

# A supercapacitor based enhancement technique for stand-alone surge protection circuits

Jayathu Fernando<sup>1</sup>, Nihal Kularatna<sup>2</sup>  
School of Engineering, The University of Waikato  
Hamilton, New Zealand  
lhdkf1@waikato.ac.nz<sup>1</sup> nihalkul@waikato.ac.nz<sup>2</sup>

**Abstract** — With the International Technology Roadmap for Semiconductors predicting below-25nm feature-size VLSIs, powered by DC power supplies of less than 1V, protection against transients has become mandatory for modern electronic systems. Surge protection circuits are usually designed using non-linear devices such as metal oxide varistors and semiconductor devices and these devices are rated for short-term energy absorption, based on transient waveforms defined by standards such as IEEE C62.41. Despite their very low voltage DC ratings, supercapacitors are characterized by large time constants and significant continuous energy absorption ratings. This paper presents details of a patent-pending technique where multi-winding magnetic core with a supercapacitor based energy absorber stage can be combined with the commonly used non-linear devices, for enhanced protection. Comparison of the supercapacitor-enhanced circuit together with a commercial surge protection circuit is provided

**Keywords**—supercapacitors, surge protection; metal oxide varistors, TVSS

## I. INTRODUCTION

During the past decade supercapacitor technology matured quite rapidly with low-voltage DC-rated devices introduced by many companies worldwide. Few examples of such manufacturers are Maxwell-USA, Cap-XX-Australia and Nesscap-Korea. Common applications of supercapacitors (SC) are short term energy storage [1-3], battery-supercapacitor hybrid combinations [4-6] and short term backup for DC power sources and supplies [7-9] and catering for short duration power peaks in portable products such as cellular phone transmit pulses and high brightness flash. Thin profile Cap-XX [10] supercapacitor family is suitable for consumer applications such as cellular phones and cameras [11-13].

Several recent publications [14-17] have highlighted the possibilities of using supercapacitors in novel and unique applications such as (i) efficiency enhancement in DC-DC converters (ii) surge resistant UPS designs [18,19] (iii) transient surge absorption. This paper provides a new approach to develop supercapacitor based surge absorption

stages suitable for power conversions circuits such as AC-DC converters, UPS front ends and similar circuits.

## II. POWER QUALITY ISSUES AND SURGE PROTECTION CIRCUITS

### A. Power Quality Issues

Ideally a commercial AC power line should be free of voltage sags and surges, blackouts and brownouts, harmonics and any transient or high frequency noise. However a practical utility AC line carries many of these undesired elements, and out of these, most damaging element is the transient high voltage surges due to acts-of-god such as lightning and inductive power dumps. Transients come in two forms; common-mode transients, which occurs between the earth terminal and any one of the live or neutral lines; differential-mode transients occur between the live line and the neutral conductors. Out of these two, common-mode transients are difficult to protect against since it is harder to identify and minimize the surge-current circulation paths. As per indications in Fig.1(a) these transient durations are in the order of few 10s of  $\mu$ s to few 100  $\mu$ s.

Commercial surge protection circuits are developed using variations of nonlinear transient energy absorption devices such as metal oxide varistors (MOV) and semiconductor devices such as bidirectional break over devices (BBD) combined with capacitor-inductor filters in typical configurations such as in Fig.1(b). These are capable of absorbing very short duration transient surges superimposed on the AC mains voltage.

In a typical surge protection scenario, the designers aim at minimizing the propagation of both common-mode and differential mode transients. When the transients are not adequately absorbed by the nonlinear devices in Fig. 1(a) they could cause component failures, component degradation and software reliability issues.

### B. Comparison of non-linear devices and supercapacitors as surge absorbing devices

Typical transient absorption devices such as MOVs or BBDs are characterized by non-linear voltage-current relationships. A typical MOV has a non-linear voltage-current relationship such as  $I = KV^n$ , where,  $I$  is the instantaneous current,  $K$  is a material based constant and  $n$  is a voltage

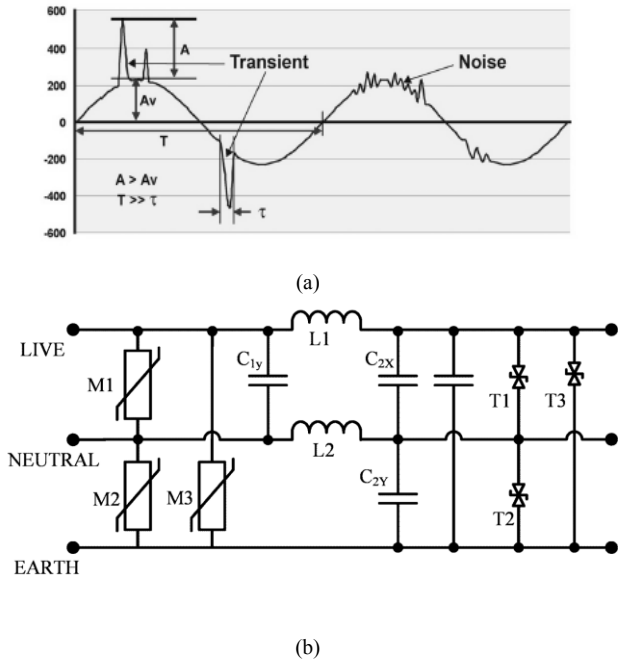


Fig.1. Transients superimposed on AC mains and a typical surge protection circuit (a) short duration transients superimposed on an AC waveform (b) typical surge protection circuit based on MOVs, LC filters and bidirectional break over devices (BBD)

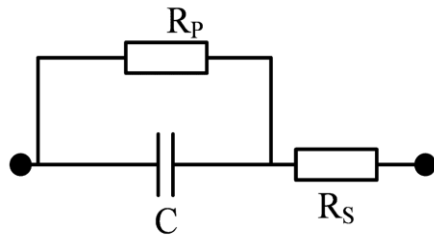
dependant parameter. A BBD is a zener diode or thyristor-based structure, where the device presents a near open circuit condition before exceeding a particular threshold voltage, and, once you exceed this breakdown voltage it conducts heavily. Typically MOVs can absorb larger amounts of transient surge energy than BBDs, but the BBDs are speed-wise faster. More details on surge protection devices and techniques are provided in [20]. Analysing surge protection circuits and non-linear device characterisation are discussed in [21-23] with the necessary experimental testing based on a lightning surge simulator (LSS). For these nonlinear devices, data sheets indicate transient energy ratings (or the Joule rating) specified for a single impulse waveform such as  $10 \times 1000\mu s$  current waveform (24, 25). It is important to appreciate that both device families are not designed to absorb surge energy on a continuous basis and if such an incident occurs device could fail permanently.

Compared to the above summary of non-linear device capabilities based on a short duration transient withstand capability, a capacitor is usually characterized by the continuous energy rating,  $\frac{1}{2}CV^2$ , device maximum DC voltage rating and the equivalent series resistance (ESR), assuming a simplified model for a typical device. A

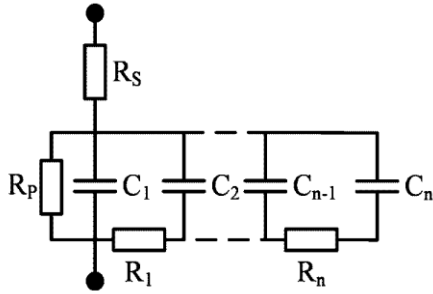
TABLE 1: A SUMMARY OF TEST RESULTS APPLICABLE TO THE THREE SUPERCAPACITOR FAMILIES USED IN THE EXPERIMENT [SOURCE: [21]]

| Capacitor data           | LSS output peak voltage | Pre-charge Voltage (mV) | Number of surges to destroy the device  |
|--------------------------|-------------------------|-------------------------|---|
| Cap-xx<br>0.18F,<br>2.3V | 6.6kV                   | 0                       | 220 to over 250   |
|                          |                         | 250                     | Over 220  |
|                          |                         | 500                     | Over 180  |
|                          |                         | 1800                    | Over 160  |
| Maxwell<br>230F,<br>2.5V | 6.6kV                   | 0                       | Did not fail after 1000   |
|                          |                         | 200                     | Did not fail after 600;<br>Charge accumulation was not observed                               |
|                          |                         | 1000                    | Did not fail after 600;<br>Over the period of 700 repeated surges 0.1V discharge was observed |
| NessCap<br>90F<br>2.7V   | 6.6kV                   | 0                       | Did not fail after 600  |
|                          |                         | 500                     | Did not fail after 600;<br>No charge accumulation observed                                    |
|                          |                         | 1000                    | Did not fail after 600;<br>Slight discharge of 0.15V observed during 700 surges               |
|                          |                         | 2000                    | Did not fail after 600;<br>Discharge of approx 350mV was observed over 700 surges.            |

supercapacitor, also known as an electrical double-layer capacitor (EDLC) is a complex device in which charge is stored in a double layer formed at the interface between a large surface area material such as activated carbon and a liquid electrolyte. Ref [26] provides useful background on the supercapacitor technology. In literature there are many models and equivalent circuits proposed for this device [27,28]. Two of the common and useful models are depicted in Fig.2. The classical equivalent circuit shown in Fig 2(a) is the most useful in circuit design environments, and represents the datasheet parameters in a very applicable manner. The ladder circuit model shown in Fig.2(b) is useful in analyzing slow discharge and pulse load applications.



(a)



(b)

Fig.2. Supercapacitor equivalent circuits (a) Classical equivalent circuit (b) Ladder circuit

In recent publications [29,30], surge withstand capability of SCs are detailed with the basic theoretical aspects and the test results for three commercial SC families. As reported in this work, supercapacitors were subjected to IEEE C62.41 based surge voltage waveforms from a lighting surge simulator (LSS). Based on testing samples of each type, the results demonstrate the fact that a limited number of high voltage transients, up to 100 microsecond duration, do not destroy most commercial supercapacitor families. This useful observation, confirms that a limited number of repeated high voltage surges can be safely tolerated by most types of commercial supercapacitor families.

As per the findings, several supercapacitor families have adequate surge withstand capabilities and the quantified test data summaries are available, based on the test results of subjecting them up to 6.6kV-peak IEEE standard waveforms. A summary is shown in Table 1. As per information in Table 1, we can see that the larger supercapacitor families were not affected by repeated surges, despite small value thin profile devices failed after repeated surges, while the number of surges to fail depended on the pre-charge voltage on the capacitor. Even these pre-charged thin profile devices could withstand repeated surges up to about 180 hits, even though such a repetition is very rare in the real world situations of surges. For more information ref [26] is suggested.

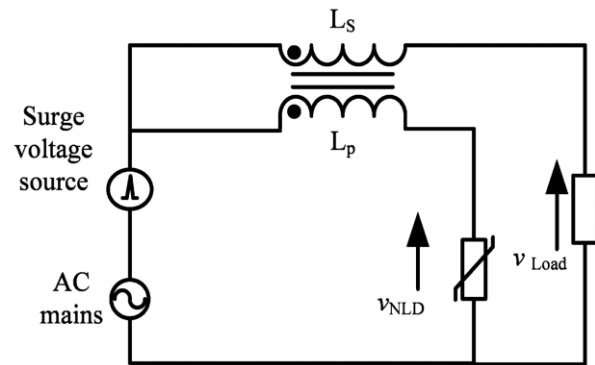
### C. New topologies based on supercapacitor assisted surge absorption technique

Supercapacitor assisted surge absorber (SCASA) technique is based on the ability of a supercapacitor to absorb short duration transient energy as per summary provided here, coupled with a suitable magnetic component such as a two

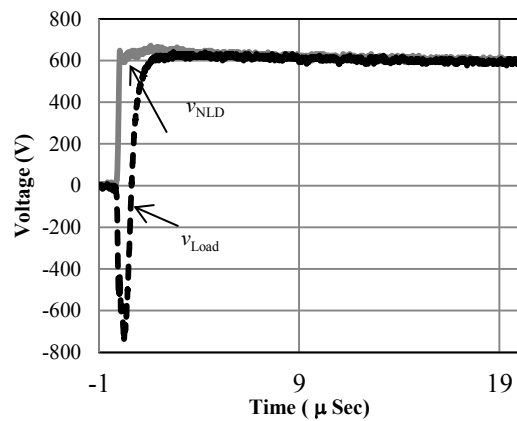
winding magnetic component which acts as a transformer-inductor combination.

This approach was developed starting from the case shown in Fig. 3(a). A non-linear device such as a MOV or a BBD is connected between the earth (or neutral) and the load side end of one of the windings of the coil. AC input end of the two coils are common and one coil's far end is connected to the critical load. The turns ratio of the two windings are suitably selected in such a way that the load end and the NLD end of the two coils do not experience any significant differential AC mains voltage component under normal operation.

Once a superimposed high voltage (HV) transient travels along the mains input, non-linear device fires and enter into conduction stage, developing a voltage across the connected winding. When the HV transient exceeds the firing voltage of the non-linear device (NLD), it conducts heavily creating a surge current through the primary coil and the NLD. Due to induction, secondary coil also develops a voltage and the two windings are configured to create this induced secondary voltage higher than that of the primary and to oppose the transient so that the critical load end sees the difference between these two voltages as shown in Fig. 3(b). Graphs in Fig. 3(b) is for a case of a varistor (type 20V275) which is having a maximum



(a)



(b)

Fig.3: Use of secondary voltage to block the surge at the critical load end (a) Transformer used to help reducing the impact of the surge at the load ends (b) Oscilloscope indicating voltage variation at the load and nonlinear device when 6kV surge applied to the circuit in Fig3(a)

clamping voltage of 710V used as the NLD. Fig. 4(a) indicates the overall technique using a supercapacitor based sub-circuit added to the base configuration in Fig 3(a), with possible variations as shown in Figure 4(b). SC based sub-circuit now receives the voltage difference between the two coils. Given this scenario, when the NLD fires we can develop the following relationships.

$$v_{surge} = v_p + v_{NLD} \quad (1)$$

$$v_p = L_p \frac{di_p}{dt} + M \frac{di_s}{dt} \quad (2)$$

$$v_{load} = v_{surge} - v_s \quad (3)$$

$$v_s = L_s \frac{di_s}{dt} + M \frac{di_p}{dt} \quad (4)$$

$$i_{sub} = (v_s - v_p) / Z_{sub} \quad (5)$$

$$v_{load} = v_{NLD} - i_{sub} * Z_{sub} \quad (6)$$

$L_p$  and  $L_s$  are the self-inductances of the primary and secondary coils and  $M$  is the mutual inductance between the two windings.  $v_p$ ,  $v_s$  and  $v_{load}$  are the instantaneous voltages at the transformer primary, secondary, and at the load respectively when the superimposed surge,  $v_{surge}$  applied to the circuit.  $v_{NLD}$  and  $i_{sub}$  are the voltage across the NLD and the transient related current flowing through the SC based sub-circuit.  $Z_{sub}$  is the overall impedance of the SC based sub-circuit.

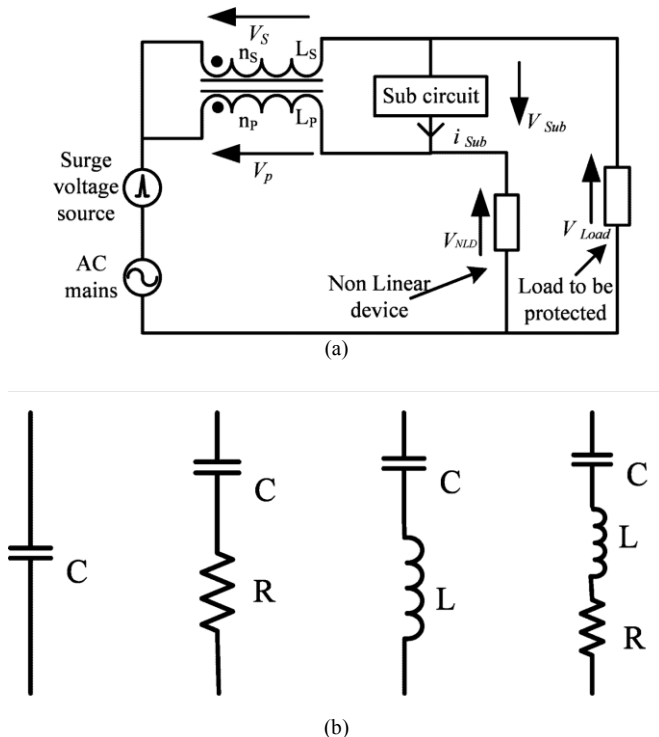


Fig.4: Supercapacitor assisted surge absorber (a) Basic circuit topology (b) Possible sub circuits

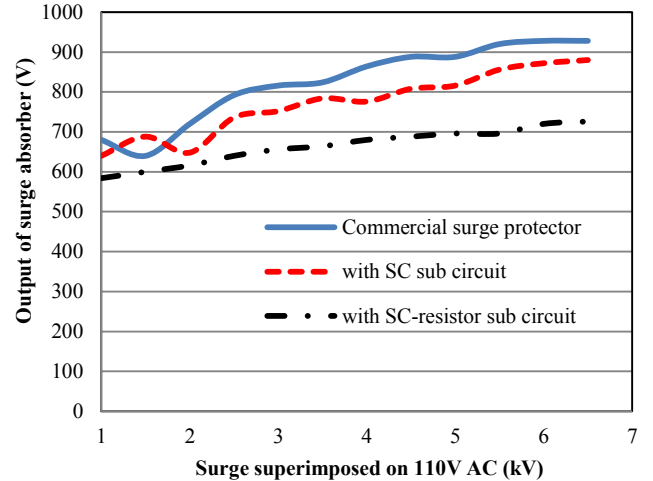


Fig. 5: Comparison of surge absorption capabilities of commercial and surge absorber with different sub circuits

Matlab based simulation and suitable mathematical techniques can be used to predict the overall effect with associated time delays occurring at each point. However a discussion of this subject is beyond the scope of the paper.

With a higher number of turns in the secondary winding it is possible to make  $(v_s - v_p) > 0$ . Therefore during the surge, current through the sub circuit,  $i_{sub}$  will generate a transient component of the voltage which makes the output transient voltage ( $v_{load}$ ) lower than the voltage across the nonlinear device ( $v_{NLD}$ ). This sub circuit acts as a filter as well and it minimizes the possible ringing at the output.

Fig. 5 shows the comparison of surge absorption capability of a typical commercial surge absorber with and without the new SCASA technique. Upper (blue) graph indicates remaining surge component (peak value) at the critical load end the with no SCASA enhancement. Middle (red) graph shows the situation when a SC of 25F is used in the sub-circuit. Bottom graph (black) indicates the peak value of the remaining

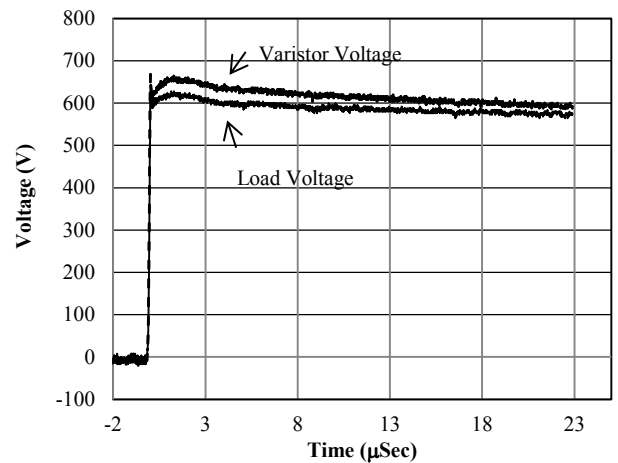


Fig. 6: Voltage variation on load and varistor when 6kV surge applied to SCASA with SC and resistor sub circuit

output transient when a  $1\Omega$  resistor and a 25F supercapacitor based series sub-circuit is used.

Different configurations of sub circuits will affect the maximum transient peak voltage occurring at the load end of the surge absorber during the occurrence of surge. As Fig. 5 indicates, the SCASA technique predicts better overall performances than a commercial surge absorber. As the applied transient surge voltage keeps increasing, SC based enhancement clearly assists reducing the transient related surge voltage at the critical load.

Fig. 6 depicts the performance of the SCASA technique, based on a 25F supercapacitor in series with a  $1\Omega$  resistor. It is clear that the load end receives a lower voltage than the clamping voltage occurring at the varistor used. There are many different combinations possible for the sub circuit and these are beyond the scope of this paper.

## VI CONCLUSION

The paper indicates a unique approach to utilize a supercapacitor sub-circuit combined with a multi-winding transformer-inductor to minimize the occurrence of a high transient surge peak at a critical load, and this technique can also help minimizing the additional LC filter requirements in a commercial surge absorber unit. Limited details are released in the paper related to this patent pending technique, due to intellectual property issues.

## REFERENCES

- [1] W. Maranda, M. Piotrowicz, "Application of photovoltaics for daytime indoor lighting," in *IEEE 2011 Mixed Design of Integrated Circuits and Systems (MIXDES) conference*, 2011, pp 529- 532.
- [2] A.B. da Cunha, D.C. da Silva, "Energy-efficient characterization of solar panel-supercapacitors systems for energy-harvesting aware wireless sensor nodes", in *IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, 2009, pp. 2275
- [3] Zhongdong Yin, Minxiao Han, Yunlong du, Zheran Zhang, "A Practical Approach for Ride Through of Super Capacitor Energy Storage Based ASD System," in *IEEE 2005/2006 Transmission and Distribution Conference and Exhibition*, 2006, pp. 744- 746.
- [4] Yu Zhang , and Zhenhua Jiang , "Dynamic power sharing strategy for active hybrid energy storage systems," in *IEEE 2009 Vehicle Power and Propulsion Conference*, 2009, pp 558-563.
- [5] A.M. Gee, and R.W.Dunn, "Novel battery / supercapacitor hybrid energy storage control strategy for battery life extension in isolated wind energy conversion systems," in *IEEE 2010 Universities Power Engineering Conference (UPEC)*, 2010, pp 1-6.
- [6] K.W. Wee, S.S. Choi, D.M. Vilathgamuwa, "Design of a renewable - hybrid energy storage power scheme for short-term power dispatch" in *IEEE 2011 Electric Utility Deregulation and Restructuring and Power Technologies (DRPT) conference*, 2011, pp. 1511- 1516.
- [7] E. Christopher, M. Sumner, A. Szabo, E. Introwicz, "Power boost unit for automotive Electric Power Steering systems," in *IET 2010 Power Electronics, Machines and Drives (PEMD 2010) conference*, 2010, pp 1-5.
- [8] E. Ribeiro, A. J. Marques Cardoso, C. Boccaletti, "Fuel cell-supercapacitor system for telecommunications," in *IET 2010 Power Electronics, Machines and Drives (PEMD 2010) conference*, 2010, pp. 1-6.
- [9] R.F. Coelho, L. Schimtz, D.C. Martins, "Grid-connected PV-wind-fuel cell hybrid system employing a supercapacitor bank as storage device to supply a critical DC load", in *IEEE 2011 Telecommunications Energy Conference (INTELEC)*, 2011 pp 1 – 10.
- [10] <http://www.cap-xx.com>
- [11] S. Harris "Supercapacitors brighten prospects for power LED flash in camera phones", , *LEDs Magazine*, February issue, UK, 2007
- [12] J. Monteiro, N. Garrido, R. Fonseca, "Efficient supercapacitor energy usage in mobile phones," in *IEEE Consumer Electronics - Berlin (ICCE-Berlin)*, 2011, pp.318-321.
- [13] P.B. Karandikar, D. Rathod, D.B Talange, "Photovoltaic Chargeable Electrochemical Double Layer Capacitor," in *IEEE Computer and Electrical Engineering conference*, 2009, Vol. 2, pp 217-219.
- [14] N. Kularatna, J. Fernando, K. Kankanamge, L. Tilakaratne, "Very low frequency supercapacitor techniques to improve the end-to-end efficiency of DC-DC converters based on commercial off the shelf LDOs", Proc. 36th Annual IECON 2010 conference of IEEE Industrial Electronics Society, 2010 , pp 721 – 726.
- [15] N. Kularatna, J. Fernando, K. Kankanamge, Xu Zhang; "A Low Frequency supercapacitor circulation technique to improve the efficiency of linear regulators based on LDO chips", Proc. 26th Annual IEEE conference and exposition on Applied power electronics 2011 (APEC 11) , 2011, pp 1161 – 1165.
- [16] N. Kularatna, J. Fernando, "A supercapacitor technique efficiency improvement in linear regulators", Proc. of 35th Annual IEEE conference on Industrial Electronics, 2009, pp 132-135.
- [17] N. Kularatna, and J. Fernando, "High current voltage regulator" United States Patent number 7,907,430, Issued March 15th 2011.
- [18] N. Kularatna, L. Tilakaratne, P.K. Kumaran, "Design approaches to supercapacitor based surge resistant UPS techniques" 37th Annual IECON 2011 conference of IEEE Industrial Electronics Society, 2011, pp 4094 - 4099
- [19] U.K Madawala, D.J. Thrimawithana, N. Kularatna, "An ICPT-Supercapacitor Hybrid System for Surge –Free Power Transfer," in *IEEE transactions on Industrial Electronics*, 2007, vol. 54, no.06, pp 3287 – 3297.
- [20] N. Kulartna, , DC Power Supplies, Power Management and Surge Protection for Power Electronic Systems, CRC Press, 2012, pp 9:1-30.
- [21] S. James, N. Kularatna, A. Steyn-Ross, R. Kunemeyer, "Modeling of surge protection circuits for the study of transient propagation in power conversion interfaces", The 18th Electronics New Zealand Conference , Nov 2011, pp.113-117.
- [22] S. James, N. Kularatna, A. Steyn-Ross, A. pandey, R. Kunemeyer, D. Tantrigoda, "Investigation of failure patterns of desktop computer power supplies using a lightning surge simulator and the generation of a database for a comprehensive surge propagation study", in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, pp. 1275-1280. No3.
- [23] S. James, N. Kularatna, A. Steyn-Ross, R. Kunemeyer, "Numerical simulation of surge protection circuits and experimental verification using a lightning surge simulator" in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*.

- [24] <http://www.nteinc.com/specs/10to99/pdf/movs.pdf>
- [25] <http://www.lepstech.com/en/pdf/Transient-source.pdf>
- [26] John M. Miller, " Ultracapacitor Applications", The Institute of Engineering and Technology, London,UK, 2011
- [27] Lingling Du, "Study on supercapacitor equivalent circuit model for power electronics applications," 2nd International conference on Power Electronics and Intelligent Transportation System (PEITS), 2009,2009, vol.2, pp 51-54
- [28] N. Rizoug, P. Bartholomeus, P. Le Moigne, " Modeling and Characterizing Supercapacitors Using an Online Method," IEEE Transactions on Industrial Electronics, 2010, vol. 57, Issue 12 pp. 3980-3990
- [29] N. Kularatna, J. Fernando, A. Pandey, "Surge endurance capability testing of supercapacitor families", Proc. 36th Annual IECON 2010 conference of IEEE Industrial Electronics Society,2010 , pp 1858 – 1863.
- [30] N. Kularatna, J. Fernando, S. James, A. Pandey, "Surge capability testing of supercapacitor families using a lightning surge simulator", IEEE transactions on Industrial Electronics,2011,vol 58, no.10,pp 4942 – 4949.