Why Are AMAROK Electric Security Fences Safe?

Mark W. Kroll, PhD, FACC, FHRS

24 July 2020

Electric security fences, that satisfy US and International regulations, are safe for human beings. These regulations have developed from over 100 years of experience and scientific testing.[1,2] The pulses are extremely short and thus the brief, high current is not able to affect the heart (electrocute). The best analogy is to a strong static shock which can be painful but has never injured anyone. Strong static shocks can damage electronics — which responds almost instantly — but the human body is not harmed by such brief shocks. A strong static shock can have a peak current of 30 A (amperes) but is too short to be dangerous.[3] Note that this is over 2x (twice) the peak current of an electric security fence.[4,5] The peak current is irrelevant to safety for short shocks.[6]

Question 1:
I saw on the internet that 0.1 amperes (100 mA) is dangerous and that electric fences can have a peak current of over 10 A. Is that dangerous?
Answer: No. An AC current of over 0.1 A can be dangerous to humans but only if the shock lasts about 1 second or more.[7] The AMAROK security fence pulse only lasts about 0.0001 seconds, so it is 10,000 times shorter than a danger shock.[4]

Question 2:
But still, that 10 amperes is 100 times as strong as the 100 mA danger level!
Answer: It is misleading to compare a peak current with an average current. Since the AMAROK security fence pulses only occur every 1.3 seconds, the average current is only 0.46 mA. Thus, the *average* current of an electric fence is 200 times less than the danger level. We rate AC currents by RMS (root-mean-square) which functions as an average.

Question 3:
How about wet conditions? How about children and wildlife?
Answer: The US and International Electric Fence Safety Standards assume a worst-case scenario of a barefoot child contacting the fence while standing on wet ground.[8,9] Historical cases of tragic pediatric fatalities involved continuous AC (alternating current), and not the modern short DC (direct current) pulses satisfying today's safety standards.[2,10] The same is true for wildlife.[11]

Question 4:
What if the person has a pacemaker?
Answer: For technical reasons, this does not present a risk. The cardiology literature warns of various dangers for pacemaker patients; the electric fence is not included as a danger.[12]

References:

1. Dalziel CF. Electric fences-their hazards, types, regulations, and safe application. *Transactions of the American Institute of Electrical Engineers.* 1950;69(1):8-15.
2. Whittaker. Electric shock as it pertains to the electric fence. *Underwriter's Laboratories Bulletin of Research.* 1939;14:1-56.
3. International_Electrotechnical_Commission. Electromagnetic compatibility (EMC) - Part 4-2: Testing and measurement techniques - Electrostatic discharge immunity test. Vol IEC 61000-4-2: IEC.
4. Kroll M, Perkins P, Pratt H, Stuart E, Bury J, Panescu D. Safety of a High-Efficiency Electrical Fence Energizer. *Conf Proc IEEE Eng Med Biol Soc.* 2020;41:in press.
5. Kroll MW, Perkins PE, Panescu D. Electric fence standards comport with human data and AC limits. *Conf Proc IEEE Eng Med Biol Soc.* 2015;2015:1343-1348.
6. Kroll MW, Panescu D, Hirtler R, Koch M, Andrews CJ. Dosimetry for Ventricular Fibrillation Risk with Short Electrical Pulses: History and Future. . *Conf Proc IEEE Eng Med Biol Soc.* 2019;41:1788-1794.
7. Ferris LP, King BG, Spence PW, Williams HB. Effect of electric shock on the heart. *Electrical Engineering.* 1936;55(5):498-515.
8. IEC. Household and similar electrical appliances – Safety – IEC 60335-2-76: Particular requirements for electric fence energizers. *International Electrotechnical Commission.* 2006.
9. Underwriters_Laboratories. UL 69: Electric fence controllers. 2003.
10. Oregon's first death from an electric fence. *International Association of Electrical Inspectors News Bulletin.* 1940;12.
11. McAtee W. The electric fence in wildlife management. *The Journal of Wildlife Management.* 1939;3(1):1-13.
12. Santini L, Forleo GB, Santini M. Implantable devices in the electromagnetic environment. *Journal of Arrhythmia.* 2013;29(6):325-333.

Safety of a High-Efficiency Electrical Fence Energizer

Mark W. Kroll, PhD, *FIEEE*; Peter E. Perkins, MSEE, *LFIEEE*; Hugh Pratt, PhD; Edward Stuart, *Member IEEE*; J. Bury, *Member IEEE*; Dorin Panescu, PhD, *FIEEE*

Introduction: Our primary goal was to evaluate the performance of a new high-efficiency electric fence energizer unit using resistive load changes. Our secondary goal was to test for compliance with the classical energy limits and the newer charge-based limits for output.
Methods: We tested 4 units each of the Nemtek Druid energizer with 2 channels each. We used a wide load-resistance range to cover the worst-case scenario of a barefoot child making a chest contact (400 Ω) up to an adult merely touching the fence (2 kΩ).
Results: The energy output was quite consistent between the 8 sources. Even at the lowest resistance, 400 Ω, the outputs were well below the IEC 60335-2-76 limit of 5 J/pulse. The charge delivered was also quite consistent. Even at the lowest resistance, 400 Ω, the outputs (679 ± 23 µC) were well below the proposed limits of 4 mC for short pulses.
Conclusions: The high-efficiency electric fence energizers satisfied all relevant safety limits. Charge, energy, voltage, and current outputs are consistent between channels and distinct units.

INTRODUCTION

Electric fence technology allows for economical and safe control of animals and humans as opposed to barbed or concertina wire which can cause injury. They use a painful brief shock intended to be well below the threshold for VF (ventricular fibrillation) and thus unable to electrocute a human being.[1] The traditional EFE (electric fence energizer) charged a capacitor and then dumped the capacitor energy into the primary of a transformer.[2] The secondary of the transformer then delivered its output to the electric fence wires. Such open-loop systems are affected by arcing (to vegetation or between wires) which can significantly reduce the charge delivered to the fence. Simply increasing the output is unacceptable due to safety concerns and there have been pediatric fatalities due to noncompliant fences.[3, 4] There are US and international safety standards governing EFEs.[5-7]

The traditional EFE output stages are not optimally efficient — in terms of energy and materials — due to the energy-material tradeoffs in the large capacitor and transformer output stage. The tested design (shown in Figure 1) uses diode current-steering to significantly reduce the size of the capacitor and transformer. The 30 µF energy-storage capacitor and the 16 µH series inductor give a resonant frequency of ~7 kHz or a period of ~ 60 µs. This is significantly underdamped as there is minimal resistance in the circuit (300 mΩ from PC board tracings). A 2nd higher-frequency resonant circuit is formed by the inductor and the 12 µF capacitor; this causes the 2nd peak superimposed onto the main discharge curve. The diode across the transformer primary eliminates the longer low-amplitude reverse flow of current through the transformer and so keeps the output pulse shorter in duration as well as eliminating useless energy delivery cancelling charge from the main discharge pulse. See Figure 2. Since many present EFE standards still include the 5 J/pulse energy limit, reducing the delivered energy is important for regulatory reasons. This design is able to use smaller and lighter inductors and capacitors without having the charge cancellation that would be otherwise seen. Due to the classical misunderstanding that energy causes sensation, this monopolarity feature was often not appreciated in the past.[8, 9] While charge stimulates, energy is what makes burns, and thus a hugher energy is useful for ablating vegetation shorts on an electric fence.

The design objective is to deliver ≥ 0.2 mC of charge as that is known to be disagreeable to adult humans.[8, 10-13] Another key objective is to keep the output energy < 2.5 J so that a 2-channel unit would still satisfy the 5 J total output allowed by international safety standards.[6]

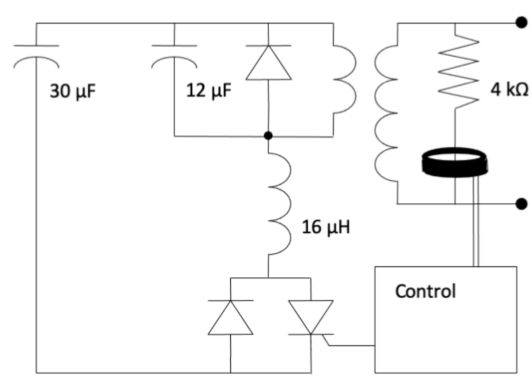

Figure 1. Ouput stage of tested energizer.

Feedback control also allows for significant energy efficiency gains. The design of a closed-loop EFE is non-trivial due to the load nonlinearities, transformer saturation, and the isolation of the high-voltages. The output load has capacitance, inductance, and transmission-line characteristics making modeling somewhat complex.[14, 15] With line distances > 1 km the input impedance of a linear electric fence approaches that of free space (377 Ω) with a reflected impedance near 0 Ω. In addition, arcing to vegetation introduces nonlinearities while

[1] M. W. Kroll is an Adjunct Professor of Biomedical Engineering at the University of Minnesota, Minneapolis, MN (e-mail: mark@kroll.name). Dr. Kroll is a consultant to Amarok.
P. Perkins is an independent consultant. peperkinspe@cs.com
Hugh Pratt, PhD, is Secretary of CPLSO
Edward Stuart (estuart@amarok.com) and J Bury(jbury@amarok.com) are employees of Amarok.
D. Panescu is Chief Technical Officer, Vice President R&D, HeartBeam, Inc. (e-mail: panescu_d@yahoo.com).

arcing to ground (or to a return wire) can introduce negative dynamic resistance which makes traditional feedback control impossible.

We evaluated the performance of the Nemtek Druid™ units with APT (Adaptive Power Technology) whose loaded waveforms are given in Figure 2. Upon initialization, it charges the output capacitors to a level that are expected to approximately generate a 4 kV pulse after passing thru a pulse transformer. The actual voltage output is then measured, and this is used to calibrate the system and then the following pulses are delivered with peak voltages of 8.5-9.5 kV for a largely open circuit. In case of arcing, the voltage waveform is distorted from that seen in Figure 2 and the system recognizes this and reduces the peak voltage until the arcing ceases. This feature was not tested in our study.

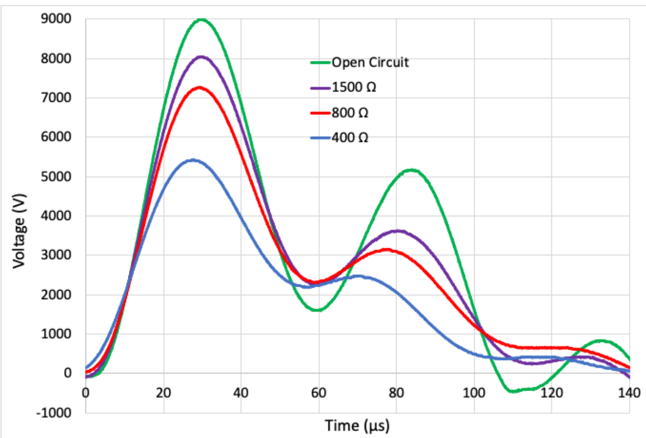

Figure 2. Typical output voltage waveforms for various loads.

For a closed-loop design a feedback signal from the energizer's output terminals is required. Although a simple resistor voltage-divider network can provide an accurate feedback signal, this is not practical due to isolation specifications which are required by the electric fence safety standards. The units tested sampled the output voltage by running it thru a high-voltage non-inductive 4 kΩ resistor. The current thru the resistor was, in turn, sampled by a current transformer (black ring in Figure 1) to provide isolated feedback to the control circuitry.

Present EFE safety standards are based on a 5-joule energy limit per pulse. However, since energy heats while charge stimulates, newer safety standards, for general applications, are now being based on the delivered charge.[16] For example, the proposed level for "low risk of fibrillation" is 4 mC. The charge is more dependent on the load resistance and thus we sought to evaluate this technology vs. the newer charge limits. We used a wide load-resistance range to cover the worst-case scenario of a barefoot child making a chest contact (400 Ω) up to an adult merely touching the fence (2 kΩ).[17]

Our primary goal was to evaluate the performance of the new high-efficiency feedback-controlled EFE units with load changes. Our secondary goal was to test for compliance with the classical energy limits and the newer charge-based limits for output.

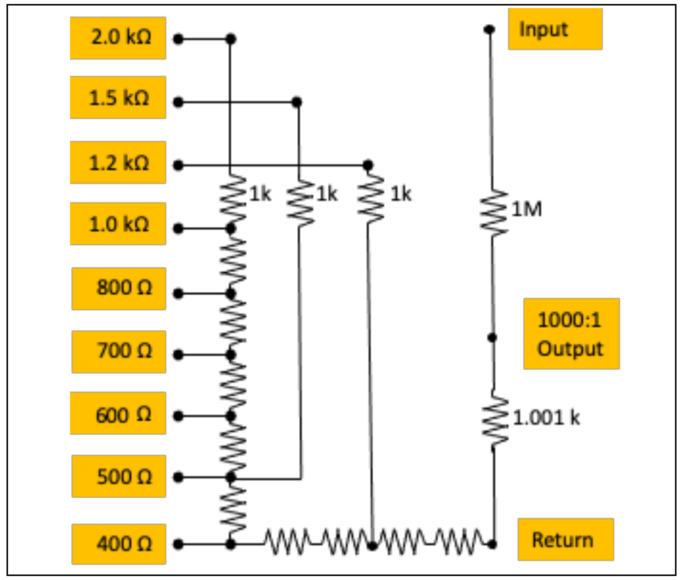

Figure 3. Voltage divider and load resistors. Unlabeled resistors are 100 Ω.

METHODS

We constructed a 1000:1 voltage divider using a 1 MΩ high-voltage low inductance Ohmite (Warrenville, Ohio, USA) MOX-3N resistor with a 30 kV pulse rating in series with 1001 Ω. The load resistance was selectable over 400, 500, 600, 700, 800, 1k, 1.2k, 1.5k, and 2 kΩ by use of the schematic shown in Figure 3. The load resistances were made up from Ohmite model OY series 100 Ω and 1 kΩ noninductive ceramic resistors rated for 20 kV and 70 J of capacitive discharge. Series trimming was done with smaller-value carbon resistors. The open circuit voltage was measured by removing the jumper going to a load resistor. Since the tested EFEs all had a 4 kΩ output resistor, the output-stage transformer was never truly operating into an open-circuit load.

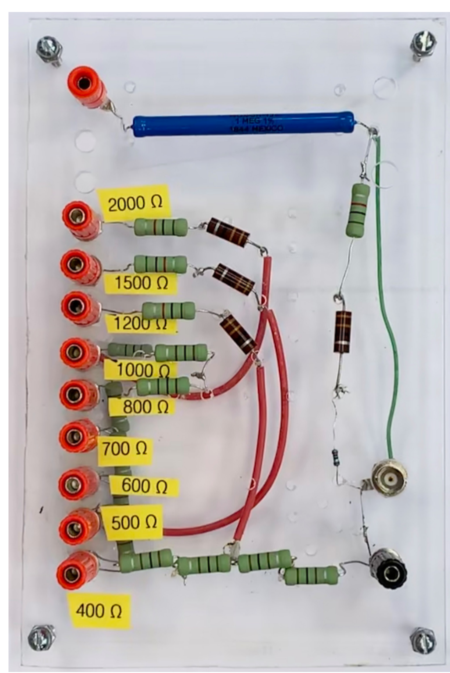

Figure 4. Voltage divider and load resistors.

All resistance values were verified to be within 1% with a Flexzion VC8145 5-digit meter which was in turn calibrated to a Vishay (0.1% 500 Ω precision resistor.) Voltage values were recorded by a calibrated Siglent SDS1202X digital storage oscilloscope sampling at 1 ns intervals.

A total of 4 Nemtek Druid™ EFE units were tested. Since each unit has 2 individual outputs, there were 8 sources tested in total. E.g. 1030/1. For determination of the peak voltage and current, the instantaneous voltages were boxcar averaged over 200 samples (200 ns duration) to reduce noise artifact.

RESULTS

The energy per pulse output was quite consistent between the 8 sources as shown in Figure 5. Even at the lowest resistance, 400 Ω, the outputs were well below the IEC 60335-2-76-limit of 5 J/pulse. At the standard test load of 500 Ω, the output was 2.23 ± 0.05 J and thus far from the 2.5 J limit ($p < 0.001$).

There is a consistent transition seen between 1 kΩ and 1.2 kΩ as the system shifts from open loop to feedback control. For loads ≤ 1.1 kΩ, the ouput voltage is limited passively by the maximum energy in the main storage capacitor.

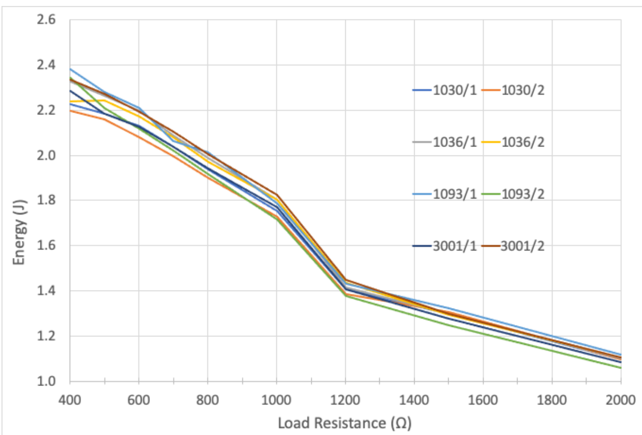

Figure 5 Energy per pulse as function of load resistance.

The charge delivered was quite consistent between the 8 sources as shown in Figure 6. Even at the lowest resistance, 400 Ω, the outputs were well below the proposed new limits of 4 mC/pulse.[16] At the standard test load of 500 Ω, the output was 0.60 ± 0.03 mC.

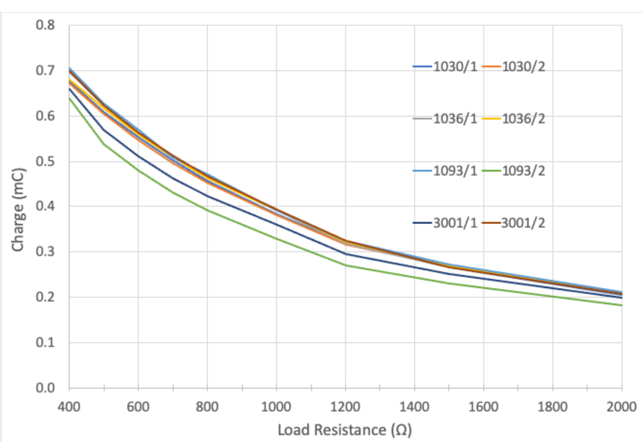

Figure 6 Charge per pulse as function of load resistance.

The peak voltage delivered was also quite consistent between the 8 sources as shown in Figure 5. None exceeded the specified 9.7 kV maximum even with an open circuit. Again, there is a consistent control transition seen between 1 kΩ and 1.2 kΩ as control shifts from passive to active feedback. The feedback adjustment converged very rapidly and appeared to settle typically within a single 2nd pulse after a load change.

Linear regression modeling found that the peak voltage was roughly modeled as an internal 9154 ± 58 V source in series with a 224 ± 54 Ω equivalent series resistance. At the standard test load of 500 Ω, the output was 5999 ± 79 V.

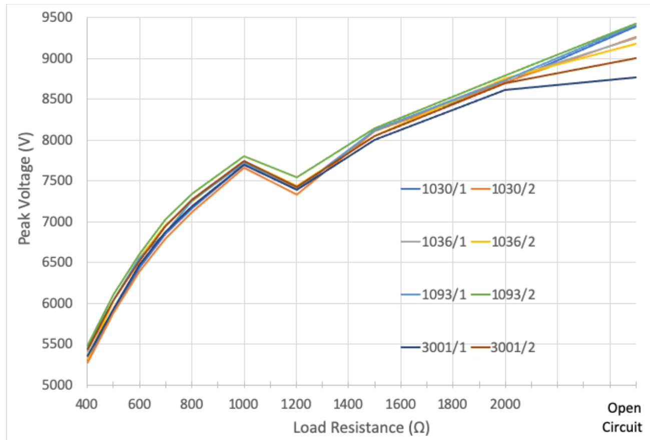

Figure 7. Peak voltage as function of load resistance.

The peak current delivered was impressively consistent between the 8 sources as shown in Figure 8. At the standard test load of 500 Ω, the output was 12.00 ± 0.16 A.

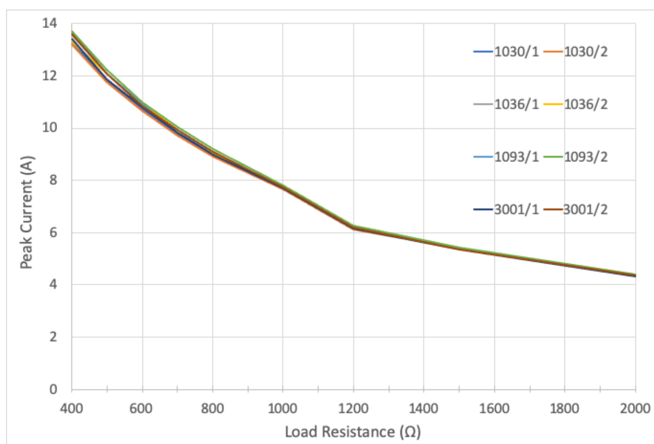

Figure 8. Peak current as function of load resistance.

DISCUSSION

We believe that this is the first paper to examine the performance and safety of advanced high-efficiency digital feedback-controlled electric fence energizers. All units tested satisfied all relevant safety limits. Charge, energy, voltage, and current outputs were consistent between both channels and distinct units.

The ubiquitous electric fence is essential to modern agriculture and has saved a great many lives by reducing the number of livestock automobile collisions.[18-22] They also provide safe protection against criminal activity. Modern safety standards such as IEC 60335-2-76 and UL 69 have certainly played a role in this positive result.[5, 23] However, the safety standards are essentially based on energy and power (RMS current) considerations, which have limited direct relationship to cardiac effects.

Upcoming safety standards, for short pulses, will be based on the more scientific charge.[16] With great prescience, UL researcher Whittaker proposed a charge-based limit, of 4 mC, back in 1939.[24] Because of electrocutions from AC electric fences, impulse-generating electric fence energizers became very popular in the 1930. Many government agencies and standards organizations then adopted charge limits to levels deemed safe.[1] The Underwriter's Laboratories (USA) proposed 4 mC as a safe impulse.[24] The Industrial Commission of Wisconsin (a USA state important for dairy production) and the U.S. National Bureau of Standards adopted 3 mC as the safe level. Most countries adopted 3 mC as the safe level including Finland, Denmark, Great Britain, and France.[1] Sweden used a 2.5 mC level and the C.E.E (IEC predecessor) also proposed 2.5 mC.[1] The IEC 60335 standard replaced the various country standards and eventually dropped the charge-based limit in 1989 in favor of a pure-energy limit.

Thus, the international standards community once had scientifically-sound *charge-based* limits for electrical impulses. Unfortunately, this understanding was somehow lost and the impulse limits became associated with the less-relevant energy and power.[16]

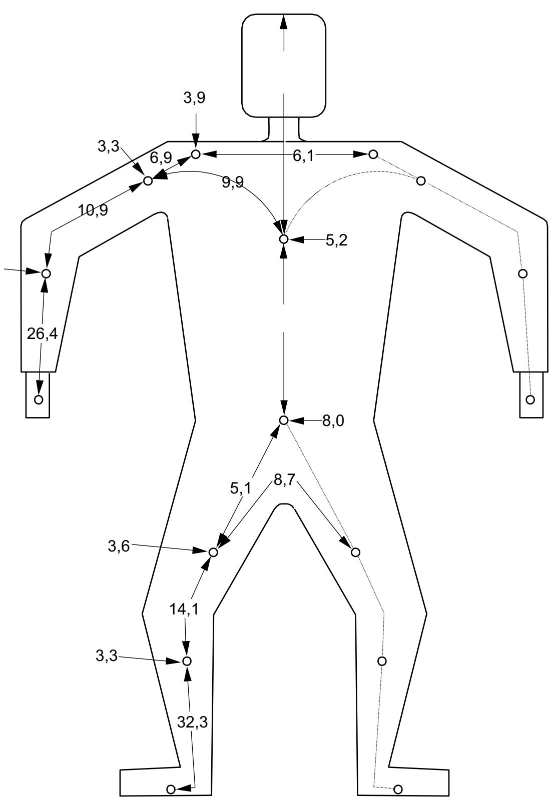

Figure 9. Body part contributions to resistance.

Based on the 37% contribution of the arm to the typical body resistance, we discounted the median 775 Ω high-voltage impedance to 488 Ω as given by our Figure 9 taken form IEC 60479-1.[6] To include the worst-case scenario of a barefoot child contacting a fence at chest height, we further deducted the 9.9% (for shoulder to center-trunk) so the resistance would be 409 Ω and thus we elected to test down to a 400 Ω load.

LIMITATIONS

We did not evaluate the performance of these units with capacitive or inductive loads. We did not evaluate the performance with long lines.

CONCLUSIONS

The digitally controlled feedback electric fence energizer tested satisfied all relevant safety limits. Charge, energy, voltage, and current outputs are consistent between channels and distinct units.

REFERENCES

[1] C. F. Dalziel, "Electric fences-their hazards, types, regulations, and safe application," *Transactions of the American Institute of Electrical Engineers,* vol. 69, no. 1, pp. 8-15, 1950.

[2] M. G. B. De Martino, F. S. Dos Reis, and G. A. Dias, "An electric fence energizer design method," in *2006 IEEE International Symposium on Industrial Electronics*, 2006, vol. 2, pp. 727-732: IEEE.

[3] M. Burke, M. Odell, H. Bouwer, and A. Murdoch, "Electric fences and accidental death," *Forensic Sci Med Pathol,* vol. 13, no. 2, pp. 196-208, Jun 2017.

[4] L. Stallones, "Fatal unintentional injuries among Kentucky farm children: 1979 to 1985," *The Journal of Rural Health,* vol. 5, no. 3, pp. 246-256, 1989.

[5] Underwriters_Laboratories, "UL 69: Electric fence controllers," June 2003.

[6] IEC, "Household and similar electrical appliances – Safety – IEC 60335-2-76: Particular requirements for electric fence energizers," *International Electrotechnical Commission,* 2006.

[7] M. W. Kroll, P. E. Perkins, and D. Panescu, "Electric fence standards comport with human data and AC limits," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2015, pp. 1343-8, Aug 2015.

[8] F. Gracanin and A. Trnkoczy, "Optimal stimulus parameters for minimum pain in the chronic stimulation of innervated muscle," *Arch Phys Med Rehabil,* vol. 56, no. 6, pp. 243-9, Jun 1975.

[9] W. Irnich, "Georges Weiss' fundamental law of electrostimulation is 100 years old," *Pacing Clin Electrophysiol,* vol. 25, no. 2, pp. 245-8, Feb 2002.

[10] W. D. Larkin and J. P. Reilly, "Strength/duration relationships for electrocutaneous sensitivity: stimulation by capacitive discharges," (in eng), *Percept Psychophys,* vol. 36, no. 1, pp. 68-78, Jul 1984.

[11] W. D. Larkin, J. P. Reilly, and L. B. Kittler, "Individual differences in sensitivity to transient electrocutaneous stimulation," (in eng), *IEEE Trans Biomed Eng,* vol. 33, no. 5, pp. 495-504, May 1986.

[12] J. P. Reilly, "Scales of reaction to electric shock. Thresholds and biophysical mechanisms," (in eng), *Ann N Y Acad Sci,* vol. 720, pp. 21-37, May 31 1994.

[13] J. P. Reilly and W. D. Larkin, "Electrocutaneous stimulation with high voltage capacitive discharges," *IEEE Trans Biomed Eng,* vol. 30, no. 10, pp. 631-41, Oct 1983.

[14] D. Thrimawithana and U. Madawala, "Modeling pulse reflections due to multiple discontinuities on electric fence structures," in *2008 IEEE International Conference on Industrial Technology*, 2008, pp. 1-6: IEEE.

[15] D. J. Thrimawithana and U. K. Madawala, "Generalised mathematical model for high-voltage pulse propagation along electric fence structures," *IET Science, Measurement & Technology,* vol. 5, no. 3, pp. 109-116, 2011.

[16] M. W. Kroll, D. Panescu, R. Hirtler, M. Koch, and C. J. Andrews, "Dosimetry for Ventricular Fibrillation Risk with Short Electrical Pulses: History and Future. ," *Conf Proc IEEE Eng Med Biol Soc,* vol. 41, pp. 1788-1794, Jul 2019.

[17] *Effects of Current on Human Beings and Livestock, CEI/IEC 60479-1: General Aspects, 5th Edition.,* IEC, 2016.

[18] K. C. VerCauteren, M. J. Lavelle, and S. Hygnstrom, "Fences and deer-damage management: a review of designs and efficacy," *Wildlife Society Bulletin,* vol. 34, no. 1, pp. 191-200, 2006.

[19] G. Bruinderink and E. Hazebroek, "Ungulate traffic collisions in Europe," *Conservation Biology,* vol. 10, no. 4, pp. 1059-1067, 1996.

[20] S. L. Webb, K. L. Gee, S. Demarais, B. K. Strickland, and R. W. DeYoung, "Efficacy of a 15-strand high-tensile electric fence to control white-tailed deer movements," *Wildlife Biology in Practice,* vol. 5, no. 1, pp. 45-57, 2009.

[21] M. Leblond, C. Dussault, J. Oellet, M. Poulin, R. Courtois, and J. Fortin, "Electric Fencing as a Measure to Reduce Moose-Vehicle Collisions," *The Journal of wildlife management,* vol. 71, no. 5, pp. 1695-1703, 2007.

[22] L. L. Mastro, M. R. Conover, and S. N. Frey, "Deer–vehicle collision prevention techniques," *Human–Wildlife Interactions,* vol. 75, 2008.

[23] *Household and similar electrical appliances – Safety – IEC 60335-2-76: Particular requirements for electric fence energizers*, 2006.

[24] Whittaker, "Electric shock as it pertains to the electric fence," *Underwriter's Laboratories Bulletin of Research,* vol. 14, pp. 1-56, 1939.