

NERC

NORTH AMERICAN ELECTRIC
RELIABILITY CORPORATION

Power Plant and Transmission System Protection Coordination

Volts Per Hertz (24), Undervoltage (27), Overvoltage (59),
and Under/Overfrequency (81) Protection

System Protection and Control Subcommittee

Protection Coordination Workshop

Phoenix, AZ

March 17-18, 2010

to ensure
the reliability of the
bulk power system

- Objectives
- Description of Protection Functions
- Underfrequency Load Shedding Scheme Fundamentals
- Undervoltage Load Shedding Scheme Fundamentals
- Discuss and Describe System Events that Could Create Conditions that Would Cause Operation of These Functions
- Seven Step Process for Functions 24, 27, 59 and 81
 - Function 24 – Volts Per Hertz Generator and Transformer Protection
 - Function 27 – Undervoltage for Generator, Plant Auxiliaries System, High-Side Point of Common Coupling Protection
 - Function 59 – Overvoltage Generator Protection
 - Function 81 – Under/Overfrequency Turbine Generator Protection

- What is Important to Coordination
 - Settings that Protect the Generator
 - Time Coordination with UFLS and UVLS
 - Islanding Conditions
 - Sufficient Studies
- Questions and Answers

- Increase knowledge of recommended generator and power plant protection for Volts per Hertz, undervoltage, overvoltage, and under/overfrequency.
- Additionally increase knowledge of recommended high-side undervoltage and plant auxiliary system undervoltage protections.
- Facilitate improved coordination between power plant and transmission system protection for these specific protection functions.

The Need for Overexcitation or V/Hz Protection – Function 24

- *“Overexcitation of a generator or any transformers connected to the generator terminals will occur whenever the ratio of the voltage to frequency (V/Hz) applied to the terminals of the equipment exceeds 105% (generator base) for a generator; and 105% (transformer base) at full load, 0.8 pf or 110% at no load at the secondary terminals for a transformer.*
- *Overexcitation causes saturation of the magnetic core of the generator or connected transformers, and stray flux may be induced in non-laminated components that are not designed to carry flux.*
- *Excessive flux may also cause excessive eddy currents in the generator laminations that result in excessive voltages between laminations. This may cause severe overheating in the generator or transformer and eventual breakdown in insulation.*
- *The field current in the generator could also be excessive.”*

The Need for Generator Unit Undervoltage Protection – Function 27

- *“For the generating unit, undervoltage protection that trips the unit is rarely applied to generators.*
- *It is frequently used as an interlock element for other protection function or schemes, such as loss-of-field relay (40), distance relay (21), inadvertent energizing relay (50/27), out-of-step relay (78), etc, where the abnormality to be detected leads directly or indirectly to an undervoltage condition.*
- *Generators are usually designed to operate continuously at a minimum voltage of 95% of its rated voltage, while delivering rated power at rated frequency.*
- *Operating a generator with terminal voltage lower than 95% of its rated voltage may result in undesirable effects such as reduction in stability limit, import of excessive reactive power from the grid to which it is connected, and malfunctioning of voltage sensitive devices and equipment.*
- *This effect however is a function of time. **If applied, the undervoltage protection is generally connected to alarm and not trip the unit**, so that the operator can take appropriate action to remedy the undervoltage condition (if possible).”*

The Need for Generating Plant Auxiliary Power Systems Undervoltage Protection – Function 27

- This function is used to protect auxiliary system equipment from severe undervoltage conditions that would have serious consequences, such as auxiliary motors stalling or voltage collapse for the generating unit(s).
- When the voltage level of the auxiliary system reaches the undervoltage set-point, this protection may initiate any one or a combination of the following actions:
 - Alarming.
 - Automatic transfer to alternative power supply.
 - Starting of emergency generator(s).
 - Tripping the generating unit, if necessary.
- This function also protects the integrity of the power supply to safety related buses applied to support the reactor of nuclear power plants. In these applications two undervoltage thresholds are utilized:
 - The first undervoltage (UV) level (function 27SB1) initiates auxiliary load transfers to an alternative power supply.
 - The second UV level (function 27SB2) initiates a unit trip. (See section 3.3.4 for further details)

The Need for Undervoltage Relays Applied at the Point of Common Coupling – Function 27

- The function of these relays is to alarm that an undervoltage on the transmission system is occurring and that the operator should be on a heightened state of awareness matching this alarm with others that may be occurring within the plant.

The Need for Generator Unit Overvoltage Protection – Function 59

- *“Generator overvoltage may occur without necessarily exceeding the V/Hz limits of the machine. In general, this is a problem associated with hydro generators, where upon load rejection, the overspeed may exceed 200% of normal.”*
- *“Protection for generator overvoltage is provided with a frequency-compensated (or frequency-insensitive) overvoltage relay. The relay should have both an instantaneous unit and a time-delay unit with an inverse time characteristic. The instantaneous unit is generally set to pick up at 130% to 150% voltage while the inverse time unit is set to pick up at about 110% of normal voltage. Two definite time-delay relays can also be applied.”*

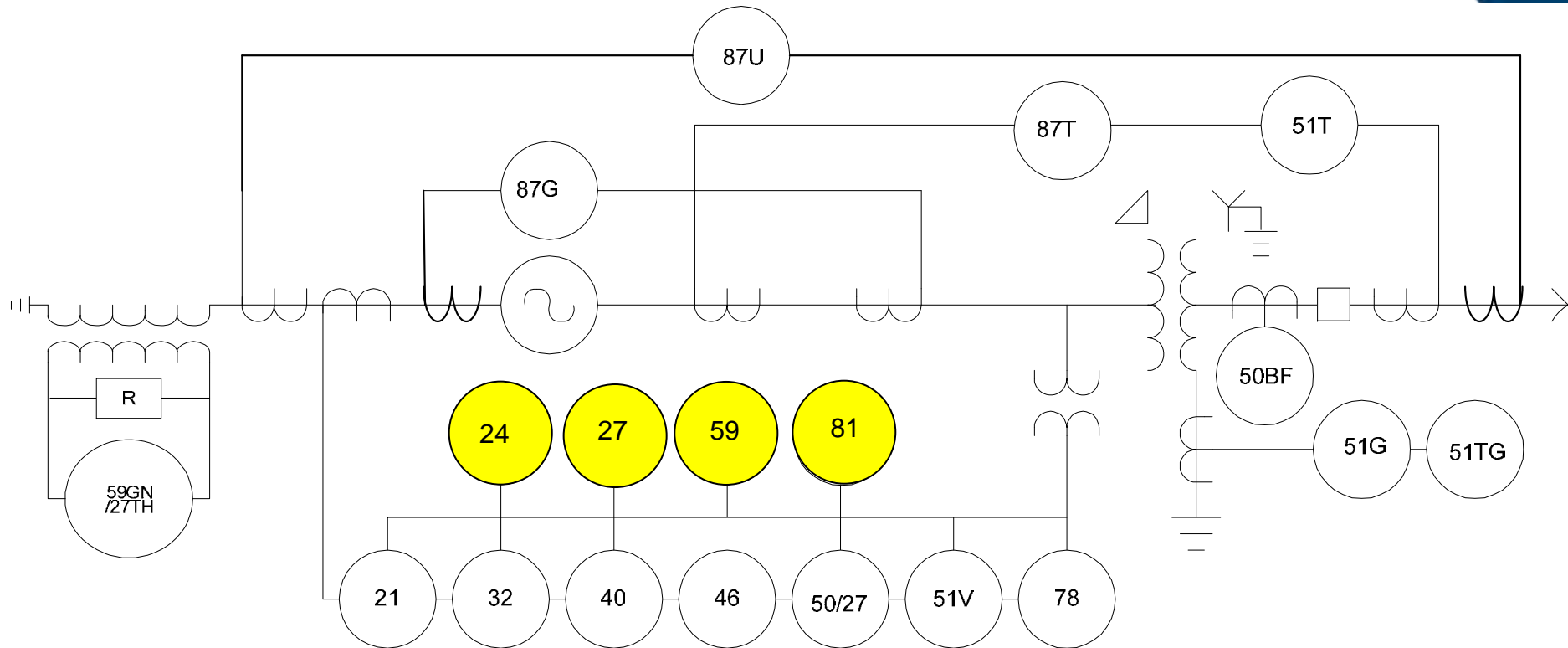
IEEE C37.102-2006 – Guide for AC Generator Protection, Section 4.5.6

- Overvoltage protection is necessary for preventing an insulation break-down from a sustained overvoltage. The generator insulation system is capable of operating at 105 percent overvoltage continuously.
- Sustained overvoltage above 105 percent normally should not occur for a generator with a healthy voltage regulator, but may be caused by the following contingencies: (1) defective automatic voltage regulator (AVR) operation, (2) manual operation w/o AVR, and (3) sudden load loss.

The Need for Generator Unit Under and Overfrequency Protection – Function 81

- *“Mismatch between load and generation may be caused by a variety of system disturbances and/or operating conditions. However, of primary concern is the system disturbance caused by a major loss of generation that produces system separation and severe overloading on the remaining system generators.”*
- *“Under this condition, the system frequency will decay and the generators may be subjected to prolonged operation at reduced frequency” and “there exists the possibility of operation at reduced frequency for sufficient time to damage steam or gas turbine generators.”*
- *“Full- or partial-load rejection may be caused by clearing of system faults or by over-shedding of load during a major system disturbance. Load rejection will cause the generator to overspeed and operate at some frequency above normal.”*
- *“In general, underfrequency operation of a turbine generator is more critical than overfrequency operation since the operator does not have the option of control action.”*

Relay One-Line Showing All Generator Protection and Identifying Functions 24, 27, 59, and 81



System Events that Could Cause Undesired Operation of These Protection Functions

- Fault Conditions
- Loss of Critical Lines
- Loss of Critical Units
- Events such as August 14, 2003 Blackout
- System Islanding Conditions

Seven Step Process for Functions 24, 27, 59, and 81

- This is the process used throughout the Coordination document to address each protective function as appropriate.
- The following slides will take a step-by-step approach through the Functions 24, 27, 59, and 81.
- The next two slides provide the general data and information requirements from the Generator, Transmission, and Distribution Owners.

General Data Exchange Requirements – Generator Owner Data and Information

- The following general information must be exchanged in addition to relay settings to facilitate coordination, where applicable:
 - Relay scheme descriptions
 - Generator off nominal frequency operating limits
 - CT and VT/CCVT configurations
 - Main transformer connection configuration
 - Main transformer tap position(s) and impedance (positive and zero sequence) and neutral grounding impedances
 - High voltage transmission line impedances (positive and zero sequence) and mutual coupled impedances (zero sequence)
 - Generator impedances (saturated and unsaturated reactances that include direct and quadrature axis, negative and zero sequence impedances and their associated time constants)
 - Documentation showing the function of all protective elements listed above

- The following general information must be exchanged in addition to relay settings to facilitate coordination, where applicable:
 - Relay scheme descriptions
 - Regional Reliability Organization's off-nominal frequency plan
 - CT and VT/CCVT configurations
 - Any transformer connection configuration with transformer tap position(s) and impedance (positive and zero sequence) and neutral grounding impedances
 - High voltage transmission line impedances (positive and zero sequence) and mutual coupled impedances (zero sequence)
 - Documentation showing the function of all protective elements
 - Results of fault study or short circuit model
 - Results of stability study
 - Communication-aided schemes

Document Format – Seven Sub-Sections for Each Protection Function

- Purpose
- Coordination of Generator and Transmission System
 - Faults
 - Loadability
 - Other Conditions, Where Applicable
- Considerations and Issues
- Setting Validation for the Coordination
 - Test Procedure for Validation
 - Setting Considerations
- Examples
 - Proper Coordination
 - Improper Coordination
- Summary of Detailed Data Required for Coordination of the Protection Function
- Table of Data and Information that Must be Exchanged

Volts Per Hertz – Function 24

■ Purpose

- Prevent damage to generators and connected transformers that may occur when the excitation (V/Hz) applied exceeds the equipment capability.
 - Generator: 105% on the generator base
 - Transformer: 105% on the transformer base at full load, 0.8 pf or 110% at no load at the secondary terminals.
- Overexcitation may result in:
 - Saturation of the magnetic core.
 - Stray flux induced in non-laminated components that are not designed to carry flux.
 - Excessive eddy currents in the generator laminations resulting in excessive voltages between laminations, severe overheating, and eventual breakdown in insulation.
 - Excessive field current in the generator.

Coordination of Generator and Transmission System – Function 24

- **Faults**
 - There are no coordination issues for system faults for this function.

- **Loadability**
 - There are no coordination issues related to loadability for this function.

- Other Operating Conditions
 - Coordination between generating plant overexcitation protection and the transmission system is necessary for off-nominal frequency events.
 - Coordination is necessary to ensure that the UFLS program can operate to restore a balance between generation and load to recover and stabilize frequency at a sustainable operating condition.
 - Without coordination, generation may trip by operation of overexcitation protection to exacerbate the unbalance between load and generation.
 - This may result in tripping of more load than necessary, or in the worst case, system collapse if the resulting imbalance exceeds the design basis of the UFLS program.

- Overexcitation withstand limit characteristics of generators and transformers should be requested from the equipment manufacturer whenever possible.
- Abnormal system voltage during UFLS events is not uncommon, particularly when such events occur during heavy load conditions when reactive sources are dispatched to meet reactive power demand.
- Following UFLS operation high voltage may occur due to:
 - Reduced demand.
 - Reduced reactive losses.
- Under such conditions restoring a balance between load and generation to recover system frequency may be insufficient to control excitation to acceptable levels.
- Additional coordination may be required to remove reactive compensation (e.g., shunt capacitor banks) or to connect shunt reactors.

- The following data and information exchange steps should be taken by the Generator Owner and Planning Coordinator. Note that in cases where the generator step-up transformer is owned by the Transmission Owner, the Transmission Owner would have the same responsibility as the Generator Owner.
- Step 1 — Generator Owner to provide Settings, Time Delays, and Protection Characteristics to the Planning Coordinator for both the Generator and Generator Step Up Transformer.
- Step 2 — The Generator Owner and Planning Coordinator confirm that the Protection settings allow the UFLS actions first and coordinate.
- Step 3 — The Planning Coordinator performs studies to verify coordination.

Setting Procedure – Function 24

- Plot the V/Hz withstand capability curves of the GSU transformer and generator similar to the ones shown in figure 3.2.3.
- Plot the overexcitation (V/Hz) protection characteristic on the same graph.
- Check proper coordination between the relay characteristic curves time and timing settings of excitation control limiter(s).
 - The limiters in the excitation control system limiter should act first.
 - The settings for the protective relay must be set so that the relay will only operate if the excitation is greater than the limiter setting, but before the capability of the protected equipment is reached.
 - Short time excursions beyond the overexcitation limit should not cause the protection systems to trip the generator because the overexcitation limiter time delay setting is used to prevent equipment damage which also prevents tripping during these conditions.
 - Protection system tripping times are generally long enough so that coordination with exciter response is not a problem.

Setting Procedure – Function 24

- The UFLS program and the overexcitation settings should be coordinated such that UFLS is given a chance to act before overexcitation protection trips the unit.
- Coordination between the overexcitation protection and the UFLS program design can be validated only through a stability study.
 - The study should either monitor excitation at all buses at which overexcitation protection is utilized for comparison against tripping characteristics, or the overexcitation protection should be modeled in the study.
 - With either approach a determination that coordination exists should be based on observing that no generators would trip by overexcitation protection.
 - Stability studies should have sufficient margin and a sufficient number of scenarios should be simulated to provide confidence in the determination.
- In a limited number of cases, conditions may exist that coordination cannot be achieved for every generating unit.
 - In such cases coordination may be deemed acceptable if tripping does not cascade and is limited to a small amount of generation (as a percentage of the load in the affected portion of the system).
 - Protection models should be added to system models for any units for which coordination cannot be obtained.

Example - Proper Coordination

– Function 24

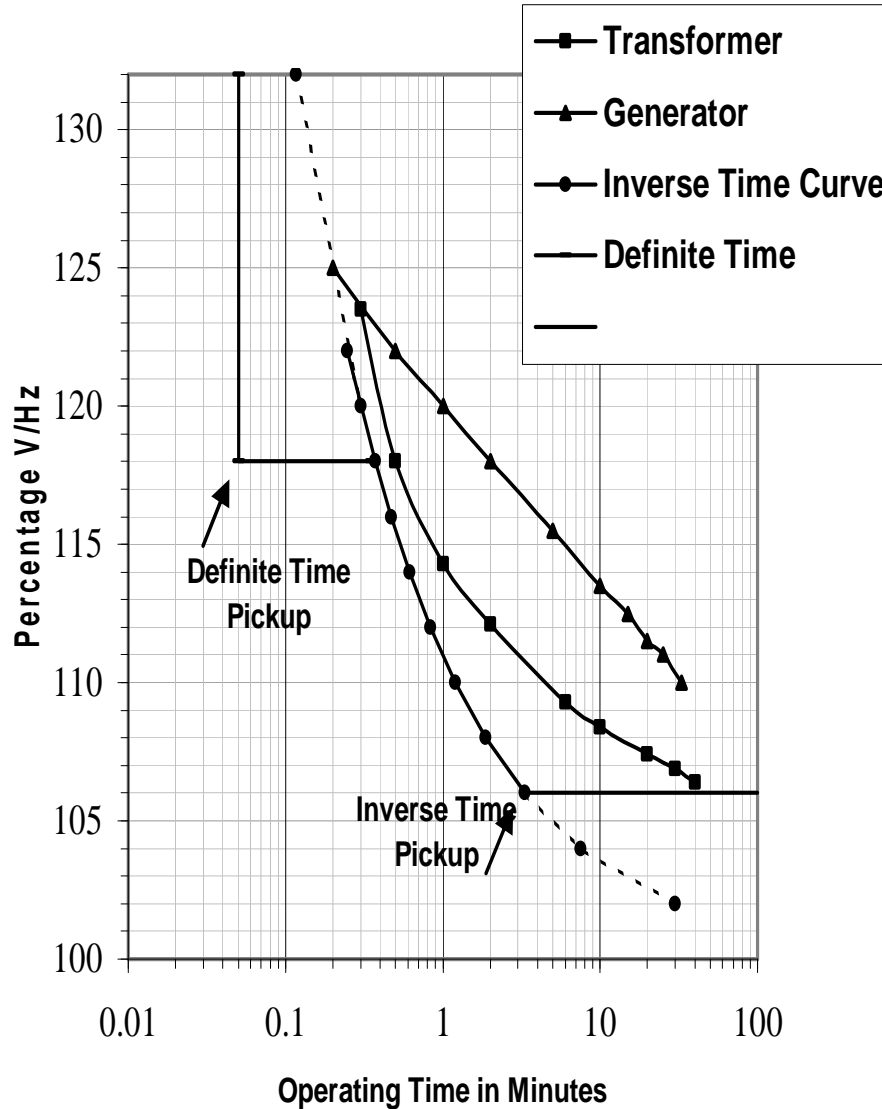
- Figure 3.2.3 shows a setting example for overexcitation protection using definite time and inverse time overexcitation (V/Hz) relays.
- Generator and transformer manufacturers should be consulted for the information on overexcitation withstand capability. An example withstand curve shown in Figure 3.2.2 is given in the Table 3.2.1.

Table 3.2.1 – Example V/Hz Withstand Capability of GSU Transformer									
Time (Min.)	40	30	20	10	6	2	1	0.5	0.3
V/Hz (%)	106.4	106.9	107.4	108.4	109.3	112.1	114.3	118.0	123.5

Table 3.2.2 – Example V/Hz withstand Capability of Generator										
Time (Min.)	33	25	20	15	10	5	2	1	0.5	0.2
V/Hz (%)	110	111	111.5	112.5	113.5	115.5	118.0	120.0	122.0	125.0

Example - Proper Coordination

- Function 24



Summary of Protection Functions Required for Coordination – Function 24

Table 2 Excerpt — Device 24 Protection Coordination Data Exchange Requirements

Generator Protection Device	Transmission System Protection Relays	System Concerns
24 – Volts/Hz	UFLS UFLS design is generally the responsibility of the Planning Coordinator	<ul style="list-style-type: none"> •Generator V/Hz protection characteristics shall be determined and be recognized in the development of any UFLS system for all required voltage conditions. The Generator Owner (and the Transmission Owner when the GSU transformer is owned by the Transmission Owner) exchange information of V/Hz setpoints and UFLS setpoints with the Planning Coordinator. •Coordinate with the V/Hz withstand capability and V/Hz limiter in the excitation control system of the generator. •Coordinate with V/Hz conditions during islanding (high voltage with low frequency system conditions that may require system mitigation actions). •Regional UFLS program design must be coordinated with these settings. •Islanding issues (high voltage & low frequency) may require planning studies and require reactive element mitigation strategies •Settings should be used for planning and system studies either through explicit modeling of the device, or through monitoring voltage and frequency performance at the device location in the stability program and applying engineering judgment.

Protection Function Data and Information Exchange Required for Coordination – Function 24

Table 3 Excerpt — Device 24 Data To be Provided

Generator Owner	Transmission Owner	Planning Coordinator
The overexcitation protection characteristics, including time delays and relay location, for the generator and the GSU transformer (if owned by the Generator Owner).	The overexcitation protection characteristics for the GSU transformer (if owned by the Transmission Owner)	Feedback on problems found between overexcitation settings and UFLS programs.

Undervoltage Protection – Function 27

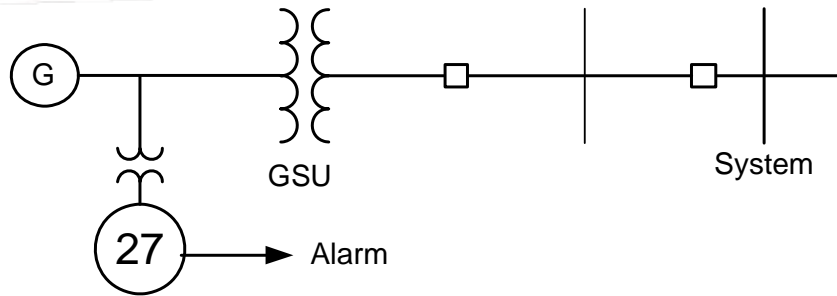


Figure 3.3.1.1 — Typical Unit Generator Undervoltage Scheme

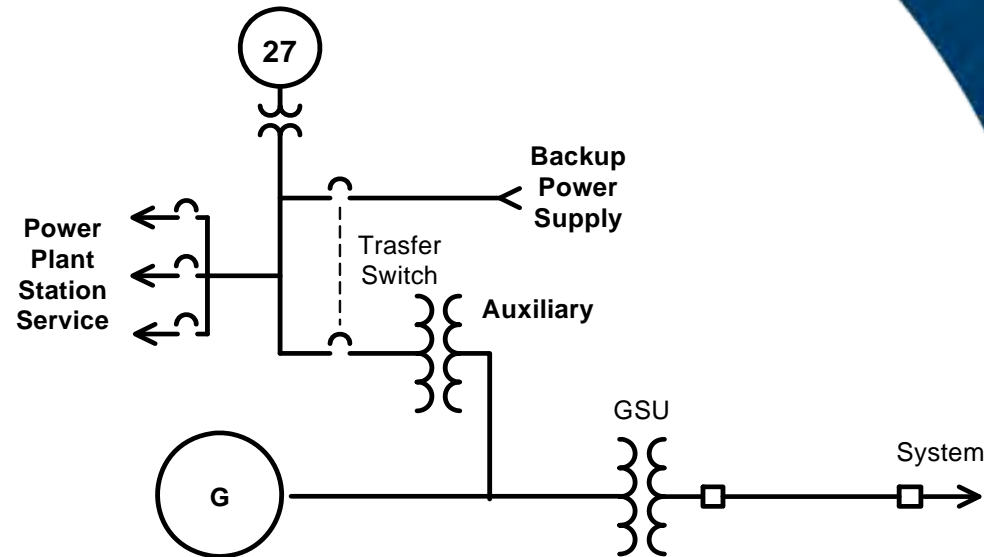


Figure 3.3.2.1 — Generating Plant Auxiliary Power System Undervoltage Protection Scheme

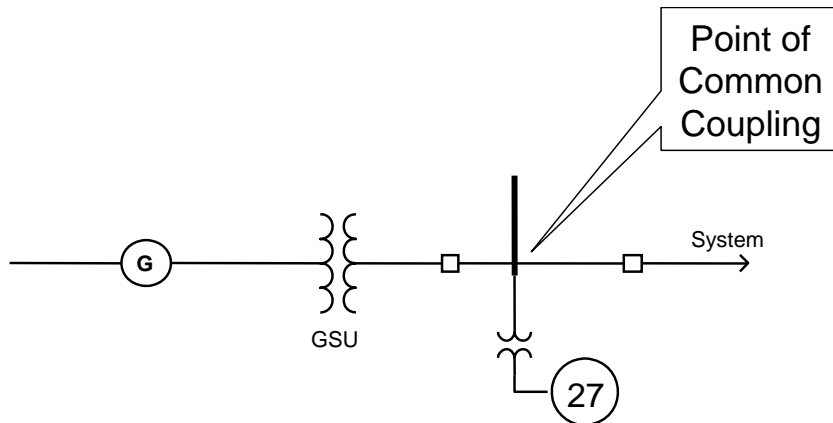


Figure 3.3.3.1 — Undervoltage Relay Applied at the Point of Common Coupling

- 1. Purpose of Generator Unit Function 27
 - Undervoltage alarms are used as an indicator of possible abnormal operating conditions on hydro, fossil, combustion and nuclear units, such as excitation problems and thermal issues within the unit.
 - Note that each type of unit (hydro, fossil, nuclear, combustion, and renewable) has different abnormal operating issues relating to system undervoltage.
 - IEEE C37.102 – IEEE Guide for AC Generator Protection does not recommend use of the 27 function for tripping, but only to alarm to alert operators to abnormal conditions that require operator intervention.
 - Manufacturers recommend operator action up to and including reduction in unit output rather than a unit trip.

- 2. Purpose of Function 27 on the Generator Auxiliary System
 - These relays are used to protect auxiliary system equipment from severe undervoltage conditions that would have serious consequences, such as auxiliary motors stalling or voltage collapse for the generating unit(s).
 - These relays initiate alarming, automatic transfer to an alternative power supply, starting of emergency generator(s), or, if necessary, generator tripping.
- 3. Purpose of Function 27 at Point of Common Coupling
 - These relays are used to alarm that an undervoltage condition is occurring on the transmission system and that the operator should be on a heightened state of awareness, matching this alarm with others that may be occurring within the plant.

Coordination of Generator and Transmission System – Function 27

■ Faults

- The undervoltage function should never trip for any transmission system fault condition.
- The Transmission Owner needs to provide the longest clearing time and reclosing times for faults on transmission system elements connected to the high-side bus.
- This coordination should be validated by both the Generator Owner and Transmission Owner.

■ Loadability

- The preferred method is to alarm only with the undervoltage function. If the undervoltage function is used to trip the unit, then additional coordination issues must be addressed by the Transmission and Generator Owners.
 - The undervoltage function should not trip the generator for a Recoverable System Event that is defined as a sustained transmission system voltage at the high side of the generator transformer of 0.85 per unit.
 - The Generator Owner needs to provide relay set point and time delay to the Transmission Owner.
 - This coordination should be validated by both the Generator Owner and Transmission Owner.

- Considerations and Issues
 - The loss of generating units due to tripping of the undervoltage elements or operator action during a system fault or a recoverable system event must be avoided.
 - A Recoverable System Event is defined as a sustained transmission system voltage at the high side of the generator transformer of 0.85 per unit.
 - If undervoltage tripping is used for the generator and an Undervoltage Load Shedding (UVLS) program is used in the transmission system, the UVLS set points and time delays must be coordinated with the generator undervoltage trips.
 - The generator set points should be modeled in system studies to verify coordination.
 - A simple relay-to-relay setting coordination is inadequate due to differences in voltage between the generator terminals and transmission or distribution buses where the UVLS protection is implemented.

- Alarm
 - IEEE C37.102 — IEEE Guide for AC Generator Protection does not recommend use of the 27 function for tripping, but only to alarm to alert operators to take necessary actions.
 - Undervoltage element (function 27) calculation:
 - $V_{27} = 90\% \text{ of } V_{\text{nominal}} = 0.9 \times 120 \text{ V} = 108 \text{ V}$ with a 10 second time delay to prevent nuisance alarms (per IEEE standard C37.102).
- Tripping (not recommended)
 - CAUTION: If the Generator Owner uses the 27 function for tripping, the following condition must be met at a minimum:
 - Time delay of the undervoltage element trip must be longer than the greater of the local or remote backup clearing times for all transmission elements connected to the high-side bus, but not less than 10 seconds.
 - Undervoltage element (function 27) calculation:
 - $V_{27} = 87\% \text{ of } V_{\text{nominal}} = 0.87 \times 120 \text{ V} = 104 \text{ V}$ with a coordinated time delay
 - Note: An 87 percent set point was chosen because the power plant is not capable of continued operation at this voltage level, and allows for a reasonable margin for extreme system contingencies.

Example – Function 27

- Proper Coordination
 - If the undervoltage function is set to trip the generator, a threshold setting below 90 percent voltage at the generator terminals and an adequate time delay is necessary to allow system recovery above this level.

- Improper Coordination
 - A threshold setting higher than 90 percent voltage at the generator terminals and/or an inadequate time delay.

Summary of Protection Functions Required for Coordination – Function 27

Table 2 Excerpt — Device 27 (Gen. Prot.) Protection Coordination Requirements

Generator Protection Device	Transmission System Protection Relays	System Concerns
<p>27 – Generator Unit Undervoltage Protection</p> <p>** Should Not Be Set to Trip, Alarm Only**</p> <p>If device 27 tripping is used for an unmanned facility – the settings must coordinate with the stressed system conditions of 0.85 per unit voltage and time delays set to allow for clearing of system faults by transmission system protection, including breaker failure times.</p>	<p>21 27 if applicable 87B 87T 50BF Longest time delay for Transmission System Protection to Clear a Fault</p>	<ul style="list-style-type: none"> • Must not trip prematurely for a recoverable extreme system event with low voltage or system fault conditions. • UVLS set points and coordination if applicable. • Settings should be used for planning and system studies either through explicit modeling of the device, or through monitoring voltage performance at the device location in the stability program and applying engineering judgment. • Must coordinate with transmission line reclosing.

Protection Function Data and Information Exchange Required for Coordination – Function 27

Table 3 Excerpt — Device 27 (Gen. Prot.) Data To be Provided

Generator Owner	Transmission Owner	Planning Coordinator
Relay settings: Under Voltage Set Point if applicable, including time delays, at the generator terminals.	Time Delay of Transmission System Protection	Feedback on problems found in coordinating with stressed voltage condition studies and if applicable, UVLS studies

Summary of Protection Functions Required for Coordination – Function 27

Table 2 Excerpt — Device 27 (Plant Aux.) Protection Coordination Requirements

Generator Protection Device	Transmission System Protection Relays	System Concerns
<p>27 – Plant Auxiliary Undervoltage If Tripping is used – the Correct Set Point and Adequate Time Delay so it does not trip for All System Faults and Recoverable Extreme Events</p>	<p>21 27 if applicable 87B 87T 50BF Longest time delay for Transmission System Protection to Clear a Fault</p>	<ul style="list-style-type: none"> •Coordinate the auxiliary bus protection and control when connected directly to High Voltage System. •Generator Owner to validate the proper operation of auxiliary system at 80-85 percent voltage. The undervoltage trip setting is preferred at 80 percent. •Generator Owners validate the proper operation of auxiliary system at 0.8-0.85 per unit voltage. •Settings should be used for planning and system studies either through explicit modeling of the device, or through monitoring voltage performance at the device location in the stability program and applying engineering judgment.

Protection Function Data and Information Exchange Required for Coordination – Function 27

Table 3 Excerpt — Device 27 (Plant Aux.) Data To be Provided

Generator Owner	Transmission Owner	Planning Coordinator
Relay settings: Under Voltage Set Point if applicable , including time delays, at the power plant auxiliary bus	Time Delay of Transmission System Protection	Feedback on problems found in coordinating with stressed voltage condition studies, and if applicable, UVLS studies

Summary of Protection Functions Required for Coordination – Function 27

Table 2 Excerpt — Device 27 (Plant HV System Side) Protection Coordination Data Exchange Requirements

Generator Protection Device	Transmission System Protection Relays	System Concerns
<p>27 – Plant High Voltage System Side Undervoltage If Tripping is used – the Correct Set Point and Adequate Time Delay so it does not trip for All System Faults and Recoverable Extreme Events</p>	<p>21 27 if applicable 87B 87T 50BF Longest time delay for Transmission System Protection to Clear a Fault</p>	<ul style="list-style-type: none"> •Must not trip prematurely for a recoverable extreme system event with low voltage or system fault conditions. •UVLS set points and coordination if applicable. •Settings should be used for planning and system studies either through explicit modeling of the device, or through monitoring voltage performance at the device location in the stability program and applying engineering judgment.

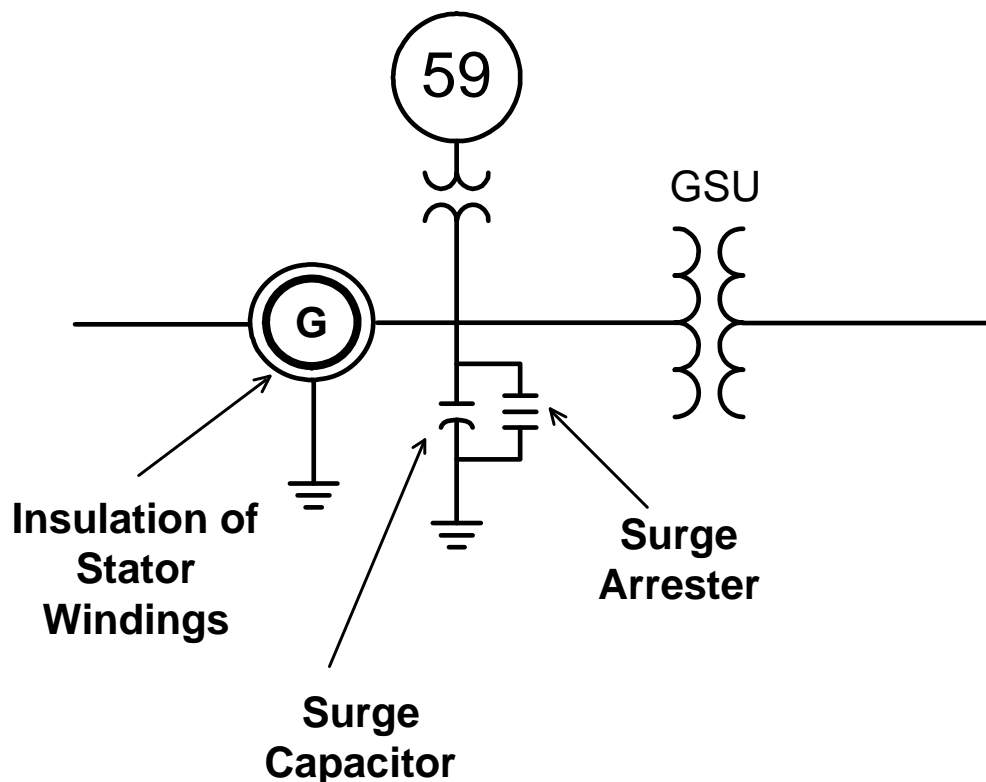
Protection Function Data and Information Exchange Required for Coordination – Function 27

Table 3 Excerpt — Device 27 (Plant HV System Side) Data To be Provided

Generator Owner	Transmission Owner	Planning Coordinator
Relay settings: Under Voltage Set Point if applicable, including time delays, at high side bus.	Time Delay of Transmission System Protection	Feedback on problems found in coordinating with stressed voltage condition studies and if applicable, UVLS studies

- Purpose

- Prevent an insulation break-down from a sustained overvoltage condition.



Coordination of Generator and Transmission System – Function 59

■ Faults

- There are no coordination requirements with the transmission protective relays for system faults given the high voltage set point and long delay; tens of seconds or longer.
- Function 59 protection is mainly provided for the generator stator winding insulation.
- Surge arrestors protect the stator from overvoltages caused by lightning, impulses, and inrush. The 59 function provides backup protection for these hazards.

■ Loadability

- If a long time setting of 1.1 per unit nominal voltage with significant time delay (as an example 10 seconds or longer is used to trip); coordination for extreme system events with overvoltage should be considered.
- This suggests that for credible contingencies where overvoltage may occur, shunt reactors near the generator should be placed in service and/or capacitor banks near the generator should be removed from service prior to the trip time setting on the generator.

- **Considerations and Issues**
 - When the generator voltage regulator is operating normally and keeps the generator terminal voltage within 105 percent of nominal, there is not any system coordination issue.
 - Planners and operational planners need to know both the performance of the voltage regulator and the overvoltage relay settings to study extended-time, overvoltage system conditions.

■ Setting Considerations

- Two types of relays of (or elements) are commonly used on a generator protection; one is an instantaneous (function 59I), and the other is a time-delay (function 59T) relay or element.
- “Generators shall operate successfully at rated kilovolts-amperes (kVA), frequency, and power factor at any voltage not more than five percent above or below rated voltage...” (By Clauses 4.1.5 of IEEE C50.12 & 4.1.7 of IEEE C50.13-2005).
- “Generators shall be thermally capable of continuous operation within the confines their reactive capability curves over the ranges of $\pm 5\%$ in voltage and $\pm 2\%$ in frequency.” (By Clauses 4.1.5 of IEEE C50.12 & 4.1.7 of IEEE C50.13-2005).

Example – Function 59

■ Proper Coordination

- The following is an example of setting the 59T and 59I element time delays.
- Step 1 – $V_{\text{nominal}} = (20,000\text{V}) (120/20,000) = 120\text{V}$
- Step 2 – 59T = 105% of 110% of $V_{\text{nominal}} = 1.05 \times 1.10 \times 120\text{V} = 139\text{V}$ (=1.155 pu), with a time delay of 10 seconds or longer.
- Step 3 – 59I = 105% of 130% of $V_{\text{nominal}} = 1.05 \times 1.30 \times 120\text{V} = 184\text{V}$ (=1.365 pu)
- Figure 3.11.3 is a typical load rejection response curve of a voltage regulator for an example of a hydro turbine generator. The regulator causes the generator to operate back near nominal voltage in about two seconds, well before any action by the overvoltage protection.

■ Improper Coordination

- A threshold setting higher than 90 percent voltage at the generator terminals and/or an inadequate time delay.

Example – Function 59

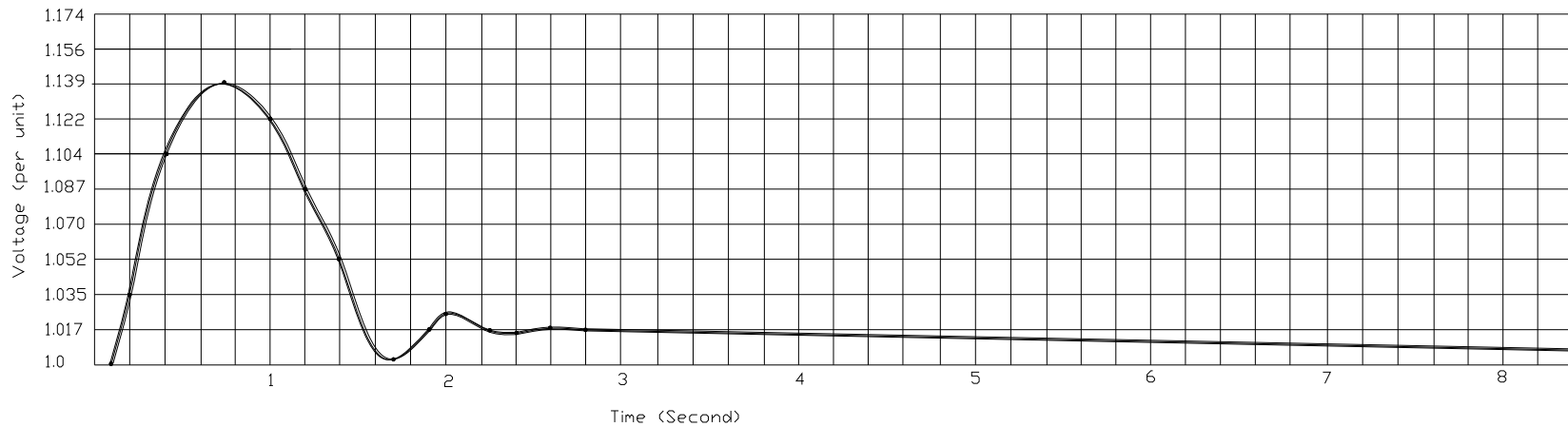


Figure 3.11.3 — Typical Example Load Rejection Data for Voltage Regulator Response Time

Summary of Protection Functions Required for Coordination – Function 59

Table 2 Excerpt — Device 59 Protection Coordination Data Exchange Requirements

Generator Protection Device	Transmission System Protection Relays	System Concerns
59 — Overvoltage	When applicable, pickup and time delay information of each 59 function applied for system protection	•Settings should be used for planning and system studies either through explicit modeling of the device, or through monitoring voltage performance in the stability program and applying engineering judgment.

Protection Function Data and Information Exchange Required for Coordination – Function 59

Table 3 Excerpt — Device 59 Data To be Provided

Generator Owner	Transmission Owner	Planning Coordinator
Relay settings: setting and characteristics, including time delay setting or inverse time characteristic, at the generator terminals.	Pickup and time delay information of each 59 function applied for system protection	None

Overfrequency and Underfrequency Generator Protection – Function 81

- Purpose
 - Protect the turbine against the potential impacts of operating at off-nominal frequency.

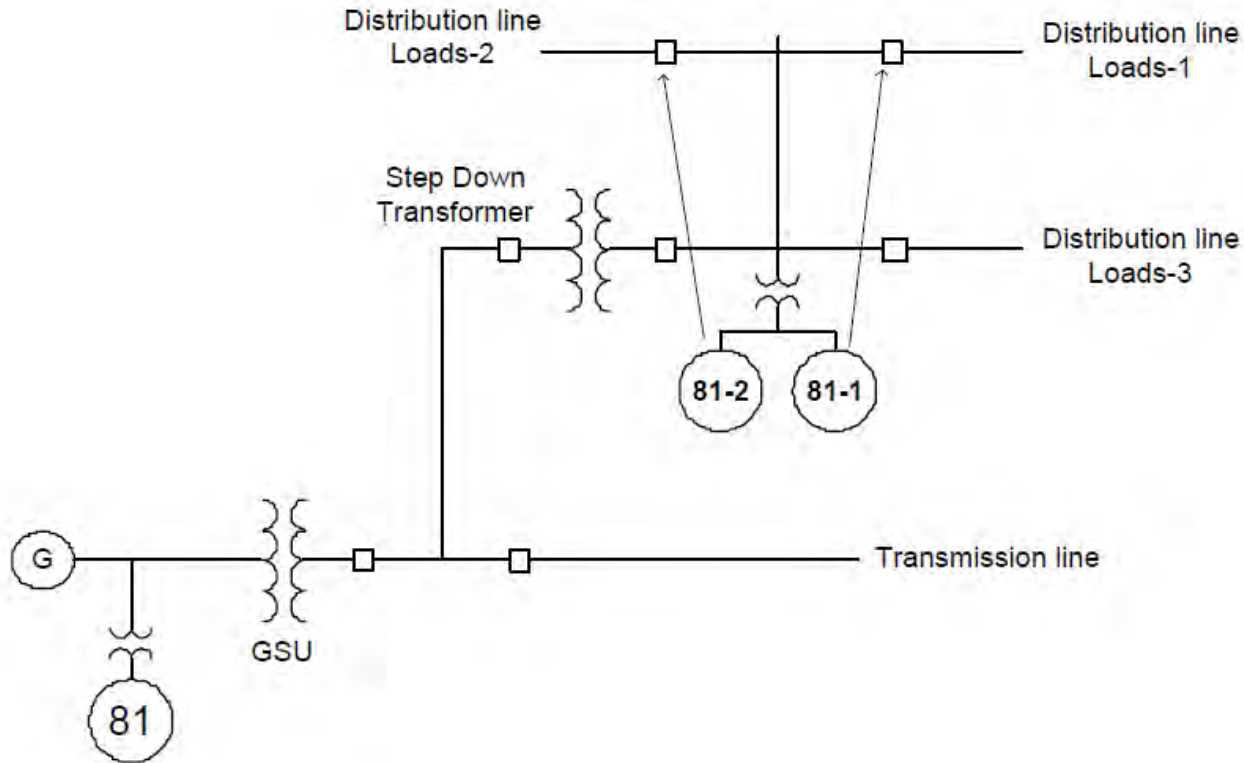


Figure 3.14.1 — Underfrequency Relay and Load Shedding Coordination

Coordination of Generator and Transmission System – Function 81

- **Faults**
 - There are no coordination issues for system faults for this function.

- **Loadability**
 - There are no coordination issues related to loadability for this function.

Coordination of Generator and Transmission System – Function 81

- Other Operating Conditions
 - Coordination is necessary to ensure that the UFLS program can operate to restore a balance between generation and load to stabilize frequency at a sustainable operating condition.
 - Without coordination, generation may trip and exacerbate the unbalance between load and generation resulting in tripping of more load than necessary, or in the worst case, resulting in system collapse.
 - Coordination also is necessary to ensure that overfrequency protection does not operate if frequency temporarily overshoots 60 Hz subsequent to UFLS operation.
 - It is important to note that the coordination is not a relay-to-relay coordination in the traditional sense; rather it is coordination between the generator prime mover capabilities, the over and underfrequency protection, and the UFLS program and transmission system design.
 - For conditions that exceed the design parameters of the UFLS program, it is possible that frequency recovery will ‘stall’ and settle at a lower than normal frequency.
 - If it is necessary to apply underfrequency protection, turbine limits that account for both frequency and time at frequency, must be obtained from the turbine manufacturer.
 - The UFLS program always should be allowed to take action well before tripping a generating unit for turbine protection. If this is not possible, most regions require accounting for unit tripping in UFLS design assessments and require UFLS program modifications such as arming additional "compensating" load shedding equal to the capacity of the unit.

- Considerations and Issues
 - Turbine limits must be obtained from the turbine manufacturer in order to properly set the over and underfrequency protection elements.
 - The limits typically are expressed as the cumulative amount of time that the turbine can operate at off-nominal frequencies.
 - IEEE Standard C50.12 (Standard for Salient-pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above) requires that “Generators shall be thermally capable of continuous operation within the confines of their reactive capability curves over the ranges of $\pm 5\%$ in voltage and $\pm 2\%$ in frequency, as defined by the shaded area of Figure 3.14.2.”

Coordination of Generator and Transmission System – Function 81

- Details for setting the protection functions are provided in Section 4.58 and Figure 4.48 of IEEE Standard C37.102-2006 (Guide for AC Generator Protection).
- Generator off-nominal frequency protection should be coordinated with the governor settings to ensure that the protection does not trip the unit for a condition from which the governor could restore the unit to an acceptable operating condition.
- In order to provide reliable, coordinated protection the over and underfrequency protection functions must have adequate pickup setting range (usually 55-65 Hz) and adequate time delay to coordinate with the UFLS program. It also is important to have adequate operating range in terms of system frequency. Most relays are designed to operate in a range of 40 – 70 Hz which is adequate.
- It is important to understand the protection function limitations as some relays are blocked automatically if the system frequency or voltage is outside the range of relay specifications, while other relays remain in-service but are subject to misoperations.

- Step 1 — Planning Coordinator provides the regional underfrequency load shedding and generator off-nominal frequency protection setting criteria.
- Step 2 — Generator Owner and Planning Coordinator verify that the generator off-nominal frequency protection is set to coordinate with the regional UFLS program design and generator off-nominal frequency protection setting criteria.
- Step 3 — If coordination cannot be achieved without compromising protection of the generating unit, the Planning Coordinator performs studies to assess the impact on the UFLS program design and identify modifications, if necessary, to accommodate the generator protection setting while ensuring the UFLS program continues to meet its design objectives.

■ Setting Validation for Coordination

- Step 1 — Plot the generator and turbine capabilities on a graph of frequency versus time similar to the graph shown in Figure 3.14.3.
- Step 2 — Plot the applicable NERC and regional requirements for setting over and underfrequency protection on generating units on the same graph.
- Step 3 — Plot the protection settings on the same graph. Note that for some plant designs, critical station service load may be supplied from a motor-generator (M-G) set. When an over or underfrequency protection is located on the load side of the M-G set, the protection function trip setting must be adjusted to account for any frequency difference between the system and the load.
- Step 4 — Verify whether the protection function settings coordinate with the generator and turbine capability and the regional requirements. If coordination cannot be achieved, set the protection based on the generator and turbine capability and follow the applicable processes to report the relay setting so the generator protection can be modeled by the Planning Coordinator in system studies.
- Note that the generator protection is not coordinated directly with the UFLS relay settings because subsequent to the UFLS program operating to shed load, a time delay will exist before frequency decline is arrested and recovery begins. This time delay, as well as the rate at which frequency recovers, is a function of the physical characteristics of the system including types of load, generating unit inertia, and governing response.

Example – Function 81

■ Proper Coordination

- The following Figure 3.14.3 illustrates an example of how generator protection settings are coordinated with the turbine capability and the underfrequency protection setting limits for generating units.
- In this example the protection setting must be set above the green curve which defines the turbine capability provided by the manufacturer and on or below the red curve that defines the applicable generator underfrequency protection setting limits.
- In this example the protection is set with an instantaneous trip threshold at 57.7 Hz and a time delayed threshold setting at 58.5 Hz with a definite time delay of 60 seconds. Both settings coordinate in this example.

Example – Function 81

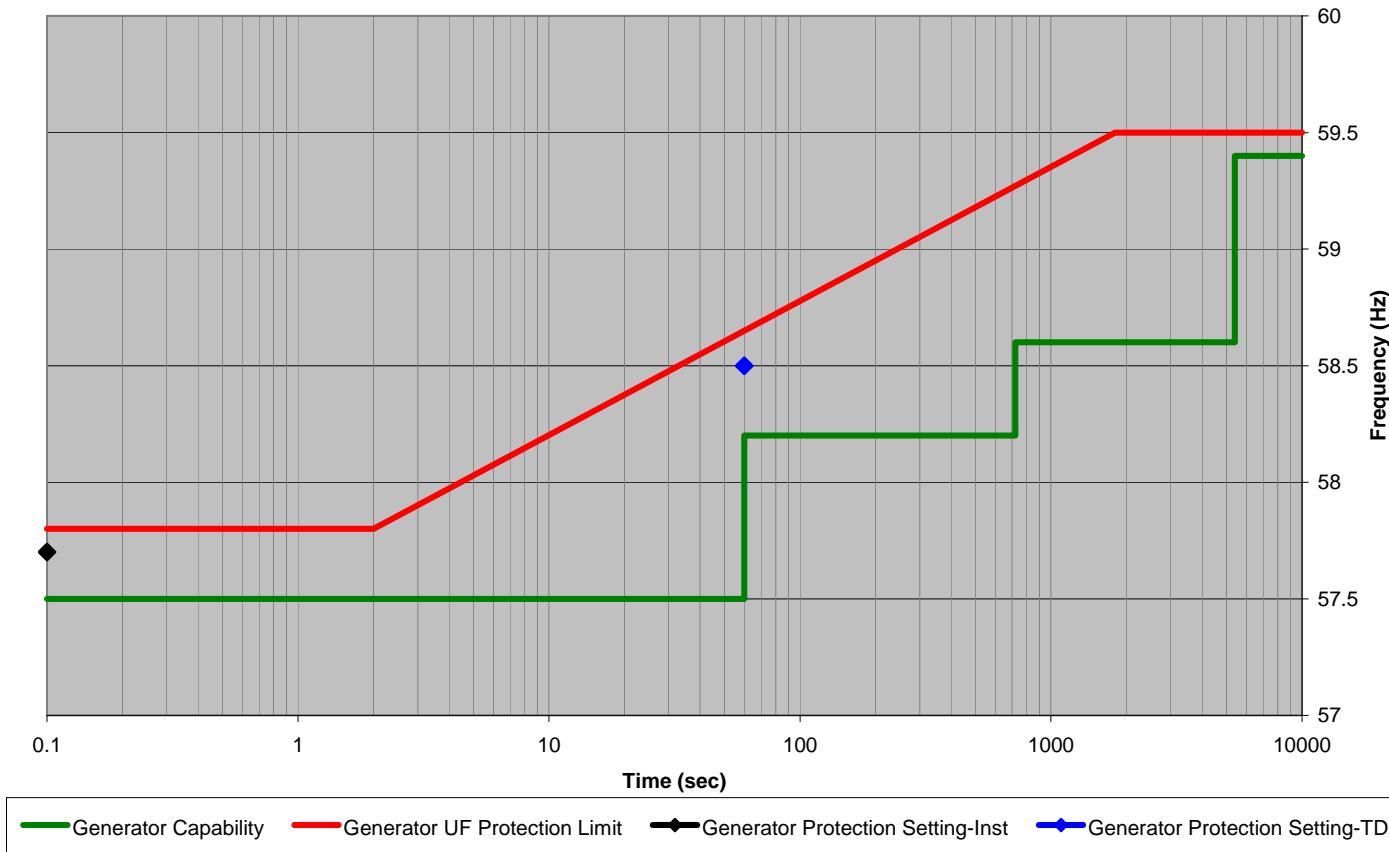


Figure 3.14.3 — Generator Underfrequency Protection Setting Example

Summary of Protection Functions Required for Coordination – Function 81

Table 2 Excerpt — Devices 81U / 81O Protection Coordination Data Exchange Requirements

Generator Protection Device	Transmission System Protection Relays	System Concerns
<p>81U – Under frequency 81O – Over frequency</p>	<p>81U (Coordination with system UFLS set points and time delay) achieved through compliance with Regional frequency standards for generators 81O (Coordinate with system over-frequency set points) UFLS design is generally the responsibility of the Planning Coordinator</p>	<ul style="list-style-type: none"> •Coordination with system UFLS set points and time delay, •Meet Standard PRC-024-2 under-and-over-frequency requirements •Caution on auto-restart of distributed generation •Wind generation during over-frequency conditions •Settings should be used for planning and system studies either through explicit modeling of the device, or through monitoring frequency performance at the device location in the stability program and applying engineering judgment.

Protection Function Data and Information Exchange Required for Coordination – Function 81

Table 3 Excerpt — Devices 81U / 81O Data To be Provided

Generator Owner	Transmission Owner	Planning Coordinator
Relay settings and time delays	None	Feedback on problems found between underfrequency settings and UFLS programs.

What is Important to Coordination

- Settings That Protect the Generator
- Time Coordination with UFLS and UVLS
- Islanding Conditions
- Sufficient Studies

Settings that Protect the Generator

- The generator protection set-points are described in the IEEE Guide for AC Generator Protection (C37.102) for Functions 24, 27, 59, and 81.
- The times to trip or alarm are adjusted based on the specific generator and application limits as well as coordination with system functions and schemes.
- Examples of these were given in the presentation, but again, specific settings need to be determined by the entities.

- Coordination of generator protection with UFLS and UVLS programs is essential to surviving extreme operating conditions from which the system is capable of recovering.
- As noted, coordination is not a typical relay-to-relay coordination.
- System studies are required to verify coordination between the generator protection, the UFLS and UVLS program settings, and the system response to severe events.

Islanding Conditions

- The protection must be set to avoid unnecessary tripping for worst case survivable conditions:
 - Operation of transmission equipment within continuous and emergency thermal and voltage limits
 - Recovery from a stressed system voltage condition for an extreme system event – i.e. 0.85 pu voltage at the system high side of the generator step-up transformer
 - Stable power swings
 - Transient frequency and voltage conditions for which UFLS and UVLS programs are designed to permit system recovery
- When coordination cannot be achieved without compromising protection of the generator, the generator protection setting must be accounted for in system studies.

- The Planning Coordinator must study a number of operating conditions sufficient to bound the worst case.
- Assess sensitivity of generator and system response to:
 - System load level
 - Generator loading (both active and reactive power)
 - Commitment and dispatch of other generators
 - System operating states (N-0, N-1, . . .)
- The most limiting operating condition may vary among protective functions or even for different settings for a single protective function.



Question & Answer

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