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An Electric Fence Energizer Based on Marx Generator

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Abstract

Non-lethal electric fence technologies gained considerable recognition in various application areas ranging from security to live-stock management and farm automation. Fence energizer, which is essentially a High Voltage Pulsed Power Supply (HVPPS), is a pivotal part of a non-lethal fence system with several design options. Marx generator, which is a well-recognized HVPPS, has never been tried as a fence energizer. This paper investigates potential of Marx generator as a fence energizer and identifies specific requirements and challenges that need to be addressed. Finally, a design of Marx generator is presented for a non-lethal electric fence having voltage rating of 40 kV, output pulse duration of 15 µs, pulse rate of up to 100 Hz and maximum output energy to be lower than 20 mJ per pulse to ensure its non-lethal nature. To meet the design requirements, a novel gate driver design is presented which is compact, cost effective and meets specific requirements of non-lethal nature of the fence.

Keywords: Non-lethal; Fencing; Security; Marx generator; Gate driver

Introduction

An electric fencing system applies electric shock to a person or an animal that touches the fence wire. Electric fences were used for the first time by Germans during World War I to stop illegal border crossing [1]. These fences were lethal due to the flow of high amperage AC current, thus, resulting in many human causalities as well as livestock damage. The drawbacks of lethal electric fences attracted researchers to work on non-lethal electric fencing for its constructive use. In this regard, initial work was carried out in late 1930s. Non-lethal electric fencing systems were initially developed for livestock and wild life management. Modern electric fencing systems use repetitive pulses of high voltage (in the range of several kV) and have various applications such as livestock management and depredation [2-5], crop protection [6-8], along highways [9,10] and security [11,12]. It is still an attractive field of research.

Non-lethal electric fencing finds a wide range of applications that require control over unauthorized/unwanted movement of humans or animals across a certain boundary. Conventionally, livestock managers use lethal methods for control of predation such as shooting, trapping, or use of devices such as M44's. These methods do not only demand more effort but their excessive use can also cause extermination of predator's specie [2,3]. Non-lethal electric fencing is an effective and more humane alternative of conventional depredation methods. It is used around aquaculture facilities to save fish from predator birds [4]. It is successfully used to protect crop against buffalo or elephant predation [6-8]. It is installed along highways to reduce human fatalities and wildlife destruction due to road accidents caused by animal vehicle collision [9-10]. Electric fencing along with an intrusion detection unit is employed for security of sensitive sites such as military bases, strategic instalments, prisons and airports [11,12]. Moreover, non-lethal fencing is used to protect private properties such as land and houses, and around private swimming pools to avoid accidents such as drowning of children [13]. It can also be used by law enforcement agencies for crowd management.

An electric fencing system has various parts such as energizer, fence wire, fence posts, insulators and ground rods. Energizer is the central part that generates high voltage pulses for the system. A simplified block diagram showing working of an electric fencing system is shown in Figure 1. One end of the energizer is connected to the fence wire

while its other end is connected to ground. Fence wire is supported by fence posts through insulators. Insulators prevent current leakages to ground through fence posts. As shown in Figure 2, when a subject makes contact between fence wire and ground, it completes the current path and suffers from a high voltage shock that causes it to deter instantly.

The lethal or non-lethal behaviour of the system depends on the nature of electric pulse. For non-lethal system, pulse duration is small (in micro-seconds) and pulse current and energy transferred to the subject are kept below a safe limit. In this regard, researches have been carried out by medical specialists and standards have been developed that define non-lethal/harmless limits of current and energy when applied to a subject [14-17]. As lethal or non-lethal behaviour of
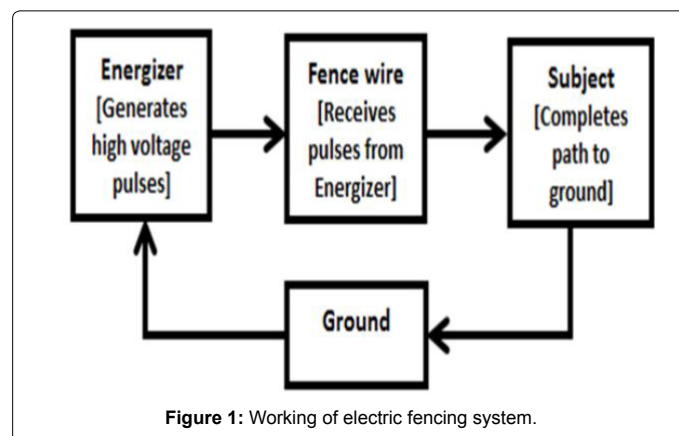

Figure 1: Working of electric fencing system.

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fencing system is a function of pulse nature, so energizer design is the most important part in development of an electric fencing system.

An energizer is a high voltage pulsed power supply that consists of two functional subunits which are energy storage unit and switching unit [18]. The energy storage unit stores electrical energy which is then released by switching unit during the output pulse. Design of an energizer for a non-lethal electric fencing system involves requirements of high output voltage, low output current, controllable pulse duration over various pulse rates and control over release of electrical energy during output pulse. In addition to that, the system must be power efficient and capable enough to store huge amount of energy so that it can work without an input source for several hours if employed in a remote area. Other requirements for energizer design are compactness and reliability.

Design options of electric fence energizer are listed below [19,20]:

i.   Direct discharge type pulse generator: In this scheme, a capacitor is charged to a very high voltage by an input DC power supply. The capacitor is connected to the fence through a semiconductor switch. The requirement of a semiconductor switch with high voltage rating demands cascading of multiple semiconductor devices (such as IGBTs). A stack of semiconductor devices need highly synchronized gate drivers for reliable switching operation. As the stack consists of series connected switches, damage or failure of one switch can lead to failure of the whole system.

ii.   Pulse transformer type pulse generator: This scheme employs a capacitor which is charged to a lower voltage as compared to the capacitor in direct discharge type. A switch connects the capacitor to the pulse transformer. This transformer steps up the low voltage pulse (from switch) to a higher voltage. The disadvantage of this scheme

is loss of power efficiency due to use of pulse transformer which is undesirable in a fencing system.

iii.   Vector inversion type pulse generator: this scheme employs a number of capacitors and transformers. During their charging, the series capacitors are connected alternatively in opposite polarities through pulse transformers and during discharging these capacitors get connected with the same polarity. This technique involves problems of complexity and inefficiency due to use of pulse transformers.

iv.   Marx generator type pulse generator: This scheme, as shown in Figure 3, employs capacitors that are charged in parallel and discharged in series giving a high voltage output pulse. Its circuit basically consists of a number of stages with each stage comprising of a switch and a capacitor, and connected to the next stage through upper and lower diodes.

Comparative study of abovementioned HVPPS schemes showed that Marx generator is a superior technology due to a number of desirable features such as low voltage stress and low current stress on semiconductor switches, diodes and capacitors, high efficiency and controllability of pulse width and pulse rate [19,20]. Marx generator has applications in various areas such as UWB radar systems [21], Microwave and X-ray generation [22], plasma sources [23,24], particle acceleration [25], water treatment, food processing and air pollution control [26] but it has never been used as a fence energizer, perhaps, due to its circuit complexity. As mentioned above, it employs diodes, capacitors and switches. If the switches are implemented using semiconductor devices, they require gate driver circuits making the overall system quite complex for a fence energizer. However, Marx generator has many superior features to make fence energizers more effective.

Our work investigates potential of Marx generator as a non-lethal electric fence energizer expanding the applications of Marx generator and broadening the design options for fence energizers. This paper presents design of a Marx generator for a 40 kV non-lethal electric fence. The novelty of this work lies in the use of Marx generator as a fence energizer with reduced circuit complexity and design of a passive gate driver that not only solved problems of complexity, high voltage isolation and synchronized switching but also provided control over release of electrical energy during output pulse. Moreover, the total energy stored in energizer is much greater than the energy released per pulse so the system can work for some time if input power source is removed.

Requirement Analysis

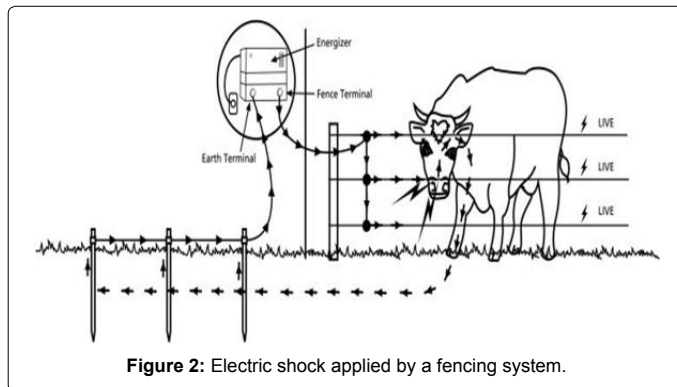The non-lethal and non-injurious electric shock applied by a

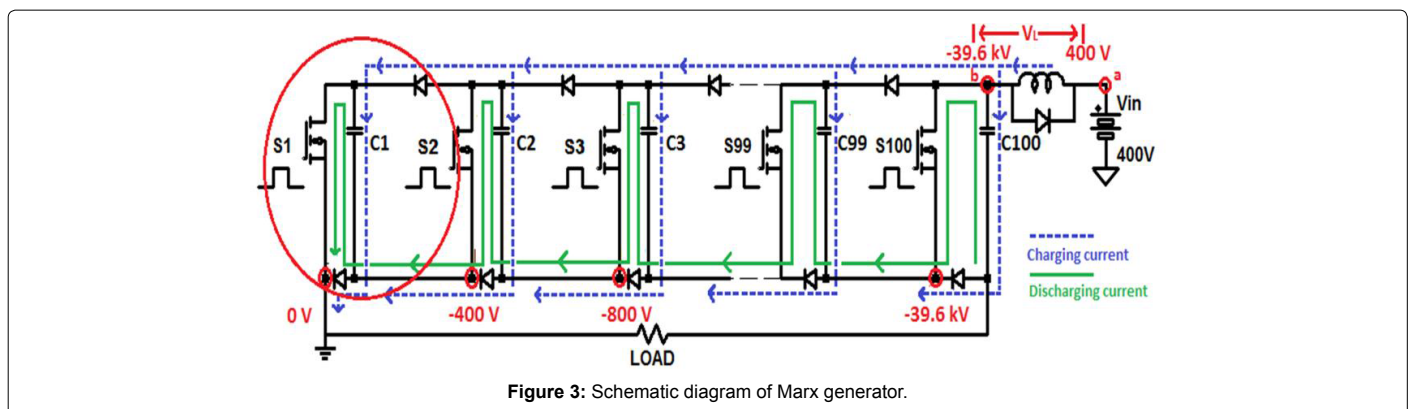**Figure 2:** Electric shock applied by a fencing system.

Figure 3: Schematic diagram of Marx generator.

fencing system must also be severe enough to deter the intruder instantly. A fencing system with more severe shock would be a stronger psychological and physical barrier for the intruder. Thus, severity of the shock is a measure of effectiveness of the system. In addition to that, the intruder must not be able to disable the system by cutting or damaging the fence wire by some normally insulated equipment. This has been achieved by keeping the output voltage as high as 40 kV (conventional systems have output up to 10 kV). High voltage will not only enhance system's effectiveness but will also render it failsafe by making the use of normally insulated equipment difficult. Moreover, to ensure an insurmountable barrier, the system must not allow any intrusion between two successive pulses. This requirement has been met by keeping the maximum pulse rate as high as 100 Hz. To save the subject of the shock from fatality or getting harmed, the pulse duration should be very short which is taken to have a maximum value of 15 μs. Moreover, energy delivered to the subject during output pulse is also an important factor in determining the harmless nature of shock. The safe limit is 5 J/s [14]. At a pulse rate of 100 Hz, the energy limit becomes 5/100=50 mJ per pulse. The system should be cost effective and compact so the use of step up/ down transformer is avoided. The input to the energizer is obtained from 220 V AC.

Design of Marx Generator

This section presents working of Marx generator and design of its circuit as a fence energizer. Design of gate driver for semiconductor switches is explained in the next section. A circuit diagram of Marx generator is shown in Figure 3. The circuit consists of cascaded similar stages. The first stage is highlighted by a circle in Figure 3. Each stage employs an energy storage unit and a switching unit. Energy storage unit consists of a capacitor that gets charged by input through a pair of diodes while the switching unit employs a semiconductor switch. The circuit multiplies the input DC voltage to the number of stages implemented and generates pulsed voltage at output. During charging, the switches are turned off and the diodes are forward biased, so the capacitors get connected in parallel. These parallel capacitors get charged to the input voltage. The charging current is shown in Figure 3 by dotted blue lines. During discharging, the switches are on and the diodes (that connect capacitors and switches in parallel) are off (discussed later) to connect the capacitors in series. The discharging current is shown in Figure 3 by solid green lines. Thus, the series connected capacitors get discharged by switches to produce a high voltage output pulse.

As shown in Figure 3, when the first switch S1 is turned on, the positive terminal of its corresponding capacitor C1 (which was previously at 400 V) drops to 0 V. As a result, the source of switch S2 (which is connected with negative terminal of C1) drops to -400 V and the diodes of first stage get reversed biased (discussed in detail later). Similarly, when the second switch S2 is turned on, the positive terminal of C2 drops to – 400 V and -800 V appear at source of S3.

In this way, the negative voltage keeps on increasing such that when all the switches are closed, a potential difference of 40 kV appears across load. The rest of the section deals with design of Marx generator circuit and selection of its components.

Input Supply

The input power supply consists of a bridge rectifier and a capacitive filter. The AC mains voltage is rectified by the bridge circuit. Its output is then fed to capacitive filter to obtain DC voltage for charging of Marx generator circuit. The DC voltage comes out to be $220 \times \sqrt{2} = 310V$.

Selection of diodes

The capacitors are charged by an input supply of 310 V. The peak charging voltage can vary due to changes in supply voltage. Moreover, the charging voltage can exceed the input voltage as charging takes place through an inductor (effect of inductor is discussed later). These variations have been accommodated by considering the charging voltage as 400 V instead of 310 V. The forward current rating of diodes is not a problem because capacitances are small and capacitors do not get completely discharged during switching. The diodes get off when the switches are turned on. So, peak inverse voltage is a major consideration in selection of diodes. As shown in Figure 4, node 'a' drops to 0 V and node 'b' drops to -400 V when switch S1 is turned on causing turning off of diode D1'. When switch S2 is turned on, node 'c' also drops to -400 V resulting in turning off of diode D1.

As shown in Figure 4, the maximum reverse voltage appearing across any diode is 400 V. Thereby, the peak inverse voltage of diodes must be greater than 400 V. Moreover, they must be fast recovery diodes to support the operation of system at faster pulse rates. To satisfy the abovementioned conditions, diodes FR305 have been selected.

Selection of switches

The switches, during their off time, are connected in parallel with capacitors. The capacitors are considered to be charged at 400 V so the maximum voltage appearing across any switch during its off time is 400 V. Thus, the selected switch must have a voltage rating greater than 400 V. The current rating of switch is not a problem because capacitances are small and little discharging takes place during switching. So, MOSFET IRF840 is selected to meet the requirements of design.

Design of capacitors

Design of a capacitor is based on evaluation of capacitance value, determination of its voltage rating and selection of its type. The charging of capacitors takes place by a DC input power supply of 310 V. The output of DC supply can fluctuate from 310 V causing variation in charging voltage of capacitors. Moreover, the inductor employed at input side can also cause overcharging of capacitors. So, to compensate these variations, the capacitors are considered to be charged at 400 V and their voltage rating is selected to be higher than 400 V. Moreover, polar electrolytic capacitors are chosen to minimize cost.

Evaluation of capacitance is a critical part of design because it dictates the energy released per pulse by each capacitor. The total energy E released during output pulse, number of stages n to be implemented and the drop in capacitor voltage (due to discharging during switching) are related by following expression
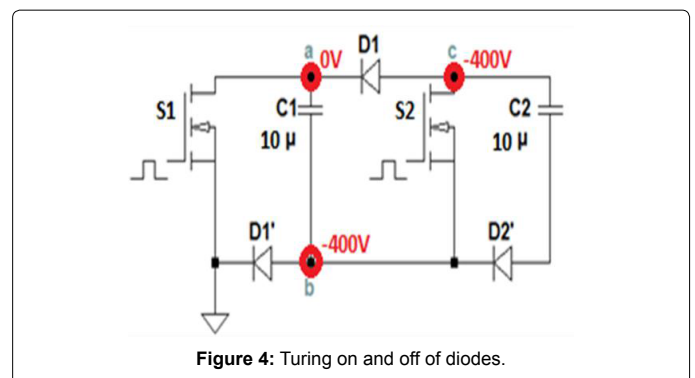

Figure 4: Turing on and off of diodes.

$$E = \frac{1}{2}nC\Delta V_c^2 \qquad (1)$$

The number of stages n is ratio of output voltage to input voltage. If an output voltage V_{out}=40 kV is to be obtained from a DC input voltage V_{in}=400 kV the number of stages n is given as $n = \frac{v_{out}}{v_{in}} = \frac{40kV}{400V} = 100$

The voltage across each capacitor can decrease up to a maximum of 6 V (ΔV_c= 6 V) due to intrinsic property of gate driver design. To ensure non-lethal behaviour of fence, the energy released during one pulse for a pulse rate of 100 Hz must be less than 50 mJ and is selected as 18 mJ. For n=100 (100 stages) capacitance comes out be

$$C = \frac{2E}{nC\Delta V_c^2} = 10\mu F$$

Design of input inductor

As shown in Figure 3, an inductor is employed between input source and the rest of the circuit. This inductor provides power efficiency and protection to the input power supply. When all the switches are turned on, a negative voltage of -39.6 kV appears at node 'b'. If the power supply is directly connected with the circuit without an inductor, its positive terminal will connect to the highly negative node (node 'b' at -39.6 kV). This will result in huge input current surge which will not only reduce the power efficiency but can also damage the supply. On the other hand, a properly designed input inductor would block changes in input current due to high potential difference created across its terminals during output pulse.

The value of inductance L is related to the voltage across terminals of the inductor V_L, pulse duration d and increase in current ΔI as follows:

$$L = V_L \frac{d}{\Delta I} \qquad (2)$$

The current profile of inductor is shown in Figure 5. There is a linear increase (with slope $\frac{V_L}{L}$) in current during output pulse of width and period. This current will charge the capacitors to a voltage higher than the input voltage. Freewheeling diodes tend to decay the inductor current when the charging voltage of capacitors exceeds the input voltage (discussed later). Thus the rising ramp in Figure 5 shows the current flowing from the supply into the circuit through inductor. The average current drawn by the circuit from the supply I_{avg} can be calculated from peak current ΔI flowing through inductor, duration of output pulse d and time period T as

$$I_{avg} = \frac{\Delta I \times d}{2T} \qquad (3)$$

Figure 5: Current through inductor.
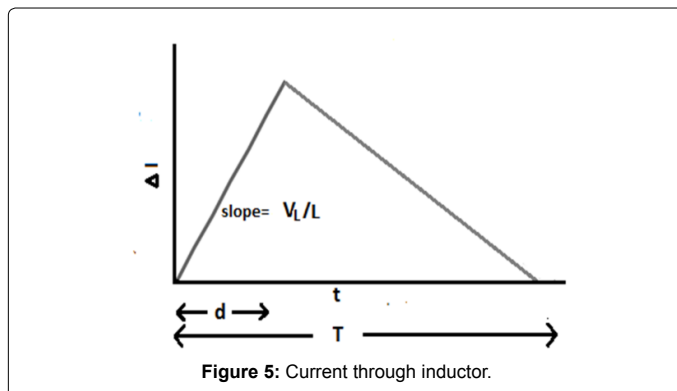
The power drawn by the circuit from the input P_{in} is related to average current from input I_{avg} and input voltage V_{in} as

$$P_{in=} V_{in} I_{avg} \qquad (4)$$

It can be seen from Equation 2 that peak current through inductor is inversely related to value of inductance. Thus, a smaller inductance will result in high peak current which would in turn result in increased average current from the input. This excessive current will be dissipated in freewheeling diodes resulting in loss of power efficiency. Moreover, higher peak current through inductor will result in an increase in size of inductor. The inductor size (taken as core area product A_CA_w), value of inductance L, peak current through inductor $\hat{I}$ and current (rms) I_{rms} are related as

$$L\hat{I} I_{rms}=K_{cu} J_{rms} B_{max} A_C A_w \qquad (5)$$

Where K_{cu} is copper fill factor, J_{rms} is current density and B_{max} is saturation limited flux density. As shown in Figure 5, $\hat{I}=\Delta I$ and $I_{rms} = \frac{\Delta I}{\sqrt{3}}$ so by putting values of I_{rms} and $\hat{I}$ we get

$$\frac{1}{\sqrt{3}}L\Delta I^2 = K_{cu}J_{rms}B_{max}A_CA_w \qquad (6)$$

To obtain a direct relation between rise in current ΔI and core size, we substitute L from Equation 2 into Equation 6. So the above expression becomes

$$\frac{1}{\sqrt{3}}\times\left(V_L\frac{d}{\Delta I}\right)\Delta I^2 = K_{cu}J_{rms}B_{max}A_CA_w \qquad (7)$$

On simplification Equation 7 takes the following form

$$\frac{1}{\sqrt{3}}\times V_L\Delta Id = K_{cu}J_{rms}B_{max}A_CA_w \qquad (8)$$

The above equation clearly shows that if we halve the value of inductance the size of inductor will become two times its original value.

Thus, the input inductor should be designed such that it fulfils the conditions listed below:

i. Inductance should be high enough to minimize the peak current ΔI which would in turn increase power efficiency of system and reduce size of the inductor.

ii. The power drawn by the circuit from input supply must be higher than the output power to compensate for losses in the diodes. Otherwise, the system will be unable to generate an output pulse with required parameters.

The output power can be calculated from the energy delivered to the load per pulse. For the presented design, the energy released per pulse is 18 mJ. When the system is operated at a pulse rate of 100 Hz this energy corresponds to an output power of 1.8 W.

As discussed before, the input power must be greater than or equal to 1.8 W. Taking V_{in}=400 V, Equation 4 becomes

1.8 W=400 V × I_{avg}

$I_{avg=}$ 4.5 mA

Using Equation 3, peak current ΔI comes out to be

$$\Delta I = \frac{2\times T \times I_{avg}}{d}$$

$$\Delta I = 6A$$

The value of inductance can now be determined from Equation 2 as

$$L = \frac{40000 \times 15 \times 10^{-6}}{6} = 100 mH$$

Any value of inductance lower than as calculated above will render the system power inefficient and bulky.

Freewheeling diode

As shown in Figure 3, a freewheeling diode is connected in parallel to the inductor with its anode connected with the positive terminal of last capacitor and cathode connected towards the supply. The diode protects the capacitors from getting damaged due to overcharging and prevents the circuit from producing undesirable resonance effects.

In absence of freewheeling diode, the inductor will continue to transfer excessive electrical energy into the capacitors due to high potential difference across its terminals during output pulse. As in case of a fencing system, no load is connected with the output (except when the subject touches the fence) the capacitors will get overcharged. This can damage the capacitors if their charging voltage exceeds their rated voltage. Moreover, the excess energy transferred to the capacitors during on time of switches will be returned to the supply during off time of switches. So, the circuit will act as a series LC resonator producing undesirable effects at output as shown in Figure 6.

The freewheeling diodes must be employed so as to meet the following essential conditions.

i.   As shown in Figure 5, the inductor current must fall to zero during off time of pulse (which equals 10 ms for pulse rate of 100 Hz and pulse duration of 15 μs).

ii.   During on time of pulse, the reverse voltage across diode must not exceed its rated peak inverse voltage.

A stack of series connected diodes is used to fulfil the abovementioned conditions. The first condition requires the diode to provide a forward voltage drop of $V = L\frac{\Delta I}{\Delta t}$. If forward voltage drop offered by one diode is assumed to be 0.5 V then 12 diodes can meet the requirement. The second condition needs the number of diodes to be equal to or greater than 40 kV/PIV (PIV of one diode). For FR305, PIV equals 600 V. So, the diode stack requires 40 kV/600=67 FR305 diodes.

Gate Driver Design

When employed as an electric fence energizer, Marx generator uses a large number of semiconductor switches to produce an output pulse of several kilovolts in accordance with its design requirement of a severe shock. Consequently, the design of gate drivers for Marx generator switches becomes a major challenge that needs to be addressed ingeniously.
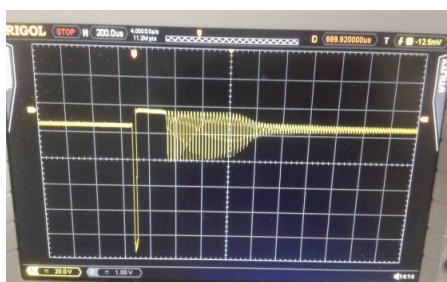

Figure 6: Resonance effect due to inductor.

Requirements

As shown in Figure 3 the source voltage increases with every stage such that when S1 is turned on, the source voltage of switch S2 drops to -400 V. Similarly, turning switch S2 on pulls the source voltage of switch S3 down to -800 V. In this way, when all the switches are turned on the source of last switch drops to -39.6 kV. This switch now requires a gate voltage with respect to -39.6 kV which demands a gate driver capable of providing voltage isolation of 39.6 kV.

A case of unsynchronized switching is shown in Figure 7. When switch S1 is on and switch S2 is off, it causes the capacitor C2 to discharge through forward biased diode D1 and switch S1, thereby reducing power efficiency. Moreover, the voltage of C2 does not add up in the output voltage. Therefore, synchronized switching is an important gate driver design requirement that ensures maximum power efficiency and a complete output pulse.

Keeping in view the electric fencing requirements, the gate driver should allow a non-lethal amount of electrical energy to be transferred to the fence wire. Moreover, it should render the system efficient for continuous operation even in the absence of an input source.

Therefore, it can be concluded that the gate driver for semiconductor switches based Marx generator (as a fence energizer) must fulfil the following design requirements:

- High voltage isolation
- Synchronized switching
- Controlled release of output energy
- Compactness of design and high efficiency

Related work

Generally used gate driver schemes for semi-conductor switches based Marx generators employ either optocouplers or pulse transformers. Two of the related designs are discussed below.

Self-supplied gate driver is an optocoupler based design that is referred from [27] and shown in Figure 8. In case of this type of gate driver, Marx generator circuit itself provides power to the gate driver through capacitor C_p which is charged to zener voltage when the switch is off. A resistor R controls the charging current of capacitor while a diode D prevents it from discharging when the switch is on.

Another gate driver scheme is referred from [28] and presented in Figure 9. It uses a pulse transformer to drive Marx generator switches. A full bridge inverter generates pulses and feeds them to the pulse transformer. These positive and negative pulses turn the main switch
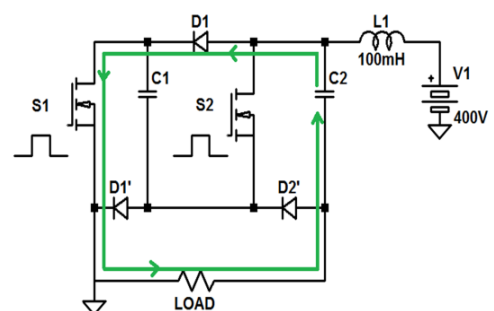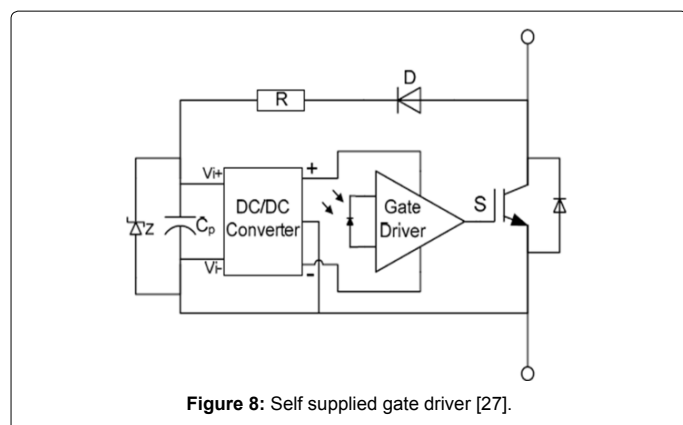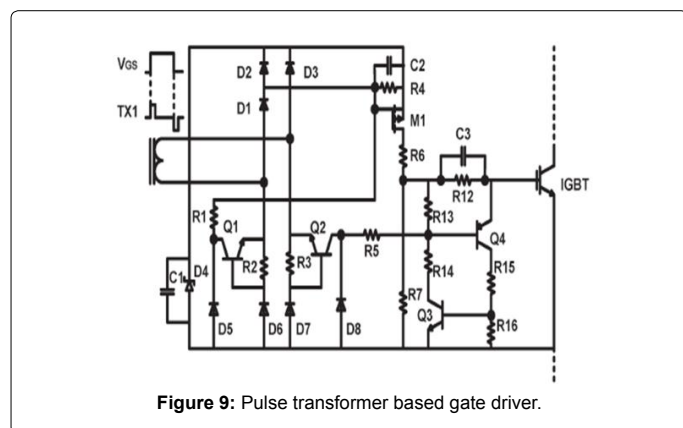

Figure 7: Discharging of capacitor due to unsynchronized switching.

Figure 8: Self supplied gate driver [27].

Figure 9: Pulse transformer based gate driver.

on and off respectively by the combined action of different elements in the gate driver circuitry.

The abovementioned designs are suitable gate drivers for pulsed generators (that employ semiconductor switches) that are required to produce high power. But when used for low power applications that use low power rating MOSFETs and diodes, and small capacitors (10 μF), such gate drivers increase circuit cost and complexity.

Therefore, a novel, compact and cost-efficient gate driver based on passive components such as diodes, capacitors and resistors has been proposed that ensures high voltage isolation as well as synchronized switching and, unlike the abovementioned schemes, makes Marx generator an attractive design option for electric fence energizer.

Proposed gate driver design

The proposed scheme employs one active driver (optocoupler) to drive the first switch and passive drivers to drive the rest of the switches. Each passive driver comprises a gate capacitor Cgn, a zener diode Zn connected in series with a diode (with opposite polarity) and another diode Dgn connected between gate and source of the corresponding switch. The gate to source voltage Vgs that is required to turn the switch on is provided through the combined action of zener diode and gate capacitor by pulling down the source to a negative voltage with respect to the gate voltage. Diode, on the other hand, contributes in turning off of the switch. This scheme is shown in Figure 10. During discharging mode of Marx generator, with its capacitors charged to input voltage Vc, the source of nth stage MOSFET is pulled down to – (nVC) volts due to which zener of voltage rating V_{gs} gets reverse biased and discharges the gate capacitor (initially charged to 0 V) to $-(nV_C$

$-V_{gs})$ volts, thus developing the required gate to source voltage Vgs to turn the MOSFET on. This is shown in Figure 10, when opto-coupler turns the first switch S1 on, the source of second switch S2 drops to –400 V, reverse biasing the zener Z1 and discharging the gate capacitor Cg1 to –(400–Vgs) volts, thus developing the required gate to source voltage Vgs.

During charging mode of Marx generator, the source terminals of all MOSFET switches get connected to the ground. The negative voltage of -(nV_C-V_{gs}) volts at gate of any switch, due to the discharged gate capacitor, forward biases diode Dg. This enables the charging of gate capacitor to 0 V by utilizing the leakage currents flowing towards the forward biased diode Dg, thus turning off the switch. As discussed earlier, when the first switch S1 is turned off, the diode D1' gets forward biased, thus connecting the source of S2 to ground. As a result, the anode of diode Dg1 also gets connected with ground while its cathode is at – (400–Vgs) volts thus forward biasing the diode and charging the gate capacitor Cg1 to 0 V, thus turning off the switch S2. The diode connected in series with zener gets reverse biased during charging of gate capacitor to block forward current surge through zener. As shown in Figure 11, the negative voltage across gate capacitor keeps increasing with each stage. This introduces problems of increase in voltage rating of gate capacitors and high forward surge currents (during charging of gate capacitor) through diodes Dgn. The first problem is solved by connecting the terminal of gate capacitor, previously connected to ground, with source of previous stage instead. This modification in gate driver circuitry, shown in Figure 11, limits the maximum potential difference across any gate capacitor to approximately 400 V.

The second problem arises due to the absence of some controlling element, which causes the current through gate capacitors to become very high during their discharging period and keep increasing for higher stages as the voltage at source of the switch with which gate capacitor is connected to becomes more negative. Therefore, a resistor is connected in series with gate capacitor to limit this surge current. Waveform of such currents (in absence of resistors) in different colours simulated for few initial stages is shown in Figure 12.

Since, zener limits gate to source voltage Vgs across the switches, the given design uses a zener diode of 10 V to obtain Vgs of 10 V as shown in Figure 13.

The selection of gate capacitor depends on its capacitance, voltage rating and current rating. A greater capacitance would draw surge current from the circuit while smaller would discharge earlier due to leakage currents resulting in turning off the switch before time. So, the value of capacitance is optimized through simulations to be 1000 pF. Its voltage rating is selected to be 450 V for DC input supply of 400 V. Accordingly, the current rating of capacitor becomes 0.45 A for gate resistance of 1 kΩ. The diode Dg1 and the diode connected in series with zener are fast recovery diodes FR305 having the voltage rating of 600 V.

The passive gate driver circuit has been simulated in LT-spice. When a control pulse is applied through opto-coupler to turn the first switch on, a negative voltage of –400 V appears at the source of second switch and the reverse biased zener discharges the gate capacitor to develop gate to source voltage of 10 V to turn the second switch on. The control pulse along with the gate to source voltage obtained through simulations is shown in Figure 13. On the other hand, in the absence of control pulse the source of switch gets connected to ground and the gate capacitor charges to 0 V due to leakage current, thus dropping the gate to source voltage to 0 V. Figure 14 shows the charging and
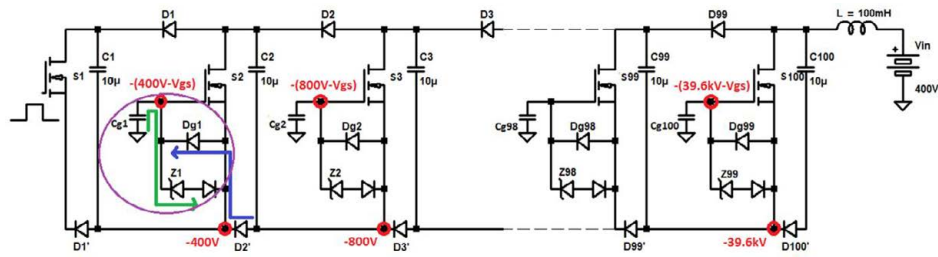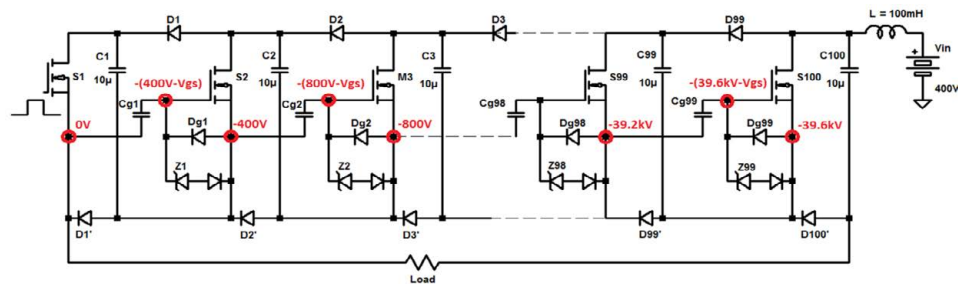
Figure 10: Proposed gate driver scheme.

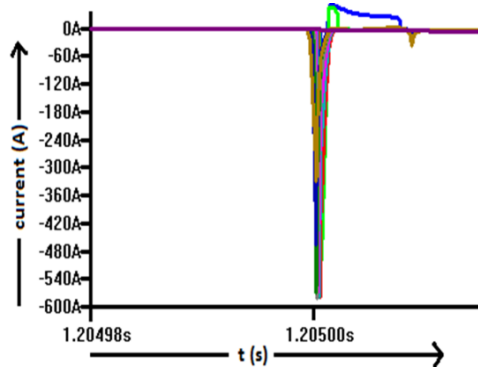**Figure 11:** Marx generator circuit with modified passive gate driver.
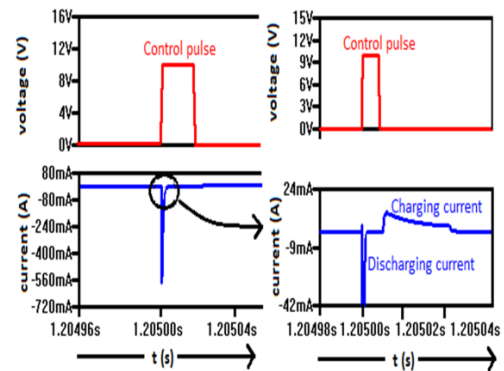

Figure 12: Surge current through gate capacitors.

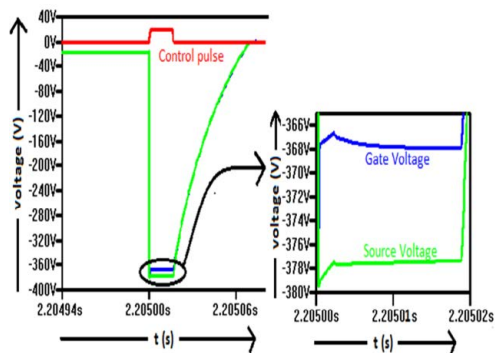**Figure14:** Charging and discharging current through gate capacitor.

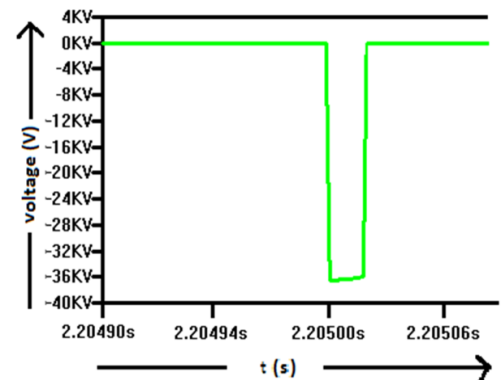**Figure 13:** Gate to Source voltage.

Figure 15: Output simulated for 100 stages.

discharging current waveforms of gate capacitor with reference to control pulse. The final output pulse of -40 kV produced by 100 stages with each stage at 400 V is shown in Figure 15.

The proposed gate driver design fulfills the requirement of controlled transfer of electrical energy to the output. It is the inherent feature of this design that the Marx generator capacitors can discharge
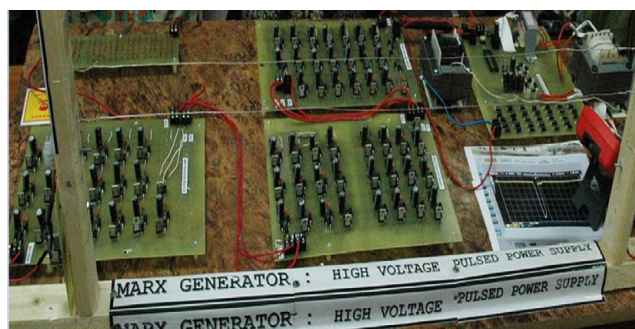
Figure 16: Final form of Marx generator circuit.

Figure 17: Output voltage measured on oscilloscope across a capacitive divider of 1/100.

a maximum voltage of 6 V (zener diode rating) only. When they tend to discharge more than 6 V, the gate to source voltage drops below 4 V and the switch gets turned off. It results in controlled release of energy per pulse, hence the maximum deliverable value of energy corresponding to a maximum drop in capacitor's voltage is 18 mJ which is well below the lethal limit of 50 mJ [14]. This unique feature of gate driver renders the overall system suitable for low power high voltage applications such as non-lethal electric fencing.

Implementation and Testing

Marx generator with proposed gate driver design is implemented and its final form is shown in Figure 16. Its implementation includes development of PCBs, winding of input inductor, and employment of a capacitive bank (as a voltage divider) for measurement of high voltage output pulse on oscilloscope.

Design of PCBs

Major consideration during PCB design of proposed circuit is to keep high potential nodes as far as possible while also maintaining compactness of the overall system.

Winding of input inductor

From Section II, it was found that ΔI=6 A, I_{rms}=3.46 A, K_{cu}=0.1, J_{rms}=3 A/mm^2 and B_{max}=0.2 T (for ferrite core). Putting these values in Equation 5 we get area product $A_{C}A_{w}$=34600000 mm^4. As I_{rms}=3.46 A, copper wire with SWG-18 is used for winding of inductor.

The potential difference between two ends of inductor is 40 kV so it needs protection against insulation breakdown of winding wire. This is done by dividing the total number of turns in multiple layers such that the potential difference between two consecutive turns is 250 V and

between two adjacent layers is 10 kV. Moreover, additional insulation is provided by placing fish paper (voltage breakdown rating of 15 kV) between adjacent layers.

Capacitive bank

To measure high voltage (up to 40 kV) on oscilloscope a capacitive voltage divider (with 100 series connected capacitors) is used. The reason behind employing capacitive divider instead of resistive divider (of value 50 MΩ) is that high resistances have inductive behaviour. So a resistive divider cannot allow flow of current during a short pulse (of duration 15 μs). The output waveform of 40 kV is shown in Figure 17.

Testing

The working of the system is tested by measuring the output voltage using capacitive voltage divider and its waveform is shown in Figure 17. Moreover, air breakdown test has been performed in a spark gap at different frequencies between 1 Hz and 100 Hz for pulse durations up to 15 μs. The reliability of system is verified by its continuous operation for more than 10 hours in the lab. Air breakdown in a spark-gap of 10 mm is performed.

Conclusions

Marx generator is one of the design options for non-lethal electric fence energizers with several attractive features such as being energy efficient and reliable. Marx generator is superior to other techniques because electronic components such as capacitor and switches are subjected to lower voltage stress and lower current stress. Its other features that make Marx generator (with proposed gate driver) a better option for a non-lethal electric fence energizer are compactness, higher efficiency, better pulse width control and most importantly control over release of output energy. It was never tried before because of its hardware complexity. In a semiconductor switches based Marx generator implementation, gate drivers are the major contributors of hardware complexity. This issue is addressed by a novel gate driver design which is simple, compact and cost effective. Moreover, it controls output energy to ensure non-lethal nature of the fence.

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