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Supercapacitor assisted surge absorber (SCASA) technique: selection of magnetic components based on permeance

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***Abstract*—Supercapacitors help building long time constant resistor-capacitor circuits. This property helps them withstand high voltage transient surges and dissipate transient energy in the resistive element of the circuit without exceeding the supercapacitor's DC voltage rating, which is usually between 2.5 to 4 V. SCASA is a patented technique, which was commercialized within the last five years. Successful implementation of this circuit topology, despite its simplicity, is quite dependent on the selection of the core of the coupled inductor utilized. This paper provides the essential details of the process of selecting the core for the magnetic component required, with a brief comparison of SCASA technique with a traditional surge protector, without any supercapacitors.**

***Index Terms*—surge-protection, supercapacitors, magnetic Permeance, coupled-inductor, power quality**

I. Introduction

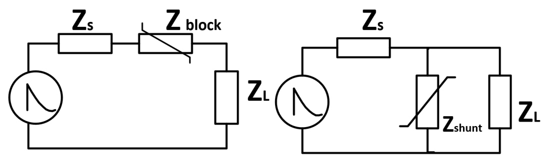
Modern electronic circuits are seriously vulnerable to transient high voltage surges such as lightning induced overvoltages or inductive energy dumps [1]. This is particularly the case with integrated circuits which carry complex mixed signal, such as CMOS data converters or digital circuits such as processors and memories [2]. Non-linear components, such as metal oxide varistors (MOV) or bidirectional break-over diodes (BBD) are coupled with inductor-capacitor filters in a traditional surge protector, as shown in Fig.1 Most important two properties of a surge protector device (SPD) is to (i) power line frequency input energy source is coupled to the critical load without significant attenuation (ii) transient high voltage superimposed on the AC mains is blocked, creating a safe clamping voltage across the critical load [3]. Referring to Fig.1(b), under normal operation, L-C filter should create a very low series impedance at 50 or 60 Hz mains, while keeping the MOV and BBD in an un-fired dormant condition. In this "normal" operation, the series impedance Z_s and Z_s + Z_{block} in Fig.1(a) becomes very low, and shunt impedance becomes very high. However, when a several kilovolt order transient surge with a typical shape such as in Figure 2 gets superimposed due to an unexpected situation, MOV and/or the BBD enter into fired condition. This in turn creates a very low impedance path, creating the opposite action, of the divider in Fig.1(c), a safe clamping voltage is created across the critical load, safeguarding it from destruction or temporary failure [3]. Commercial SPDs are tested in industry test laboratories, usually following the Underwriter's Laboratory UL 1449 3rd Edition test procedure [4], [5]. Surge endurance level of SPDs is evaluated based on these standard protocols.

II. An Overview

A. Supercapacitor Assisted Surge Absorber Technique

Supercapacitors (SCs) can be described as a family of very large capacitors where the capacitance is almost six to seven order larger than a traditional electrolytic or a film capacitor of the same canister size [6]. These devices come in capacitance values of 1 f to 70,000 F in single cell devices, where their DC rated voltage can be between 2.5 V to 4.0 V. Symmetrical SCs in the range of 1 F to 100 F are pretty small in size and they are only 15 to 20 % more expensive than a similar can size traditional capacitor [7]. When a SC of 1 - 100F range is coupled with an ohms order loop resistance, it creates time constant in the range of few seconds to several 100 seconds. If such an R-C circuit is subjected to a transient voltage source of several kV typically lasting for a period of less than 100 µs, capacitor and resistor voltages and energy absorbed or dissipated are shown in Fig.3(a) and 3(b). Fig.3(b) depicts the ratio of resistor energy dissipation/capacitor stored energy in such a R-C circuit for different values of capacitors, indicating that the capacitor just creating a safe current carrying path to dissipate most transient energy in the loop resistance [8].

The above discussion leads to the development of a SC assisted surge absorber with some unique useful properties (i) lesser number of components (ii) clamping voltage is lesser than varistor voltage (iii) high endurance for repeated surge pulse applications [9]– [11]. The challenge in developing the SCASA technique was mainly due to the low DC voltage rating of the SC and its very low AC impedance at line frequency, which prohibits placing it across the live-neutral pair. Fig.4 depicts the patented technique [15] now known as SCASA, within the family of SC assisted (SCA) techniques [6]– [13].



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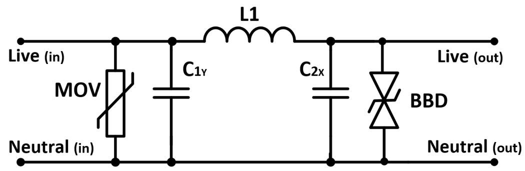

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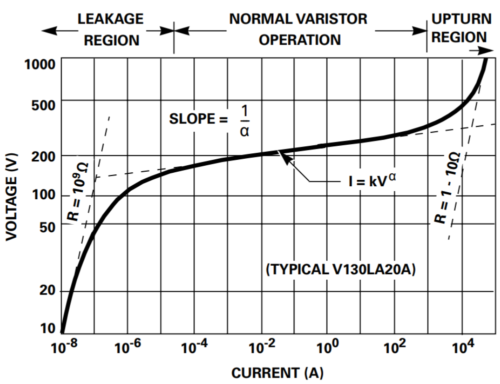

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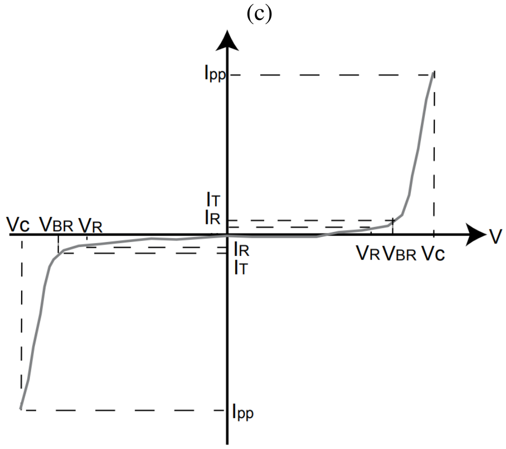

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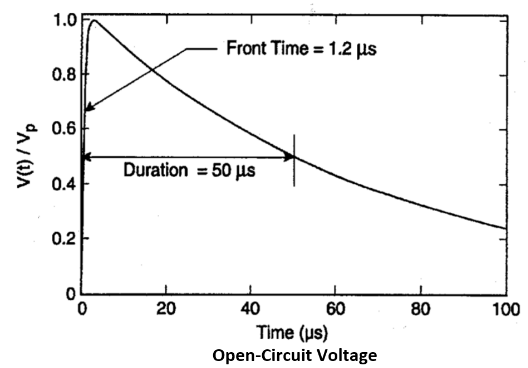
Fig. 1: Traditional Surge protector, simplified to show differential mode operation case - (a) simplified concept with impedance divider action [3] (b) circuit configuration (c) non-linear behavior of a MOV [14] (d) non-linear behavior of a BBD [15]



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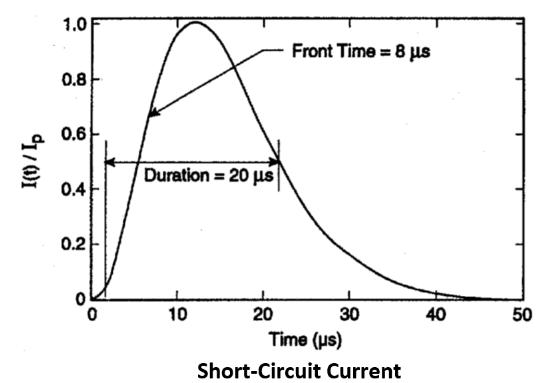


(b)

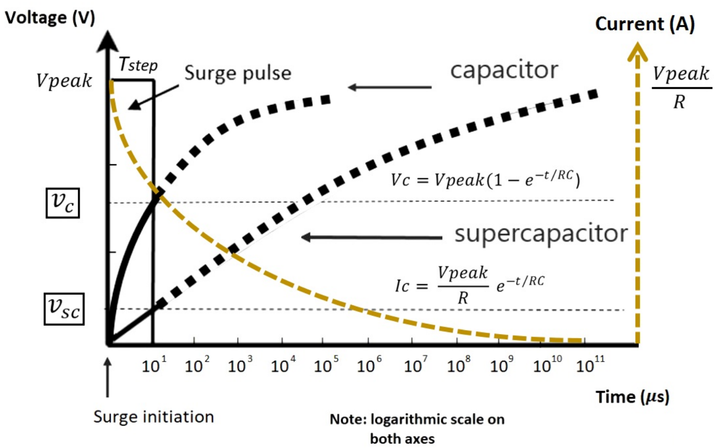
Fig. 2: An example of an IEEE C62.41.2 standard combined voltage waveform used to test a surge protector device (SPD) [16]

III. USE OF A PERMEANCE MODEL TO DEVELOP THE COUPLED-INDUCTOR

Given the above summary of first successful implementation of the SCASA protector [9], one major problem faced was the selection of the magnetic core, within the cost restrictions of a commercial product. Commercially available ferrite cores did not perform well (Table II), while a powdered alloy such as 0077071A7 from Magnetics Inc. [17] was able to satisfactorily perform. Given the need to estimate the required coupled-inductor turns ratio, self-inductance and the mutual inductance parameters based on core specifications, varying the number of primary and secondary turns helped in only a limited way [18], a new analytical approach based on permeance model was used. This allowed the research team to accurately estimate the total self-inductances of the primary (Lp) and secondary (Ls) based on data-sheet specifications, "Λ_m" (magnetizing permeance) and "Λ_σ" (leakage permeance). More importantly, Λ_m is derived from the fundamental magnetic property of permeability (μ_r) [19]– [20], and is dependent on both permeability and geometrical configuration (magnetic path length l_c and cross-sectional area A_c) of the core [19]– [20]. A comparison of magnetizing permeance and permeability of the toroidal core types used in our research is presented in Table I. The following equation shows the relationship between Λ_m, μ_r, A_c and l_c:

$$\Lambda_m = \frac{\mu_r \mu_o A_c}{l_c} \tag{1}$$

where μ_r is the relative permeability and μ_o is the perme-



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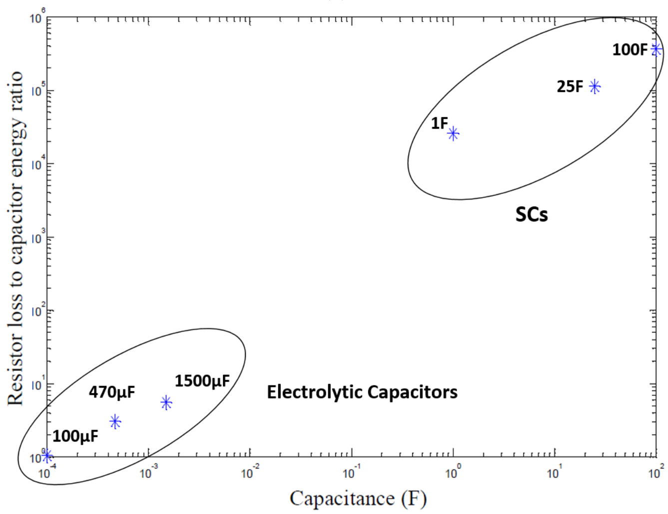

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Fig. 3: Effect of a supercapacitor in an R-C loop compared to a capacitor (a) waveforms (b) energy dissipated/ energy absorbed (ratio) for different capacitor values [6]

ability of free space. This further justifies how magnetizing permeance has a dependency on magnetic material and core geometry, whereas permeability only depends on material properties. This lead to the useful relationships in Equations (2) to (6) as per details in [21].

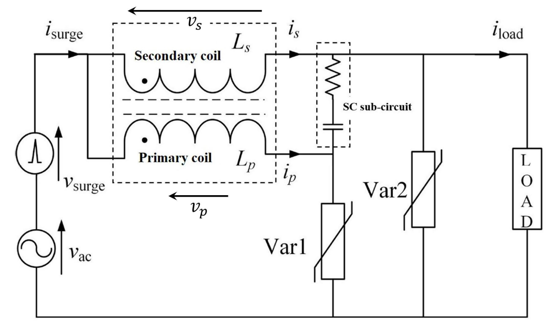
Fig. 5 illustrates magnetizing inductances (L_1,L_2) and leakage inductances (l_1,l_2) associated with primary and secondary coils of SCASA transformer core.

$$L_p = L_1 + l_1 \tag{2}$$

$$L_s = L_2 + l_2 \tag{3}$$

By incorporating both magnetizing permeance (Λ_m) and leakage permeance (Λ_σ) [two books]:

$$L_1 = \Lambda_m {N_1}^2 \text{ and } l_1 = \Lambda_\sigma {N_1}^2 \tag{4}$$



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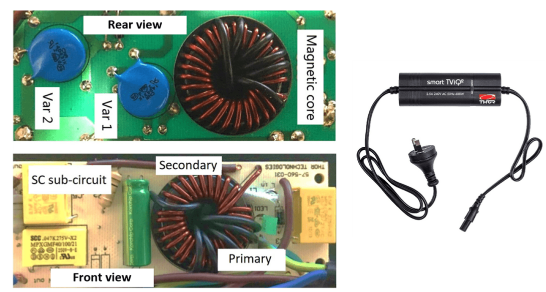

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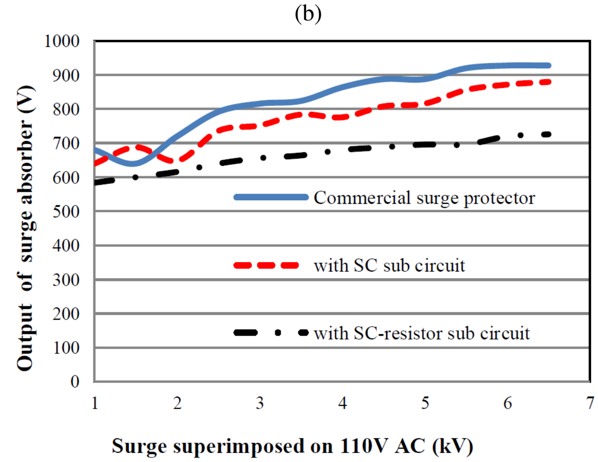

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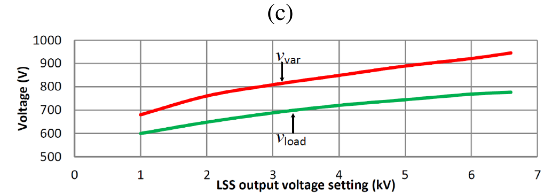

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Fig. 4: SCASA Technique (a) concept [22] (b) commercial implementation [22] (c) performance graph [6] (d) load voltage lower than the varistor voltage [18]

$$L_2 = \Lambda_m {N_2}^2 \text{ and } l_2 = \Lambda_\sigma {N_2}^2 \tag{5}$$

Then, Eqs. (2) and (3) can be expressed as:

$$L_p = \Lambda_m {N_1}^2 + \Lambda_\sigma {N_1}^2 \tag{6}$$

TABLE I: Comparison of relative permeability, saturation level and permeance coefficient (A_L) of different powdered-iron and ferrite based alloys used in SCASA prototype design [24]– [26]

Magnetics Part No.	Material	Relative Permeability (μ_r)	Saturation Flux Density $\vec{B}_{max}$ (Gauss)	Permeance Coefficient (Λ_m) Inductance factor - A_L (nH/turns^2)
0077071A7	Kool mu	60	10,500	61
058071A2-4	High Flux	60	15,000	61
078550A7	X Flux	26	16,000	28
ZW43615TC	W Ferrite	10,000	3,900	13,400
VJ42206TC	J Ferrite	5,000	4,300	3,020
0W43515A275 (Air-gapped)	W Ferrite	10,000	3,900	275
0J43515A120 (Air-gapped)	J Ferrite	5,000	4,300	120

$$L_s = \Lambda_m {N_2}^2 + \Lambda_\sigma {N_2}^2 \tag{7}$$

This approach allowed us to accurately estimate the individual transient currents flowing in the primary and secondary windings, matching well with the experimental values [21]. Currently, the research team is working with Magnetics Inc. (USA) to model the potential core samples based on materials such as "Kool Mμ, High Flux, X Flux and W-Ferrite", with the expectation of selecting the optimum core material and the shape, within the commercial price constraints applicable to the product family known as Smart TVIQ2/3 [23]. Table I presents a summary of magnetic properties and magnetizing permeances (known as the inductance factor - A_L according to manufacturer specifications) of above materials. Our experiments were primarily focused on investigating the surge absorption levels of below toroid samples as per their

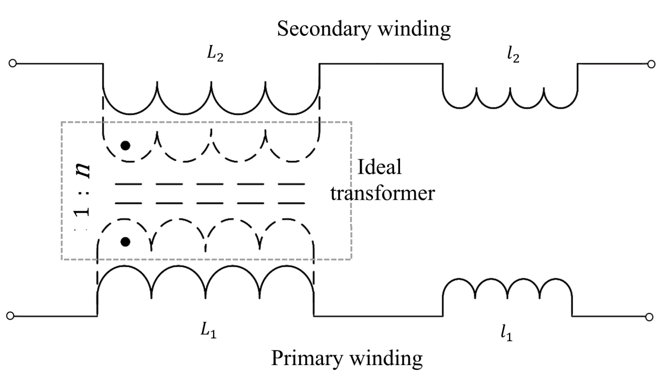


Fig. 5: Equivalent circuit model of the transformer core of SCASA design [17]

performance in SCASA prototypes. Test results are discussed in the following section.

IV. EXPERIMENTAL SETUP AND TEST RESULTS

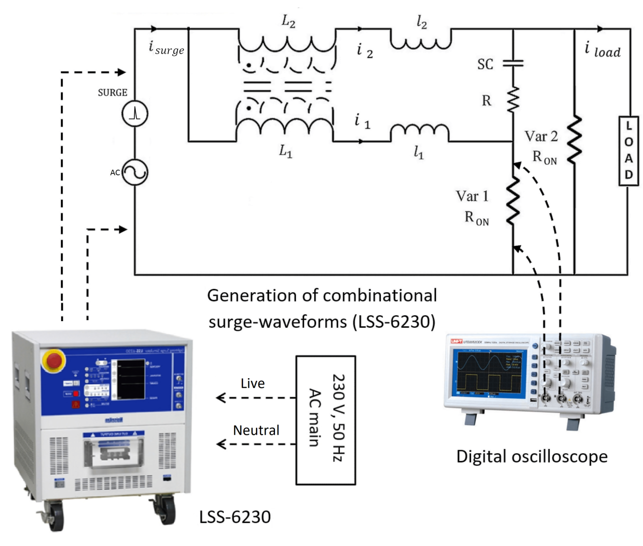
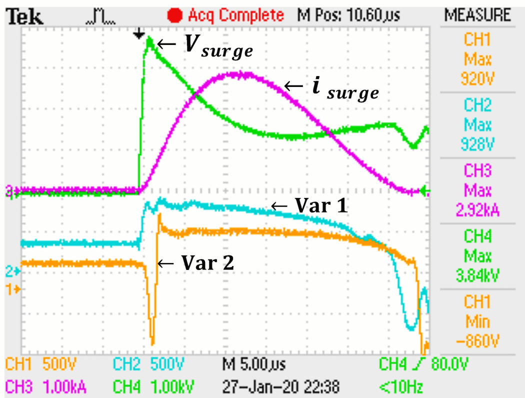


Fig. 6: Experimental setup and transient operation of the non-ideal transformer core of SCASA design [17]

In order to facilitate surge testing of SCASA prototypes, a lightning surge simulator (NoisenKen LSS-6230) and a digital oscilloscope (Tektronix TPS2014) were used as the main instruments. Fig. 6 depicts the experimental setup implemented for combinational surge-waveform generation. Here, standard 1.2/50 μs surge pulses were generated using the LSS-6230;



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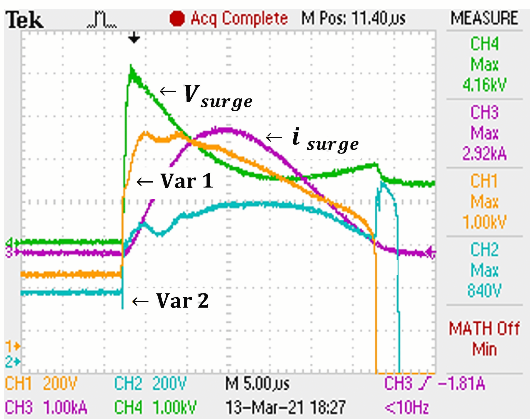

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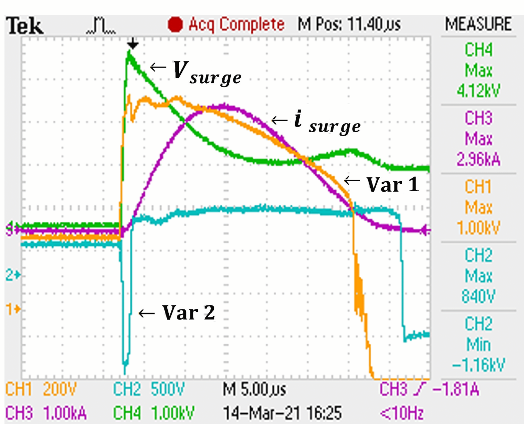

(c)

Fig. 7: Oscilloscope waveforms for different toroidal cores under a transient of 6 kV/3 kA: (a) Kool Mu toroid (0077071A7); (b) High Flux toroid (058071A2-4) and (c) X Flux toroid (078550A7)

hence, oscilloscope waveforms were recorded for 6.6 kV peak voltages across Var1 and Var2 as shown in Fig. 7.

To understand the surge absorption of magnetic core, we looked into the fine operation of the coupled-inductor design under transient conditions. As described above in Fig. 4(a), the coupled primary and secondary coils are wound to a toroidal core which stores transient-related magnetic flux during current propagation. In a separate research given by [17] and [22], we proved that a clear indication about the energy storage capability is given by the difference $(v_s - v_p)$ between secondary induced voltage v_s and primary induced voltage v_p. This effect is due to the design configuration of SCASA topology where secondary coil possesses a much larger self-inductance L_s (∼60 μH) than the primary self-inductance L_p (∼3.8μH). Therefore, as transient current propagate through the core windings $v_s >> v_p$ resulting an inductive energy release given by $v_s - v_p$. In identifying this fine operation, we captured oscilloscope waveforms across Var1 and Var2, and compared with SCASA prototypes designed using different powdered-iron and ferrite based toroids. Test results are presented next.

Fig. 7 illustrates oscilloscope waveforms captured for different toroidal cores under a transient of 6 kV/3 kA. As described above, the inductive energy release (from the magnetic core) given by $v_s - v_p$ is indicated by the voltage variation across Var2, specially the reverse sided (negative) voltage peak shown by all waveforms in Fig. 7 reveal the extent of energy storage shown by corresponding toroids. By comparing the magnitudes of negative voltage peak $(v_s - v_p)$ relating to different cores under test, it is possible to identify that the most substantial voltage fluctuation (–1160 V) is demonstrated by the X flux toroid (078550A7) as per Fig. 7(c). Thus, we can argue X Flux core shows relatively better capacity in storing surge energy. Conversely, as shown in Fig. 7(b), High Flux toroid (058071A2-4) with a minor reversed voltage (~ -100 V) indicates the least flux storage capability. Noticeably, Kool Mu toroid (0077071A7) which is presently utilized in the original SCASA design exhibits a substantial, yet a moderate energy absorption level with –860 V according to Fig. 7(a). This is relatively a lower voltage magnitude in comparison with High Flux , and based on this observation we can infer High Flux toroid is superior to Kool Mu toroid in terms of its energy absorption. Usability of these powdered-

TABLE II: Performance comparison (surge absorption level) of different powdered-iron and ferrite based alloys used in SCASA prototype design

Magnetics Part No.	Material	Usability in SCASA surge protector based on surge absorption
0077071A7	Kool mu	Usable
058071A2-4	High Flux	Limited
078550A7	X Flux	Highly Usable
ZW43615TC	W Ferrite	Highly Limited
VJ42206TC	J Ferrite	Highly Limited

iron cores in SCASA surge protector design is summarized in Table II.With regard to pure ferrite based toroids (W and J ferrites), we conducted experiments as specified by [17] and [22] to prove that these cores have very much limited capability of storing surge related flux. Moreover, pure ferrites are magnetically soft materials with extremely narrow hysteresis behaviour [27] having lower saturation levels compared powdered-iron materials. This is further reflected by the high magnetizing permeance (Λ_m) shown by W and J ferrites (Table II). However, when an air-gap is inserted into ferrite toroids, these perform much better with improved surge endurance. The discussion about air-gapped ferrites is beyond the scope of this paper, hence this research was aimed at testing various powdered-iron cores as predicted by our permeance model.

V. CONCLUSION

SCASA is a new surge absorber technique where a supercapacitor sub-circuit improves the repeat surge endurance capability, under UL 1449 test standards. It also reduces the number of components used for a commercial implementation. The information provided in this publication clearly indicates that the magnetic-permeance parameter based approach helps the selection of the correct magnetic core from commercially available magnetic components.

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