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COMPLAINT OF PETTY GROUP, LLP	§	BEFORE THE
AGAINST RIO GRANDE ELECTRIC	§	STATE OFFICE OF
COOPERATIVE, INC.	§	ADMINISTRATIVE HEARINGS

DIRECT TESTIMONY

OF

ROBERT D. GRUBB, P.E.

ON BEHALF OF

PETTY GROUP, LLP

Sponsoring Petty Exhibit Nos. RG-1 through RG-10

April 3, 2020

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COMPLAINT OF PETTY GROUP, LLP AGAINST RIO GRANDE ELECTRIC COOPERATIVE, INC.	**§ § §**	**BEFORE THE STATE OFFICE OF ADMINISTRATIVE HEARINGS**

DIRECT TESTIMONY OF ROBERT D. GRUBB, P.E.

I. INTRODUCTION, EXPERIENCE AND QUALIFICATIONS

Q. PLEASE STATE YOUR NAME, EMPLOYER, TITLE AND BUSINESS ADDRESS.

A. My name is Robert D. Grubb. I am the founder and Principal Engineer for Grubb Engineering. Inc. ("GEI"). My business address is 2727 North Saint Mary's Street, San Antonio, Texas 78212.

Q. ON WHOSE BEHALF ARE YOU SUBMITTING THIS TESTIMONY?

A. I am testifying on behalf of Petty Group, LLP ("Petty").

Q. PLEASE OUTLINE YOUR EDUCATIONAL BACKGROUND.

A. I have a Bachelor of Science in Electrical Engineering from the University of Texas at Austin. I have also attended 85 classroom hours (equivalent to a graduate course) for "Modeling and Analysis of Modern Power Systems" at the University of Texas at Arlington.

Q. ARE YOU A REGISTERED PROFESSIONAL ENGINEER?

A. Yes. I am a registered professional engineer in the State of Texas and the State of California.

Q. PLEASE DESCRIBE GEI'S CERTIFICATIONS AND ACCREDITATIONS.

A. GEI is registered as an engineering firm with the Texas Board of Professional Engineers. Its technical services division is an accredited, full-time member of the InterNational Electrical Testing Association ("NETA"). GEI's eleven Technical Service employees are certified Electrical Test Technicians ("ETT") Levels 1 through 3.

Q. ARE YOU A MEMBER OF ANY PROFESSIONAL ORGANIZATIONS?

A. I am a Senior Life member of the Institute of Electrical and Electronic Engineers ("IEEE"), and a member of the IEEE Power Engineering Society.

Q. PLEASE DESCRIBE YOUR PROFESSIONAL EXPERIENCE.

A. I have nearly 50 years of experience in electrical engineering. I founded GEI in 1981 after working for 11 years at City Public Service Energy ("CPSE") (formerly, City Public Service Board, *et. al.*). The firm provides planning, design, engineering studies, and technical services for electrical power systems. The firm has significant experience in the design, analysis, commissioning, and maintenance of low, medium, and high voltage electrical power systems, as well as instrumentation, control, and supervisory control and data acquisition ("SCADA") design.

Since its inception, GEI has provided engineering services to electric utility companies, water and wastewater utilities, and large industrial customers with electrical infrastructure design needs. This includes utilities such as CPSE, New Braunfels Utilities, Medina Electric Cooperative, Austin Energy, Bandera Electric Cooperative, Magic Valley Cooperative, Cal-Energy, Philippine National Oil Company, Magma Geothermal, Central and Southwest, Central Power & Light, Guadalupe Valley Electric Coop. and Texas State University Co-Gen. GEI has also provided engineering services to a number of water and wastewater municipalities. Services have included low and medium voltage electrical distribution design, instrumentation system design, SCADA systems design, control system design, security system design, radio path studies, power system studies, and acceptance and maintenance testing. Municipalities include the San Antonio Water System, San Antonio River Authority, Canyon Regional Water Authority, and Guadalupe Blanco River Authority.

Prior to founding GEI, I served as Chief System Protection Engineer for City Public Service (now CPSE) where I worked for 11 years. My duties at City Public Service included planning, electrical design, coordination, and management of a wide range of electric power substation, electric transmission, electric distribution, and water and wastewater plant projects. I had oversight of electric substation design, transmission planning, distribution planning, and relay testing and maintenance. I left City Public Service in 1981 to found GEI.

Q. AS THE PRINCIPAL ENGINEER FOR GEI, DO YOU HAVE OVERSIGHT OF GEI'S TECHNICAL, DESIGN, AND ENGINEERING SERVICES?

A. Yes.

Q. PLEASE DESCRIBE GEI'S EXPERIENCE WITH ENGINEERING SERVICES FOR ELECTRICAL POWER SYSTEMS.

A. In the beginning, GEI clients were primarily electric utilities and large industrial power users. The firm has done a number of Protective Device Coordination Studies primarily for electric cooperatives and municipal utilities to assure reliability. Some were done as a sub-consultant to other engineering firms lacking the expertise in those studies. One of the first projects GEI completed was for a mini steel mill where it designed an electric demand control scheme removing electrodes from the furnace when a targeted not-to-exceed demand was approached. In 1983, GEI began designing medium-voltage plant electrical distribution for San Antonio Water Systems ("SAWS," formerly City Water Board). That SAWS association is still intact today.

Q. PLEASE DESCRIBE THE SERVICES PERFORMED BY GEI'S TECHNICAL SERVICES DIVISION.

A. GEI's technical services division employees are NETA accredited. The technical services division provides power system testing and maintenance for high, medium, and low voltage equipment. This includes transformer testing, power cable testing and cable identification, switchgear circuit breaker testing and maintenance, relay testing and calibration, auto transfer switch testing and maintenance, low-voltage circuit breaker testing and repair, motor testing, current transformer, potential transformer and control power transformer testing, and panelboard and switchboard testing. The technical services division also provides additional services, such as power quality and power consumption monitoring, ground testing, thermal infrared scanning, load bank testing, and maintenance shutdowns.

Q. PLEASE DESCRIBE GEI'S QUALIFICATIONS IN POWER QUALITY MONITORING.

A. The mechanics of power quality monitoring are the same as any other voltage and current measurement on a power system. A device capable of measuring voltage and current with powerful resolution is connected to the system and captures data pertinent to power consumption, frequency, and harmonic content. The software inside the machine performs calculations providing levels for measured parameters. The analysis of these levels are the key to successful power quality monitoring. I was first introduced to harmonics 50 years ago, when a college senior, through a lab project wherein I had to analyze a distorted waveform using Fourier Analysis to determine harmonic content. Over the next 50 years, there have been a number of instances where my working knowledge was put to use. During my employment at CPSE, I worked with settings for "harmonic restraint transformer differential relays." I have also worked with clients on investigations related to harmonics issues.

Q. WHAT TRAINING DO YOU HAVE IN POWER QUALITY MONITORING?

A. Over the years GEI has had numerous informational presentations provided by suppliers of harmonic monitoring and harmonic mitigating equipment. I have also had project and research experience on harmonics.

Q. HAVE YOU PREVIOUSLY TESTIFIED BEFORE THIS COMMISSION?

A. No.

Q. HAVE YOU PREVIOUSLY TESTIFIED BEFORE ANY REGULATORY COMMISSIONS OR COURTS?

A. A list of the court proceedings where I have offered expert testimony is attached as Exhibit RG-1. I also attach my current resume as Exhibit RG-2.

Q. WAS THIS TESTIMONY PREPARED BY YOU OR UNDER YOUR DIRECT SUPERVISION AND CONTROL?

A. Yes.

II. SCOPE OF TESTIMONY

Q. WHAT IS THE SCOPE OF YOUR TESTIMONY?

A. My testimony will address the following:

- An explanation of harmonics and IEEE Standard 519, *IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems*;
- Safety and reliability problems caused by excessive harmonics;
- Third-party engineering reports notifying Rio Grande Electric Cooperative ("RGEC" or "the "Cooperative") of excessive harmonics on the Brundage line;
- GEI's investigation of the electric service disruptions experienced by Petty and the results of its power quality monitoring;
- The basis of GEI's conclusion that Petty's load did not cause or contribute to the excessive harmonics; and

- Petty's disconnection from the grid as a result of the ongoing reliability problems on the RGEC distribution line and impaired power quality.

Q. DESCRIBE THE POWER QUALITY INVESTIGATION SERVICES GEI HAS PROVIDED PETTY.

A. GEI was hired by Petty on or about April 2, 2019 to analyze power quality problems at the Petty Ranch that Petty's electrician, Nathan Morgan, observed during construction of new residences at the Petty Ranch in early 2019. GEI's technical services division installed a power quality meter to monitor the point of common coupling ("PCC") between Petty and the RGEC distribution system on or about April 29, 2019. GEI's technical services division monitored harmonics at the PCC and provided technical support to Petty when the meter readings showed excessive voltage harmonics on the RGEC distribution system that were negatively impacting the electric power quality at the Petty Ranch. GEI provided technical support to Petty during meetings with RGEC regarding the power quality problems at the ranch. It also investigated the harmonics on Petty's load current after RGEC claimed that the Petty load was not compliant with IEEE Standard 519. GEI investigated whether Petty's load had caused the harmonics issues raised in Petty's complaint, and it provided Petty a report to share with RGEC that concluded that the power quality problems at the ranch were not created by the Petty Ranch load. GEI's report "Harmonic Analysis at the Petty Ranch" is attached as Exhibit RG-3.

Q. IN ADDITION TO POWER QUALITY MONITORING, WHAT TROUBLESHOOTING DID GEI DO TO DETERMINE WHAT CAUSED THE ELECTRICAL PROBLEMS AT THE PETTY RANCH?

A. The power quality monitoring included examination of voltage surges, sags, spikes, and current impulses, along with harmonics. All of these parameters are measured by the same machine. Before GEI started the monitoring, we had not confirmed what was causing the problems, so all of these parameters needed to be measured. As a result of analyzing the recordings, GEI determined that the electric service impairments were caused by excessive harmonics in the RGEC supply voltage.

III. EXPLANATION OF HARMONIC DISTORTION AND IEEE STANDARD 519

Q. WHAT IS HARMONIC DISTORTION?

A. Harmonic distortion is a misshaping of waveforms, voltage, and current due to the addition multiples of the fundamental frequency in an electrical distribution system. In a normal alternating current system, the sine wave varies at a specific fundamental frequency, e.g., 60 hertz. Harmonic distortion in a 60 hertz system is effectively a distortion of the 60 hertz sine wave by multiples of the fundamental being added to the fundamental frequency sine wave, *i.e.,* 3rd harmonic is 180 hertz, 5th is 300 hertz, etc.

Q. WHAT CAUSES HARMONIC DISTORTION?

A. Harmonics are caused by non-linear loads on electric power systems. All non-linear loads can create some minor level of harmonic distortion on electrical current, but excessive harmonic distortion from non-linear loads causes unsafe, unreliable and impaired electric power, or what in the industry is called “dirty power.” The main culprit of excessive harmonic distortion on RGEC’s electric distribution system are variable speed electronic motor controls, i.e., variable frequency drives (“VFDs”), that are used to start large industrial motors.[1] VFDs are known to cause harmful harmonics by drawing a nonsinusoidal current and introducing nonlinear voltage throughout the distribution system.

Q. IS VFD USAGE COMMON ON THE DISTRIBUTION LINE THAT SERVES THE PETTY RANCH?

A. Yes.

Q. PLEASE EXPLAIN.

A. The Petty Ranch is located in South Texas in the Eagle Ford Shale region. As described in the direct testimony of Kyle Haley, the area has seen a large increase in oil and gas drilling operations in the last ten years. Service to the Petty Ranch is from a 53-mile long distribution line that originates at the RGEC Brundage Substation (the "Brundage line").[2] The Brundage line serves primarily oil and gas loads and several operators. In 2019, load on the line was 78.3% industrial and 6.3% residential.[3] Oil and gas customers commonly use large motors and, as a result, they install VFDs to satisfy utility requirements of service for soft starts to mitigate voltage drop during motor starts. For example, RGEC's tariff requires that any customer with a large motor load in excess of 100 horsepower have "a reduced voltage start device as specified by the Cooperative's engineering department."[4] VFDs are approved by RGEC's engineering department for this purpose and widely used by oil and gas loads, but installation of VFDs without harmonic mitigating equipment such as a filter is known to cause excessive harmonic distortion, impaired power quality, and problems with electrical equipment.

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[1] See Deposition Exhibit 5, Notice letter from RGEC.

[2] Deposition Exhibit 7, Eaton Report at RGEC 1041.

[3] *See* Exhibit RG-4, Deposition Exhibit 12, RGEC Response to RFI 1-25.

[4] *See* RGEC Tariff at Sheet 20.

Q. WHAT STANDARDS GOVERN RECOMMENDED UTILITY PRACTICE FOR PERMISSIBLE LEVELS OF HARMONICS ON AN ELECTRIC POWER SYSTEM?

A. IEEE Standard 519, *IEEE Recommended Practice for Requirements for Harmonic Control in Electric Power Systems*, is the electric utility industry standard for recommended practices addressing harmonics. I am not a lawyer or an electric regulatory expert, but I understand the Public Utility Commission of Texas ("PUCT" or the "Commission") Power Quality Rule, PUCT Subst. R. 25.51(c), has adopted IEEE Standard 519 as the applicable standard in addressing harmonics problems.[5] RGEC CEO Roger Andrade also testified that the Cooperative must comply with the Commission's Power Quality Rule.[6]

Q. PLEASE EXPLAIN HOW IEEE STANDARD 519 DEFINES HARMONICS.

A. IEEE Standard 519 defines a harmonic as "a component of order greater than one of the Fourier series of a periodic quantity. For example, in a 60 Hz system, the harmonic order 3, also known as the 'third harmonic,' is 180 Hz." PUCT Subst. R. § 25.51 adopts the IEEE 519 definition. Subsection (c) of the Power Quality Rule states: "In 60 Hertz electric power systems, a harmonic is a sinusoidal component of the 60 Hertz fundamental wave having a frequency that is an integral multiple of the fundamental frequency." In layman's terms, too much harmonics in a power system means that the harmonic values either add to, or subtract from, the fundamental value of voltage in such a way as to cause overvoltage or undervoltage and create power quality problems. The same can be said for current harmonics.

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[5] *See* 16 Tex. Admin. § 25.51(c).

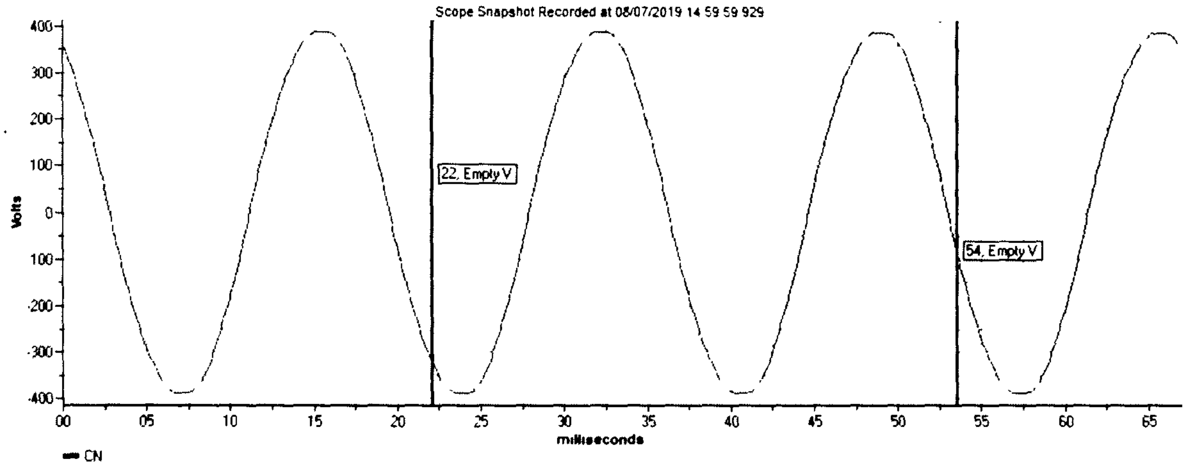
[6] Deposition Tr. R. Andrade at 37-43 (Jan. 31, 2020).

Q. WHAT DO HARMONICS ON A WAVEFORM LOOK LIKE?

A. Figures 1, 2, and 3 below show-depictions of voltage and current waveform distortion due to harmonics distortion.

<u>DISTORTION EXAMPLES</u>

<u>Figure 1</u>: Sinusoidal Voltage with less than 3% Total Harmonic Distortion



<u>Figure 2</u>: Distorted Voltage Sine Wave with 5% Total Harmonic Distortion

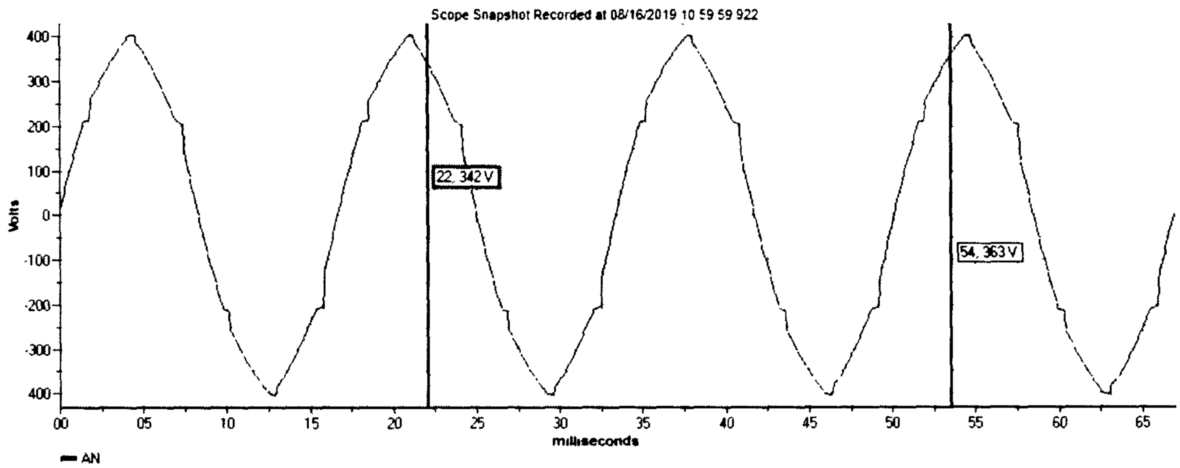
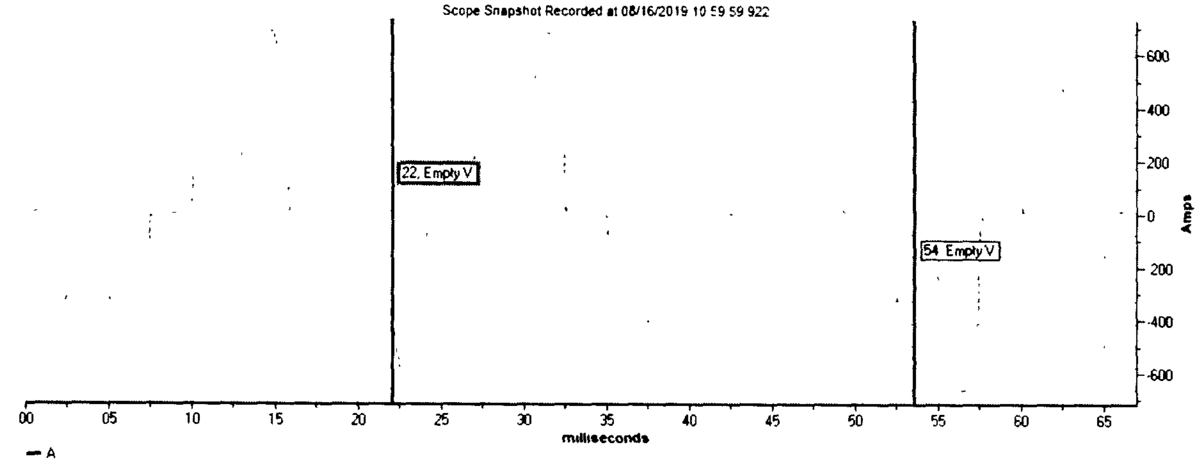


Figure 3: Distorted Current Sine Wave with 40% Total Harmonic Distortion



Q. WHAT ARE EXCESSIVE HARMONICS?

A. All non-linear loads can create harmonics, but excessive harmonics on an electrical power system are harmonics at a level that jeopardize safe and reliable power to other customers and damage electrical equipment on the system. The Commission's Power Quality Rule defines "excessive harmonics" as "levels of current or voltage distortion at the point of common coupling between the electric utility and the customer outside the levels recommended in [IEEE Standard 519]."[7] IEEE Standard 519 is attached to my testimony as Exhibit RG-5. The standard establishes both voltage distortion limits and current distortion limits for systems rated 120 V through 69 kV.

Table 1 of IEEE 519 sets Total Harmonic Distortion ("THD") voltage distortion limits at the PCC as follows:

[7] 16 TAC § 25.51(c).

Table 1 – Voltage Distortion Limits

Bus voltage V at PCC	**Individual harmonic (%)**	**Total harmonic distortion THD (%)**
$V \leq 1.0$ kV	5.0	8.0
$1 \text{ kV} < V \leq 69$ kV	3.0	5.0
$69 \text{ kV} < V \leq 161$ kV	1.5	2.5
$161 \text{ kV} < V$	1.0	1.5

Table 2 of IEEE 519 sets current distortion limits as follows:

Table 2 – Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)						
I_{SC}/I_L	$3 \leq h < 11$	$11 \leq h \leq 17$	$17 \leq h \leq 23$	$23 \leq h \leq 35$	$35 \leq h \leq 50$	TDD
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

In calculating current distortion limits, IEEE Standard 519 states that current distortion limits should be calculated using maximum demand current during each of the twelve previous months divided by twelve.

Q. WHAT IS THE PCC?

A. IEEE 519 defines the PCC as the "point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation."

Q. WHY IS THE DEFINITION OF PCC RELEVANT?

A. Per IEEE 519 and Table 1 above, the bus voltage at PCC determines the voltage THD percent limit. For example, if bus voltage at the PCC is less than 1 kV, the voltage THD limit is 8%. If bus voltage at the PCC is greater than 1 kV and less than or equal to 69 kV, the voltage THD limit is 5%.

Q. PLEASE DESCRIBE THE VOLTAGE OF ELECTRIC SERVICE AT THE PETTY RANCH.

A. The Petty residences and hunting lodge are served off single-phase distribution service. The 250kVA service is 240/120V on the low side of the transformer and 14.4 kV on the high (or primary) side of the transformer. A simplified line drawing of the service is attached as Exhibit RG-6.

Q. ARE ANY OTHER CUSTOMERS SERVED OFF THE LOW SIDE OF THE PETTY TRANSFORMER?

A. No.

Q. HOW MANY METERS ARE SERVED OFF THE LOW SIDE OF THE PETTY TRANSFORMER?

A. One.

Q. IF THERE ARE NO OTHER CUSTOMER LOADS SERVED ON THE LOW SIDE OF THE PETTY TRANSFORMER, WHERE IS PETTY'S PCC WITH THE RGEC DISTRIBUTION SYSTEM?

A. Based on the IEEE 519 definition referenced above, the PCC is on the high side of the Petty transformer, which is 14.4 kV. Based on IEEE 519's Table 1 above, this means excessive harmonics at the Petty PCC would be voltage harmonics greater than the THD limit of 5.0%.

Q. HAS GEI MONITORED VOLTAGE HARMONICS ABOVE 5% AT THE PETTY PCC WITH RGEC?

A. Yes, and on multiple occasions. I will address the results of GEI's monitoring in Section VI of my testimony.

IV. SAFETY AND RELIABILITY PROBLEMS CAUSED BY EXCESSIVE HARMONICS

Q. WHAT DANGERS DO EXCESSIVE VOLTAGE HARMONICS CAUSE TO PETTY AND OTHER RGEC CUSTOMERS ON THE BRUNDAGE LINE?

A. Harmonic distortion can cause severe problems with electrical equipment connected to a system. The most dangerous problem with excessive harmonics is the over-heating they cause in electrical wiring and equipment, which can result in fires. Also, they can cause equipment failures in motors and in electronic control devices, which are both problematic and costly.

Q. DO EXCESSIVE VOLTAGE HARMONICS CAUSE THE ELECTRIC SERVICE DISRUPTIONS DESCRIBED BY PETTY'S ELECTRICIAN NATHAN MORGAN IN HIS DIRECT TESTIMONY?

A. Yes.

Q. DO EXCESSIVE VOLTAGE HARMONICS CAUSE THE ELECTRIC SERVICE DISRUPTIONS DESCRIBED BY PETTY'S AIR CONDITIONING ("AC") TECHNICIAN GILBERT MARQUEZ IN HIS DIRECT TESTIMONY?

A. Yes.

Q. DO EXCESSIVE VOLTAGE HARMONICS CAUSE THE DAMAGE TO ELECTRIC EQUIPMENT DESCRIBED IN DIRECT TESTIMONY OF KYLE HALEY?

A. Yes.

Q. IS IT REASONABLE TO CONCLUDE THAT EXCESSIVE VOLTAGE HARMONICS ON RGEC'S DISTRIBUTION LINE CAUSED THE PROPERTY DAMAGE DESCRIBED BY PETTY WITNESS KYLE HALEY?

A. Yes.

Q. WHAT IS THE BASIS OF THAT CONCLUSION?

A. As stated above, excessive harmonics are known to cause electrical equipment damage and the type of damage experienced by Petty. Further, while the Petty residences and hunting lodge were connected to the grid, the Brundage line exhibited excessive harmonics. When the Petty residences and hunting lodge were disconnected from the grid and served by generator power, the Petty electrical equipment functioned as designed. GEI also observed that the electrical facilities at the ranch were properly designed. Accordingly, the dirty power from the Cooperative's line caused the property damage.

Q. ARE THERE ANY FACILITIES A CUSTOMER CAN INSTALL TO PROTECT ELECTRICAL EQUIPMENT AT A RESIDENCE IF THE CUSTOMER IS SERVED BY A DISTRIBUTION LINE THAT IS EXHIBITING EXCESSIVE HARMONICS?

A. There is effectively nothing a residential customer can reasonably do to protect its facilities or equipment on its site against excessive voltage harmonics. Customers are at the mercy of their utilities to monitor and police the power quality on their systems because they have no authority over other customers who contribute to excessive harmonics on a utility system. All a customer like Petty can do is hope that RGEC will monitor quality on its system and timely require industrial and commercial customers that create excessive harmonics to install equipment to mitigate negative harmonic impacts or follow the appropriate steps to disconnect the customer.

Q. DID PETTY ASK GEI TO INVESTIGATE EQUIPMENT IT COULD INSTALL TO PROTECT ITS RESIDENCES FROM DIRTY POWER?

A. Yes. Petty asked GEI to investigate whether there were any facilities or equipment Petty could install to protect its residences and lodge against the dirty power. GEI could not find any alternative on the market for a small customer like Petty with single phase service. Petty then solicited the opinion of another engineering firm, which reached the same conclusion. The direct testimony of Justin Lankutis describes the investigation and analysis Mr. Lankutis conducted on this matter.

Q. ARE YOU AWARE OF ANY PROVISION IN RGEC'S TARIFF THAT PLACES AN AFFIRMATIVE DUTY ON PETTY TO HAVE FACILITIES OR EQUIPMENT ON SITE TO PROTECT AGAINST EXCESSIVE HARMONICS?

A. No. RGEC's tariff only addresses equipment that a customer may be required to install if the customer is the source of harmonics that are adversely affecting other customers. Section 323.3(D) of the RGEC tariff states:

> *D. Equipment Necessary to Limit Adverse Effects.*
>
> *Cooperative may require Consumer to provide, at Consumer's expense, suitable apparatus to limit the effect of voltage fluctuations caused by electric equipment in Consumer's installation where Consumer is found to be operating electrical equipment which produces voltage fluctuations, interference, harmonics or distorted wave forms* ***which adversely affect electric service provided by Cooperative to other Consumers****.*
>
> *Consumers utilizing nonlinear loads, such as, but not limited to, adjustable speed drives and uninterruptible power supplies, must employ devices that limit the harmonic voltage and current distortion limits to those set out in IEEE Std 519 5.1 and 5.2.*
>
> *In lieu of requesting* Consumer *to install such suitable or special equipment limiting such adverse effect, Cooperative may, at its option, install at Consumer's cost, additional transformer capacity (which may or may not be dedicated solely to such Consumer) or other equipment specially designed to reasonably limit such adverse effect.*

Q. WHAT FACILITIES CAN A CUSTOMER THAT IS CAUSING EXCESSIVE VOLTAGE HARMONICS INSTALL TO MITIGATE THE HARMONICS FROM VFDS?

A. Mitigation of harmonics caused by the customer can be achieved by using filters which limit harmonic voltage caused by the harmonic current flow. Another approach might be to install phase-shifting transformers in various locations within the offending customer's electrical system.

V. RGEC'S THIRD PARTY REPORTS NOTIFIED THE COOPERATIVE OF EXCESSIVE HARMONICS ON THE BRUNDAGE LINE

Q. WAS RGEC AWARE THAT VFDS WERE CAUSING EXCESSIVE HARMONICS ON THE BRUNDAGE LINE?

A. Yes. During his deposition, RGEC engineer Larry Powell testified that he was not aware of harmonics on the Brundage line prior to 2010.[8] Mr. Powell testified that in 2010 [redacted] an oil and gas operator, paid the Cooperative to upgrade the capacity of the Brundage line to serve its operations.[9] After the expansion, harmonics problems arose on the Brundage line. Discovery in this case indicates that RGEC was first notified of excessive harmonics on the Brundage line in 2014.

Q. HOW WAS RGEC INFORMED OF EXCESSIVE HARMONICS ON THE BRUNDAGE LINE IN 2014?

A. In 2014, RGEC commissioned a report by Eaton Electrical Services & Systems ("Eaton") in response to a power quality complaint from [redacted].[10] The Eaton report, entitled "Power Quality Measurements for Rio Grande Electric Cooperative, Inc.," was dated October 2014 ("Eaton Report"). It is attached to my testimony as Exhibit RG-7. The

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[8] Deposition Tr. of L. Powell at 52-53 (Jan. 29, 2020).

[9] Deposition Tr. of L. Powell at 53-54 (Jan. 29, 2020).

[10] Deposition Tr. G. Delfin at 36 (Jan. 29, 2020).

Eaton Report examined several power quality problems on the Brundage line, including harmonics.

[redacted]

Q. AFTER THE EATON REPORT WAS ISSUED DID RGEC INVESTIGATE WHETHER [redacted] HAD INSTALLED FILTERS TO MITIGATE HARMONICS?

A. No. RGEC engineer Gerry Delfin testified in his deposition that he [redacted].[11] Mr. Delfin and Mr. Powell both testified that the Cooperative did not make it a practice to inquire about or specify equipment on the customer's side of the

[11] Deposition Tr. of G. Delfin at 40-41 (Jan. 29, 2020).

meter.[12] Mr. Powell also testified that RGEC did not require members that utilized VFDs to install filters when they energized their sites. Nor did the Cooperative monitor power quality when large loads with large motor loads were energized.[13] Accordingly, after RGEC closed out [redacted] complaint, the Cooperative did not inquire into whether the company (which had paid RGEC in 2010 for the capacity expansion of the Brundage distribution line) or other oil and gas loads were causing harmonics that would negatively impact power quality of other customers taking service on the line.

Q. DID OTHER OUTSIDE ENGINEERING FIRMS WARN RGEC ABOUT ANY HARMONICS ON THE BRUNDAGE LINE?

A. Yes. RGEC was warned of harmonics on the line by another engineering consultant in 2015. [redacted]

[redacted]

[redacted]

[redacted]

[12] Deposition Tr. of G. Delfin at 74-75, 94-95 (Jan, 29, 2020); Deposition Tr. of L. Powell at 34-36 (Jan. 29, 2020).

[13] Deposition Tr. of L. Powell at 42 (Jan. 29, 2020).

[redacted]

Q. WHAT OTHER RECOMMENDATIONS DID TXUE MAKE?

A. [redacted]

Q. DID RGEC IMPLEMENT A MOTOR START EVALUATION REQUIREMENT?

A. No. Both Mr. Delfin and Mr. Powell, RGEC's engineers, testified that RGEC did not test customer compliance with their new motor starting requirements upon energization.[14] Nor did RGEC begin collecting or tracking usage of VFDs or filters on the customer side of the meter until after Petty filed its complaint with the Cooperative.

Q. DO ANY OTHER FACTS INDICATE THAT RGEC WAS AWARE OF THE EXISTENCE OF EXCESSIVE HARMONICS ON THE BRUNDAGE LINE?

A. Yes. Mr. Powell testified in his deposition that RGEC became aware of additional power quality problems on the Brundage line in the spring of 2018. RGEC subsequently sent a letter on July 27, 2018 to customers on the Brundage line stating:

> *[The Brundage line] is currently exhibiting very poor power quality such that electric service of several customers connected to this line are being affected. The root cause of this problem has been identified as being due to a condition called "harmonic distortion." The presence of this condition is now preventing other customers from receiving acceptable power quality from the electric grid. At RGEC, we strive to provide all of our customers with very reliable and "clean" power. Unfortunately, we are unable to achieve this for all of our customers connected to this Brundage distribution line.*
>
> *Harmonic distortion is injected into the power system directly from certain customer's equipment. The most significant contribution to this phenomenon are variable speed electronic motor controls (VFDs), which are used to start large industrial type motors.*

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[14] Deposition Tr. of G. Delfin at 74-75, 82 (Jan. 29, 2020).

> *Harmonic distortion can cause severe problems with other electrical equipment connected to the system. This includes excessive heating, vibration, metering issues and interference with other electronic motor control systems. In extreme cases, some customers are unable to even operate their electrical equipment due to the unacceptable power quality caused by harmonic distortion.*

RGEC admitted that the Brundage substation distribution lines "are currently experiencing THD levels that are many orders of magnitude greater than [the] IEEE limit." The letter is attached to the direct testimony of Kyle Haley as Exhibit KH-15.

[redacted]

[redacted]

[redacted]

Q. BASED ON THE REPORTS THAT RGEC RECEIVED, HOW LONG HAS THE COOPERATIVE BEEN AWARE OF HARMONICS PROBLEMS ON THE BRUNDAGE LINE?

A. Based on the reports RGEC received, the Cooperative has been aware of the harmonics problems on the Brundage line since 2014.

Q. AS OIL AND GAS LOAD GREW ON THE BRUNDAGE LINE, SHOULD RGEC HAVE BEEN AWARE THAT HARMONICS PROBLEMS WOULD GET WORSE?

A. Yes.

Q. PLEASE EXPLAIN.

A. RGEC had a [redacted] increase in energy sales to oil and gas loads from 2010 to 2018, accompanied by a [redacted] increase in energy revenues to those loads.[15] Mr. Powell testified during his deposition that these large power loads typically have large motors with VFDs. He also testified that the Cooperative did not track whether the large power loads installed harmonic filters with the VFDs. During his deposition, he testified:

[redacted]

[redacted]

[15] Deposition Tr. of L. Powell at 46-50 (Jan. 28, 2020). *See also* Exhibit RG-10.

[redacted][16]

In short, RGEC was notified of the harmonics problems in 2014, but it did not do anything to mitigate the problem until after Petty filed a complaint in February 2019.

VI. GEI POWER QUALITY MONITORING RESULTS SHOWING EXCESSIVE HARMONICS ON THE RGEC SIDE OF THE METER

Q. WHY DID GEI CONCLUDE THAT EXCESSIVE VOLTAGE HARMONICS FROM THE RGEC SIDE OF THE METER CAUSED THE ELECTRICAL PROBLEMS AT THE PETTY RANCH?

A. GEI's conclusion was based on its own investigation and power quality metering, the reports conducted by RGEC's outside engineering consultants, and RGEC's own data. For example, RGEC's March 6, 2019 reading showed [redacted][17] RGEC and GEI's monitoring also showed voltage THD above the IEEE Standard 519 limit of 5% after Petty was disconnected from the grid.

Q. HOW DID GEI INDEPENDENTLY MONITOR POWER QUALITY AT THE PETTY RANCH?

A. GEI installed a Fluke 1750 Power Quality Meter on the existing electrical service, on the line-side terminals of the automatic transfer switch (i.e., the first customer-owned device just below the RGEC meter). The Fluke meter was installed on April 29, 2019. A second Fluke 1750 Power Quality Meter was also installed on the new electrical service that was connected to the generator, on the line side terminals of the main breaker. That meter was also installed on April 29, 2019. The meters were installed at the 240V locations stated

[16] Deposition Tr. of L. Powell at 40 (Jan. 29, 2020).

[17] *See* Direct Testimony of Kyle Haley (Exhibit KH-17, RGEC Updated Brundage Harmonics Location Summary (12-30-19)).

above and used the utility transformer as an instrument voltage and current transformer to monitor the primary medium voltage parameters where applicable.

Q. DO GEI'S METERING METHODS COMPORT WITH STANDARD ENGINEERING PRACTICES?

A. Yes.

Q. DESCRIBE THE RESULTS OF THE POWER QUALITY MONITORING THAT GEI CONDUCTED.

A. Power quality data received from the monitor installed on the existing electrical service indicated high voltage harmonic content above the IEEE Standard 519 limits. GEI recorded data from April 29, 2019 to March 27, 2020. A summary showing the voltage harmonic levels is attached as Exhibit RG-11. Power quality data received from the monitor installed on the new electrical service did not indicate high voltage harmonic content.

Q. WERE GEI'S RESULTS IMPACTED BY PETTY'S LOAD?

A. No. Petty had been disconnected from the grid since March 18, 2019. Since that time, its load ran off a generator. Accordingly, the voltage harmonics recorded at the PCC were unaffected by Petty's load.

Q. RGEC WITHDREW GENERATOR SERVICE FROM PETTY ON APRIL 18, 2019. WAS IT SAFE FOR PETTY TO RECONNECT TO THE GRID AT THAT TIME?

A. No. RGEC's own records showed that voltage THD around that time was above [redacted]. For the period April 29, 2019 through May 8, 2019, GEI's monitoring data showed max voltage THD of 12.9%. GEI's monitoring also showed sustained excessive harmonic levels at the PCC above the IEEE Standard 519 THD limit of 5% throughout most of 2019.

Q. WHEN DID GEI FINALLY NOTICE IMPROVEMENT IN THE POWER QUALITY AT THE PETTY PCC?

A. GEI observed in late October 2019 the THD at the PCC finally improved.

Q. WHAT DID YOU LEARN WAS SIGNIFICANT ABOUT THE OCTOBER 2019 TIME PERIOD?

A. GEI learned during the deposition of RGEC witnesses that took place January 28 through 31, 2020 that the Cooperative temporarily [redacted] in late October 2019. Thereafter, GEI monitored levels as high as 6.4% voltage THD, but nevertheless closer to the 5% voltage THD prescribed by IEEE Standard 519.

VII. PETTY'S LOAD DID NOT CAUSE OR CONTRIBUTE TO THE EXCESSIVE HARMONICS

Q. DO YOU HAVE ANY REASON TO BELIEVE THAT CURRENT HARMONICS FROM THE PETTY SIDE OF THE METER CAUSED ITS ELECTRICAL EQUIPMENT TO FAIL WHEN THE RANCH WAS CONNECTED TO THE GRID?

A. No. After the Petty Ranch was removed from the RGEC service, it was placed on generator power. During the ensuing months of operation there were no additional failures and the equipment performed as designed and installed.

Q. DO YOU HAVE ANY REASON TO BELIEVE THAT ANY OTHER ELECTRICAL PROBLEMS ON THE PETTY SIDE OF THE METER CAUSED PETTY'S ELECTRICAL EQUIPMENT TO FAIL WHEN THE PETTY RANCH WAS CONNECTED TO THE GRID?

A. No, using the same reasoning as above. The Petty Ranch's loads and equipment performed as expected when connected to generator, so there is no reason to believe that any other electrical problem on the Petty side of the meter caused its electrical equipment to fail.

Q. DID YOU MEET WITH RGEC TO DISCUSS THE POWER QUALITY PROBLEMS AT THE PETTY RANCH?

A. Yes. Petty and GEI met with RGEC on April 4, 2019 at RGEC's Brackettville headquarters. At that meeting, RGEC made the claim that the Petty Ranch was out of compliance with IEEE Standard 519 based on the amount of current THD levels the Cooperative said it observed during a previous monitoring period. RGEC claimed it was Petty's responsibility to "clean up" its load to reduce the THD. RGEC claimed that Petty THD was a contributor to the harmonics seen on the Brundage line. However, RGEC did not acknowledge that there had already was significant voltage harmonic content on the Brundage line prior to the connection of the residences. Nor did RGEC offer information on its efforts to make it safe for Petty to reconnect by offering a timetable on the reduction of harmonics on the Brundage line.

Q. WAS RGEC'S CONCLUSION REASONABLE?

A. No. Per GEI's report attached as Exhibit RG-3, the current harmonic content measured by RGEC was not outside the limits as determined by IEEE Standard 519. Discovery in this case reveals that RGEC's employees reached this flawed conclusion by taking an isolated snapshot of Petty's current THD percentage measured at 14.8/14.4 on March 6, 2019 at 2:35 p.m. based on current measured at 11.2/11.1 amps.[18] At that time, the only load on the Petty side was small construction load such as drills and saws, AC units and other equipment being tested, and a battery charger for the Petty stand-by generator battery. However, IEEE Standard 519 states that current distortion limits should be established at the PCC and should be taken using average maximum demand current over a 12-month

[18] *See* Exhibit RG-12, RGEC Response to Petty 5-3 (reporting data collection for the 3/6/2019 snapshot from 3/6/2019 starting at 2:28 pm and ending at 3/8/2019 at 10:22 am). *See also* Direct Testimony of Kyle Haley (Exhibit KH-17, RGEC Updated Brundage Harmonics Location Summary (12-30-19)).

period. RGEC did not use average maximum demand or even an estimate of average maximum demand, but instead cherry-picked an isolated reading, which did not yield a reasonable conclusion or comply with IEEE Standard 519. The Cooperative's conclusion was, therefore, not reasonable.

VIII. CONCLUSION

Q. BASED ON YOUR EXPERIENCE IN THE UTILITY INDUSTRY, RGEC'S OWN THIRD-PARTY REPORTS, AND GEI'S MONITORING, WAS THE POWER DELIVERED TO THE PETTY PCC BY RGEC SAFE AND RELIABLE?

A. No. The overheating of wiring and equipment is dangerous and a definite safety issue; in particular, it is a fire hazard. Reliability is greatly affected by causing equipment failures and by causing electronically controlled features to function improperly. Excessive harmonics are known in the industry to cause problems and that is the reason that IEEE Standard 519 was developed.

Q. BASED ON YOUR EXPERIENCE IN THE UTILITY INDUSTRY, RGEC'S OWN THIRD-PARTY REPORTS, AND GEI'S MONITORING, WAS THE POWER DELIVERED TO THE PETTY PCC IMPAIRED BY EXCESSIVE HARMONICS?

A. Yes. All of the reports commissioned by RGEC with Schneider, Eaton and TXUE pointed out that the RGEC distribution line had excessive harmonic content attributable to the larger industrial customers connected to the line. The GEI monitoring for a much longer period of time affirmed those previous findings.

Q. WAS IT SAFE FOR PETTY TO RECONNECT TO THE GRID AFTER RGEC PULLED GENERATOR SERVICE AND WHILE THE PCC WITH RGEC CONTINUED TO EXHIBIT POWER QUALITY IMPAIRED BY EXCESSIVE HARMONICS?

A. No. RGEC system's excessive harmonics caused equipment failures at the Petty Ranch previously. Those failures ceased to occur when Petty was removed from the RGEC system and placed on generator. It is logical that, since the harmonics on the RGEC system remained high, reconnection would result in a resumption of equipment failures.

Q. IS IT SAFE FOR PETTY TO RECONNECT TO THE GRID AFTER THE CUSTOMER THAT CAUSED THE PROBLEM WAS TEMPORARILY DISCONNECTED?

A. It depends on whether RGEC will meet its obligations to provide safe and reliable electric service to Petty upon reconnection. I understand that [redacted] intends to reconnect to RGEC upon the purchase of certain filtering equipment.[19] I also understand that [redacted] has previously installed filtering equipment that did not work and that RGEC nevertheless allowed the member to stay online for 14 months after Schneider Engineering issued a report to the Cooperative identifying the operator as one of the leading culprits of the excessive harmonics. Accordingly, there is certainly risk that the high harmonic content will return.

Q. WHAT DO YOU RECOMMEND RGEC DO TO PROVIDE PETTY SAFE AND RELIABLE POWER?

A. RGEC should timely identify and work with commercial and industrial customers who create system harmonic problems on the Cooperative's distribution line. If the customer cannot timely resolve the problem, the Cooperative should either disconnect the customer or pay to install the necessary facilities to correct the problem and charge the customer. Once the problems are resolved to a point where the RGEC system is constantly in compliance with IEEE 519, RGEC also needs to implement a plan to monitor and police customer impacts on the their system.

Q. DOES THIS CONCLUDE YOUR TESTIMONY?

Yes.

[19] Deposition Tr. of A. Conrad at 51 (Jan. 30, 2020).

VERIFICATION

Robert D. Grubb, swearing under penalty of perjury, states:

I am the witness identified in the preceding testimony. I have read the testimony and am familiar with the contents. Based upon my personal knowledge, I affirm that the facts stated in the testimony are true and correct to the best of my knowledge. In addition, in my judgment and based upon my professional experience, the opinions and conclusions stated in the testimony are true, valid, and accurate.

Robert D. Grubb

Date: 4/2/2020

EXHIBIT RG-1

Exhibit RG-1
List of Prior Appearances

Docket No. 3:01cv54, *SMS Demag vs. North American Stainless,* U.S. District Court, Eastern District of Kentucky, Arbitration Board in Fall 2003

Wendlands Feed vs. Miller's Mutual, Waco, Texas 2000

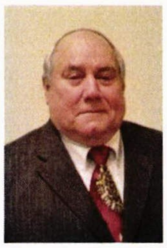
Sanchez vs. City of San Antonio, Sub-contractor to Independent Test Firm Raba-Kistner directed by Judge Pat Boone, San Antonio, Texas 2001

EXHIBIT RG-2

Robert Grubb, P.E.

GEI

Principal Engineer



Education: B.S., Electrical Engineering / University of Texas at Austin / 1970
Registration: Professional Engineer / Texas #38772 / 1975
Title: Principal Engineer
Location: San Antonio, Texas
Experience: He has more than 48 years of experience in the planning, design, coordination and management of a wide range of water and wastewater plants, electric power substation, electric transmission, and electric distribution projects. Robert Grubb's background experience includes 11 years of electric substation design, transmission planning, distribution planning and relay testing and maintenance for the City Public Service Board (now CPS Energy) of San Antonio. Prior to his resignation, Mr. Grubb served as Chief System Protection Engineer. Robert Grubb formed Grubb Engineering, Inc. in 1981. Grubb Engineering has had a role in the design of many different projects ranging from water/wastewater facilities to electric transmission systems and substations. Robert Grubb is the author of two papers presented at the Annual International Conference for Protective Relay Engineers at Texas A&M University, as well as a paper presented at Cebu City, Philippines to the IIEE.

REPRESENTATIVE PROJECTS:

- **Alliance Water Owner's Representative / Alliance Water / Central Texas / 2018 – Present:**
  Serves as electrical system advisor to Alliance. Duties include negotiation/planning with electrical utilities.

- **Power Quality Monitoring/Harlingen Water Works/Harlingen, Texas/2019**
  Served as engineering manager for analysis of power quality monitoring at two water plants and one wastewater treatment plant. Helped troubleshoot reasons for equipment damage involving motors and electronic controls.

- **Vista Ridge Technical Advisor / SAWS / San Antonio, Texas / 2016 – Present:**
  Serves as electrical system advisor to SAWS for the supply side of the Vista Ridge Project. Duties include negotiation/planning with electrical utilities and design submittal review.

- **DSP Water Production Facility Upgrades / SAWS / Bexar County, Texas/ 2013-2015:**
  Project Manager for the new electrical distribution and SCADA system design for four (4) existing DSP Pump Stations. Stations include well pump(s), pump control valves and chlorine system.

- **(DSP) Somerset Facility High Service Pump Upgrades/ SAWS / Somerset, Texas/ 2012–2016:**
  Served as Project Manager for the electrical, control, and instrumentation design for this upgrades project which involves the replacement of the entire electrical distribution and SCADA system to serve the new pump station and control valves.

- **Mission Pump Station Improvements / SAWS / San Antonio, Texas / 2008-2014:**
  Served as Principal Project Manager for the upgrades which included new electrical motor control center, piping, chlorine scrubber, well rehabilitation and a new site plat. GEI was the prime consultant.

- **Lift Stations SCADA Project / SAWS / San Antonio, Texas / 2008-2010:**
  Served as Principal Project Manager for the SCADA system upgrades of 14 lift stations. GEI was the prime consultant.

EXHIBIT RG-4

PUBLIC UTILITY COMMISSION OF TEXAS

PUC NO. 49795

REQUEST NUMBER ONE: QUESTION NO. PETTY 1-25

COMPANY NAME: **Rio Grande Electric Cooperative, Inc.**

INFORMATION REQUESTED:

Petty 1-25: Please identify the class characteristics of the customers served by the Brundage Line for the years 2015 to the present. In your answer, please identify by year the percentage of load that is residential, commercial, industrial, seasonal or other customer classification.

REQUESTED BY: Petty Group, LLP

RESPONSE:

Will supplement.

SUPPLEMENTAL RESPONSE:

See attachment 1-25.

SPONSOR:

Roger Andrade

Attachment 1-25

	Residential	Seasonal	Irrigation	Commercial	Industrial	Total
2015	9.6%	2.0%	10.2%	6.3%	71.8%	100.0%
2016	8.9%	1.9%	8.9%	5.8%	74.5%	100.0%
2017	8.4%	1.9%	12.4%	5.4%	71.8%	100.0%
2018	6.7%	1.6%	9.7%	4.5%	77.5%	100.0%
2019	6.3%	1.5%	9.8%	4.2%	78.3%	100.0%

EXHIBIT RG-5

IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

IEEE Power and Energy Society

Sponsored by the
Transmission and Distribution Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 519™-2014
(Revision of
IEEE Std 519-1992)

IEEE Std 519™-2014
(Revision of
IEEE Std 519-1992)

IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

Sponsor

Transmission and Distribution Committee
of the
IEEE Power and Energy Society

Approved 27 March 2014

IEEE-SA Standards Board

Abstract: Goals for the design of electrical systems that include both linear and nonlinear loads are established in this recommended practice. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling and observance of the design goals will reduce interference between electrical equipment.

This recommended practice addresses steady-state limitations. Transient conditions exceeding these limitations may be encountered. This document sets the quality of power that is to be provided at the point of common coupling. This document does not cover the effects of radio-frequency interference; however, guidance is offered for wired telephone systems.

Keywords: harmonics, IEEE 519™, power quality

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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At the time this IEEE recommended practice was completed, the Harmonics Working Group had the following membership:

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Jim Burke
Randy Collins
Doug Dorr
Russell Ehrlich
Thomas Gentile
David Gilmer
Daryl Hallmark
Dennis Hansen
Fred Hensley
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Steve Tatum
Alfredo Testa
Rao Thallam
Timothy Unruh
Dan Ward
James Wikston
Charlie Williams
Wilson Xu
Francisc Zavoda

The following members of the individual balloting committee voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

William Ackerman
Ali Al Awazi
Roy Alexander
Saleman Alibhay
Thomas Barnes
G. Bartok
David Bassett
Thomas Basso
Steven Bezner
Wallace Binder
Michael Bio
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S. Patel
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Introduction

This introduction is not part of IEEE Std 519-2014, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.

The uses of nonlinear loads connected to electric power systems include static power converters, arc discharge devices, saturated magnetic devices, and, to a lesser degree, rotating machines. Static power converters of electric power are the largest nonlinear loads and are used in industry for a variety of purposes, such as electrochemical power supplies, adjustable speed drives, and uninterruptible power supplies. These devices are useful because they can convert ac to dc, dc to dc, dc to ac, and ac to ac.

Nonlinear loads change the sinusoidal nature of the ac power current (and consequently the ac voltage drop), thereby resulting in the flow of harmonic currents in the ac power system that can cause interference with communication circuits and other types of equipment. These harmonic currents also lead to increased losses and heating in numerous electromagnetic devices (motors, transformers, etc.). When reactive power compensation, in the form of power factor improvement capacitors, is used, resonant conditions can occur that may result in high levels of harmonic voltage and current distortion when the resonant condition occurs at a harmonic associated with nonlinear loads.

Common sources of harmonic currents in power systems include power electronic converters, arc furnaces, static VAR systems, inverters for distributed generation, ac phase controllers, cycloconverters, and ac-dc converters (rectifiers) commonly used in switched mode power supplies and pulse width modulated (PWM) motor drives. Each of these harmonic-producing devices can have fairly consistent harmonic current emission characteristics over time or each may present a widely-varying characteristic depending on the control of the device, the characteristics of the system, and other variables. This recommended practice is to be used for guidance in the design of power systems with nonlinear loads. The limits set are for steady-state operation and are recommended for "worst case" conditions. Transient conditions exceeding these limits may be encountered. In any case, the limit values given in this document are recommendations and should not be considered binding in all cases. Because of the nature of the recommendations, some conservatism is present that may not be necessary in all cases.

This recommended practice should be applied at interface points between system owners or operators and users in the power system. The limits in this recommended practice are intended for application at a point of common coupling (PCC) between the system owner or operator and a user, where the PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user. Frequently for service to industrial users (i.e., manufacturing plants) via a dedicated service transformer, the PCC is at the HV side of the transformer. For commercial users (office parks, shopping malls, etc.) supplied through a common service transformer, the PCC is commonly at the LV side of the service transformer.

The limits in this recommended practice represent a shared responsibility for harmonic control between system owners or operators and users. Users produce harmonic currents that flow through the system owner's or operator's system, which lead to voltage harmonics in the voltages supplied to other users. The amount of harmonic voltage distortion supplied to other users is a function of the aggregate effects of the harmonic current producing loads of all users and the impedance characteristics of the supply system.

Harmonic voltage distortion limits are provided to reduce the potential negative effects on user and system equipment. Maintaining harmonic voltages below these levels necessitates that

— All users limit their harmonic current emissions to reasonable values determined in an equitable manner based on the inherent ownership stake each user has in the supply system and

— Each system owner or operator takes action to decrease voltage distortion levels by modifying the supply system impedance characteristics as necessary.

In order to allow the system owner or operator to control the system impedance characteristics to reduce voltage distortion when necessary, users should not add passive equipment that affects the impedance characteristic in a way such that voltage distortions are increased. In effect, such actions by a user could amount to producing excessive voltage harmonic distortion. Such passive equipment additions (that lead to undesirable system impedance characteristics) should be controlled by the user in the same manner as current harmonic-producing devices operated by the user.

Contents

IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems

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1. Overview

The uses of nonlinear loads connected to electric power systems include static power converters, arc discharge devices, saturated magnetic devices, and, to a lesser degree, rotating machines. Static power converters of electric power are the largest nonlinear loads and are used in industry for a variety of purposes, such as electrochemical power supplies, adjustable speed drives, and uninterruptible power supplies. These devices are useful because they can convert ac to dc, dc to dc, dc to ac, and ac to ac.

Nonlinear loads change the sinusoidal nature of the ac power current (and consequently the ac voltage drop), thereby resulting in the flow of harmonic currents in the ac power system that can cause interference with communication circuits and other types of equipment. These harmonic currents also lead to increased losses and heating in numerous electromagnetic devices (motors, transformers, etc.). When reactive power compensation, in the form of power factor improvement capacitors, is used, resonant conditions can occur that may result in high levels of harmonic voltage and current distortion when the resonant condition occurs at a harmonic associated with nonlinear loads.

Common sources of harmonic currents in power systems include power electronic converters, arc furnaces, static VAR systems, inverters for distributed generation, ac phase controllers, cycloconverters, and ac-dc converters (rectifiers) commonly used in switched mode power supplies and pulse width modulated (PWM) motor drives. Each of these harmonic-producing devices can have fairly consistent harmonic current emission characteristics over time or each may present a widely-varying characteristic depending on the control of the device, the characteristics of the system, and other variables.

1.1 Scope

This recommended practice establishes goals for the design of electrical systems that include both linear and nonlinear loads. The voltage and current waveforms that may exist throughout the system are described, and waveform distortion goals for the system designer are established. The interface between sources and loads is described as the point of common coupling and observance of the design goals will minimize interference between electrical equipment.

This recommended practice addresses steady-state limitations. Transient conditions exceeding these limitations may be encountered. This document sets the quality of power that is to be provided at the point of common coupling. This document does not cover the effects of radio-frequency interference; however, guidance is offered for wired telephone systems.

1.2 Purpose

This recommended practice is to be used for guidance in the design of power systems with nonlinear loads. The limits set are for steady-state operation and are recommended for "worst case" conditions. Transient conditions exceeding these limits may be encountered. In any case, the limit values given in this document are recommendations and should not be considered binding in all cases. Because of the nature of the recommendations, some conservatism is present that may not be necessary in all cases.

This recommended practice should be applied at interface points between system owners or operators and users in the power system. The limits in this recommended practice are intended for application at a point of common coupling (PCC) between the system owner or operator and a user, where the PCC is usually taken as the point in the power system closest to the user where the system owner or operator could offer service to another user. Frequently for service to industrial users (i.e., manufacturing plants) via a dedicated service transformer, the PCC is at the HV side of the transformer. For commercial users (office parks, shopping malls, etc.) supplied through a common service transformer, the PCC is commonly at the LV side of the service transformer.

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Harmonic voltage distortion limits are provided to reduce the potential negative effects on user and system equipment. Maintaining harmonic voltages below these levels necessitates that

— All users limit their harmonic current emissions to reasonable values determined in an equitable manner based on the inherent ownership stake each user has in the supply system and

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In order to allow the system owner or operator to control the system impedance characteristics to reduce voltage distortion when necessary, users should not add passive equipment that affects the impedance characteristic in a way such that voltage distortions are increased. In effect, such actions by a user could amount to producing excessive voltage harmonic distortion. Such passive equipment additions (that lead to undesirable system impedance characteristics) should be controlled by the user in the same manner as current harmonic-producing devices operated by the user.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC Standard 61000-4-7, General Guide on Harmonics and Interharmonics Measurement and Instrumentation, for Power Supply Systems and Equipment Connected Thereto.[1]

IEC Standard 61000-4-30, Power Quality Measurement Methods.

IEC Standard 61000-4-15, Testing and Measurement Techniques—Flickermeter—Functional and Design Specifications.

IEEE Std 1453™, IEEE Recommended Practice—Adoption of IEC 61000-4-15:2010, Electromagnetic compatibility (EMC)—Testing and Measurement Techniques—Flickermeter—Functional and Design Specifications.[2]

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[3]

harmonic (component): A component of order greater than one of the Fourier series of a periodic quantity. For example, in a 60 Hz system, the harmonic order 3, also known as the "third harmonic," is 180 Hz.

interharmonic (component): A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating (e.g., 50 Hz or 60 Hz).

I-T product: The inductive influence expressed in terms of the product of root-mean-square current magnitude (I), in amperes, times its telephone influence factor (TIF).

kV-T product: Inductive influence expressed in terms of the product of root-mean-square voltage magnitude (V), in kilovolts, times its telephone influence factor (TIF).

maximum demand load current: This current value is established at the point of common coupling and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12.

notch: A switching (or other) disturbance in the normal power voltage waveform, lasting less than 0.5 cycles, which is initially of opposite polarity than the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to 0.5 cycles.

[1] IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (http://www.ansi.org/).

[2] IEEE publications are available from the Institute of Electrical and Electronics Engineers, Inc., 445 Hoes Lane, Piscataway, NJ 08854, USA (http://standards.ieee.org/).

[3] IEEE Standards Dictionary Online subscription is available at:
http://www.ieee.org/portal/innovate/products/standard/standards_dictionary.html.

notch depth: The average depth of the line voltage notch from the sine wave of voltage.

notch area: The area of the line voltage notch. It is the product of the notch depth, in volts, times the width of the notch measured in microseconds.

point of common coupling (PCC): Point on a public power supply system, electrically nearest to a particular load, at which other loads are, or could be, connected. The PCC is a point located upstream of the considered installation.

pulse number: The total number of successive nonsimultaneous commutations occurring within the converter circuit during each cycle when operating without phase control. It is also equal to the order of the principal harmonic in the direct voltage, that is, the number of pulses present in the dc output voltage in one cycle of the supply voltage.

short-circuit ratio: At a particular location, the ratio of the available short-circuit current, in amperes, to the load current, in amperes.

telephone influence factor (TIF): For a voltage or current wave in an electric supply circuit, the ratio of the square root of the sum of the squares of the weighted root-mean-square values of all the sine-wave components (including alternating current waves both fundamental and harmonic) to the root-mean-square value (unweighted) of the entire wave.

total demand distortion (TDD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the maximum demand current. Harmonic components of order greater than 50 may be included when necessary.

total harmonic distortion (THD): The ratio of the root mean square of the harmonic content, considering harmonic components up to the 50th order and specifically excluding interharmonics, expressed as a percent of the fundamental. Harmonic components of order greater than 50 may be included when necessary.

4. Harmonic measurements

For the purposes of assessing harmonic levels for comparison with the recommended limits in this document, any instrument used should comply with the specifications of IEC 61000-4-7 and IEC 61000-4-30 The most relevant portions of the IEC specifications are summarized in 4.1 through 4.4.

4.1 Measurement window width

The width of the measurement window used by digital instruments employing Discrete Fourier Transform techniques should be 12 cycles (approximately 200 ms) for 60 Hz power systems (10 cycles for 50 Hz power systems). With this window width, spectral components will be available every 5 Hz (e.g., 0, 5, 10…50, 55, 60, 65, 70,… Hz). For the purposes of this document, a harmonic component magnitude is considered to be the value at a center frequency (60, 120, 180, etc. and 50, 100, 150, etc. Hz for 60 Hz and 50 Hz power systems, respectively) combined with the two adjacent 5 Hz bin values. The three values are combined into a single rms value that defines the harmonic magnitude for the particular center frequency component.

4.2 Very short time harmonic measurements

Very short time harmonic values are assessed over a 3-second interval based on an aggregation of 15 consecutive 12 (10) cycle windows for 60 (50) Hz power systems. Individual frequency components are aggregated based on an rms calculation as shown in Equation (1) where F represents voltage (V) or current (I), n represents the harmonic order, and i is a simple counter. The subscript vs is used to denote "very short." In all cases, F represents an rms value.

$$F_{n,vs} = \sqrt[2]{\frac{1}{15}\sum_{i=1}^{15} F_{n,i}^2} \tag{1}$$

4.3 Short time harmonic measurements

Short time harmonic values are assessed over a 10-minute interval based on an aggregation of 200 consecutive very short time values for a specific frequency component. The 200 values are aggregated based on an rms calculation as shown in Equation (2) where F represents voltage (V) or current (I), n represents the harmonic order, and i is a simple counter. The subscript sh is used to denote "short." In all cases, F represents an rms value.

$$F_{n,sh} = \sqrt[2]{\frac{1}{200}\sum_{i=1}^{200} F_{(n,vs),i}^2} \tag{2}$$

4.4 Statistical evaluation

Very short and short time harmonic values should be accumulated over periods of one day and one week, respectively. For very short time harmonic measurements, the 99th percentile value (i.e., the value that is exceeded for 1% of the measurement period) should be calculated for each 24-hour period for comparison with the recommend limits in Clause 5. For short time harmonic measurements, the 95th and 99th percentile values (i.e., those values that are exceeded for 5% and 1% of the measurement period) should be calculated for each 7-day period for comparison with the recommended limits in Clause 5. These statistics should be used for both voltage and current harmonics with the exception that the 99th percentile short time value is not recommended for use with voltage harmonics.

5. Recommended harmonic limits

Because managing harmonics in a power system is considered a joint responsibility involving both end-users and system owners or operators, harmonic limits are recommended for both voltages and currents. The recommended values in this clause are based on the fact that some level of voltage distortion is generally acceptable and both system owners or operators and users must work cooperatively to keep actual voltage distortion below objectionable levels. The underlying assumption of these recommended limits is that by limiting harmonic current injections by users, voltage distortion can be kept below objectionable levels. In the event that limiting harmonic currents alone does not result in acceptable levels of voltage distortion, system owners or operators should take action to modify system characteristics so that voltage distortion levels are acceptable. The acceptable voltage distortion levels form the basis of the harmonic voltage limits in 5.1.

The recommended limits in this clause apply only at the point of common coupling and should not be applied to either individual pieces of equipment or at locations within a user's facility. In most cases, harmonic voltages and currents at these locations could be found to be significantly greater than the limits recommended at the PCC due to the lack of diversity, cancellation, and other phenomena that tend to reduce the combined effects of multiple harmonic sources to levels below their algebraic summation.

5.1 Recommended harmonic voltage limits

At the PCC, system owners or operators should limit line-to-neutral voltage harmonics as follows:

— Daily 99th percentile very short time (3 s) values should be less than 1.5 times the values given in Table 1.

— Weekly 95th percentile short time (10 min) values should be less than the values given in Table 1.

All values should be in percent of the rated power frequency voltage at the PCC. Table 1 applies to voltage harmonics whose frequencies are integer multiples of the power frequency.

Table 1—Voltage distortion limits

Bus voltage V at PCC	Individual harmonic (%)	Total harmonic distortion THD (%)
$V \leq 1.0$ kV	5.0	8.0
1 kV < $V \leq 69$ kV	3.0	5.0
69 kV < $V \leq 161$ kV	1.5	2.5
161 kV < V	1.0	1.5[a]

[a]High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal whose effects will have attenuated at points in the network where future users may be connected

Information on voltage interharmonic limits is given in Annex A and is based on lamp flicker assessed using the measurement technique described in IEEE Std 1453 and IEC 61000-4-15. The information of Annex A is not based on the effects of interharmonics on other equipment and systems such as generator mechanical systems, motors, transformers, signaling and communication systems, and filters. Due consideration should be given to these effects and appropriate interharmonic current limits should be developed starting from the information in Annex A on a case-by-case basis using specific knowledge of the supply system, connected user loads, and provisions for future users.

5.2 Recommended current distortion limits for systems nominally rated 120 V through 69 kV

The limits in this subclause apply to users connected to systems where the rated voltage at the PCC is 120 V to 69 kV. At the PCC, users should limit their harmonic currents as follows:

— Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table 2.

— Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table 2.

— Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in Table 2.

All values should be in percent of the maximum demand current, I_L. This current value is established at the PCC and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12. Table 2 applies to harmonic currents whose frequencies are integer multiples of the power frequency.

Table 2—Current distortion limits for systems rated 120 V through 69 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{SC}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	4.0	2.0	1.5	0.6	0.3	5.0
20 < 50	7.0	3.5	2.5	1.0	0.5	8.0
50 < 100	10.0	4.5	4.0	1.5	0.7	12.0
100 < 1000	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L
where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

For interharmonic current components with frequencies that are not integer multiples of the power frequency, users should limit the components to sufficiently low levels so as to not produce undesirable effects on the power system and connected equipment. Limiting values and appropriate statistical indices should be developed on a case-by-case basis starting from the guidance of Annex A and considering the specifics of the supply system, connected user loads, and provisions for other users.

5.3 Recommended current distortion limits for systems nominally rated above 69 kV through 161 kV

The limits in this subclause apply to users connected to systems where the rated voltage V at the PCC is 69 kV < $V \le$ 161 kV. At the PCC, users should limit their harmonic currents as follows:

— Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table 3.

RGEC 003755

— Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table 3.

— Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in Table 3.

All values should be in percent of the maximum demand current, I_L. This current value is established at the PCC and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12. Table 3 applies to harmonic currents whose frequencies are integer multiples of the power frequency.

Table 3—Current distortion limits for systems rated above 69 kV through 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{sc}/I_L	$3 \le h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h \le 50$	TDD
< 20[c]	2.0	1.0	0.75	0.3	0.15	2.5
$20 < 50$	3.5	1.75	1.25	0.5	0.25	4.0
$50 < 100$	5.0	2.25	2.0	0.75	0.35	6.0
$100 < 1000$	6.0	2.75	2.5	1.0	0.5	7.5
> 1000	7.5	3.5	3.0	1.25	0.7	10.0

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e.g., half-wave converters, are not allowed.

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L
where
I_{sc} = maximum short-circuit current at PCC
I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

For interharmonic current components with frequencies that are not integer multiples of the power frequency, users should limit the components to sufficiently low levels so as to not produce undesirable effects on the power system and connected equipment. Limiting values and appropriate statistical indices should be developed on a case-by-case basis starting from the guidance of Annex A and considering the specifics of the supply system, connected user loads, and provisions for other users.

5.4 Recommended current distortion limits for systems nominally rated above 161 kV

The limits in this subclause apply to users connected to general transmission systems where the rated voltage V at the PCC is greater than 161 kV. At the PCC, users should limit their harmonic currents as follows:

— Daily 99th percentile very short time (3 s) harmonic currents should be less than 2.0 times the values given in Table 4.

— Weekly 99th percentile short time (10 min) harmonic currents should be less than 1.5 times the values given in Table 4.

— Weekly 95th percentile short time (10 min) harmonic currents should be less than the values given in Table 4.

RGEC 003756

All values should be in percent of the maximum demand current, I_L. This current value is established at the PCC and should be taken as the sum of the currents corresponding to the maximum demand during each of the twelve previous months divided by 12. Table 4 applies to harmonic currents whose frequencies are integer multiples of the power frequency.

Table 4—Current distortion limits for systems rated > 161 kV

Maximum harmonic current distortion in percent of I_L						
Individual harmonic order (odd harmonics)[a, b]						
I_{sc}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	TDD
< 25[c]	1.0	0.5	0.38	0 15	0.1	1.5
25 < 50	2 0	1 0	0.75	0.3	0.15	2 5
≥ 50	3.0	1.5	1 15	0.45	0 22	3.75

[a]Even harmonics are limited to 25% of the odd harmonic limits above.

[b]Current distortions that result in a dc offset, e g., half-wave converters, are not allowed

[c]All power generation equipment is limited to these values of current distortion, regardless of actual I_{sc}/I_L

where

I_{sc} = maximum short-circuit current at PCC

I_L = maximum demand load current (fundamental frequency component) at the PCC under normal load operating conditions

For interharmonic current components with frequencies which are not integer multiples of the power frequency, users should limit the components to sufficiently low levels so as to not produce undesirable effects on the power system and connected equipment. Limiting values and appropriate statistical indices should be developed on a case-by-case basis starting from the guidance of Annex A and considering the specifics of the supply system, connected user loads, and provisions for other users.

5.5 Recommendations for increasing harmonic current limits

It is recommended that the values given in Table 2, Table 3, and Table 4 be increased by a multiplying factor when actions are taken by a user to reduce lower-order harmonics. The multipliers given in the second column of Table 5 are applicable when steps are taken to reduce the harmonic orders given in the first column.

Table 5—Recommended multipliers for increases in harmonic current limits

Harmonics orders limited to 25% of values given in Table 2, Table 3, and Table 4	Multiplier
5, 7	1.4
5,7,11,13	1 7
5,7,11,13,17,19	2.0
5,7,11,13,17,19,23,25	2.2
↓	↓

The multipliers in Table 5 can be obtained as shown in Equation (3) where p is the pulse-order of a three-phase rectifier-based converter ($p = 6, 12, 18, 24$, etc.). These converters produce dominant or characteristic harmonic currents at orders of $p(n \pm 1)$, where n is a simple counter, $n = 1, 2, 3$ etc., and significantly lower current magnitudes at other orders. However, the recommended multipliers in Table 3 apply regardless of the method used to reduce the harmonics that would be considered "non-characteristic harmonics" for a p-pulse converter as long as all "non-characteristic harmonics," including even-order harmonics, are kept below 25% of the limit values given in Table 2, Table 3, or Table 4 as appropriate.

$$\text{Multiplier} = \sqrt{\frac{p}{6}} \qquad (3)$$

Annex A

(informative)

Interharmonic voltage limits based on flicker

For interharmonic components that are not integer multiples of the power frequency, system owners or operators may limit the weekly 95th percentile short time harmonic voltages to the values shown graphically in Figure A-1 up to 120 Hz for 60 Hz systems. Depending on the voltage level, the integer harmonic limits in Table 1 may be more restrictive and should be used. The portions of the 0–120 Hz range where the integer harmonic limits of Table 1 are more restrictive are appropriately labeled in Figure A-1. The numerical values corresponding to Figure A-1 are given in Table A-1 for voltages at the PCC less than 1 kV. It is important to recognize that the suggested voltage interharmonic limits are based on lamp flicker assessed using the measurement technique described in IEEE Std 1453 and IEC 61000-4-15. These voltage interharmonic limits correlate with a short-term flicker severity Pst value equal to 1.0 for 60 Hz systems; different (but similar) limit values can be derived for 50 Hz systems. The recommended limits in Figure A-1 are not based on the effects of interharmonics on other equipment and systems such as generator mechanical systems, motors, transformers, signaling and communication systems, and filters. Due consideration should be given to these effects and appropriate interharmonic current limits should be developed on a case-by-case basis using specific knowledge of the supply system, connected user loads, and provisions for future users.

There is no limit on the 60 Hz component in Figure A-1. The 5% maximum applies to frequency components very near (but not equal to) 60 Hz.

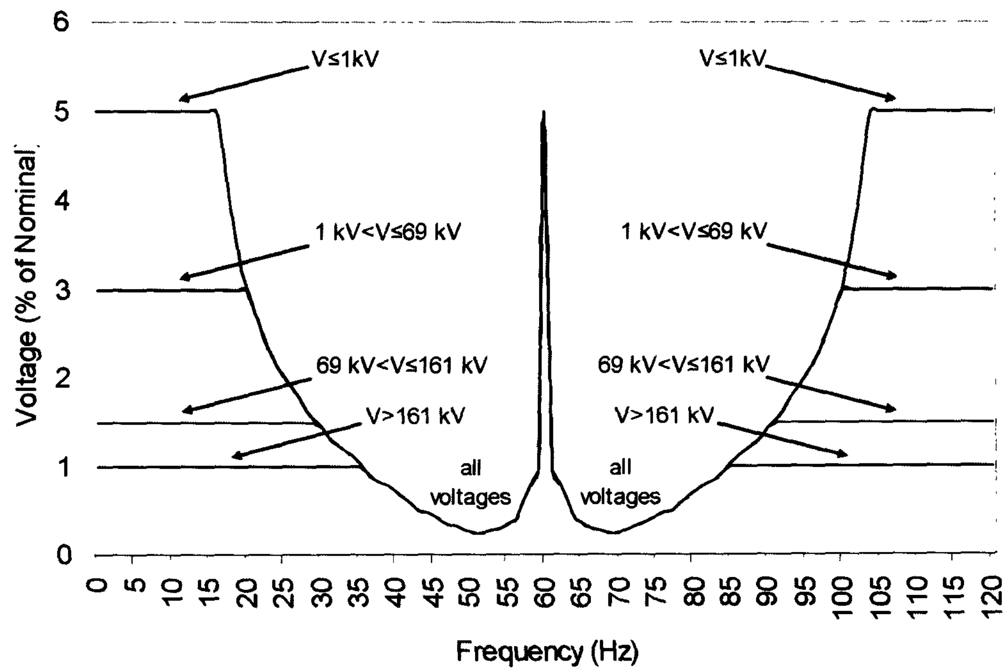

Figure A-1—Interharmonic voltage limits based on flicker for frequencies up to 120 Hz for 60 Hz systems

Table A-1—Voltage interharmonic limits corresponding to Figure A-1 for PCC voltage less than 1 kV[a, b]

Frequency (Hz)	Magnitude (%)	Frequency (Hz)	Magnitude (%)	Frequency (Hz)	Magnitude (%)	Frequency (Hz)	Magnitude (%)
16	5.00	27	1.78	38	0.81	49	0.28
17	4.50	28	1.64	39	0.78	50	0.25
18	3.90	29	1.54	40	0.71	51	0.23
19	3.45	30	1.43	41	0.64	52	0.25
20	3.00	31	1.33	42	0.57	53	0.27
21	2.77	32	1.26	43	0.50	54	0.29
22	2.53	33	1.20	44	0.48	55	0.35
23	2.30	34	1.13	45	0.43	56	0.40
24	2.15	35	1.05	46	0.38	57	0.58
25	2.03	36	0.95	47	0.34	58	0.77
26	1.90	37	0.85	48	0.31	59	0.95

[a]The values for frequencies above 60 (but less than 120) Hz are identical to those given in this table except the frequency of interest must be subtracted from 120 Hz before reading the corresponding value. For example, the interharmonic voltage limit for 61 Hz is equal to that given in the table for 120 – 61 = 59 Hz, which is 0.95%

[b]The frequency resolution in Table A-1 is 1 Hz. The resolution available using the methods recommended in Clause 4 is 5 Hz. Special instrumentation to be agreed upon at the time of its use, may be needed to obtain 1 Hz resolution.

Annex B

(informative)

Telephone influence factor (TIF)

The TIF weighting is a combination of the C message weighting characteristic, which accounts for the relative interfering effect of various frequencies in the voice band (including the response of the telephone set and the ear), and a capacitor, which provides weighting that is directly proportional to frequency to account for the assumed coupling function. TIF is a dimensionless quantity that is indicative of the waveform and not the amplitude and is given by Equation (B.1).

$$\mathrm{TIF} = \sqrt{\sum\left[\frac{(X_n \cdot W_n)}{X}\right]^2} \tag{B.1}$$

where

X = total rms voltage or current
X_n = single frequency rms current or voltage at the frequency corresponding to harmonic order n
W_n = single frequency TIF weighting at the frequency corresponding to harmonic order n

In practice, telephone interference is often expressed as a product of the current and the TIF, i.e., the *I-T* product, where the *I* is rms current in amperes and *T* is TIF as calculated in Equation (B.1). Alternatively, it is sometimes expressed as a product of the voltage and the TIF weighting, where the voltage is in rms kV, i.e., the *kV-T* product. The single frequency weighting values, based on 1960-vintage C-message weighting, are listed in Table B-1. Linear interpolation may be used as necessary in Table B-1.

Table B-1—Weighting values (W_f)

FREQ	W_f	FREQ	W_f	FREQ	W_f	FREQ	W_f
60	0 5	1020	5100	1860	7820	3000	9670
180	30	1080	5400	1980	8330	3180	8740
300	225	1140	5630	2100	8830	3300	8090
360	400	1260	6050	2160	9080	3540	6730
420	650	1380	6370	2220	9330	3660	6130
540	1320	1440	6560	2340	9840	3900	4400
660	2260	1500	6680	2460	10340	4020	3700
720	2760	1620	6970	2580	10600	4260	2750
780	3360	1740	7320	2820	10210	4380	2190
900	4350	1800	7570	2940	9820	5000	840
1000	5000						

B.1 Guidelines for *I-T* product

Table B-2 provides representative *I-T* guidelines for distribution systems operating at voltages less than (or equal to) 34.5 kV where it is more likely to have joint use of facilities, particularly poles and structures, involving electric power and telephone/communications companies. These guidelines should not be considered as recommended limits due to the wide range of variability in system and equipment compatibility that is encountered in practice. The use of categories is for illustration purposes only and is provided in the event that it is desirable to assess or compare interference potentials in multiple areas of a particular electrical system.

Table B-2—*I-T* guidelines for distribution systems[a]

Category	Description	*I-T*
I	Levels most unlikely to cause interference	Up to 10 000[b]
II	Levels that might cause interference	10 000 up to 25 000
III	Levels that probably will cause interference	Greater than 25 000

[a]These values of *I-T* product are for circuits with an exposure between overhead systems. both power and telephone. Within an industrial plant or commercial building, the exposure between power distribution cables and telephone lines with twisted pairs is extremely low and no interference is normally encountered. the use of fiber optic cables for communications virtually eliminates the entire concern.
[b]For some areas that use a ground return for either telephone or power circuits, this value may be as low as 1500.

Annex C

(informative)

Limits on commutation notches

C.1 Recommended limits on commutation notches

The notch depth and the notch area of the line-to-line voltage at PCC should be limited as shown in Table C-1.

Table C-1—Recommended limits on commutation notches

	Special applications[a]	General system	Dedicated system[b]
Notch depth	10%	20%	50%
Notch area (A_N)[c, d]	16400	22800	36500

[a]Special applications include hospitals and airports
[b]A dedicated system exclusively supplies a specific user or user load
[c]In volt-microseconds at rated voltage and current.
[d]The values for A_N have been developed for 480 V systems. It is necessary to multiply the values given by V/480 for application at all other voltages.

These limits are recommended for low-voltage systems in which the notch area is easily measured on an oscilloscope or power quality monitor with oscilloscope capability. In the event that direct measurement is not possible, detailed simulations including advanced models of the supply system and loads may provide approximate waveforms that may be used in place of oscilloscope measurements. The relevant variables for use in Table C-1 are defined in Figure C-1.

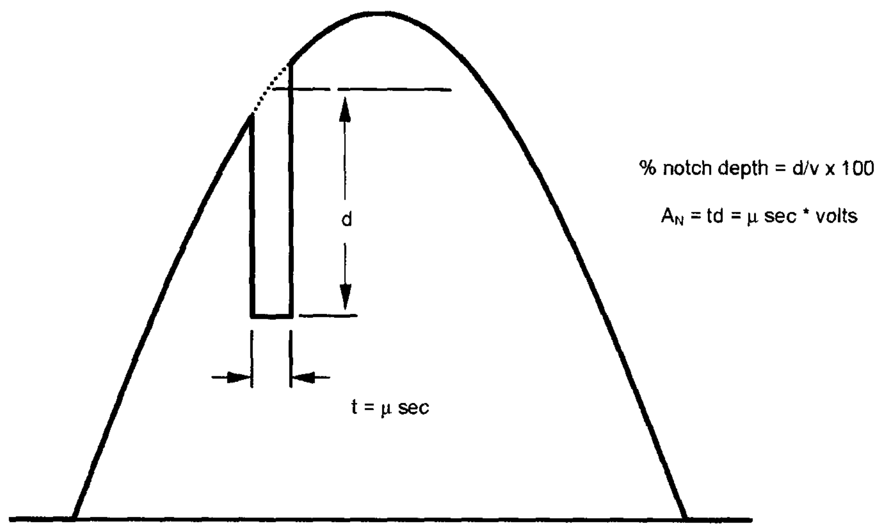

Figure C-1—Definition of notch depth and notch area

EXHIBIT RG-12

PUBLIC UTILITY COMMISSION OF TEXAS

PUC NO. 49795
SOAH DOCKET NO. 473-20-1118

COMPANY NAME: **Rio Grande Electric Cooperative, Inc.**

INFORMATION REQUESTED:

Petty 5-3: Please refer to the "Current" tab of Deposition Exhibit 34. Over what time period did the PMI recorder record data for the following entries? Please specify start date and time and end date and time.

a. Petty Ranch Prior to Generator at 2:35 pm, Data Collection Date 3/6/2019
b. Petty Ranch — Generator Data at 10:41 am, Data Collection Date 3/21/2019
c. Petty Ranch — Generator Data at 12:16 pm, Data Collection Date 3/21/2019

REQUESTED BY: Petty Group, LLP

RESPONSE:

a. Petty Ranch prior to generator at 2:35pm, data collection date 3/6/2019. PMI recorded data from 3/6/2019 starting at 2:28pm and ending at 3/8/2019 at 10:22am.

b. Petty Ranch generator data at 10:41am, data collection date 3/21/2019. PMI recorded data from 3/19/2019 starting at 1:22pm and ending at 3/21/2019 at 1:40pm.

c. Petty Ranch generator data at 12:16pm, data collection date 3/21/2019. PMI recorded data from 3/19/2019 starting at 1:22pm and ending at 3/21/2019 at 1:40pm.

SPONSOR:

Roger Andrade

CONFIDENTIAL EXHIBITS RG-3, RG-6, RG-7, RG-8, RG-9, RG-10, RG-11 ARE BEING SUBMITTED UNDER CONFIDENTIAL COVER