Abstract: Modern semiconductor technology is vulnerable to transient surges such as lightning. Transient voltage suppressor systems (TVSSs), which are installed to protect modern electronics, use non-linear components such as varistors and transient voltage suppressor diodes in their design. In the case of low-voltage (1000 V and less) AC power circuits, there is no clear approach to estimate the energy absorption and associated time delays in individual components in relation to the propagated transient surge. Numerical simulation techniques can be used to analyse the phenomenon of surge propagation within a TVSS and estimate the energy transferred to each component with associated time delays. Suitable mathematical models must be used for the non-linear components. This study presents the development of reasonably accurate models for the non-linear circuit elements and formulation of state equations for the TVSS, together with simulation results; results are experimentally validated using a lightning surge simulator. The method of analysing surge propagation presented here could be extended to analyse the phenomenon of surge propagation within power conversion stages which buffer the complex electronic circuits and the power source. The results discussed here indicate that the theoretical energy calculations are within 10% of the experimental results for the individual circuit elements.

1 Introduction

Proliferation of complex multi-million transistor semiconductor devices into a wide range of equipment from automated industrial assembly lines to sophisticated computer systems, has increased the vulnerability of such equipment to power quality problems [1]; these complex devices which are ultra-large-scale integrated circuits have progressed towards advanced system-on-chip concepts with feature size dropping towards 22 nm [2–4]. The switch mode power supply (SMPS) that sits between the utility AC and the processor-based equipment also carry complex circuitry. Both the power supply and the processor-based load are prone to damage by very short duration high-voltage transients such as lightning. Hence an end-to-end approach on transient propagation studies from the utility AC to final DC rails is of utmost importance.

An appropriate point to begin a transient propagation study would be at the transient voltage suppressor system (TVSS) that usually sits between the utility AC and the SMPS. Our objective here is to analyse the phenomenon of surge propagation in a TVSS and estimate the energy transferred to each one of its components. A representative schematic of a TVSS with two levels of protection, suitable for operation in the location categories A and B, are shown in Fig. 1a. The varistors M2 and M3 along with TVS diodes T2 and T3 would act in the case of a common-mode transient such as lightning, while the varistor M1 and TVS diode T1 would protect the load from a difference-mode transient. Category of the protector refers to the location category for which the protector is designed. These locations are defined within the IEEE Ċ62.41 standard [5] and are depicted in Fig. 1b.

In this work presented here, we have performed numerical simulations to analyse the transfer energy to individual components and associated time delays for a simplified 2-wire version of a TVSS in the event of a lightning transient occurrence. As the TVSS represents a typical power electronic interface with a combination of linear and non-linear electronic components, we believe that this work can be continued to encompass downstream electronics that would be encountered in power electronic systems. Appropriate mathematical models had to be used for the non-linear metal oxide varistor (MOV) and the transient voltage suppressor (TVS) diode. A lightning surge simulator (LSS) that conforms to IEC 61000-4-5 and IEEE Ċ62.41 standards, capable of generating transient waveforms up to a maximum peak voltage of 6.6 kV, was used to validate the analysed results.

A TVSS is based on non-linear bidirectional break-over components such as MOVs and TVS diodes in combination with capacitors and inductors. The quality of the TVSS and the protection it provides is governed by the test procedures adopted by the manufacturer; the energy absorbent capacity of the non-linear protection components and their speed of the response [6–11]. Over 90% of the contemporary TVSSs designated for protection of low-voltage AC power circuitry are of parallel type with an MOV being the major component responsible for the suppression of surges and transient voltages. MOVs across the input wires are responsible for first-level protection from transients expected through the line-input. In order to handle extended transient stress, TVS diodes are connected as shown to provide a second-level of protection. If the output capacitors are charged by the extended stress up to the breakdown voltage of the diodes, heavy conduction will occur in the diodes instantly [12]. In Section 2, a basic approach to modelling non-linear devices used in a TVSS is discussed. Approximate power-law models will be used in the development of the differential equations, which will represent the total system to be analysed. Section 3 provides information pertaining to the Lightning Surge Simulator Noiseken LSS-6230, which was used to experimentally validate the numerical results. In Section 4, we discuss step-by-step MATLAB-based numerical simulations, which help us to analyse...
component-wise energy transfers to the TVSS with reasonable error margins and experimental procedures adopted using an LSS to validate the computer simulation predictions. Such simulations will allow us to predict the incipient failure of particular electronic components in the TVSS because of the propagation of a transient voltage across it.

2 Development of models for the non-linear transient suppression components

The electrical equivalent circuit for the varistor that could relate to the three regions of its operation is shown in Fig. 2a. At low-current levels, the non-linear resistance is in a high-resistance mode (approaching $10^9 \Omega$) and approximates an open circuit, which is represented by the leakage resistance $R_{\text{OFF}}$. At high currents, approaching the maximum rating, the non-linear resistance is in a low-resistance mode and approximates a short circuit. This is represented by $R_{\text{ON}}$. A simplified version of this circuit was employed for our simulations and the same is shown in Fig. 2b. $R_{\text{OFF}} \approx \infty$ and $R_{\text{ON}} = 0$ has been neglected.

Different mathematical models are used for the non-linear resistance $R_X$, which plays the major role in surge absorption by the varistor [13–15]. The relationship that we use for the work presented here is given by the following equation

$$i(v) = kv^\alpha$$

(1)

where $i$ is the current through and $v$ is the voltage across the varistor. The parameters $k$ and $\alpha$ of (1) are unique to each varistor type.

![Fig. 1 Representative schematic of a TVSS, and location categories](image1)

*a* Typical TVSS designed for AC mains operation with two levels (shaded areas) of protection

*b* Location categories as per IEEE/ANSI C62.41, where category A is more than 20 m from category C; category B extends between categories C and A; category C is outside and service entrance

![Fig. 2 Electrical equivalent circuit for the varistor](image2)

*a* Varistor equivalent circuit model [13]

*b* Simplified varistor equivalent circuit used for the simulations

![Fig. 3 MOV and TVS diode V–I characteristics drawn on log–log graph for the determination of power-law exponent $\alpha$](image3)

('ON' region points were obtained by detecting the transient peaks and the 'leakage' region points were obtained in the steady state)

| Device | Type | Continuous maximum $V_{\text{MMS}}$, V | Maximum transient energy (2 ms), J | Exponent $\alpha$ |
|--------|------|--------------------------------------|-----------------------------------|------------------|
| varistor varistor V271HA32 | 275 | 360 | 16.9 ± 5% |
| 275L40C | 275 | 320 | 26.2 ± 5% |
| Minimum breakdown voltage, V | Peak power dissipation (1 ms), W |
| 162 | 1500 | 68.8 ± 3% |
| 380 | 1500 | 65.2 ± 3% |
| TVS diode | 1.5KE170CA |
| TVS diode | 1.5KE400CA |

Table 1 Degree of non-linearity ($\alpha$) for some of the devices characterised [18]
Exponent α defines the degree of non-linearity in the normal varistor region of operation. Equation (1) represents the MOV only in its 'normal varistor operation' region [13, 16, 17] and provides fairly accurate results when used in computer simulations as shown in Section 4.

\[
\log i = a \log v + \log k
\]

(2)

Table 2 Parameters for the Noiseken LSS-6230

| Parameter | Value      | Parameter | Value      |
|-----------|------------|-----------|------------|
| C_1       | 10 µF      | R_1       | 7 Ω        |
| L_1       | 2.7 µH     | R_2       | 1.1 Ω      |
| L_2       | 6 µH       | R_3       | 1 MΩ       |

Although an analysis of a circuit representation containing a non-linear model based on a power-law would be mathematically complex using Laplace methods, we demonstrate in Section 4 that computer simulation employing numerical methods can be used successfully in the presence of such a model.

We also modelled two TVS diodes using a power-law relationship similar to (1). The two characteristics that were used to develop the models for the 275L40C varistor and the 1.5KE170CA TVS diode are displayed side-by-side in Fig. 3 for the comparison. The line plots are the best curve fits for the points shown. The degree of non-linearity α, and the leakage current can be easily compared using these plots.

It is clear from these plots that the value of α (slope of the device for the 'on' part of the characteristic) is much greater for the TVS diode than the MOV. The almost linear leakage regions of both models can be ignored in our investigation of surge propagation.
since these currents are very small and do not contribute significantly to the energies absorbed by the components. Typical \( \alpha \) values, obtained for several break-over components by means of a curve fit, are given in Table 1.

Leakage current can be an area of misconception when comparing a varistor and a TVS diode. For example, we see from Fig. 3, that the TVS diode leakage current is about 100 times higher, at 100 V, than the varistor. This difference is greatly reduced if the TVS diode is a higher voltage device [19].

3 Lightning surge simulator model

The results, obtained through the process of simulation and analysis for the surge propagation study, are validated using a LSS in the laboratory. Since the validating voltage and current waveforms during surge testing of TVSSs are governed by the LSS characteristics, an accurate surge simulator model should be an integral part of the circuit being analysed or simulated [14, 20, 21]. The LSS characteristics are governed by the requirements set by the surge immunity testing standards IEEE/ANSI C62.41 and the IEC publication 61000-4-5. The equivalent circuit given in Fig. 4, which was used in our analysis and computer simulations, was supplied by the manufacturer (Noise Laboratory Co., Japan) of the LSS Noiseken LSS 6230.

The initial voltage of the discharging capacitor \( C_1 \) of the impulse source can be set to voltages in the range 100 V – 6.6 kV, in 100 V steps. In order to match the standards above, the model parameters given in Table 2 are specified by the manufacturer.

The Laplace solutions for open-circuit voltage and short-circuit current of this linear circuit with parameter values given in Table 2 were validated with experimental results of the LSS open-circuit voltage and short-circuit current. These results are shown in Figs. 5a and b.

The waveforms in Figs. 5a and b corresponds to the 1.2/50 \( \mu \)s open-circuit voltage and the 8/20 \( \mu \)s short-circuit current specified in the IEEE/ANSI C62.41 and the IEC publication 61000-4-5 standards, respectively.

The network equations in the time-domain were formulated as a system of coupled first-order differential equations (DEs), which govern the dynamic behaviour of the network. These first-order DEs (state equations), which fit the universal format given in (3)
were programmed using MATLAB. Three state variables (two loop currents and one derivative of a loop current) are required for the LSS circuit

$$\frac{dx}{dt} = Ax + Bu$$

where $x$ is the statevector and $u$ is the input vector; $A$ is the state matrix and $B$ is the input matrix.

Owing to the presence of the initial charge in LSS capacitor $C_1$, the DE for the first loop gives rise to an exposed delta function as seen in the following equation

$$\frac{d^2i_1}{dt^2} + \frac{R_1}{L_1} \frac{di_1}{dt} + \frac{1}{L_1 C_1} i_1 - \frac{R_1}{L_1} \frac{di_2}{dt} = \frac{V_{C_1}(0)}{L_1} \delta(t)$$

This can be resolved for accurate MATLAB coding by using the initial condition that arises from the impulse input [22] (see Appendix 1).

4 Numerical simulation of surge propagation

Our goal is to simulate and predict power and energy dissipations in individual components of a 2-wire version of the TVSS shown in Fig. 1a. In order to build robust code for our numerical simulations a step-by-step approach was followed [18]. The first two circuits that we simulate here are purely linear in nature. These simulations were helpful to eliminate certain difficulties that arose in coding such circuits where the stimulus is a high energy transient.
The first circuit attempted, given in Fig. 6a simulates the 'off' state of the varistor. This could be done by considering the equivalent circuit given in Fig. 2b and taking the series LC combination as the 'off' state of the varistor since the non-linear resistance $R_x$ can be approximated to an open-circuit in this state. To write the set of state equations in the form of (3), five state variables (three loop currents and two derivatives of loop currents) had to be used. The loop currents are denoted by $i_n$, where $n$ is the loop number. The first two loop currents circulate within the LSS and the third one $i_d(t)$ is seen flowing through the 'off' state of the MOV. The resulting plot of the decaying MOV current shown in Fig. 6b has high frequency ringing at the start. This kind of waveform with multiple timescales presents a stiff problem especially when one of the processes has a very small time constant. As a consequence we found that the fixed-step DE solver, the fourth-order RK (Runge-Kutta) and the variable-step MATLAB DE solver ode45 both failed to perform this simulation. This problem can be overcome by using the ode15s or ode23t MATLAB solvers which are designed for solving stiff problems [23].

The second circuit we present here is also linear in the nature and the simulation would give us an opportunity to study static instances in the operation of the non-linear varistor. We have used three different values ($7 \Omega$, 500 $\Omega$ and 30 M$\Omega$) for the static varistor resistor $R_m$ and these values correspond to the 'leakage', 'knee' and 'breakdown' regions of the varistor V-I characteristic. The circuit simulated is shown in Fig. 7a. Here we require six state variables to complete the state equations. In the MATLAB coding, it was important to provide the Jacobian matrix of the state equations to the ODE solver, in order to obtain uncompromised performance. This provision removes the need for the solver to estimate the Jacobian elements numerically [24]. Simulations of varistor currents for two assumed static instances of varistor resistance are shown in Figs. 7b and c. The SPICE simulations used to validate the numerical simulations are also shown.

In this paper, our interest is to estimate the energies delivered to individual components of a TVSS block and determine the respective time delays in the event of a lightning transient. We have been able to adapt the robust code developed for the earlier circuits to do this successfully. As we have seen earlier a TVSS consists of both linear and non-linear elements. We have worked with the power-law model given by (1) for both the MOV and the TVS diode in formulating the state equations. Simulations based on the above were carried out for circuit blocks containing (a) an MOV, and (b) an MOV and a noise filter. Circuit diagrams and simulation/experimental validation comparison plots for (a) are shown in Fig. 8 and for (b) in Fig. 9, respectively. A similar simulation was also compared with a PSpice simulation; the results were almost identical [25]. The model for the MOV used in PSpice was available from the manufacturer.

The set of state equations developed for the circuit of Fig. 2a is presented in Appendix 2.

As can be seen in Fig. 8a, the current peak in the simulation coincides with the voltage peak although for a real varistor as seen in the validation, the current peak lags the voltage peak by about 2 $\mu$s. This discrepancy could be attributed to the approximate nature of the model used for the non-linear resistance of the MOV. Despite this, we see that the maximum energy absorbed by the varistor given in Fig. 8d is within 10% of the validation. This difference in energies absorbed by the varistor could be minimised by using more accurate models for the varistor. Improvements to varistor modelling are discussed in Section 5. The energy delivered to the varistor obtains dissipated as heat within a short period of time.

Next we introduce the second stage of the TVSS, which is an LC line filter connected in parallel with the varistor and the circuit is shown in Fig. 9a. While the winding resistance and the inductance provide a series impedance to limit the transient current, it also prevents voltage switching transients generated on the load side from feeding back into the supply [12].

In Fig. 9b, we see that the varistor current tends to ring for a few cycles at the oscillation frequency of the line-filter components, in the process of clamping the incoming surge. This simulation compares well with the validation in spite of the ringing in the simulation current not being damped as much as the validation. The reason for this discrepancy is clear as we have not accounted for the bulk resistance of the MOV during conduction and also have neglected parasitic resistances arising from device leads and so on. The simulated energy absorption by the varistor also given in Fig. 9b is within 6% of the validation. This difference in energies could be minimised by using more accurate models for the varistor and the passive inductor and capacitor elements.

A primary task of the project is to find the energy absorption in each component of the TVSS and also to study the time lags of the maximum energy instances with respect to the occurrence of the lightning surge. We have addressed this by also studying the surge propagation through the line filter capacitor $C_f$ and the inductor $L_f$. The results and validations are illustrated in Figs. 9c and d.

It is seen that the energy stored in the capacitor $C_f$ falls as the voltage across it falls as expected. Again the energy simulation compares well with the experimental validation except that the simulation for the energy absorption in the capacitor is slightly higher than the validation; the reason for this discrepancy is clear since we have not accounted for the resistive parts of the filter inductor and capacitor and also other stray circuit resistances. These resistive components do absorb a bit of the energy leaving less energy for the filter capacitor and the inductor. The approximate time delays to transfer maximum energies to each component of the TVSS are also shown clearly in Fig. 10.

These simulations allow us to predict the power dissipation and energy patterns in each of the components of a TVSS unit. The methodology indicated here can be put to detailed analytical use in future research projects to predict the failures in downstream power electronic blocks, provided the non-linear electronic devices can be represented by suitable mathematical models.

Fig. 10  Maximum energies handled by each component of the TVS with associated time delays
(Note the logarithmic scale on the y-axis)
5 Improvements to nonlinear device modelling

Fig. 11a shows experimental plots for voltage and current of a varistor, driven by a 1 kV surge, along with the corresponding simulations. We also show the associated measured dynamic hysteresis curve in Fig. 11b. The associated dynamic I–V curve for the simulation based on the power-law fit, which is also shown in Fig. 11b, does not account for the hysteresis seen in the measured curve.

The hysteresis effect needs to be accounted for if the modelling of the varistor is to be completely accurate [14]. Although the curve-fitting, according to the power-law given by (1), is not a very accurate model of the varistor dynamics, it is adequate for the purpose of predicting energy absorption by various components of the protector circuit.

6 Conclusion

This paper shows that MATLAB-based numerical simulation which solves appropriately chosen sets of state equations is suitable for predicting the actual energy transfers into the individual components of surge protector circuits. The approach presented also gives clear indication of the approximate time delays associated with the energy transfers. These predictions will assist in designing effective surge protectors and also the approach could be extended to general power converters in the power conversion interface of an electronic system. The development of sufficiently accurate models for the non-linear devices encountered is essential for these predictions. All numerical simulations presented here have been validated experimentally using a lightning surge simulator. Error margins for simulations with significant levels of energy were found to be within 10%.

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8 Appendices

8.1 Appendix 1

We will use (3) to provide the resolution that justifies the use of the initial condition that arises from an impulse input. Integrating (3)

\[ x = \int (Ax + Bu) \, dt \]  

and (4)

\[ x = A \int (u) \, dt + B \int (u) \, dt \]  

For the impulse response, \( u \) is a delta function which has an area of

\[ \int u = 1 \]
one from $-\infty$ to $+\infty$. Therefore

$$x = A \int_{-\infty}^{t} (x) \, dt + B \cdot 1 = A \int_{t=0}^{t} (x) \, dt + B \tag{7}$$

To determine the initial conditions that corresponds to an impulse, we need to determine the value of $x$ at $t=0$. Assuming that $x=0$ from $t=-\infty$ to $t=0$, the integral can be evaluated from 0 to time $t$. Since we are interested in the initial condition at $t=0$, we need to evaluate the integral from $t=0$ to $t=0$. Hence the result is

$$x(t=0) = A \int_{t=0}^{t=0} (x) \, dt + B = 0 + B = B \tag{8}$$

Therefore an impulse may be simulated by using an input of all zeros and initial conditions of $B$.

Resolving the second-order DE given by (4) into a couple of first-order DEs, we obtain

$$\frac{di_1}{dt} = j_1 \tag{9}$$

$$\frac{dj_1}{dt} = -aj_1 - (b - ac)i_1 - adi_2 + \frac{V_c(0)}{L} \delta(t) \tag{10}$$

where $a = R_1/L_1$, $b = 1/L_1 C$, $c = R_2/L_2$ and $d = R_1 + R_2 + R_3/L_2$.

Hence from (8) and (10), we obtain the initial condition

$$j_1(t=0) = \frac{V_c(0)}{L} \tag{11}$$

which will be used in all our simulations.

8.2 Appendix 2

Equations (5)–(10) make up the set of six state equations for the circuit of Fig. 9a. The subscript $n$ in the loop currents $i_n$ and in the derivatives of loop currents $j_n$ refers to the loop number. The voltage across the non-linear resistance is given by $v_4$

$$\frac{di_1}{dt} = j_1 \tag{12}$$

$$\frac{dj_1}{dt} = -aj_1 - (b - ac)i_1 - adi_2 + aci_3 \tag{13}$$

$$\frac{di_2}{dt} = ci_1 - di_2 + ei_3 \tag{14}$$

$$\frac{di_3}{dt} = j_3 \tag{15}$$

$$\frac{dj_3}{dt} = -fj_3 + cgi_1 - gdi_2 + (eg - h)i_3 + h(kv_4^2) \tag{16}$$

$$\frac{dv_4}{dt} = m(i_3 - kv_4^2) \tag{17}$$

where $a = R_1/L_1$, $b = 1/L_1 C$, $c = R_2/L_2$, $d = R_1 + R_2 + R_3/L_2$, $e = R_3/L_2$, $f = (R_3 + R_3)/L_m$, $g = R_2/L_m$, $h = 1/L_m C_m$ and $m = 1/C_m$. 

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