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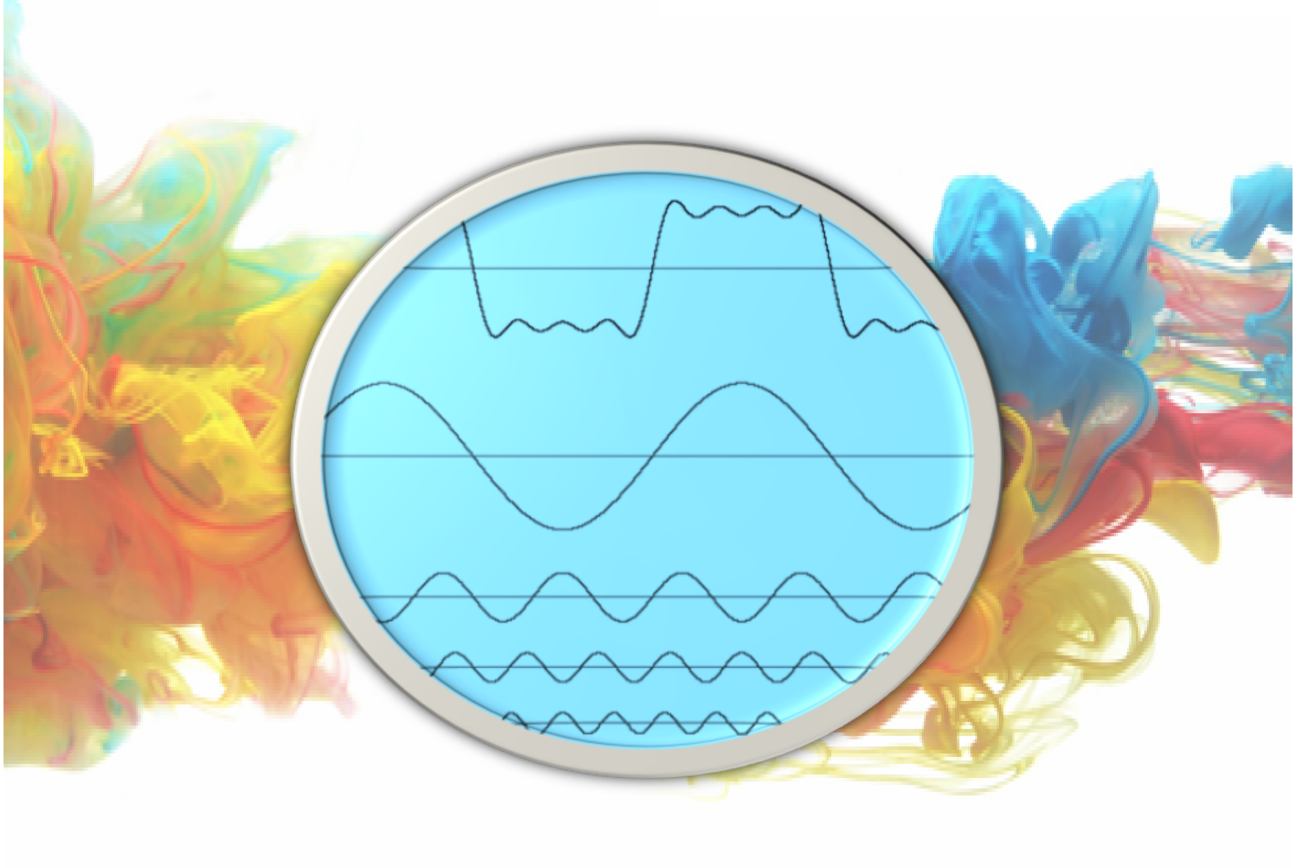

An Assessment of the Harmonics Effects on Undervoltage Relays in Nuclear Power Plants

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AN ASSESSMENT OF THE HARMONICS EFFECTS ON UNDERVOLTAGE RELAYS IN NUCLEAR POWER PLANTS (NPPS), ORDER NO. 31310022F0122

Task 5 - Final Technical Letter Report: Evaluation and Analysis of Results of Literature Search and Identification of Potential Gaps

UNDER TECHNICAL SUPPORT SERVICE AREA 3.5 “INSTRUMENTATION AND CONTROLS (I & C) AND ELECTRICAL SYSTEMS FOR NPP AND NPUF’S” CONTRACT NO. 31310020D0004

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June 06, 2023	0	Task 5 deliverable
June 08, 2023	1	Per customer request, removed an outdated note and added a clarification footnote, both in Appendix A.

Abstract

Electrical power systems in nuclear power plants can experience voltage and/or current waveform distortions resulting in harmonic waveforms that can have detrimental effects on plant operating equipment. The impact of harmonics on electrical safety-related circuitry is the focus of this study. The aim of this project is to conduct a search of open literature to identify current knowledge about the potential effects of persistent harmonics produced by the electrical system, test sources, and transient operation of equipment on protective electrical relays, specifically degraded and loss-of-voltage relays. The goal is to understand the effect of electrical harmonic distortions on the electrical protection relay operation and setpoints. Electrical harmonics can cause these relays to spuriously actuate when not required, fail to actuate when required, or reset in the presence of an actual degraded voltage event. Such effects can delay the protective function beyond the time delays stipulated in the design basis. The study found that the U.S. Nuclear Regulatory Commission (NRC) and the nuclear industry have devoted significant amounts of effort and diligence in developing the setpoint guidelines for these relays to prevent the three types of failures described earlier. However, it is important to note that all these documents and guidelines are developed based on the electrical power flow, which is not contaminated by harmonics; assuming 60 cycles per second (CPS) or Hertz (Hz) fundamental frequency. The effect of harmonics on the operation of these relays will depend on the magnitude of different harmonic components, both sustained and transient, and the existing safety margins of the relay setpoints. Therefore, these relays will perform properly for some unknown level of harmonic distortions. Several past studies have speculated that harmonic distortions of 5% to 10% will not impact the proper operation of loss-of-voltage relay (LOVR)/degraded-voltage relay (DVR). This study recommends additional research to better understand the level of harmonic distortions that can be tolerated by current design practices, how they could be improved, and what would be the reduction in risk if changes are implemented to protect against harmonics.

Acknowledgements

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Abbreviations and Acronyms

AC	alternating current
ADAMS	Agencywide Documents Access and Management System
AI	artificial intelligence
ALWR	advanced light-water reactor
ASD	adjustable speed drive
BTP	Branch Technical Position
BWR	boiling-water reactor
CDF	core damage frequency
COR	Contracting Officer’s Representative
CPS	cycles per second
DC	direct current
DCAV	direct current average voltage
DFT	discrete Fourier transform (filter)
DOE	U.S. Department of Energy
DR	digital relays
DVM	digital voltmeter
DVR, DVRG	degraded voltage relay
EDG	emergency diesel generator
EMI	electromagnetic interference
EPRI	Electric Power Research Institute
ESF	engineered safety feature
ETAP	Electrical Transient Analyzer Program
EV	electric vehicle
FSAR	final safety analysis report
GDC	General Design Criterion
GIC	geomagnetically induced current
GSI	Generic Safety Issue
hp	horsepower
HVF	harmonic voltage factor
Hz	Hertz
IAEA	International Atomic Energy Agency
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IN	Information Notice
INL	Idaho National Laboratory
ISL	Information Systems Laboratories, Inc.
kV	kilovolts

LER	licensee event report
LLNL	Lawrence Livermore National Laboratory
LOCA	loss-of-coolant accident
LOOP	loss-of-offsite power
LOVR	loss-of-voltage relay
NEI	Nuclear Energy Institute
NEMA	National Electrical Manufacturers Association
NLP	Natural Language Processes
NLWR	Non-light-water reactor
NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NSWP	normal service water pump
OPC	Open Phase Condition
PCC	point of common coupling
PEAK	peak voltages
PWM	pulse width modulated
PWR	pressurized-water reactor
RES	NRC Office of Nuclear Regulatory Research
RFI	radio frequency interference
RG	Regulatory Guide
RIS	Regulatory Issue Summary
rms	root mean squared
SBO	station blackout
SCR	silicon-controlled rectifiers
SIAS	safety injection actuation signal
SMR	small modular reactor
SRP	Standard Review Plan
THD	total harmonic distortion
TS	technical specifications
UPS	uninterrupted power supply
UVR	undervoltage relay
V	volts
VSD	variable speed drive
WANO	World Association of Nuclear Operators

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1. Introduction

Electrical power systems in nuclear power plants (NPPs) can experience voltage and/or current waveform distortions resulting in harmonic waveforms that can have detrimental effects on plant operating equipment. Typical sources of such waveform distortions are:

- Non-linear loads.
- Power systems transients such as switching surges.
- Variable frequency drives.
- Uninterruptible power supplies.
- Unbalanced system loading.
- Fault conditions in the power system.

Additionally:

- Geomagnetic storms can produce harmonic distortions that can persist at various voltage levels within the on-site power distribution system.
- Harmonic frequencies in the power system frequency can cause power quality problems, resulting in increased heating in the equipment and conductors, misfiring in variable speed drives, and torque pulsations in motors.
- Equipment used to calibrate control equipment (e.g., relays) and instrumentation can result in calibration shifts and inaccurate setpoints if harmonics are present in the test power supply source.
- Transient harmonic conditions can cause a spurious actuation of relays resulting in plant transients or an adverse impact to the plant's safe shutdown capability.

Guidance on how to assess and understand the harmonic waveform distortion effects on the electrical protection relay setpoints is needed, as these waveform distortions can cause relays to spuriously reset in the presence of an actual degraded-voltage event. This could delay the protective function beyond the time delays stipulated in the design basis. This would prevent the safety-related equipment from functioning during emergency and/or shutdown events. The ability to understand and assess the transient harmonic effects will be useful for both inspectors and technical reviewers.

The objective of this study is to provide technical insights in the following areas:

1. Understanding of the harmonic effects that can negatively impact NPP emergency and shutdown protocols.
2. Determination of the need for a technical guidance document for evaluating the potential phenomenon in NPPs.
3. The integration of operating experience, codes and standards, generic communications, as well as other relevant available information that will be of use to inspectors and technical reviewers.

The outline of this report is as follows:

Section 1.1 includes a brief description of the emergency electrical power system at nuclear power plants. It illustrates the base example system for the discussions in the remaining sections of this report.

Section 2 provides a summary of the magnitudes of harmonics that could be experienced in US NPPs with varying probability and duration (Objective 1 above). This section also documents the current practices in limiting the harmonics magnitudes at US facilities.

Section 3 presents the role and the function of undervoltage and degraded voltage relays (UV/DVR) within a typical emergency power system at a nuclear power plant (supporting Objective 1). It discusses the basis for the relay settings and the associated tolerances for a case when the power system is purely sinusoidal with harmonics present. It also discusses different types of relays used for UV/DVR and discusses the impact of power system harmonics on the operation of each type of these relays.

Section 4 discusses the operating experience with the UVR/DVR (Objective 3) in general and specifically for the application for emergency power systems in NPPs. This section also addresses the current best practices for relay testing, calibration, and maintenance.

Section 5 discusses all requirements, standards, and the U.S. Nuclear Regulatory Commission (NRC) Regulatory Guides (RGs) relevant to controlling the effects of harmonics on UV/DVRs (Objective 3).

Section 6 summarizes additional insights and supplemental information extracted from the Chat GPT, an open artificial intelligence (AI) tool.

Finally, **Section 7** addresses Objective 2 noted above and summarizes the current issues and gaps, including identification of methods and approaches for a possible path forward.

Citations in this report are in the form of numbers in square brackets "[]s". The number corresponds with the reference listed (under that number) in NRC's Agencywide Documents Access and Management System (ADAMS) document ML 23094A084[1] .

1.1 Description of Emergency Electrical Power System at Commercial Nuclear Power Plants

Nuclear plant electrical power systems consist of offsite and onsite power systems. Onsite power distribution systems are divided into safety and non-safety distribution systems. The objective for the safety power system is to furnish adequate electrical power to ensure that safety-related loads function in conformance with the design criteria associated with design basis events. All safety-related electrical distribution systems are designated as Class 1E and must meet strict requirements. Class 1E equipment can be fed from the preferred offsite power source or a standby onsite power source (e.g., emergency

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[1] USNRC ADAMS, "Harmonic Effect Study, Technical Letter Report Attachment 1 to ISL document List of References," ML 23094A084, Date Added 4/10/2023. In addition, an ADAMS package has been created to house this document and all ensuing reports and files. All documents placed Package ML23094108, will have their own unique accession numbers.

diesel generators [EDGs]) during emergencies, or from offsite power through the step-down transformer during normal operation. A dedicated safety-related direct current (DC) system with emergency battery backup is also provided to support the Class 1E equipment.

The emergency buses are protected against loss of voltage due to internal faults in their loads through breaker protection, which isolates the faulted load prior to bus undervoltage trip by a scheme known as the breaker coordination. The emergency buses are also equipped with LOVRs and DVRs that initiate transfer from the normal supply to the standby (diesel generator) power supply. The selection of DVR is based on the minimum voltage at the safety buses (i.e., “safety division”) required to support both safety-related equipment starting and running voltage limits.

The degraded grid voltage scheme utilizes two distinct time delay relays. The first-time delay is long enough to establish the existence of a sustained degraded voltage condition and to prevent spurious alarms/trips during motor starting transients; an alarm is actuated on the main control board to alert the operator of the degraded condition. The first-time delay is also consistent with the maximum time delay considered in the design basis accident analysis and will prevent spurious tripping due to short-time transient conditions. After the expiration of the first-time delay, automatic tripping actions are initiated to separate the emergency power system from the offsite power system. If no safety injection actuation signal is present, a longer time delay is allowed before the automatic tripping actions are initiated. This second time delay has been selected to ensure Class 1E loads will not be damaged; it is based on the maximum time for which the most sensitive load can perform its safety function without impairment from the degraded voltage.

The selection of LOVR is indicative of loss-of-offsite power, and it is based on the voltage threshold at the safety buses (i.e., “safety division”) required to support running of the safety equipment demanding the highest voltage limits. The relay is equipped with a short time delay prior to tripping the supply breakers to the emergency buses.

2. Magnitudes of Harmonic Distortions and Currently Acceptable Limits

Major sources that generate electrical harmonics are identified and discussed in Section 1. The overall harmonics in a facility consist of those harmonics transferred into facility from the grid, and the harmonics generated within the facility by some electrical components such as variable speed drives (VSD) or rectifiers as a part of uninterrupted power supply (UPS) units. The magnitudes of the internal and the external harmonic components and the currently used acceptable limits of these magnitudes are discussed below.

The harmonic components of voltage and current are expressed as the root mean squared (rms) values of a specific harmonic component (e.g., at 2 or 5 times the fundamental frequency for second and fifth harmonic components) over the rms value of the fundamental frequency.

The equation for the harmonic expansion of a periodic function y (t) is presented below:

$$y(t) = Y_0 + \sum_{h=1}^{h=\infty} Y_{h-rms}\ \sqrt{2}\sin(h\omega t - \varphi_h) \quad Eq.1$$

where:

- Y_0: value of the DC component, generally set to zero and considered as such hereinafter,
- Y_{h-rms}: rms value of the harmonic of order h,
- ω: angular frequency of the fundamental frequency,
- φ_h: displacement of the harmonic component at t = 0.

The equations for total harmonic distortion for the current and voltage (I_{thD} and V_{thD}) are shown below:

$$I_{thD} = \frac{\left\{\left[\sum_{h=2}^{h=\infty}(I_{h-rms})^2\right]\right\}^{\frac{1}{2}}}{I_{1-rms}} \qquad Eq.2$$

Using simple manipulations, one could show a relationship for the rms value of the total current (I_{rms}) as a function of the rms value of the fundamental component of the current (I_{1-rms}):

$$I_{rms} = I_{1-rms}\sqrt{1 + ({I_{thD}}^2)} \qquad Eq.3$$

Similarly for the overall rms of voltage components the V_{thD} and V_{rms} are expressed by:

$$V_{thD} = \frac{\left\{\left[\sum_{h=2}^{h=\infty}(V_{h-rms})^2\right]\right\}^{\frac{1}{2}}}{V_{1-rms}} \qquad Eq.4$$

$$V_{rms} = V_{1-rms}\sqrt{1 + ({V_{thD}}^2)} \qquad Eq.5$$

Equations 3 and 5 provide an important relationship between the rms values of the current and voltage against the measured values of the total harmonic distortions. The two relationships show that the rms values for voltage and current will not change significantly for small values of total harmonic distortions. The effect of harmonic distortion, however, could be more pronounced for the peak and the average DC values for the current and voltage. Unfortunately, similar relationships for the peak and average DC values between the overall and the fundamental component cannot be easily established.

Table 2-1 below provides the insights gained from the review of the open literature regarding both internal and external harmonic magnitudes. These are generally considered as common practices, rather than enforced by regulations and requirements. Based on information provided in Table 2-1, which resulted from an extensive review of the literature, the total external harmonic distortions are generally maintained under 10%, whereas the internal harmonic distortions are kept below 5%. Additional limits are sometimes set for single harmonic components, e.g., below 3%.

Table 2-1 Insights Gained from Review of Open Literature Regarding the Magnitudes of Various Types of Harmonics (Reference # correspond to the list of references in Attachment 2)

Reference #.	Reference	Results of Initial Review
[1]	Solar Geomagnetically Nuclear Power Plants (BNL NUREG-48242)	Geomagnetically-induced currents (GIC) cause saturation and nonlinearity in transformers. This in turn can cause total harmonic distortion (THD) of 4 to 11% on safety buses.
[2]	Power System Harmonic Study for Peach Bottom Nuclear Power Plant (ML20072PS579)	Variable Speed Drives (VSD) analysis shows between 5 to 7% THD generation on the bus at 100% speed. The THD drops at lower speeds.
[5]	NUREG/CR-5990, "The Effect of Solar - Geomagnetically Induced Currents on Electrical Systems in Nuclear Power Plants," Brookhaven National Laboratory BNL-NUREG-52359, January 1994	It indicates that THD greater than 8% was observed in some low-voltage buses.
[17]	The Effects of Solar-Geomagnetically Induced Currents on NPS NUREG/CR-5990.pdf	The magnitude of voltage THD caused by GIC on 4.16 KV emergency buses can vary but, in most cases, it is shown to be below the 5% IEEE limit. The study provides the modeling results of the impact of solar GICs on protective relays.
[20]	DOEDNFSB-tr_2012927_20361, Waste Treatment and Immobilization Project Response to the Defense Nuclear Facilities Safety DNFSB Concerns: Electrical Distribution System, (2012)	DOE was concerned about using UPS feeding and adjustable speed drive (ASD) to run three fan motors until gas turbine can be started and load the safety loads (~120 seconds). The uninterrupted power supply (UPS) was using SCR with pulse width modulated (PWM) DC, which even after filtering may have high frequency harmonics. As a result of DOE concerns, they used the Electrical Transient Analyzer Program (ETAP)[2] to make sure that the harmonics are below IEEE 915 (5% total and 3% for single harmonics).

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[2] ETAP harmonic analyzer module facilitates the harmonic evaluations. This module provide the capabilities to perform harmonic load flow analysis, evaluate the magnitude of harmonic distortions, and design the required filters to meet the harmonic limits.

Reference #.	Reference	Results of Initial Review
[55]	IEEE 141-1993 Standard, Electric-Power-Distribution-for-Industrial-Plant, 1994 (Inactivated in 2021)	IEEE recommended practice for electric power distribution for industrial plants. Section 9 Discusses harmonics. Section 9.8.2.7 discusses the effect of harmonics on switching and relaying. See the quote below: “Protective relays generally do not respond to any one identifiable parameter such as the rms value of a primary quantity or the fundamental frequency component of that quantity. As a related consideration, the performance of a relay to a range of single frequency inputs is not an indication of how that relay will respond to distorted wave containing those frequencies. Superposition does not apply. Multi-input relays may be more unpredictable than single input relays in the presence of wave distortion. Relay response under distorted conditions may vary among relays having the same nominal fundamental frequency characteristics, not only among different relay manufacturers, but also among different vintages of relays from the same manufacturer.” It states that harmonic levels required to cause the miss-operation of relays are greater than 10% (10% to 20%).
[65]	IEEE Standard 519-2014, "IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems," January 2022.	US limits of THD are set at 10% per this standard measured at common coupling point. This is the magnitude of harmonics an industry can inject to the power grid. It does not provide any guidance of what the limit for the harmonics is internal to the facility. The discussion for selecting the limits in this standard can be expanded to show a comparison with other international standards and the degree to which they are harmonious.

3. Role and the Function of Undervoltage and Degraded Voltage Relays

There are two levels of undervoltage protection in commercial NPPs through LOVRs and DVRs. LOVRs are the first level of the undervoltage protection scheme provided to detect loss of offsite power at the Class 1E buses. DVR is the second level of undervoltage protection (with time delay) provided to protect the Class 1E equipment from damage or becoming unavailable upon transfer to an alternate source. These protective relays monitor the Class 1E safety bus voltages and automatically initiate the disconnection of offsite power whenever the low voltage setting, and time delay limits have been exceeded.

Although the necessity, role, and use of LOVRs is straight forward, some explanation may be necessary for the role and function of DVRs. General Design Criteria (GDC) 17 requires that Class 1E loads perform their respective safety functions when powered from the preferred offsite power supply or the onsite power supply independently. A logical extension to GDC 17 is that a degraded voltage condition on the Class 1E buses (when powered by offsite power) should not prevent any Class 1E load from becoming unavailable such that it cannot be automatically transferred to the onsite supply and operate successfully. The inability to transfer the Class 1E loads would occur if the voltage on the Class 1E buses was low enough to cause excess current to individual loads and those load overcurrent protective devices operated in a way that prevents automatic re-sequencing to the onsite supply (see NEI 15-01 [32] and IEEE 741-2007 [57]).

Four examples of the relay setpoints for DVR and LOVR; extracted from plant final safety analysis reports (FSARs) are shown in Table 3-1. This table shows the various strategies and set points for both the current generation of boiling water reactors (BWRs) and pressurized water reactors (PWRs). There could be some quantitative safety margins built into the setpoints for both voltage and time delay settings, however, these appear to be plant specific and vary across the plants.

Table 3-1 Examples of Relay DVR and LOVR Setpoints

Plant Name	DVR and LOVR Setpoints
Peach Bottom [53]	0.9978 (99.78% of nominal voltage) if no loss-of coolant accident (LOCA) is detected. It has a long 61-second time delay, for allowing voltage recovery. 0.9138 (91.38% of nominal voltage) if LOCA is detected, it has a 10-second delay, which includes the internal delay of 1 second 0.87 (87.00% of nominal voltage) start the inverse time relay and trips the source breaker when voltage reaches 0.6 (60%). 0.25 (25% of nominal voltage) initiates load shedding and provides a permissive signal to allow the affected bus to transfer to the alternate source.

Plant Name	DVR and LOVR Setpoints
Watts Bar [26 and 27]	0.96 (96.00% of nominal voltage) on two out of three coincidence logic to initiate a 10-second (nominal) time delay prior to trip of shutdown board supply breaker. 0.87 (87.00% of nominal voltage) for LOVR with two out of three coincidence logic to initiate a 0.75-second time delay prior to trip of shutdown board supply breaker. Once the supply breakers have been opened, a second set of induction disk-type undervoltage relays, 27D, which has a voltage setpoint of 70% of 6.9kV (nominal, decreasing) and an internal time delay of 0.5 seconds (nominal) at zero volts, will start the diesel generator. A third set of induction disk-type undervoltage relays, 27S, which has a voltage setpoint of 70% of 6.9kV (nominal, decreasing) and an internal time delay of 3 seconds (nominal) at zero volts, will initiate load shedding of the loads on the 6.9kV shutdown board, selected loads on the 480V shutdown board, and closure of the 480V shutdown-board current-limiting reactor bypass breaker.
Clinton [48]	The first level of undervoltage relays is set at approximately 69% of 4160-V (time dial 2) for Divisions 1 and 2. A similar characteristic for Division 3 has been created using instantaneous undervoltage relays with a timer. Division 3 setting is approximately 60% of 4160-V. Spurious transfers are precluded by the 69% setting (Divisions 1 and 2) and 60% (Division 3). No specific voltage setpoints for DGVR* are specified in the FSAR. A time delay of 15 seconds, however, is specified. The following is a brief description of FSAR information. An independent second level of undervoltage protection is provided at 4160-V Class 1E buses 1A1, 1B1, and 1C1. Class 1E buses 1A1, 1B1, and 1C1 have a second level undervoltage scheme that utilizes two undervoltage relays; one sensing voltage across A-B phase, and the other across B-C phase. The output contacts of all the second level of undervoltage relays are wired in series requiring both relays for a bus to be picked up before a timer starts. Once the undervoltage relays indicate degraded voltage causing the 15-second time delay relay to time out, the system automatically trips the offsite sources causing

Plant Name	DVR and LOVR Setpoints
	load shedding and the "slow" transfer to the onsite power source.
Harris [46]	The FSAR discusses the criteria used to establish the voltage and time delay setpoints of the undervoltage relays, but it does not specify their values. However, a detailed discussion for DGVR is provided in a separate document (See HNP-13-001LAR, [43]). The information provided is summarized below. The DGVR dropout trip setpoint is > 6420 V (90%) with less than 16 seconds time delay with SIAS, and less than 54 seconds without SIAS. An “allowable value” of more than 6392 V with less than 18 seconds time delay with SIAS, and less than 60 seconds without SIAS. The information provided above can also be used to arrive at the safety margin embedded in the setpoints.
* DGVR = degraded voltage relay; DVR = degraded-voltage relays; FSAR = final safety analysis report; kV = kilovolts; LOVR = loss-of-voltage relays; SIAS = safety injection actuation signal; V = volts;	

An initial investigation of advanced reactors and small modular reactors (SMRs) was performed, but a detailed evaluation was not conducted in this study. The characteristics of these reactors and their reliance on electrical power vary significantly. For example, The AP1000 is designed with passive safety-related systems for core cooling and containment integrity, thus the risk significance of the loss of offsite power (LOOP) and station black out (SBO) is less. This feature of the AP1000 diminishes the impact of electrical harmonics on operations of DVR/LOVR. The AP1000 safety analyses assume that the reactor coolant pumps can receive power from either the main generator or the grid for a minimum of 3 seconds following a turbine trip. If, during power operation of the plant, a turbine trip occurs, the motive power (steam) to the turbine will be removed. The generator will attempt to keep the shaft rotating at synchronous speed (governed by the grid frequency) by acting like a synchronous motor. The reverse-power relay monitoring generator power will sense this condition and, after a time delay of at least 15 seconds, open the generator breaker. During this delay time, the generator will be able to provide voltage support to the grid if needed.

3.1 Types of Relays Used for UV/DVR in Operating NPPs and the Impact of Power System Harmonics

There are three types of relays used in electrical power systems in NPPs: electromechanical relays, solid-state relays, and digital relays. These same types of relays could be used for LOVR and DVR applications. These relays are actuated based on peak voltages (PEAK) of the fundamental frequency, which is proportional to its rms value, the average of the rectified voltage referred to here as the direct current average voltage (DCAV), or programmable relays such as digital relays (DR). Information is mainly gleaned from two references [5 and 21].

Electromechanical relays are sometimes used in support of LOVR and DVR functions. The responsiveness of electromechanical relays (defined by the response ratio or relative response) to harmonic distortion of the measured quantity (i.e., current or voltage) is dependent on the details of the relay design. Some electromechanical relays will dampen higher harmonics, and some may not. [See Figure 13-3 of Reference 21]. These relays work based on peak voltage (PEAK), which is proportional to rms voltage at fundamental frequency. Filtering out the harmonics could be the best solution for the use of LOVR electromechanical relays and provides a consistent process for testing and calibrations. In addition, electromechanical negative sequence relays use passive components (i.e., resistors, inductors, and capacitors) to create the phase shifts necessary to derive a negative sequence quantity from phase quantities. These phase shifting networks only create the desired phase shift at the fundamental frequency. Filtering out the harmonics can also help this aspect of the measurements.

Static relays (solid state relays) must transform an input alternating current (AC) quantity to a direct current (DC) quantity representing the DCAV or the PEAK to be compared with a reference value in an electronic comparator device. How this AC to DC transformation occurs, along with any signal filtering, determines the relay's responsiveness to harmonic distortion of the input quantity. These characteristics are at the discretion of the relay designer, and generalizations are not useful.

The following describes two examples of electromechanical relays as discussed in Reference [5].

Example 1: These relays like GE Type NGV[3] are high-speed electromechanical relays operating based on DCAV. They are designed to operate continuously in the pickup mode at rated voltage. The relay element consists of a telephone-type relay in series with a Zener regulator connected across a full-wave rectifier. A capacitor is connected across the rectifier AC supply to protect the rectifier from severe voltage surges. A rheostat is also connected in series with the rectifier to provide pickup adjustment. The relay is intended for general applications where instantaneous detection of undervoltage conditions is required. A typical application would be for undervoltage detection for emergency throw-over control equipment. See Figure 6-4 of Reference [5] for the schematic diagram of this type of relay.

Example 2: The second type of relay is like the ABB *type* ITE-27 voltage relay. Figure 6-5 of Reference [5] presents a block diagram of the basic components in this type of relay. It is available in a high-speed instantaneous trip model or a delayed time trip version. Typical applications include undervoltage protection of motor feeder circuits and initiation of transfer in automatic bus transfer schemes. This relay is an electronic circuit consisting of a regulated reference voltage, an input signal processing circuit, a pickup circuit, a timing circuit (only for delayed-trip models), and a final output stage. There is also an optional harmonic filter circuit that interfaces with the input circuit. The input circuit is a step-down transformer feeding an adjustable amplifier to provide a nominal 10-V peak AC voltage when the measured bus voltage is at its normal operating value. The pickup circuit is an op-amp comparator circuit that maintains the pickup

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[3] NGV is the product family of instantaneous under voltage relays.

(normal) state if the input stage is continuously maintained at peak AC voltage signal of at least 10 V. If the peak AC voltage of the input circuit falls below a selectable dropout level, typically 96% of nominal voltage, the pickup circuit latches in the dropout (trip) condition until the peak ac voltage returns to at least 10 V. If a delayed-trip signal is desired, a capacitor charging circuit is initiated from the dropout pulse to provide the time delay.

Programmable digital relays can be programmed to consider the effects of harmonics if needed (e.g., second harmonic restraint on a transformer differential relay). The sampling rate plays a key role in the operation and accuracy of digital relays. For example, the sampling of the input values is done a specified number of times per fundamental cycle, typically 32 or 64. To avoid the creation of aliasing artifacts, the signal is preconditioned prior to sampling by a low-pass analog filter that has a cutoff frequency typically one-third of the sampling frequency. This equates to cutoff frequencies near the 10th (for a sampling rate of 32 per cycle) or 21st harmonics (for a sampling rate of 64 per cycle). After sampling, a digital filter may be used to attenuate signals with frequencies above the fundamental. A discrete Fourier transform (DFT) filter is used to extract the fundamental component of the signal, using either a full-cycle or a half-cycle algorithm. A full-cycle DFT filter can filter out any integer harmonics. A half-cycle DFT filter can filter out any odd harmonics. See Figures 13-1 and 13-2 of Reference [21].

3.2 Current Practices for Setting the Relay Setpoints

Robert L. White of Lawrence Livermore National Laboratory (LLNL) documented the earliest study on the concept of DVRs in the report, UCID 18690, in October 1980 [47]. This report included a technical evaluation of design modifications and changes to Technical Specifications (TS) proposed by the Rancho Seco Nuclear Power Plant for the use of DVR for electrical protection. A formal approach, to be used across plants, for developing the set point limits for DVRs was first presented by Joseph R. Jancauskas [7] [IEEE transaction on Energy Conversion, March 1994]. This paper suggested a six-step approach.

1. Understand Your System
2. Develop A DVR Setpoint Criterion
3. Determine the Minimum Operating Point Based on the Selected Criterion
4. Evaluate All Equipment to Confirm the Minimum Operating Point
5. Determine Setpoint Tolerances
6. Determine Allowable Offsite Voltage Ranges

NRC also devoted a significant effort along with nuclear industry, to develop specific guidelines for proper considerations for voltage and time delay settings of LOVR/DVR post 1994. NRC issued a comprehensive guideline in December 2011 [42]. The industry task force performed a comprehensive review of the NRC guideline and Nuclear Energy Institute (NEI) published their review results in February 2012 [31].

Several licensees submitted plant-specific applications for changes to Technical Specifications (TS) associated with DVR/LOVR to NRC. Some applications dated prior to the publication of RIS 2011-12 [42] and some after (see Duane Arnold in 2008 [48], and Shearon Harris from 2012 to

2013 [46]). Some general lessons and insights gained from the plant-specific applications, as well as the industry task force review of NRC guidelines, are identified below.

1. The time delay associated with the undervoltage relays are to be consistent with the maximum time delay considered in the design basis accident analysis.
2. To ensure no spurious operation of the LOVR/DVR, the applicants shall show that these protective relays will not actuate under the worst case expected voltage drop during normal operation. Such voltage drop can be initiated by starting a large pump/motor (for example the normal service water pump [NSWP]) or any other transient large demand. For example, at Shearon Harris, the NSWP is 3000 horsepower (hp). The starting of this pump was considered for the worst-case condition to justify the DVR time delay.
3. There are some quantitative safety margins built into the setpoints for both voltage and time delay settings, however, these appear to be plant-specific and vary across the plants. There are also qualitative margins (non-quantitative conservative assumptions) built into the analysis for estimating the minimum and the maximum setpoints. Increased conservatism could result in additional unnecessary losses of offsite power (LOOP).
4. An easy option to ensure that the DVRs will not reset during the transient period of starting the emergency loads (i.e., motors) is by demonstrating that the DVR reset time delay is longer than the voltage transients due to starting the class 1E equipment. This eliminates additional calculations needed to justify the DVR reset settings, therefore reducing the complexity of the analyses.
5. Increased DVR settings (dropout) would increase the probability of spurious LOOP and an increase in reset value (if used) may increase the probability of delayed LOOP with double sequencing effects as discussed in NRC GSI-171[4], “ESF Failure from Loop Subsequent to a LOCA.”
6. The beneficial effects of transformer tap changes and accounting for the voltage drop due to the impedances up-stream of the emergency buses are permitted when the applicant needs the credit to support the DVR setting. Such evaluations, however, must be performed by detailed load flow analyses, which may cause additional complexities.

The insights and experience gained from these submittals and the insights from industry task force reviews were integrated into a guidance document set forth by the nuclear industry in NEI 15-01, Rev.1, released November 2015[32].

The brief discussion provided above demonstrates that a significant amount of effort and diligence on the part of NRC and the nuclear industry have been devoted to developing the setpoint guidelines for LOVR/DVR. It is important to note that all these documents and guidelines are developed based on the electrical power flow that is not contaminated by harmonics (only 60 CPS fundamental frequency). The effects of harmonics on operation of LOVR/DVR will depend on the magnitude of different harmonic components both sustained and transient, and the existing safety margins of the relay setpoints. Several past studies have speculated (no

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[4] Generic Safety Issue (GSI) 171, see ADAMS ML091260540, “REPRIORITIZATION AND PROPOSED RESOLUTION OF GENERIC SAFETY ISSUE-171, "ENGINEERED SAFETY FEATURES FAILURE FROM LOSS OF OFFSITE-POWER SUBSEQUENT TO A LOSS-OF-COOLANT ACCIDENT". November 23, 1998.

calculational or operational evidence has been provided) that harmonic distortions of 5% to 10% will not impact the LOVR/DVR partly due to the built-in safety margins of the relay settings.

4. Operating Experience with DVR and LOVR

Reviews and safety evaluations of the implications of operational events in nuclear power plants have resulted in new requirements and have improved the current understanding of the safety issues. For example, electrical grid events at the Millstone Station, in July of 1976 demonstrated that when the Class 1E buses are supplied by the offsite power system, sustained degraded voltage conditions on the grid can cause adverse effects on the operation of Class 1E loads. These degraded voltage conditions will not be detected by the LOVRs, that are set at a much lower voltage and a very short delay time, which are designed to detect loss of power to the bus from the offsite circuit(s).

Lessons learned from the past events from licensee event reports (LERs) or NRC generic communications (based on the evaluation of a set of events with a common theme) establish the basis for corrective actions, through regulatory requirements or the voluntary actions by the industry.

4.1 Experiences with LOVR/DVRs’ Operation Based on LERs

An LER search, which focused on the selected events that can potentially provide insights, identify issues, or lessons related to DVR and LOVR, was conducted as a part of this study. A somewhat convoluted process was followed starting with the review of an Excel spreadsheet develop by Idaho National Laboratory (INL) [72], which included all initiating events (529 initiating events) from the beginning of 1987 through the end of 2017. Focusing on LOOP, the number of events reviewed was reduced to about 100 instances. Selecting events that could potentially provide insights relating to LOVR/DVR reduced the number to 12. Additional searches of LERs focusing on the events related to LOVR/DVR but not LOOP (calibration error discovery, Technical Specification violations, etc.) resulted in an additional 4 events for a total of 16. An Excel spreadsheet[5], “Operating Events Insights-LOV_DVR.xlsx,” (Attachment 2) was developed for these 16 events containing the following columns:

1. Plant Docket Number.
2. LER number with an embedded link to the PDF.
3. Actual link to NRC/INL site.
4. Summary description of the event.
5. Main insights and lessons extracted from the event. When there is no entry for this column, it means the event did not provide any new insights.
6. Identifying if the event is indicative of a proper actuation (working) of LOVR/DVR, and occurrence of Under Voltage (UV) or Degraded Voltage (DV) condition.

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[5] This reference will eventually be housed in NRC’s ADAMS under the accession number ML23094108.

Additional searches regarding the operating experience at NPPs yielded a presentation by Mr. Roy Lyon from Southern Nuclear [69]. This presentation refers to EPRI Report 1023147, dated May 2011, and indicates that the study reviewed 64 NRC LERs related to power grid events from 2001 through 2010. It discusses Salem and Duane Arnold events as potential grid instability events requiring DVR operation. It estimates that LOOP due to grid instabilities, which demand the operation of DVRs, will have a frequency around 1.0E-3 per year (about 1% of all losses of offsite power). This value cannot be verified without access to the EPRI Report 1023147 dated May 2011 (currently only available to EPRI members).

We also performed searches for inspection reports using the INL/NRC site related to DVR/LOVR findings. This search provided only one hit on Columbia Generating Station [69]. The inspection finding was related to the failure of the licensee to assess the cumulative effects of the 4160 Vac system, test source, and transient harmonics on the secondary level undervoltage relays prior to August 22, 2013. These were well-known lessons that have been identified by several different NRC documents and discussed in detail in the remainder of this section.

The lessons and insights gained from this exercise are summarized below.

1. Review of the procedure and activities of LOVR/DVR testing and calibration to ensure that if an error trips the offsite power from the 1E bus, the EDG can be connected to the bus under any condition [LER #2542018005].
2. There have been several events that indicated that there could be demands on LOVR/DVR from plant-centered activities and components and not due to the degradation of offsite power (e.g., possibility of unnecessary losses of offsite power). Included are testing activities in the plant that resulted in a trip of the 1E bus due to LOVR/DVR setting [LER # 2512013002 and # 2471999015], and transfer of loads from the auxiliary transformer to the startup transformer (LER # 2191997010] due to such causes as slower than expected bus transfers.
3. In one case in LER # 2442003002, the operator stripped all 1E buses due to a switching transient caused by voltage swells and dips but not long enough or large enough to actuate LOVR/DVR. Such manual stripping of offsite power can cause unnecessary LOOPs.
4. There is a general issue regarding the sustained Open Phase Condition (OPC) event, which may not trip the LOVR/DVR [See LER# 4542012001 for example]. One possibility suggested is to add a new negative sequence voltage relay designed to detect an OPC.
5. For some of the manufacturers of LOVR and DVR, calibration drifts could be an issue [See LER # 3111991008]. A program to monitor the industry-wide calibration drifts and identify the relays that need changing could be beneficial.
6. The impacts of harmonics from the calibration and measurement equipment on the setpoint and calibration of the LOVR/DVR were the subject of several events [See for example LER # 3311994012]. Some manufacturers recommend the harmonic distortion level below 3% for power sources used for calibration equipment.

4.2 Experiences with Test, Calibration, and Maintenance of LOVR/DVR

NRC through Information Notice (IN) 95-05[43] and the International Atomic Energy Agency (IAEA), as part of IAEA-SSG34-Pub1673web-53477409 [29], have provided specific guidelines related to controlling the effect of electrical harmonics on testing and calibration of LOVR/DVRs. Both documents have identified the impact of harmonics on LOVR/DVR settings based on operating experiences and provided guidelines for eliminating the harmonics effects during testing/calibrations.

The following summarizes the most important guidelines from IAEA-SSG34.

1. Harmonics due to switching surges or rotating equipment should be considered for operability. Switching operations, rectifiers, inverters, and rotating equipment can generate harmonics and electrical noise that may be detrimental to equipment designed to operate at nominal frequency and voltage. Additional equipment to filter or suppress electrical noise may be necessary for the reliable operation of equipment sensitive to electrical noise in the power system.
2. Measuring circuits should be immune to harmonics.
3. The design of static inverters should ensure that the voltage harmonics produced by the inverter itself, as well as other non-sinusoidal loads, do not degrade the operation of protective relays.
4. A typical scheme for degraded voltage relay involves two separate time delay relays to address the following conditions:

   (a) The duration of the first-time delay is sufficient to establish the existence of a sustained degraded-voltage condition and it should be longer than the transient duration of starting a motor. Following this delay, an alarm in the control room alerts the control room operators to the degraded condition. The subsequent occurrence of an accident signal immediately separates the safety distribution system from the off-site power system.
   (b) The duration of the second time delay is selected to be less than the duration of sustained degraded voltage conditions that would damage the permanently connected safety loads. Following this delay, if adequate voltages have not been restored, the safety distribution system is automatically or manually (by operator action) separated from the off-site power system.

More comprehensive instructions and guidelines are provided in Information Notice (IN) 95-05 with detailed discussion of some major operating experiences. The following summarizes the portion of guidance as it relates to calibration and testing of LOVR/DVR.

1. Test equipment used for undervoltage relay settings (LOVR/DVR) should be equipped with power supply with low harmonic distortion (clean supply). Some relay manufacturers such as ABB recommend an AC-voltage test source free from harmonics.

2. Peak voltage changes rather than RMS values are more indicative of harmonic distortion for UV/DV relay operation.
3. Do not use a digital voltmeter (DVM), which measures RMS rather than peak for relay setting.
4. Harmonic filters are needed on LOVR/DVR; however, they may be sensitive to temperature and radiation. The harmonic filters should be qualified for the operating and accident environment, specifically temperatures and radiation.

5. Requirements, Guides, and Standards

Design and operation of onsite electrical systems at NPPs must comply with NRC guidelines and industry standards or provide adequate technical justification for using alternate methods. With the focus on undervoltage protection (LOVR/DVR) and the impact of harmonics, the following three sections of this report discuss the NRC requirements, the NRC guides, and the relevant industry standards.

5.1 NRC Requirements

The NRC requirements for LOVR/DVR are summarized in RIS 2011-12 [42]. This document is referred to and has overlap with several other NRC regulatory documents. The following summarizes the most relevant NRC guidelines and acceptable methods and practices as they relate to LOVR/DVR.

1) The selection of voltage and time delay setpoints is to be determined from an analysis of the voltage requirements of the safety-related loads at all station electric power system distribution levels.
2) The voltage protection shall include coincidence logic (redundancy) to preclude spurious trips of the offsite power source.
3) The allowable time delay, including margin, shall not exceed the maximum time delay that is used in the FSAR accident analyses.
4) The time delay shall override the effects of expected short duration grid disturbances, preserving availability of the offsite power source(s). The allowable time duration of a degraded voltage condition at all distribution system levels shall not result in the failure of safety-related systems or components.
5) The DVR/LOVR shall automatically initiate the disconnection of offsite power source(s) whenever the voltage and time delay limits have been exceeded.
6) LOVR/DVRs shall be designed to satisfy the requirements of IEEE Standard 279-1971, “Criteria for Protection Systems for Nuclear Power Generating Stations.” The guidelines are provided in Appendix 7.1B of the Standard Review Plan [70].
7) The Technical Specifications shall include limiting conditions for operation, surveillance requirements, trip setpoints with minimum and maximum limits, and allowable values for voltage setpoints for LOVR/DVR.

The NRC incorporated the staff positions to meet GDC-17 requirements and the guidance for the Branch Technical Position (BTP) in the Standard Review Plan (SRP/NUREG-0800), for example, see BTP 8-3 [36]and 8-6 [37].

5.2 NRC Guidelines for Onsite Electrical Systems

There are several NRC guides related to onsite electrical systems and various aspects of LOVR/DVRs. The following summarizes the most relevant NRC requirements as they relate to LOVR/DVR and electrical harmonics.

1) BTP 8-6 [37]: Among other things, this BTP focuses on guidelines for DVR setpoints. It indicates that the first time delay should be long enough to establish the existence of a sustained degraded voltage condition. Following this time delay, an alarm in the control room should alert the operator to the degraded condition. The subsequent occurrence of a safety injection actuation signal (SIAS) should immediately separate the Class 1E distribution system from the offsite power system. In addition, the degraded voltage relay logic should appropriately function during the occurrence of an SIAS followed by a degraded voltage condition. The second time delay should be limited to prevent damage to the permanently connected Class 1E loads. Following this delay, if the operator has failed to restore adequate voltages, the Class 1E distribution system should be automatically separated from the offsite power system. The basis and justification for such an action must be provided in support of the actual delay chosen.

2) RG 1.180 [39]: This RG provides guidance on design, installation, and testing practices for addressing the effects of electromagnetic and radio-frequency interference (EMI/RFI) and power surges on safety-related instrumentation and control (I&C) systems. It endorses IEEE 603, IEEE 279, IEEE C52.41 and IEEE C52.45 in addition to IEC 61000-4 and Military Standard MIL-STD-461E. This RG does not mention IEEE 519.

3) Regulatory Issue Summary (RIS) 2011-12 [42]: This RIS details all the relevant issues related to DVR and closely overlaps with the information in BTP 8-6.

4) RG 1.32 and RG 1.81 [59 and 71]: RG 1.32 provides guidelines for endorsing IEEE 308-2001, “Criteria for Class 1E Power Systems for Nuclear Power Generating Stations,” however, the NRC does not endorse the IEEE Std. 308-2001 criteria for sharing safety-related DC power systems in multi-unit nuclear power plants including the advanced reactors. More detailed guidance on sharing electrical power systems at multi-unit nuclear power plants, is discussed in Revision 1 of RG 1.81, “Shared Emergency and Shutdown Electric Systems for Multi-Unit Nuclear Power Plants.” The potential for harmonics injection from shared systems, however, is not addressed.

5.3 Industry Standards Applicable to Electrical Systems at Nuclear Power Plants

There are several standards that could be used in relation to electrical power systems at NPPs; some of which are endorsed by NRC. These are (1) IEEE standards 141, 308, 741, 765, and 519, (2) NEMA standard MG-01-2009, and (3) European standard EN 61000-3-2. These standards provide guidelines for design and operation of safety-related electrical systems but do not explicitly address the issues of electrical harmonics and its impact on safety-related electrical systems. Two of these standards, IEEE std. 741 and IEEE std. 308, could be expanded to address the impact of electrical harmonics more explicitly on safety-related electrical systems and the associated protection devices such as LOVR/DVRs. It is our understanding that this option may be considered by NRC.

Currently, four of the standards do address the issues related to electrical harmonics. These are briefly discussed below:

1. **IEEE Std 519-2014,** “IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.” This standard specifies limits on the magnitude of harmonics that an industrial facility can inject to the electrical grid at the Point of Common Coupling (PCC). The THD limits are set at 10% with no single harmonic component to contribute more than 3% to THD. It does not provide any guidance of what the limits for the harmonics are within the industrial facility. The amount of THD injected into an industrial facility from the grid is controlled by this standard and it is expected to be less than 10%. NRC does not currently endorse this standard.

2. **IEEE Std-141-1993,** “IEEE Recommended practice for electric power distribution for industrial plants.” Section 9 of this IEEE standard discusses harmonics. Section 9.8.2.7 discusses the effect of harmonics on switching and relaying. See the quote below:

   > “Protective relays do not respond to any one identifiable parameter such as the rms value of a primary quantity or the fundamental frequency component of that quantity. As a related consideration, the performance of a relay to a range of single frequency inputs is not an indication of how that relay will respond to distorted wave containing those frequencies. Superposition does not apply. Multi-input relays may be more unpredictable than single input relays in the presence of wave distortion. Relay response under distorted conditions may vary among relays having the same nominal fundamental frequency characteristics, not only among different relay manufacturers, but also among different vintages of relays from the same manufacturer.”

   It states that harmonic levels required to cause the mis-operation of relays are greater than 10%, but it does not substantiate this claim with any data or analysis.

3. **British Standards Document BS EN 61000-3-2 (2000) and EN 61000-3-4 (1998):** Provides guidance on limits for harmonic current emissions (equipment input current ≤ 16 A per phase), and limits for harmonic currents produced by equipment connected to public low-voltage systems with input current > 16 A and ≤ 75 A per phase.

4. **National Electrical Manufacturers Association** (**NEMA) MG-01 (2009):** NEMA MG1 is a comprehensive document providing detailed information related to electrical portions of motors and generators. The specific section of interest to this study is Section 30.1,

"Application Considerations for Constant Speed Motors used on a sinusoidal bus with harmonics." It introduces the harmonic voltage factor (HVF), which is used to arrive at a derating of motors when their electrical supplies are contaminated with harmonics. This concept can be used to evaluate the impact of harmonics on motor loads in case DVRs are not actuated as planned. NEMA MG-01 also provides guidance on the application of power capacitors to a bus with a harmonic current. It highlights the importance of avoiding harmonic resonance caused by these capacitors combined with the inductance from the transformers.

There is a possibility that NRC endorses additional standards or some standards with exceptions. For example, the IEEE standards such as IEEE Std. 741 and IEEE Std. 308 can be expanded to address the impact of electrical harmonics more explicitly on electrical protective devices such as LOVR/DVRs.

6. Other Information Sources

ChatGPT is an Artificial Intelligence system designed to respond to text-based queries and generate natural language responses. ChatGPT represents a significant advancement in the field of Natural Language Processes (NLP) and has the potential to expedite the research project by providing an understanding of the current state of knowledge. A detailed inquiry of ChatGPT was conducted early in this project. A transcript from a ChatGPT interaction (Questions, "Q" and Answers, "A") is included as Appendix A.

7. Summary, Conclusions, and Path Forward

The emergency buses at NPPs are provided with LOVRs and DVRs that initiate transfer from the normal supply to the standby (emergency) power supply (e.g., diesel generators). A combination of LOVRs and DVRs with associated setpoints and time delays constitute a double scheme of protection against both instantaneous loss of offsite power (low voltage below a set limit) and long-duration, degraded voltage events.

Each U.S. NPP has performed a set of comprehensive calculations to determine the voltage setpoints and the appropriate time delays for LOVR/DVR that ensure high-reliability, Class 1E power, consistent with assumptions made in the analysis of design-basis accidents. All these calculations are performed assuming that the offsite power is at the base fundamental frequency of 60 CPS, which excludes any effect from harmonic components.

The calibration and testing of these relays are also performed with a power source free from harmonic contamination, i.e., at the fundamental frequency of 60 CPS. In addition, all DVRs/LOVRs in operating NPPs in the U.S. are equipped with harmonic filters to eliminate the higher frequency harmonics prior to voltage measurements for actuation or for establishing the set points. Therefore, it would be precise to say that these relays are designed, calibrated, and will be actuated based on the voltage magnitudes at the fundamental frequency. However, it is expected that LOVR/DVR will operate as intended with a small amount of THD.

In actual service applications, all Class 1E equipment is exposed to electrical power contaminated by harmonics of varying magnitude. The equipment is expected to operate based on the aggregate voltages resulting from all harmonic components, rather than just the voltage at the fundamental frequency. It is anticipated that Class 1E equipment is protected by LOVR/DVR and it will respond properly, even under the presence of some harmonic contamination (e.g., THD < 5%). A limit on the magnitude of sustained harmonics on emergency buses, therefore, may become necessary to ensure the proper response of Class 1E components. Such a requirement is not currently imposed for NPPs, although some plants have voluntarily performed the required calculations to show that sustained harmonics, from both the offsite grid and internal loads, are controlled.

In addition to sustained harmonics, transitory harmonics from sources such as power system transients (e.g., switching surges) or external causes, like geomagnetic storms, may exist. The duration of transient harmonics and their magnitudes can vary and separation from the offsite power during the periods of excessive harmonics may be necessary.

A review of the operational experience with the current designs of these relays has not yet shown any adverse impact on plant safety. The safety significance of this issue is currently considered small due to its low frequency of occurrence. We did not find any formal analysis to support this conclusion. Due to low frequency of occurrence, a risk analysis of this issue will be beneficial. A formal risk evaluation of the impact of harmonics should address the following two issues:

A. When the voltage of the fundamental component of harmonically contaminated electrical power (sustained or transient) is above the relay set points, can we assure that the safety systems will operate properly if needed? Can the aggregate voltage (effect of harmonics included) reliably start and run the Class 1E equipment? What is the likelihood that the safety components can properly operate under this condition and at the rated capacity? What is the incremental risk? Is the incremental risk acceptable and consistent with the NRC risk-informed framework?

B. When the voltage of the fundamental component of harmonically contaminated electrical power (sustained or transient) is below the relay setpoint such that the offsite power is stripped, can the aggregate voltage (effect of harmonics included) reliably start and run the safety equipment? Is the incremental risk of the induced loss of offsite power when not needed within the acceptable risk limits?

Scenario B is of less interest to evaluate and it is expected to be screened out. It is noted here for completeness.

The risk-informed analysis would estimate the magnitude and duration of harmonics to arrive at the frequency of the harmonics-related initiating events. The risk analyses also require estimates of the failure probability of the safety components during such initiating events when the LOVR/DVR do not respond properly. The failure probability of the impacted safety components depends on the types of loads fed by the emergency buses. The failure likelihood of LOVR/DVR protection under excessive harmonic conditions depends on the built-in safety margins in LOVR/DVR settings. The risk-informed evaluation should be performed in several screening phases (starting from the least complicated models and data to more complex models/data) to ensure that the levels of analysis and degrees of conservatisms commensurate with the answers are explored.

Risk informed evaluation can be addressed by a combination of deterministic, and a risk-informed analyses. The process can be facilitated by voluntary industry initiatives or in response to NRC initiatives. For example, the IEEE standards such as IEEE Std. 741 and IEEE Std. 308 can be expanded to address the impact of electrical harmonics more explicitly on safety-related electrical systems and the associated protection devices such as LOVR/DVRs. Such standards then could be directly endorsed by NRC in one or more regulatory guides requiring industry action.

At the outset, further technical characterization of the impact of harmonics on safety-related electrical equipment is warranted. A simplified and somewhat conservative evaluation, accounting for both the frequency and duration of grid disturbances causing harmonics, is to be conducted to determine the bounding harmonic limits at an NPP. Note that the current limits of harmonics may change depending on the future grid conditions. For example, the effect of extensive use of electric vehicles (EVs) and their charging stations can significantly affect the magnitude of harmonics on the electrical grid. If the bounding limits of harmonics are small (e.g., THD < 5%), or the risk significance associated with the impact of harmonics on the nuclear power plants is below regulatory concern, no further action may be required. Section 7.1 discusses a proposed approach for evaluating the risk significance associated with the impact of harmonics on nuclear power plants.

However, if the risk impact of harmonics is within the regulatory concern, there are means of reducing the magnitude of harmonics injected to Class 1E buses. These are referred to as deterministic or engineering solutions for harmonic reductions. In cases when deterministic solutions for harmonic reduction are not sufficient, the harmonics on Class 1E buses should be monitored using a computerized digital meter (relay) with the ability to override the existing LOVR/DVR actuation setpoints and time delays. Section 7.2 discusses the considerations for a deterministic approach including the use of digital harmonic monitors. This issue may not be generic and varies significantly among plants. A combined deterministic and risk-informed evaluation may be required to address plant-specific configurations.

7.1 Risk Significance Evaluation

This section discusses a preliminary conceptual process for performing a risk-significant evaluation to address the impact of electrical harmonics. A detailed approach can be developed later, if needed. Example risk scenarios are described below for estimating the incremental risk from the operation of DVR's when the electrical power is contaminated with harmonics.

1. **Spurious or pre-mature separation of offsite power [Expected to be screened]**

In this scenario, the offsite power is stripped when not needed. It is referred to as spurious actuation of DVR relays due to electrical harmonics per design (no failure involved)[6]. A bounding estimate of the incremental risk (Core Damage Frequency) can be formulated as follows:

Risk estimation: Frequency of Grid Degraded Voltage (f_{GD}) * the probability of actuation due to externally induced grid harmonics $(P_{SA})*$ Conditional Core Damage Probability due to LOOP-$P(CD|LOOP)$; no credit for recovery action from LOOP.

2. **Failure to actuate during the grid degraded voltage, when it is contaminated by harmonics**

In this scenario, the offsite power is not stripped (the voltage of the fundamental frequency component is above the DVR threshold). However, the harmonically contaminated voltage may impact the operation of Class 1E equipment. It could impact the rating of the pumps, or it can cause excess current to individual loads and trip those protective relays. A bounding estimate of the incremental risk (core damage frequency) for this case is the following:

Risk Estimation: Frequency of Grid Degraded voltage (f_{GD}) * failure probability to actuate due to externally induced grid harmonics $(P_{NA})*$ Probability of recovery (has to be re-estimated), Conditional Core Damage Probability due to SBO (Station Blackout)-- $P^{*}(CD|SBO)$; where "*" indicates that the AC recovery actions must be revisited/re-estimated and incorporated to the risk model.

3. **Probability that DVR resets after proper actuation during load sequencing**

This is a plant-specific issue applicable to those plants that sequence the loads to the emergency bus fed from offsite power and have a DVR setpoint such that it will actuate during the loading voltage transient. These plants should ensure that the voltage is recovered above the reset point within the DVR time delay. Harmonics could impact the voltage and prevent the DVR reset, causing the sequencing of the loads to emergency diesel generators (EDGs). This is sometimes referred to as double sequencing (GSI 171).

A bounding estimate of the incremental risk (core damage frequency) for this case can be formulated like the risk assessment of GSI-171[7].

The parameters used in the above risk formulations are discussed below.

- Estimates for the conditional core damage probabilities $P(CD|LOOP), and\ P(CD|SBO)$ are currently available for all operating reactors.

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[6] DVR is either auto-actuated or offsite power is manually stripped since the voltage of the fundamental frequency component of voltage is below threshold; however, the offsite power may have sufficient capacity to start and run the Class 1E components.

[7] U.S. Nuclear Regulatory Commission, NUREG/CR-6538, "Evaluation of LOCA With Delayed Loop and Loop with Delayed LOCA Accident Scenarios, "July 1997.

- Frequency of Grid Degraded Voltage (f_{GD}) caused by harmonics can be obtained from the data for harmonic monitors at each plant site. A generic estimate with uncertainty can be determined.
- Recovery actions can be estimated using plant procedures and operator training.
- Estimating the Probability of spurious reset (P_{SR}), can be initially generated from the current load sequencing analysis. In some cases, it may require plant-specific electrical load flow and spectrum analysis calculations.

Risk Criteria should be selected consistent with RG 1.174, to show that the incremental risk of harmonics is below Region III, that is Delta core damage frequency (CDF)<1.0E-06. Assuming 1.0E-4 and 1.0E-2 for conditional CDF for LOOP and SBO, respectively; one can arrive at the generic limits for sequence frequencies. With the use of the conditional core damage probabilities as noted above, frequency limits can be established for various scenarios. A generic example of such limits is provided below for clarification purposes only.

For Scenario 1, the frequency should be less than 1.0E-2 (less than one in 100 reactor years of operation) and for Scenario 2, 1.0E-4 (Less than one in 10,000 reactor years of operation). The review of 10 years of operating data (for ~100 plants) should have given some insights for Scenario 1, but not 2. However, the LERs do not investigate electrical harmonics as the root cause for the events, so such information is not yet available. Based on the initial review of LERs, only one event was suspected of initiating Scenario 1, which translates into a frequency of ~ 1.0E-3 per year.

7.2 Deterministic Approach

This section discusses the path forward for addressing the cases where the risk significance is high enough to require additional NRC participation. There are several ways for NRC to act. Early communication and coordination with industry may become necessary to arrive at an optimum path forward. For example, NRC could issue a generic communication requesting voluntary actions from the industry. NRC could endorse a specific standard or modified version of an existing standard within a regulatory guide, and regardless of regulatory process for addressing the issue, the following technical steps/analysis could be followed:

1. Determine the current built-in safety margins in LOVR/DVR setpoints. What is the level of harmonics afforded by these safety margins?
2. Identify the most sensitive safety loads for harmonic contamination at the emergency buses that may not operate properly if the offsite power is not stripped. This is a plant-specific issue and will be different for the current generation of reactors, the advanced light-water reactors (ALWRs), and the next-generation non-light-water reactors (NLWRs).
3. Identify the available information and models that can be used to determine the response of the harmonically sensitive equipment and determine the associated harmonic limits that they can tolerate. For example, for induction motors, see National Electrical Manufacturer’s Association (NEMA)-MG-01, “Motors and Generators,” for the

reduced rating of induction motors in response to the varying magnitudes of harmonic components.

4. What are the external (offsite grid) harmonic magnitude limits that are ensured by standards such as Institute of Electrical and Electronics Engineers (IEEE) 519, International Electrotechnical Commission (IEC) 61000, etc.? What are additional sources of the internal harmonic magnitudes induced by plant equipment such as variable speed drives (VSDs), and the use of other nonlinear electrical components such as silicon-controlled rectifiers (SCRs), etc.?
5. Can the aggregate harmonics from the sources (internal and external) in (4) meet the requirements for harmonic limits determined in (3)?
6. If the magnitude of harmonic components resulting from sources identified in (4) does not meet the requirements in (3), deterministic methods for reducing the magnitude of harmonics at the Class 1E buses should be considered. The licensee may have to demonstrate that the harmonics generated from offsite sources as measured at the point of common coupling (PCC) and the harmonics generated from the internal loads on the Class 1E bus are within acceptable limits. This demonstration at minimum would involve an integrated load flow analysis from external and internal sources to the Class 1E bus.
7. For cases where the issues addressed in (6) cannot be met or the applicant may not want to do these evaluations, digital relays with override capability of LOVR/DVR may be considered.
8. A simplified but bounding risk-informed evaluation can show if the risk has been reduced such that a decision can be made. Either the risk is reduced to a degree where further regulatory actions are not warranted, or the use of the digital relays (7) is required. The applicant/licensee should demonstrate that all applicable regulations associated with safety related digital I&C systems are adhered to.

Accomplishing these tasks could require coordination and input from several different organizations, including NRC, the Nuclear Energy Institute (NEI), IEEE, the U.S. Department of Energy (DOE), and other government organizations. This is an important and complex undertaking that requires coordination and communication among several stakeholders.

Appendix A Brief Q&A with ChatGPT About Harmonics[8]

Q: Explain the potential impact of Harmonics on nuclear power plants' electrical safety systems.

A: Harmonics can impact the electrical safety systems of nuclear power plants in several ways:

- Overloading: Harmonics can increase the current levels in the electrical systems, potentially leading to equipment overload and failure.
- Interference: Harmonic currents can interfere with protective relays, causing them to act erratically, potentially compromising safety.
- False Trips: Harmonics can cause false trips of safety systems, leading to unexpected shut down of the power plant and risking the safety of the reactor.
- Equipment Damage: Harmonics can lead to overheating and damage to electrical equipment, compromising its reliability and increasing maintenance costs.
- Therefore, it is important to control and mitigate harmonics in the electrical systems of nuclear power plants to ensure the safety and reliability of the power plant.

Q: What design features can we include to prevent the negative impact of harmonics?

A: Design features that can prevent the negative impact of harmonics in electrical systems include:

- Harmonic Filters: Installing filters that block or dampen harmonic frequencies can reduce the overall level of harmonics in the system.
- Active Harmonic Correction: Using active harmonic correction devices such as harmonic mitigation drives can actively correct harmonic distortions in real-time.
- Power Factor Correction: Installing power factor correction capacitors can improve the power factor of the electrical system, reducing the level of harmonic currents.
- Isolation Transformers: Using isolation transformers with sufficient impedance can limit the number of harmonics that enter or leave a system.
- Grounding and Shielding: Proper grounding and shielding of electrical equipment can reduce the level of electromagnetic interference caused by harmonics.
- Load Balancing: Balancing the load on different phases of a system can reduce the overall level of harmonics.
- Proper Cable Sizing: Proper cable sizing and routing can prevent excessive voltage drops and minimize the amount of harmonic current generated by the system.

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[8] We used ChatGPT as additional help on our search for relevant documentation, and not as a facts source. For example, it helped us use different words, or even different lines of inquiry, when searching for published titles. We are responsible for the questions we posed (the Q's); ChatGPT answers (the A's) are reproduced here unedited and unverified. The answers are not to be taken as facts, or even as correct without further verification.

- Implementing these design features can help prevent the negative impact of harmonics on electrical systems, ensuring their reliability and safety.

Q: What are the most recent relevant regulatory measures to mitigate harmonics in nuclear power plants?

A: Harmonics mitigation in nuclear power plants is regulated by various organizations, including international and national electrical standards organizations and nuclear safety agencies. Some of the most recent relevant regulatory measures include:

- IEEE 519-2014: The Institute of Electrical and Electronics Engineers (IEEE) Standard 519-2014 provides guidelines for the acceptable levels of harmonic distortion in electrical power systems.
- IEC 61000-3-2: The International Electrotechnical Commission (IEC) Standard 61000-3-2 defines the limits for harmonic currents generated by equipment connected to low-voltage power systems.
- NRC Regulatory Guide 1.174: U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.174 provides guidance[9] on electrical power system harmonics for commercial nuclear power plants.
- WANO Guidance on Harmonic Distortion: The World Association of Nuclear Operators (WANO) provides guidance on harmonic distortion and its impact on the safe and reliable operation of nuclear power plants.
- These regulatory measures ensure that nuclear power plants implement adequate measures to mitigate the negative impact of harmonics on their electrical safety systems and to maintain their reliability and safety.

Q: Are there any gaps in the regulation of harmonics that may allow increased risk?

A: Yes, there may be gaps in the regulation of harmonics that allow for increased risk in nuclear power plants. Some of the common gaps include:

- Lack of uniformity: Regulations and standards for harmonics mitigation vary between countries, regions, and organizations, leading to a lack of uniformity in the implementation of harmonics mitigation measures.
- Lack of enforcement: While regulations exist, the lack of enforcement and monitoring of harmonics mitigation measures can lead to non-compliance and increased risk.
- Evolution of technology: The rapid evolution of technology and electrical equipment can lead to new sources of harmonic generation that are not covered by existing regulations.

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[9] This is an example of ChatGPT flawed output. This regulatory guide (1.174) does not deal with harmonics and the word “harmonic” is not anywhere in its text.

- Limited scope: Some regulations and standards only cover specific aspects of harmonics mitigation, such as the levels of harmonic distortion, and do not address other important factors, such as the impact of harmonics on safety systems.
- No consideration of specific site conditions: Regulations and standards may not consider the specific site conditions and electrical configuration of each nuclear power plant, leading to one-size-fits-all solutions that may not adequately address the harmonics risk at a specific site.
- Therefore, it is important for regulators and industry to continuously evaluate and update regulations and standards for harmonics mitigation in nuclear power plants to ensure their safety and reliability.

Q: what are the mitigation measures that need to be explored

A: To mitigate the negative impact of harmonics on solid-state technology in electrical safety systems in nuclear power plants, the following mitigation measures should be explored:

- Harmonic Filters: Installing filters that block or dampen harmonic frequencies can reduce the overall level of harmonics in the system and prevent interference with digital control systems.
- Active Harmonic Correction: Using active harmonic correction devices such as harmonic mitigation drives can actively correct harmonic distortions in real-time, improving the accuracy of digital control systems.
- Power Factor Correction: Installing power factor correction capacitors can improve the power factor of the electrical system, reducing the level of harmonic currents and preventing overheating of solid-state components.
- Isolation Transformers: Using isolation transformers with sufficient impedance can limit the number of harmonics that enter or leave a system and prevent false trips in safety systems.
- Grounding and Shielding: Proper grounding and shielding of electrical equipment can reduce the level of electromagnetic interference caused by harmonics and improve the accuracy of measurement systems.
- Load Balancing: Balancing the load on different phases of a system can reduce the overall level of harmonics and prevent overheating of solid-state components.
- Proper Cable Sizing: Proper cable sizing and routing can prevent excessive voltage drop and minimize the amount of harmonic current generated by the system.
- These mitigation measures can help reduce the negative impact of harmonics on solid-state technology in electrical safety systems in nuclear power plants, ensuring their reliability and safety. It is important to evaluate the specific site conditions and electrical configuration of each nuclear power plant to determine the most appropriate harmonics mitigation measures.

Q: What parameters make the electrical safety system more vulnerable to the impact of harmonics

A: The electrical safety system in a nuclear power plant can become more vulnerable to the impact of harmonics due to several parameters, including:

- System Configuration: The electrical configuration of the system, including the type of equipment and the distribution network, can impact the level of harmonics generated and the susceptibility of the system to harmonic-related problems.
- Load Profile: The load profile of the system, including the type and size of the electrical loads, can impact the level of harmonics generated and the susceptibility of the system to harmonic-related problems.
- Power Quality: The power quality of the electrical supply, including the level of voltage and frequency stability, can impact the level of harmonics generated and the susceptibility of the system to harmonic-related problems.
- Cable Impedance: The impedance of the electrical cables can impact the amount of harmonic current generated by the system and the susceptibility of the system to harmonic-related problems.
- Grounding and Shielding: The grounding and shielding of electrical equipment can impact the level of electromagnetic interference caused by harmonics and the susceptibility of the system to harmonic-related problems.
- Age and Condition of Equipment: The age and condition of the electrical equipment, including transformers and switchgear, can impact the level of harmonics generated and the susceptibility of the system to harmonic-related problems.
- By understanding these parameters, it is possible to identify areas of the electrical safety system that are particularly vulnerable to the impact of harmonics and implement appropriate mitigation measures to reduce the negative impact of harmonics on the system.