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A novel overvoltage protection scheme for power electronics switching under differential surge conditions

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ABSTRACT

The proposed scheme is employed for the efficient operation of a DC-DC-based buck converter. This protection scheme shows the optimal placement of a varistor in the power electronics converter side under different surge conditions. Advanced varistors have excellent electrical material properties and electrothermal behavior for the enhancement of power absorption capability. Varistors have been examined widely in the last four decades that are employed for surge protection applications. The advantage of power surge protection using varistor-based power devices is vital due to the great sensitivity of the equipment integrated into the grid and emerging power electronics-based DC systems with low and high voltage ratings. In this research, a varistor can be placed to protect the switching devices such as MOSFETs in power electronic-based buck converter side due to uncertain overvoltage under differential surge. The proposed MATLAB simulation study shows the peak voltage stress on the grid due to the surge and its enhancement scheme.

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1. INTRODUCTION

Power lines have a significant impact on the reliability and safety of power grids. Insulation synchronization of multiconductor transmission lines (MTLs) must provide safety for quick and slower front transient overvoltage strains induced by lightning assaults or swapping because they can be crucial for shielding and present a threat to linked devices due to their long ranges and high capacity power transmission [1]. Wind farms and high-voltage (HV) substations are built with surge protection in mind [2]. Voltage transients are short-lived and unpredictably unstable. Because of these two features, they are challenging to detect and quantify [3]. A lot of work is being done to better understand these transients, and a lot of data is currently accessible from the power eminence community [4]. Power quality problems are becoming more prevalent in low-voltage power distribution arrangements. Switching mode power supplies are used in fax machines, scanners, lifts, handrails and ballasts, as well as variable-frequency drives (VFDs) for energy-efficient heating, airflow, and air-conditioning heating ventilation and air conditioning (HVAC) systems. Current harmonics are produced by such loads, resulting in warped voltage. In addition to the skewed voltage, transient overvoltages are caused by shifting and lightning surges promulgating via the distribution network. In the present control systems, both digital and analog circuits use complicated components, which are fundamentally vulnerable to harm or failure from electrical surges. The current tendency to improve effectiveness in a smaller package has exacerbated the problem of noise. Noise is generated due to digitized circuits with high-frequency variation and the switching-mode power supply units used for their higher efficiency. Transient voltage surge suppressors should be used to avoid damage to sensitive control circuits caused by transient overvoltages (TVSSs). The issue is determining the size, magnitude, and energy limits of the surge to better assess and choose TVSS devices. A temporary spike or intermittent overvoltage and overcurrent in electrical or electronic circuits is known as a power surge [5]. Power surges can be caused by lightning, switching on and off of the sizeable induction motor, inductive and magnetic coupling, and electrostatic emancipation, to name a few. Since it only lasts a fraction of a second, usually in microseconds, the implications may vary from negligible impairment like circuitry deterioration to severe impairment like perpetual equipment failure. An appropriate surge protection device and grounding technique are essential for lightning and surge safety to minimize damage [6]. Permanent equipment damage in vans, especially watercraft, aircraft and spacecraft, can result in catastrophic accidents. In the automotive, marine, and aviation industries, integrated circuits and solid-state electronics, which are prone to intrusion, have made their systems more susceptible to a power surge. Safety from the surge is also critical in electronic and electrical structures. The melting of metal surfaces, the scorching wires, and the combustion of fuel are some of the consequences of straight lightning on vehicles [7]. Transient voltage surge suppressors (TVSSs) should be used to avoid damage to sensitive control circuits caused by transient overvoltages. The issue is determining the amount, size, and energy limits of the surge to better assess and choose TVSS devices.

2. CAUSE OF SURGES AND NOISE

Internal and external overvoltage are the two forms of overvoltage that can occur in a power system. Inner overvoltage is driven by fluctuations in the power system's surroundings [8]. Surge overvoltage and related noise have several causes that have been well established. Surges happen when there is a massive spike in the electrical system’s current [9]. It only lasts about a fraction of a second, but can cause lifelong damages to any outlets or plugged-in appliances. This is due to the surge overloading the circuits connected to the electrical system. If an appliance cannot handle the overload, it can be damaged or even completely ruined.

2.1. Lightning

Lightning can cause a number of noise and transient disruptions, including the following [10], [11]; (i) common-mode and normal-mode, also known as differential mode; (ii) electrostatic coupling triggered by lightning; (iii) magnetic coupling caused by lightning; and (iv) conductive coupling caused by lightning.

2.2. Capacitors with a power factor correction

Power factor correction capacitor [12] could generate oscillation noise. The oscillation frequencies are in the range from 1 to 20 kHz. It could cause malfunction to a sensitive equipment.

2.3. Power system switches

Fault-clearing systems, electronic switching and load switching devices are all part of the power system switching. They are unavoidable device to be used in the system. The switching of the device will generate noise and electrical surge.

2.4. Surge intensity and lightning exposure

Lightning exposure affects the likelihood of surge voltage reaching particular peak values. A single lightning bolt can deliver up to 300 kV voltages and nearly 30 kA of current, which is extremely high and can damage devices and shielding. As a result, it is essential to control the power system so that the predicted overvoltage is less than what the device can handle. However, such a device would be prohibitively expensive and impractical in real-world applications. The best method is to build the power system to ensure that overvoltage damage is prevented. Overvoltage safety is critical for ensuring the smooth functioning of the power system and protecting the protection of power equipment that is responsive to the voltage [13].

3. OVERVOLTAGE PROTECTION

Overvoltage can be either temporary or permanent. Internal and external are the two groups. This overvoltage can destroy insulators and substation equipment. As a result, facilities to protect insulators and other equipment from overvoltage damage are needed. Overvoltage protection is the method of preventing the electrical device from being destroyed by the surge with the use of electronic circuits such as bent sirens near the power line and zener diodes. Overvoltage safety can be achieved in several ways, each with its own number of traits. Different types of circuits are used for the protection of the surges, such as:

3.1. Spark gap arrestors

Spark gap arresters are a collection of silicon carbide (SiC) resistances and spark gaps located in porcelain cover and are usually referred to as "spark gap arresters". Overvoltage has a unique voltage rating. The measured surge capacity and realistic level of safety are key qualities that distinguish overvoltage protection products.

a. Level 1 surge arrester: Protects against overvoltage and high currents triggered by direct or indirect lightning strikes.
b. Level 2 surge arrester: Protects against overvoltage caused by electrical switching processes.
c. Level 3 surge arrester: Protects electrical loads from overvoltage.

3.2. Silicon controlled rectifier (SCR) crowbar

Figure 1 depicts the crowbar circuit, which seats a short circuit across the output in the event of an overvoltage condition. Thyristors, such as SCRs, are often used because they can reverse large currents while continuing to operate until some charge has been removed. The thyristor is usually connected to a fuse that prevents the device from requiring any additional voltage. Once triggered with completely conducting, the voltage drop across the TR1, which decreases the requirement of a higher, more vigorous switch OFF is to attach the related fuse. In surge conditions, the proposed fuse prevents the higher voltage limit.

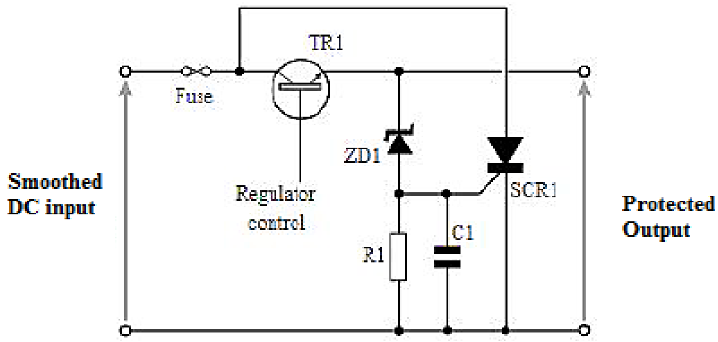

Figure 1. Crowbar circuit [14]

4. VOLTAGE CLAMPING

As shown in Figure 2, the simplest protection scheme can be in the situation where a zener diode is placed crossways the output. When the zener diode voltage is set to be marginally higher than the defined line voltage, it will not perform below standard settings. If the voltage upsurges too high, it will begin to conduct, clamping the voltage at a value marginally higher than the line voltage.

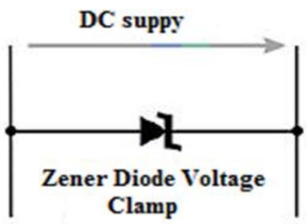

Figure 2. Zener voltage clamper [14]

5. LITERATURE SURVEY

Erika *et al*. [15] introduced an effective computational model based on an implicit Crank–Nicolson finite alteration procedure domain system for insulated coordination research; then, the IEEE suggested surge arrester design is tested and applied using a local implicit scheme based on a series of nonlinear formulas that are recast in an appropriate way for the adequate outcome. The model has been shown to be reliable and accurate to second order. The inclusion of the arrester design in the implied Crank–Nicolson scheme is an example of the study's added value. Compared to the well-known finite modification time-domain technique founded on the explicit leap-frog system, it maintained consistency for larger time steps, allowing for a 60% reduction in running time. The reduced computation period permitted for faster repetitive approaches, which are required when evaluating lightning efficiency with the parameters like rising time, peak current, vertical leader channel position, tail time, footing resistance, phase conductor voltages, insulator power, and so on will have to be modified thousands of times if modified arbitrarily.

Mohan *et al*. [16] have explained DC faults' features in the voltage source converters-high voltage direct currents (VSC-HVDC) results in detail in their paper. High-speed fault detecting and isolation approaches are vital in a high voltage direct currents (HVDC) grid. The DC fault current has a broad peak and steady value within milliseconds. As a result, designing a security outline for a multi-terminal voltage source converter (VSC)-based HVDC device is difficult. Numerous strategies for DC fault recognition, position, and separation in both current source converter (CSC) and VSC-based HVDC transmission methods in two-terminal and multi-terminal network configurations have been created, and their paper provided a detailed overview of the different techniques for DC fault detection, location, and isolation in both CSC and VSC-based HVDC transmission systems in multi-terminal and two-terminal network configurations.

Florkowski *et al*. [17] have explained over-voltages that strain transformer insulation methods happen when switching off transformers in systems with vacuum circuit breakers. Laboratory tests of switching over-voltages at transformer terminals and within the winding in a model medium-voltage electrical network with a vacuum circuit breaker were used in their study. Jinghan *et al*. [18] examined the fault properties and described the growth of the versatile DC grid. The applicability, benefits, and drawbacks of the current security theory and recovery schemes and fault isolation are then discussed. Lastly, the future versatile DC grid's major issues and potential growth trends are identified and predicted.

Radulović *et al*. [19] performed a detailed study of this type of overvoltage protection device with a broad range of factors are controlled via experimental measurements and a variety of simulations. The findings demonstrated that the amount of built-in varistors inside electronic devices with low-security voltages create updraft damage because of insufficient surge energy distribution among varistors and surge protection devices (SPDs). The paper explained and addressed the criteria for an effective protection system that will ensure the existence of built-in varistors and appropriate overvoltage protection features.

Chodagam *et al*. [20], in their work, talked about the advances in condensing HVDC circuit breakers that involve late critical endeavors in the production of cutting-edge HVDC electrical switches. Every invention is given a brief utilitarian analysis. Various advancements that take into account data obtained from written works are often examined. Finally, plans for circuit breaker production are on view. Guillod *et al*. [21] described the various applicable pressures, specifies the safety requirements, and recommends appropriate shield devices and circuitries. The existing safety mechanisms for low-frequency transformers are examined, and a modified version for solid-state transformers (SSTs) is suggested. The most dangerous conditions, such as MV short circuits and overvoltages, are established and thoroughly investigated. Guidelines for developing robust SSTs are taken from the provided in-depth investigation and applicable to a 1 MVA, 10 kV SST.

Patil *et al*. [22] define various forms of transformer safety, which will be more useful in detecting the transformer's protection mechanism. The goal of their paper is to bring together recent developments in transformer security. To that end, efforts were made to cover all of the methods and theories used. The article addressed both the most current and conventional transformer strategies. Many essential parts are mounted in the transformer, and they are costly, so they must be protected in an abnormal state.

Thornton *et al*. [23] proposed that marine ship traffic's emission of airborne particulates and byproducts cause a macroscopic quantum enhancing the convection and storm electrification in the shipping lanes' vicinity. These internal processes or external perturbations from otherwise clean areas provide a once-in-a-lifetime chance to learn more about the vulnerability of maritime deep convection and lightning to aerosol particles. Schork *et al*. [24] have shown the faults that existed during spike current stress in this paper and the limits of the named devices. The gate control of switching power devices during surge current affairs, which will be addressed, is another essential feature. The impulse results are all rated for potential use in voltage spikes safety.

6. PROPOSED METHODOLOGY

In this work, MATLAB is used for the simulation of the parameters. A surge generator and voltage sensor are developed using the MATLAB. Following are the various parameters we have used for the simulation.

6.1. Proposed system parameters

Operation of the varistor or voltage-dependent resistor (VDR): The linear current-voltage parameterization uses a constant resistance in each of their off and on states. The power-law parameterization divides the current-voltage characteristic into three bias regions: leakage, normal, and upturn. Varistor is an asymmetrical bipolar device where it clamps both positive and negative voltages. It also shows that the voltage is an independent variable and current as of the dependent variable. A basic varistor can be modeled by components like inductor, capacitor and resistors as shown in Figure 3 and can be represented by (1) and (2) [25]:

$$I = kV^{\alpha} \quad (1)$$

$$\log(u) = B1 + B2 \log(i) + B3 \exp(-\log(i)) + B4 \exp(\log(i)) \quad (2)$$

where,
V = Voltage across the ideal varistor RL, not including voltage across RB
I = Current through the ideal varistor, not include the current through RB
K = Constant with value normally less than 10-100
i = Current through the varistor, RI
u = Voltage across the varistor, RI
B1, B2, B3, and B4 = Unique for each varistor type obtained from varistor manufacturer datasheet
α is the value that causes (1) to be nonlinear. It will determine the performance of the varistor. The greater the value of α, the better the varistor's performance. A normal transistor will have the value of α = 1. Varistor will have a typical value of α is between 25 and 60. Table 1 shows the values of various simulation parameters.

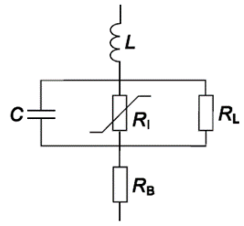

Figure 3. Equivalent circuit model of a varistor

where,
L = Inductance of the conducting leads
C = Capacitance of the device package zinc oxide material
R_L = Resistance when varistor at low current
R_B = Resistance when varistor conduct large currents
R_I = Ideal varistor property represented by nonlinear (1)

Table 1. Values of various simulation parameters

No.	Subsystem parameters	Rating
1	Varistor/voltage-dependent resistor (VDR)	Leakage to normal voltage transition: 30 Volt. Normal to upturn voltage transition: 300 Volt Leakage-mode resistance: 30e8 Ohm. Normal-mode power-law exponent: 45 Upturn-mode resistance: 0.07 Ohm Terminal resistance: 100e-6 Ohm Capacitance: 4.4 nF
2	N-Channel MOSFET 1 and N-channel MOSFET-2	Drain-source on resistance, RDS (on) = 0.025 Ohm Drain current (Ids) for RDS (on)= 6 Amp Gate-source voltage Vgs for RDS (on): 10 V Gate-source threshold voltage, Vth =1.7 V Source ohmic resistance=1e-4 Ohm Input capacitance, Ciss: 350 Pf Reverse transfer capacitance, Crss: 80 pF
3	Resistor	15 Ohm
4	Capacitor	1e-4 F
5	Inductor-1 and Inductor-2	1.5e-3 H

6.2. Simulation models

The simulation models and its results are shown on Figures 4 to 14. The characteristics of the MOSFET voltage stress with low and high voltages are illustrated. They also are divided into subsystem models as described on section 6.2.1 to 6.2.3.

6.2.1. Subsystem model of surge generator

Currently, in superfluous high voltage transmission lines and power systems, switching surges is a significant issue that has an impact on the design of protection. Figure 4 shows a surge generator circuit with R1 is 1 kΩ, R2 is 25.1 kΩ, R3 is 0.94 kΩ, R4 is 19.8 kΩ, C1 is 6.04 µF, and C2 is 18 µF. The switching surges of extremely high peaks could be attained with the help of the circuit, as shown in Figure 4. A surge generator condenser C1 is being charged to a low voltage. The high voltage is linked in parallel to a load capacitance C2 and a potential divider R2. 6.2.2.

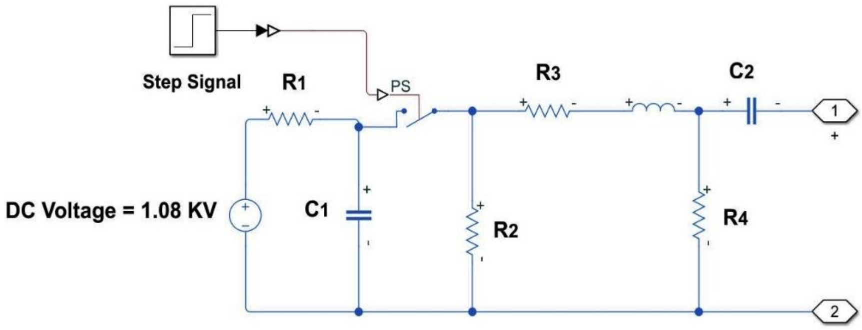

Figure 4. Surge generator circuit

6.2.2. Subsystem model of gate driver circuit

Figure 5 shows a gate driver circuit (GDC). The gate driver is a power amplifier that admits a low-power input and generates a high-current drive input for the gate of a high-power for power MOSFET. A pulse generator is used as an input to the gate driver circuit.

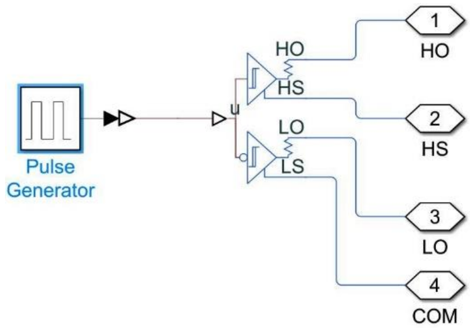

Figure 5. Gate driver circuit

6.2.3. Subsystem model of voltage sensors

The voltage sensor block signifies an ideal voltage sensor, a device that translates voltage measured among 2 points of an electrical circuit into a physical signal proportional to the voltage. The voltage profile is sensed by the voltage sensors (sensor 1 and sensor 2).

- Low voltage

Figure 6 shows the simulation circuit of the voltage sensor coupled with N-channel MOSFET 1 at low voltage. They are connected to the surge generator terminal 1 and 2. The connection of the voltage sensor will be described later at the simulation circuit of the proposed protection scheme.

- High voltage

Figure 7 is a simulation circuit with a voltage sensor coupled with N-channel MOSFET 2 at high voltage. They are connected to the surge generator terminal 1 and 2. For the detail connection refer to Figure 8. Figure 8 shows the connection of low voltage and high voltage sensors with N-channel MOSFET 1 and N-channel MOSFET 2.

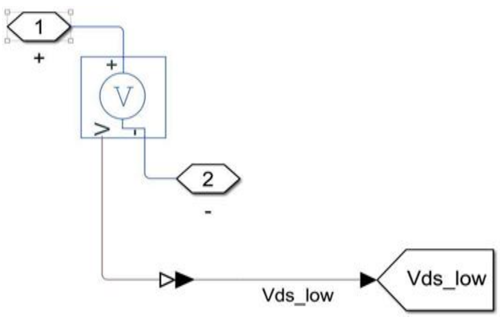

Figure 6. Voltage sensor coupled with N-channel MOSFET 1 at low voltage

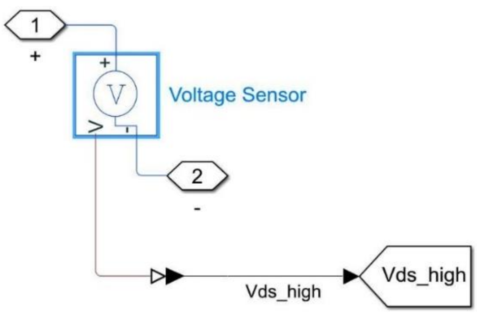

Figure 7. Voltage sensor coupled with N-channel MOSFET 2 at high voltage

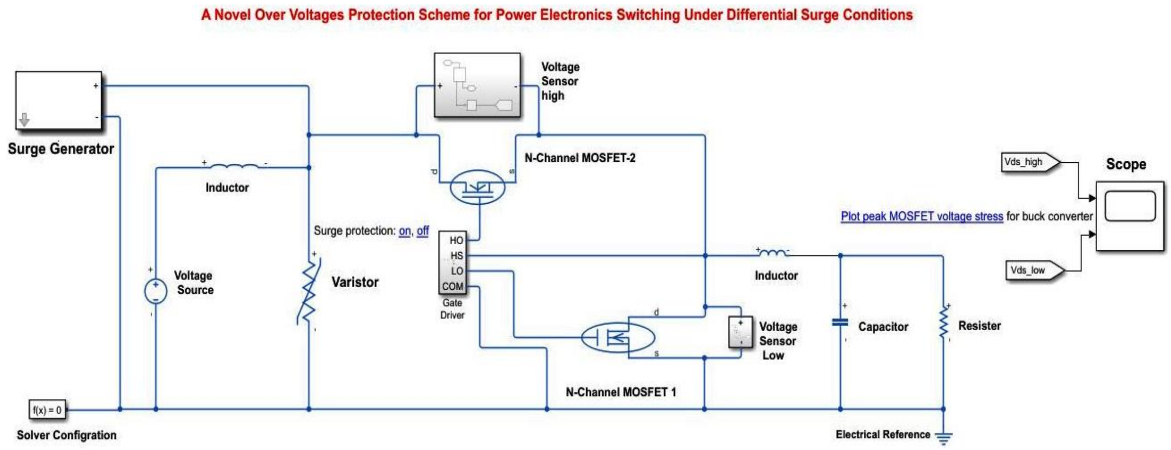

Figure 8. Simulation circuit of the proposed protection scheme

- Simulation results at high voltage

This model showed that a varistor is applied to a power electronics-based buck-converter to protect the switching MOSFETs from overvoltages due to a differential surge. Case A: In this case, the surge protection scheme is off, so will find out the voltage profile during a high voltage surge. The simulation circuit is set up as per Figure 9.

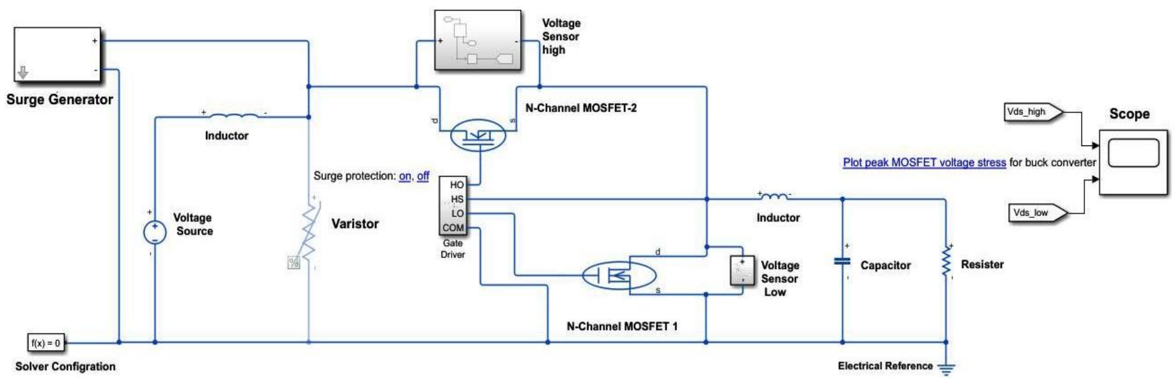

Figure 9. Simulation circuit when surge protection is off

Figure 10 shows the voltage profile which is sensed by voltage sensors (sensor 1 and sensor 2). The Vds coupled with N-channel MOSFET-1 that providing the low value of voltage (marked as “1”) during surge operation. While Vds coupled with N-channel MOSFET-2, so the circuit experiencing a high value of voltage (marked as “2”). In this case, surge protection does not operate. In Figure 11, it can be seen that MOSFET experiencing voltage stress of a peak value (marked as “3”) of 1100 volt occurs at 0.025 sec. after oscillation surge will not die out up to 0.03 sec. On the other hand, on the low side, MOSFET also at that instant proposed system experienced the high peak of 400 V (marked as “4”).

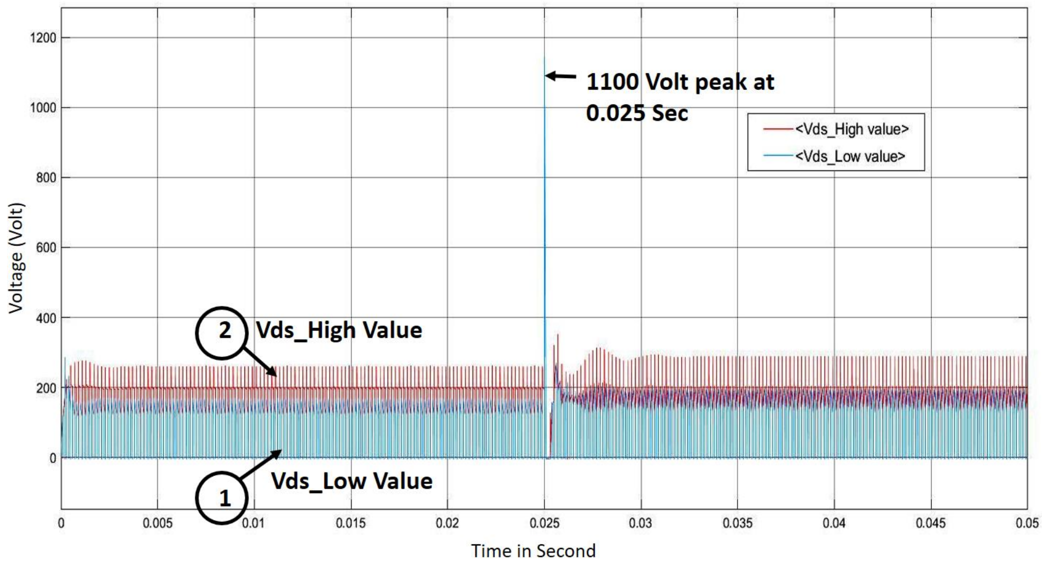

Figure 10. Characteristics of MOSFET voltage stress which is 1100-volt peak and occurs at 0.025 sec

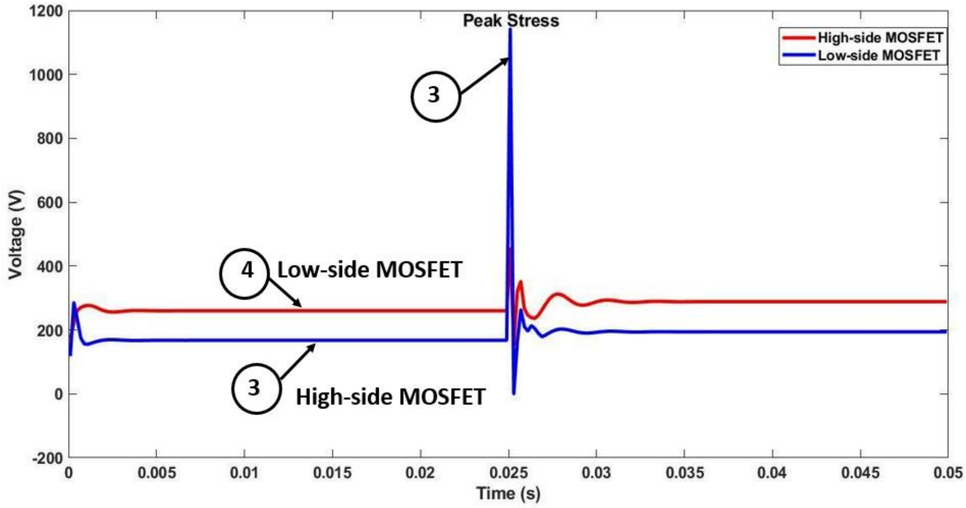

Figure 11. The proposed MATLAB simulation study showing the peak voltage stress on the grid due to surge

Case B*:* In this case surge protection scheme is on, so will find out the voltage profile when the voltage surge is dies out. Here the varistor is active so that its configuration is directly associated with the voltage sensor so that it provides compensation for peak value at regular intervals. The simulation circuit is set up as Figure 12.

Figure 13 is showing the voltage profile, which is sensed by voltage sensors when surge protection is on. Vds coupled with N-channel MOSFET-1 that provide the low value of voltage (marked as “5”) during surge protection operation. While Vds is coupled with N-channel MOSFET-2, so that circuit doesn't not experiencing a high value of surge voltage (marked as “6”). In this case, MOSFETS remains stable and settles at that instant. In Figure 14, we can conclude that MOSFET does not experience any voltage stress of a peak value and after oscillation surge will die out. On the other hand, on the low side, MOSFET remains stable and settles at that instant due to after activation of the surge protection scheme, marked as “7”.

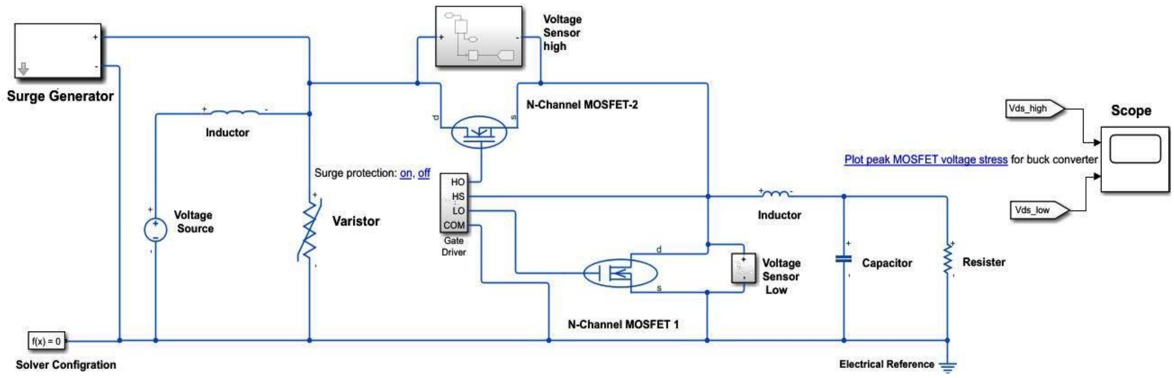

Figure 12. Simulation circuit when surge protection is on

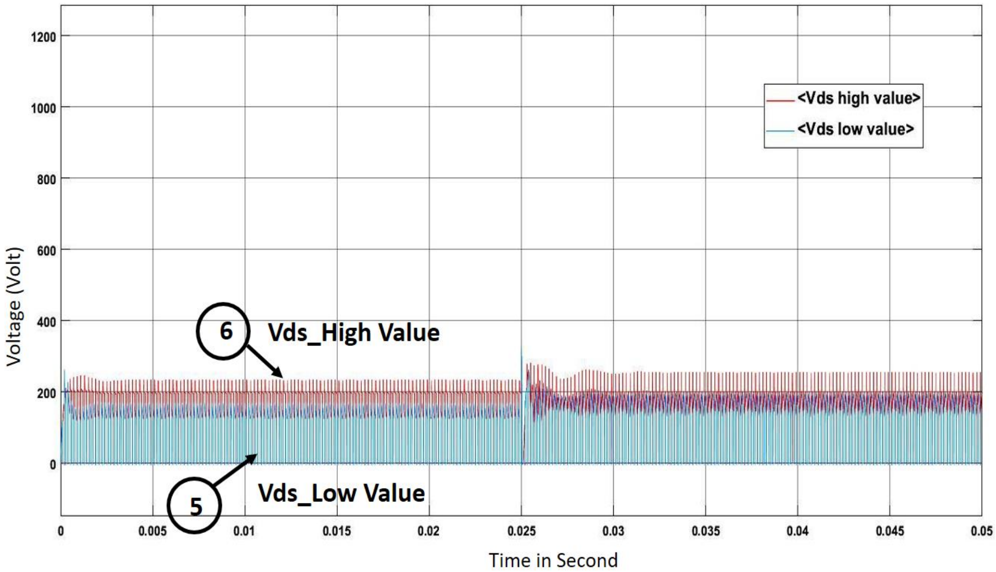

Figure 13. Surge is enhanced due to varistor action

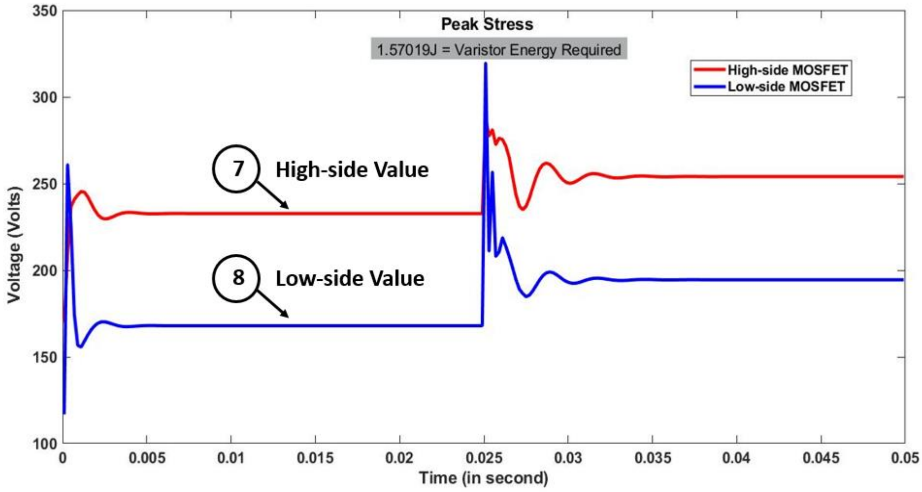

Figure 14. Characteristics of MOSFET voltage stress compensated at 0.025 sec using varistor operation

7. CONCLUSION

Therefore, we required 1.57019J varistor energy to protect and enhance the overvoltage peak. The advantage of power surge protection using varistor-based power devices is vital due to the great sensitivity of the equipment integrated into the grid and for emerging power electronics-based DC systems having low and high voltage ratings. In this research, the varistor is successfully placed to protect the switching devices such as MOSFETs in power electronic-based buck converter side due to uncertain over-voltages under differential surge.

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