inject additional energy into the system, which in turn halts the frequency decline.

6.1. Suggestions for a more robust response to loss of communications:

The following suggestions form the basis for a broader set of practices and procedures that may provide for a more robust response to a partial or total loss of communication.

6.1.1. Establish system-wide planning modification sto mitigate a complte or partial loss of communications

- Develop emergency operating procedures which coordinate interconnection-wide operation. As a minimum, such procedures must include a means to ensure system balance, load management and tripping priorities, maintain operation within transfer limits, secure dispatching and redispatching (e.g. TLRs), operation without RAS, and the management of local protection such as transfer trip schemes.
- Develop a procedure to coordinate the system-wide transition from normal operation to operation without communications.
- Develop an out-of-band grid-wide system that identifies the pervasiveness of any communication loss for each Balancing Authority, generation station, major substation, and control center. This system should be continually polling to determine the extent of the loss of communications in terms of geography, type, and quality of service. This is necessary since procedures for a loss of communications will likely depend on its pervasiveness and

[6] Note that local controllers may be affected by malicious attacks and cybersecurity breaches, but those events are outside the scope of the loss of communication scenario.

entities will not have this knowledge. This system can be dually employed to identify cyber security abnormalities.

- Establish emergency dispatch schedules to be used if communications are lost. The "blind" dispatch could be designed such that no RAS schemes are necessary for secure operation and transmission stability margins are maximized for the current and expected operation. A interconnection-wide process would continuously publish these schedules, for use if a loss of communication occurs.
- Develop an advanced under frequency load shedding (UFLS) system. Organize UFLS frequency trip settings formally within the interconnection (not organized within each Balancing Authority). A robust variant of this would be to begin a DOE program to encourage residential, commercial, and industrial electricity consumers to embed stochastic micro-UFLS into prioritized non-critical loads. These can be used for UFLS (without communications) and demand response for normal and emergency procedures (with communications).
- Consider a new type of generation reserve which ensures that sufficient locational capacity exists in the event of a pervasive loss of communications.

6.1.2. Establish system-wide <u>operating</u> procedures in a case of a complete or partial loss of communications

- Ensure the existence of Generation reserve which provide sufficient locational capacity in the event of a loss of communications.
- If emergency dispatch schedules exist, implement them immediately
- All connected generators capable of speed governing, go to droop control mode. These should include steam units for combined cycles, and capable renewable energy resources
- All offline generators capable of synchronizing, should synchronize to the grid. Set power to as near zero MW as possible. Set governors to droop mode.
- Consider taking variable resources offline to minimize frequency fluctuations if sufficient replacement generation capacity exists. This should be determined in advance.
- Man all major substations. Replace all lines back into service that tripped on Zone 3. Consider disabling Zone 3 relay trip settings. Consider restoring lines to service that are suspected of having tripped on impedance, due to contact with vegetation.
- SOCs to establish telephone and/or radio communications with powerplants as first priority and major manned substations as a second priority.
- Establish a means to conduct a security constrained dispatch without the use of SCADA, State Estimators or EMS.

7. CONCLUSIONS

The results of this analysis show that:

- The use of communications in power systems operations reduces the cost of operations
- The use of communications in power systems operations increases system reliability
- A reduction in power delivery is required to preserve system reliability when communication is lost.
- A prudent and economical approach to mitigate the impacts of a complete loss of communications is possible. There are numerous solution variants that can be employed, but generally, they include the elements identified in 6.1.
- There are ways to provide secure operation of the grid without any communications, but they are unfeasible. Such operation implies a significant reduction in power transfer capacity, increase in operating cost, and a significant increase in infrastructure buildout.
- A decrease in power delivery is required to preserve system reliability when communication is lost.
- We have not analyzed the effects of a partial loss of communications, but doing so would require
    - A significant model development endeavor which combines power system models with communications models.
    - Identifying and collection communication system models which interact with the grid, major control systems, and RAS Systems
- There is a need to develop strategies, procedures and apply technologies which can make a loss of communications to our power grid less costly financially and socially. These strategies should be incorporated into ongoing infrastructure planning and operating processes. This approach should be used as a reinforcement to enhance cyber security, not as an alternative.

7.1. Further Study

There are several research areas that would provide significant benefit to the topic area of managing system operation with a limited to no communications. They include:

7.1.1. The development of planning and operating procedures

These procedures are needed to coordinate and manage system operation without communication systems in place. This work would focus on establishing systems and methods to allow secure operation in terms of frequency stability, line and path loading, voltage control, redispatch and changing dispatch schedules, real-time balancing, and voltage, transient and small signal stability management. The work would also recognize that the most probable cases will include only a partial loss of communication, and procedures should allow for different scenarios in this respect. Rules which establish optimization objectives, decision variables and constraints for emergency dispatch should be established. These would be used to continuously calculate emergency dispatch schedules during normal operation, for use in the event of a pervasive loss of communication.

7.1.2. The development of resilience communication systems

Mixed and multiple modes of communication, which are anticipated to have different failure modes, will increase the reliability of system operation. For example, if one mode of communication is vulnerable to an electromagnetic pulse, consider a redundant mode of communications that is not.

7.1.3. The use of advanced UFLS and demand response

Advanced UFLS has a significant potential to help the grid maintain stability. Although allowable, grid operation procedures prevent the use of load shedding except in extreme circumstances as it is counter to the operators intent of serving load. New systems are needed That can discriminate and prioritize load shedding based on its criticality. Such a system will improve the usefulness of the grid's UFLS system with minimal consequences, and will provide a significant means for the survivability of the grid during from multiple contingencies to near-blackout conditions. The use of this system can also be used as an advanced demand management system, allowing operators to employ load shedding for critical but non-emergency situations, discriminating between loads with low high criticality.

7.1.4. The integration of communications into system planning studies

Interdependent modeling which links system electrical performance to communications system performance is only used in academic environments at this time. Such analysis and assessment capabilities are critical to the reliability of the current grid, and should be further developed for use by grid planning and operations engineers. Although standards exist to ensure that communications systems are reliable, these requirements do not require the assurance of grid performance while modeling communication contingencies. NERC communication standards do exist which aid the overall system reliability such as NERC COM-001 and COM-002, communication systems, but are not integrally modeled with power assets to determine system performance, but by exception. Overall system planning studies should be considered comprehensively with both communications and power systems infrastructure. Doing such, especially at the interconnection scale, would be a major undertaking.

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