Capacitive Discharge - Harvester 8L x 4W x 5.8H

Capacitive coupling between equipment positioned within a transmission feeder easement and the phase conductors of the high voltage transmission feeder results in a standing voltage on the equipment. The voltage impressed on the object is the result of a capacitive voltage divider between the phase to object capacitances and the object to ground capacitance.

High open circuit voltages (up to several kV) can be present on equipment within the feeder easement. This voltage drops significantly when an alternative resistive path such as a person or other object is provided between the equipment and the earth.

The discharge waveform resulting from contact by a person or other grounded object is determined by the switched RC network resulting from the mutual capacitances and the switched resistance to ground introduced into the circuit.

Analysis is performed for contact with an object positioned under the high voltage transmission feeder to find the maximum specific fibrillating energy (F_e) and specific fibrillating charge (F_q) for assessment against IEC TS 60479-2:2007.

System Info / Inputs

Inputs

$$V_{line} = 500.000 \text{ kV}$$

$$R_{body} = 581 \quad \text{(ohm)}$$

$$\rho_{soil} = 100 \quad \text{(ohm.m)}$$

$$R_{shoe} = 2000 \quad \text{(ohm)}$$

$$c = 1.1 \quad \text{(p.u.)}$$

$$\alpha = 0$$

Constants

$$\rho_{air} = 10000 \quad \text{(air resistivity value used in CDEGS model)}$$

$$\epsilon_{air} = 8.854 \times 10^{-12}$$

$$f = 50.000 \text{ Hz}$$

$$\omega = 314.159$$

$$V_{lg} = \frac{V_{line}}{\sqrt{3}} = \frac{500.000 \text{ kV}}{\sqrt{3}} \qquad = 288.($$

$$V_{pkpk} = V_{lg} \cdot \sqrt{2} = 288.675 \text{ kV} \cdot \sqrt{2} \qquad = 408.\text{:}$$

$$R_{person} = \left(R_{body} + \frac{\frac{\rho_{soil}}{4 \cdot 0.08} + R_{shoe}}{2} \right) \cdot \text{Ohm} = \left(581 + \frac{\frac{100}{4 \cdot 0.08} + 2000}{2} \right) \cdot Ohm \qquad = 1.737 \text{ k}\backslash($$

Capacitances Calculations

Capacitances between the three phase conductors and the object as well as the capacitance between the object and earth are modelled in CDEGS. The current passing between the objects is used to calculate the capacitance between the objects using the following formulas. Note the resistivity of air is set to any finite value, e.g. 10,000 ohm.m, for the purposes of this calculation.

Capacitance - Phase 1 to Object

$$I_{ph1} = 113.000\ \mathrm{A}$$

$$Q_{ph1} = I_{ph1} \cdot \epsilon_{air} \cdot \rho_{air} \cdot \frac{F}{m} \cdot \mathrm{Ohm} \cdot m = 113.000\ \mathrm{A} \cdot 8.854 \times 10^{-12} \cdot 10000 \cdot \frac{F}{m} \cdot Ohm \cdot m$$

$$C_{ph1} = \frac{Q_{ph1}}{V_{lg}} = \frac{10.005\ \mu\mathrm{C}}{288.675\ \mathrm{kV}}$$

Capacitance - Phase 2 to Object

$$I_{ph2} = 43.800\ \mathrm{A}$$

$$Q_{ph2} = I_{ph2} \cdot \epsilon_{air} \cdot \rho_{air} \cdot \frac{F}{m} \cdot \mathrm{Ohm} \cdot m = 43.800\ \mathrm{A} \cdot 8.854 \times 10^{-12} \cdot 10000 \cdot \frac{F}{m} \cdot Ohm \cdot m$$

$$C_{ph2} = \frac{Q_{ph2}}{V_{lg}} = \frac{3.878\ \mu\mathrm{C}}{288.675\ \mathrm{kV}}$$

Capacitance - Phase 3 to Object

$$I_{ph3} = 25.500\ \mathrm{A}$$

$$Q_{ph3} = I_{ph3} \cdot \epsilon_{air} \cdot \rho_{air} \cdot \frac{F}{m} \cdot \mathrm{Ohm} \cdot m = 25.500\ \mathrm{A} \cdot 8.854 \times 10^{-12} \cdot 10000 \cdot \frac{F}{m} \cdot Ohm \cdot m$$

$$C_{ph3} = \frac{Q_{ph3}}{V_{lg}} = \frac{2.258\ \mu\mathrm{C}}{288.675\ \mathrm{kV}}$$

Capacitance - Object to Ground

$$I_{gnd} = 1.181\ \mathrm{kA}$$

$$Q_{gnd} = \epsilon_{air} \cdot I_{gnd} \cdot \rho_{air} \cdot \frac{F}{m} \cdot \mathrm{Ohm} \cdot m = 8.854 \times 10^{-12} \cdot 1.181\ \mathrm{kA} \cdot 10000 \cdot \frac{F}{m} \cdot Ohm \cdot m$$

$$C_{gnd} = \frac{Q_{gnd}}{V_{lg}} = \frac{104.566\ \mu\mathrm{C}}{288.675\ \mathrm{kV}}$$

Equivalent Thevenin Circuit

A Thevenin equivalent circuit model can then be produced for the capacitively coupled system and with this the impressed voltage on the object becomes a capacitive voltage divider based on the equivalent mutual capacitances as below.

$$C_{eq} = C_{ph1} + C_{ph2} + C_{ph3} = 34.658\ \mathrm{pF} + 13.434\ \mathrm{pF} + 7.821\ \mathrm{pF}$$

$$\begin{aligned}\zeta &= \sqrt{(C_{ph1})^2 + (C_{ph2})^2 + (C_{ph3})^2 - C_{ph1} \cdot C_{ph2} - C_{ph1} \cdot C_{ph3} - C_{ph2} \cdot C_{ph3}} \cdot \mathrm{pF} \\ &= \sqrt{(34.658\ \mathrm{pF})^2 + (13.434\ \mathrm{pF})^2 + (7.821\ \mathrm{pF})^2 - 34.658\ \mathrm{pF} \cdot 13.434\ \mathrm{pF} - 34.658\ \mathrm{pF} \cdot 7.} \\ &\quad \cdot 1.000\ \mathrm{pF} \\ &= 24.518\ \mathrm{pF}\end{aligned}$$

$$V_{th} = \left(\frac{\zeta}{C_{eq}}\right) \cdot V_{pkpk} = \left(\frac{24.518\ \mathrm{pF}}{55.914\ \mathrm{pF}}\right) \cdot 408.248\ \mathrm{kV}$$

Circuit with Switched Resistor

The resulting waveform when switching a resistor into the RC network is calculated using the following.

$$V_o = \left(\frac{C_{eq}}{C_{eq} + C_{gnd}} \right) \cdot V_{th}$$

$$\tau = (C_{eq} + C_{gnd}) \cdot R_{person}$$

$$\gamma = \arctan\left(\frac{\sqrt{3} \cdot (C_{ph2} - C_{ph3})}{2 \cdot (C_{ph1} - 0.5 \cdot (C_{ph2} + C_{ph3}))} \right)$$

$$\alpha_1 = \alpha + \gamma$$

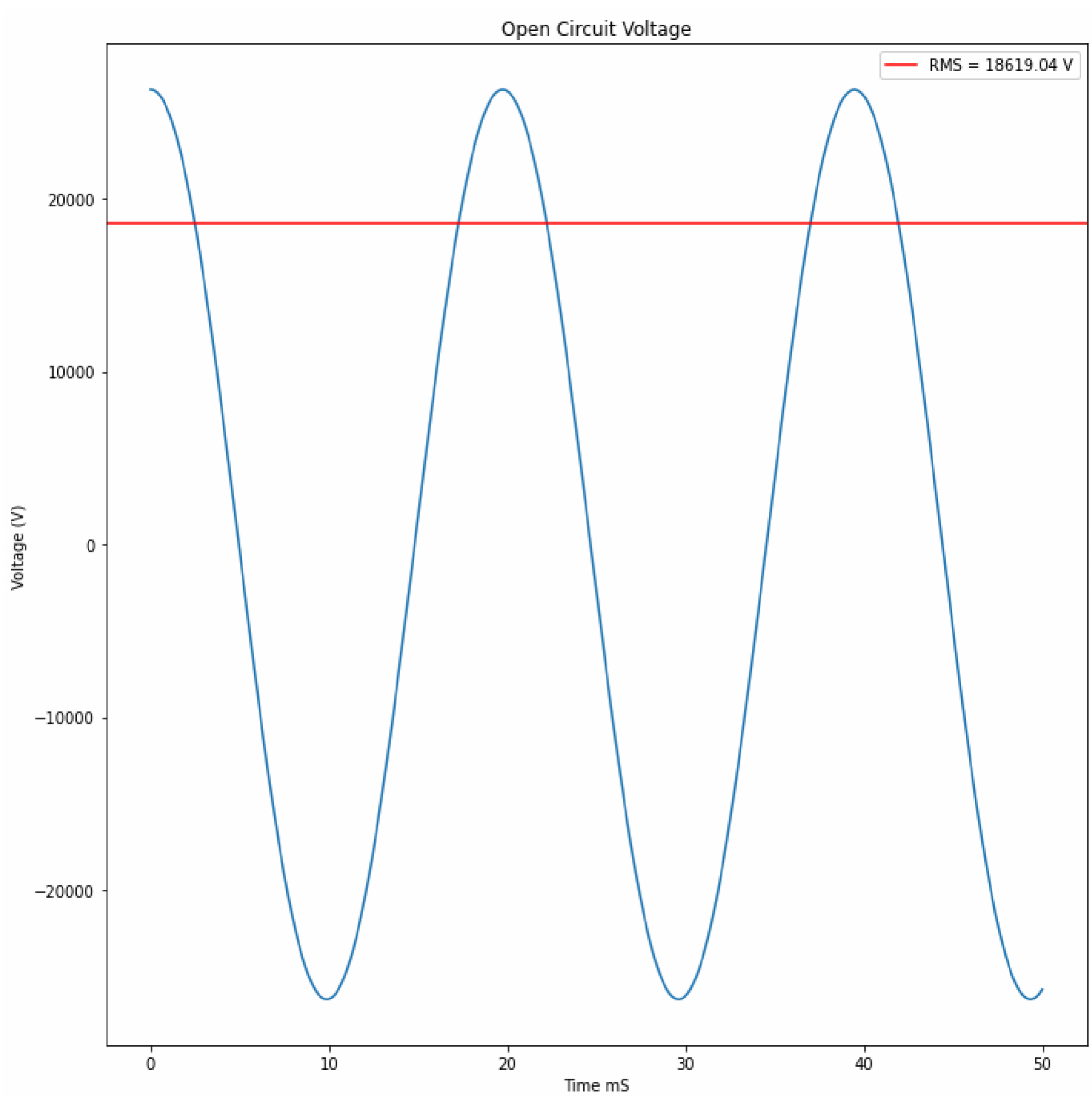
$$a = \frac{1}{\tau}$$

$$\beta = \arctan\left(\frac{a}{\omega} \right)$$

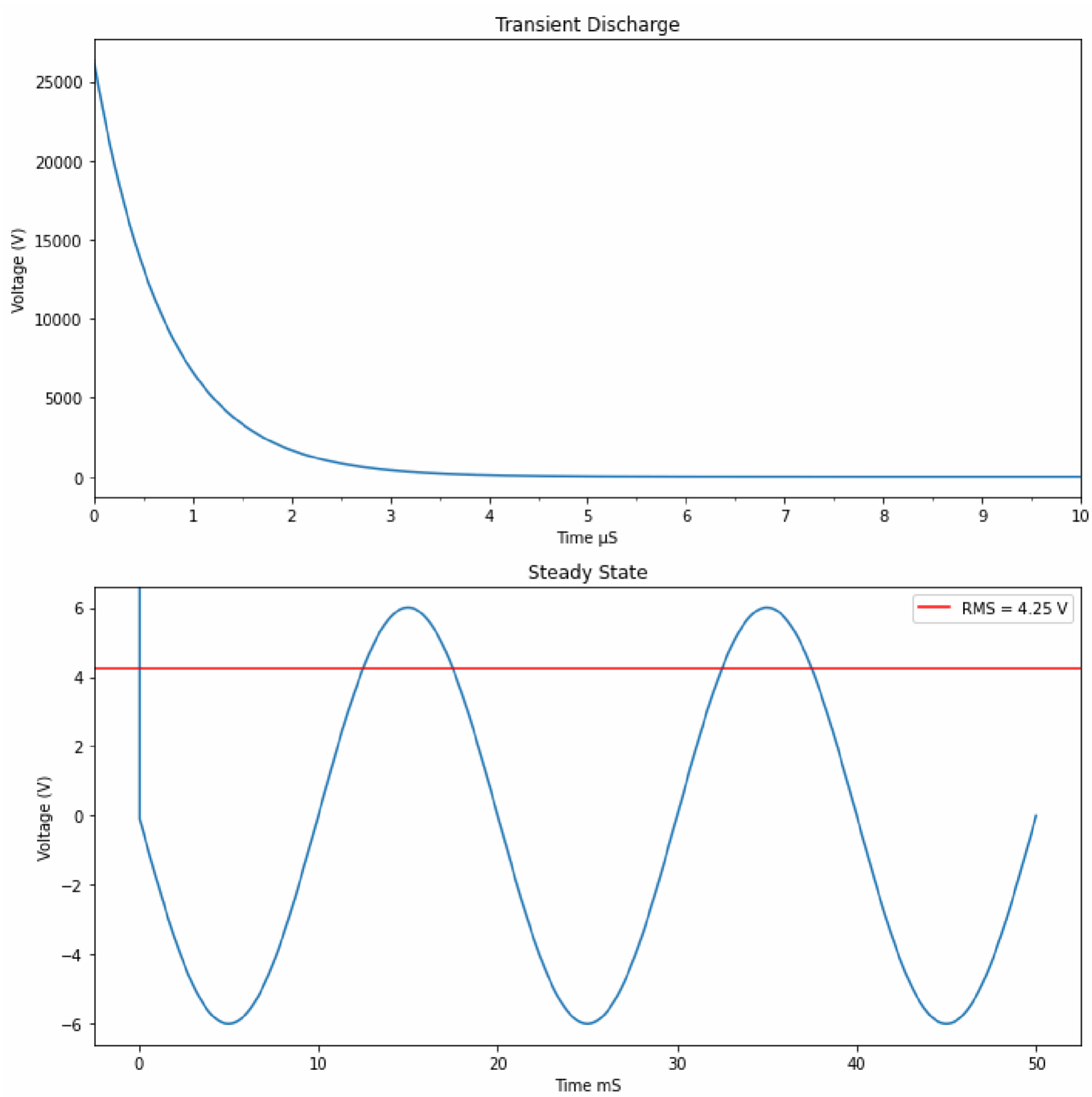
$$V_{out} = V_o \cdot c \cdot \Big(\cos(\omega \cdot t_1 + \alpha_1) - \sin(\beta) \cdot \Big(\sin(\omega \cdot t_1 + \alpha_1 + \beta) - \exp\left(\frac{(-t_1)}{\tau} \right) \cdot \sin(\alpha_1 + \beta)$$

Results

Open Circuit Waveform



Transient Discharge Waveforms



Human Discharge Assessment

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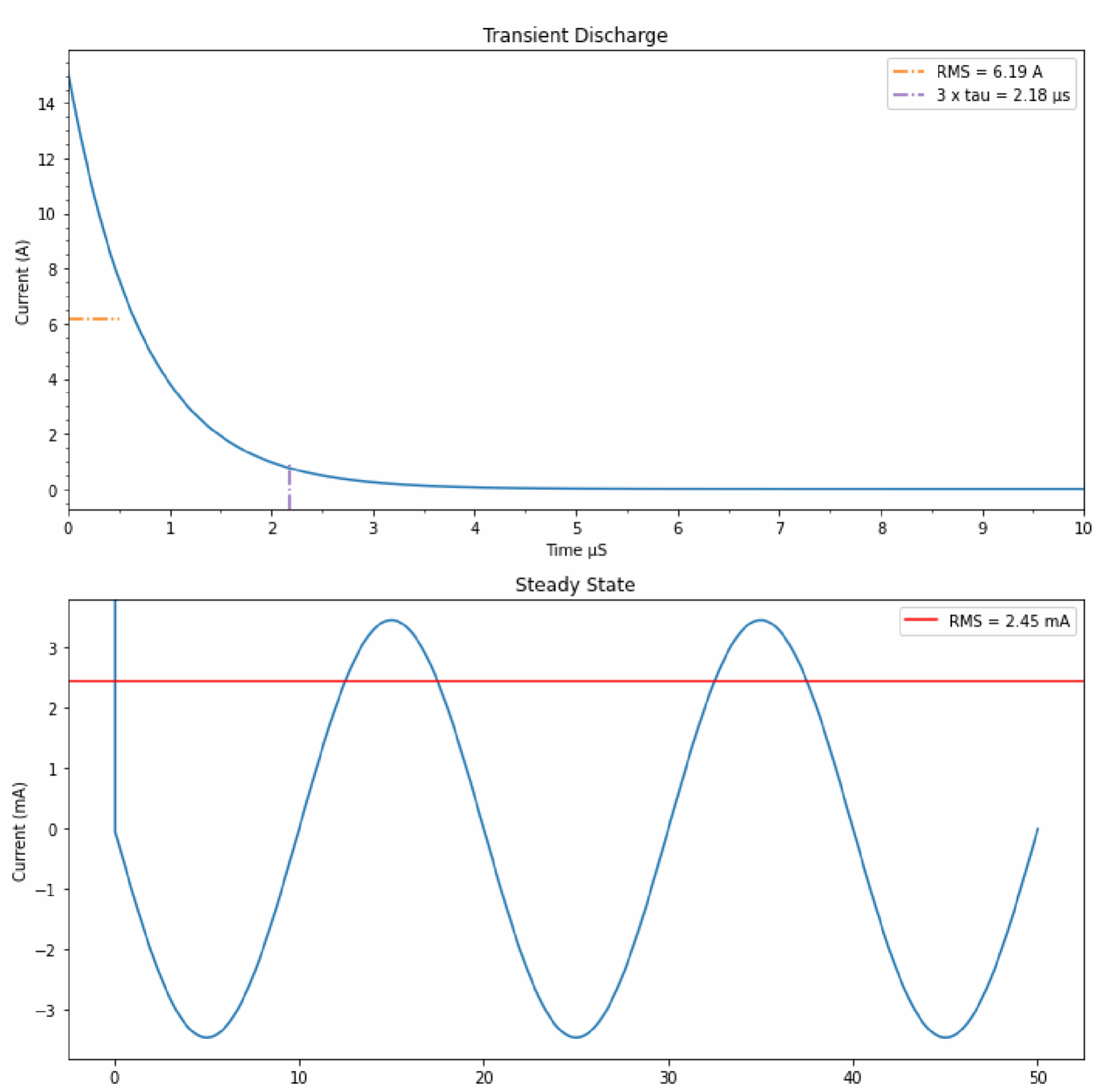

Energy and Charge Transfer Calculations

Total Discharge Energy

Total discharge energy is found using the following

$$W_t = \int_0^{t_{end}} \frac{(V)^2}{R_{person}} \, dt$$

$$W_t = 144.956 \text{ mJ}$$

Specific fibrillating energy

Specific fibrillating energy is found using the following

$$F_e = \int_0^{t_{end}} (I)^2 \, dt$$

$$F_e = 8.344 \times 10^{-5}$$

Specific fibrillating charge

Specific fibrillating charge is found using the following

$$F_e = \int_a^{t_{end}} I \, dt$$

$$F_q = 11.010 \ \mu\text{C}$$