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A Battery/Supercapacitor Hybrid Combination in Uninterruptible Power Supply (UPS)

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Abstract

This study presents a design of internal parameters of supercapacitor using charging/discharging characteristics of a battery. We aim at investigating the optimal supercapacitors-battery combination .This investigation is twofold first, supercapacitors and battery models are developed using MATLAB/Simulink and are presented and. Second, the architecture and the simulation of the designed system that combines the Supercapacitor and the battery are shown. The supercapacitors are used as high-power storage devices to smooth the peak power applied to the battery during backup time and to deliver full load power during short grid failures. By charging the supercapacitor through the battery at a suitable rate, all impulse power demands would be satisfied by the supercapacitors.
Keywords- Supercapacitors, UPS, hybrid, battery, Energy Storage Systems (ESS)

I. Introduction

In Many industrial sectors, high reliability power supply is required for critical load. Uninterruptible power supplies (UPS) are used to improve power quality and guarantee the reliability of backup power. During voltage sags or complete interruptions of the power supply, the energy has to be supplied by local energy storage systems (ESS). Conventional ESS for UPS is basically relying on the choice of good lead-acid batteries [3].However, there are many disadvantages associated with batteries such as low-power density and limited charge/discharge cycles.

Super capacitor is a new device for storage of energy; it fulfills the gap between capacitor and battery. It has large capacitance value and excellent charge-discharge performance as, compared to normal battery. It shares the characteristics of both batteries and conventional capacitors and has an energy density about 20% of a battery. The important features are short charge-time, long service life, good temperature characteristics, energy conservation, and green environmental protection. Super capacitor is also known as ultra-capacitor, electro-chemical double layer capacitor. It utilizes the high surface area electrode materials and thin electrolytic dielectrics to achieve capacitances several orders of magnitude larger than conventional capacitors. Super capacitor can store much more energy than conventional capacitors and offer much higher power density than battery. Supercapacitors have a much higher capacitance than traditional capacitors because of the large equivalent area of the plates and the small effective separation distance of the plates [2][4]. One gram of the electrode material can have an equivalent area of 2000sq.m.[7]

The separation distance between an electrode and the layer of ions, the double layer, is in the nanometer range. Batteries are mostly efficient when used to supply low, reasonably steady power levels. Supercapacitors are very effective in storing charge for later use. Their leakage rate and series resistance are quite small [7], [8]. The power sharing between supercapacitors, fuel cells (FCs), and batteries is a promising solution for improving system performance due to the dynamic behaviour of the SCs and their long life [9], [10]. In UPS applications, batteries usually provide 5–15 min of backup power before a generator starts and is ready to accept the full load. Supercapacitors can supply only 5–20 s of backup at full power. This means that SCs could be a good battery replacement only when long runtime is not required because of their high price, their high size and mass [15][17]. Nowadays, it is better to combine traditional battery for higher energy UPS and SCs for higher power UPS. It is worth mentioning that supercapacitors are experiencing high development and becoming more and more competitive in price [15].

The big advantage of a super capacitor is that it can store and release energy almost instantly much more quickly than a battery. That's because a super capacitor works by building up static electric charges on solids, while a battery relies on charges being produced slowly through chemical reactions, often involving liquids. Batteries and supercapacitors compared in terms of their energy density and power density. Batteries have a higher energy density (they store more energy per unit mass) but super capacitors have a higher power density (they can release energy more quickly). That makes super capacitors particularly suitable for storing and releasing large amounts of power relatively quickly, but batteries are still king for storing large amounts of energy over long periods of time. Super capacitors work at relatively low voltages (maybe 2-3 volts), they can be connected in series (like batteries) to produce bigger voltages for use in more powerful equipment. Since super capacitors work electro statically, rather than through reversible chemical reactions, they can theoretically be charged and discharged any number of times.[13]

In this paper, we present a power-sharing method between the supercapacitors and the lead-acid battery for single phase output. Combining supercapacitors with battery-based UPS system gives the best of high energy and high-power configurations.

The supercapacitors ensure the power impulses and reduce high power demands away from the battery during the 10-min backup time. They also deliver full load power during short outages lasting less than 10 s. The life of the batteries could then be extended.

II. PROPOSED SYSTEM

A. Topology

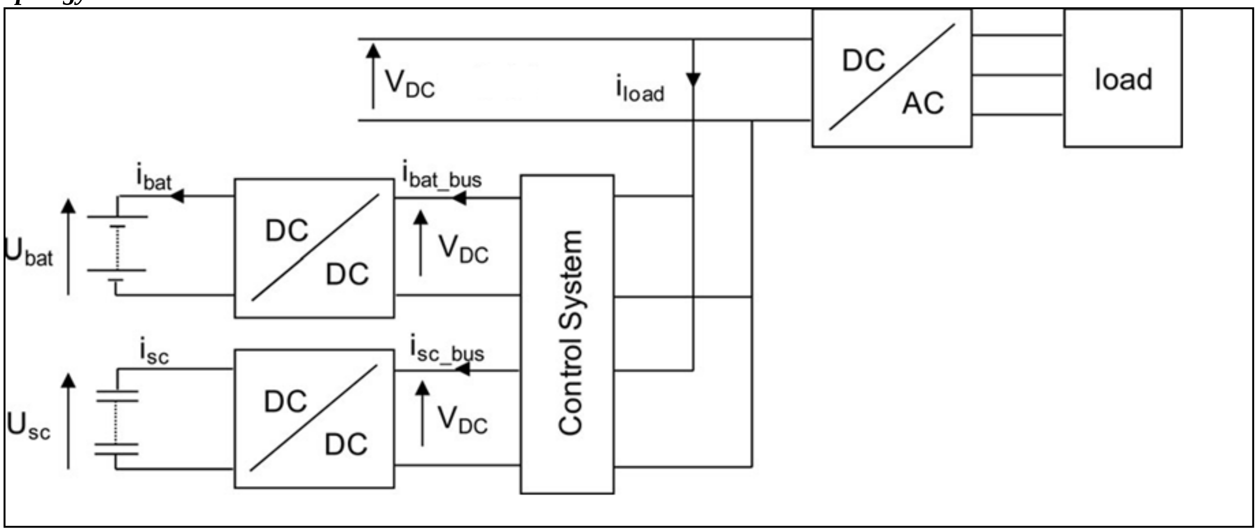
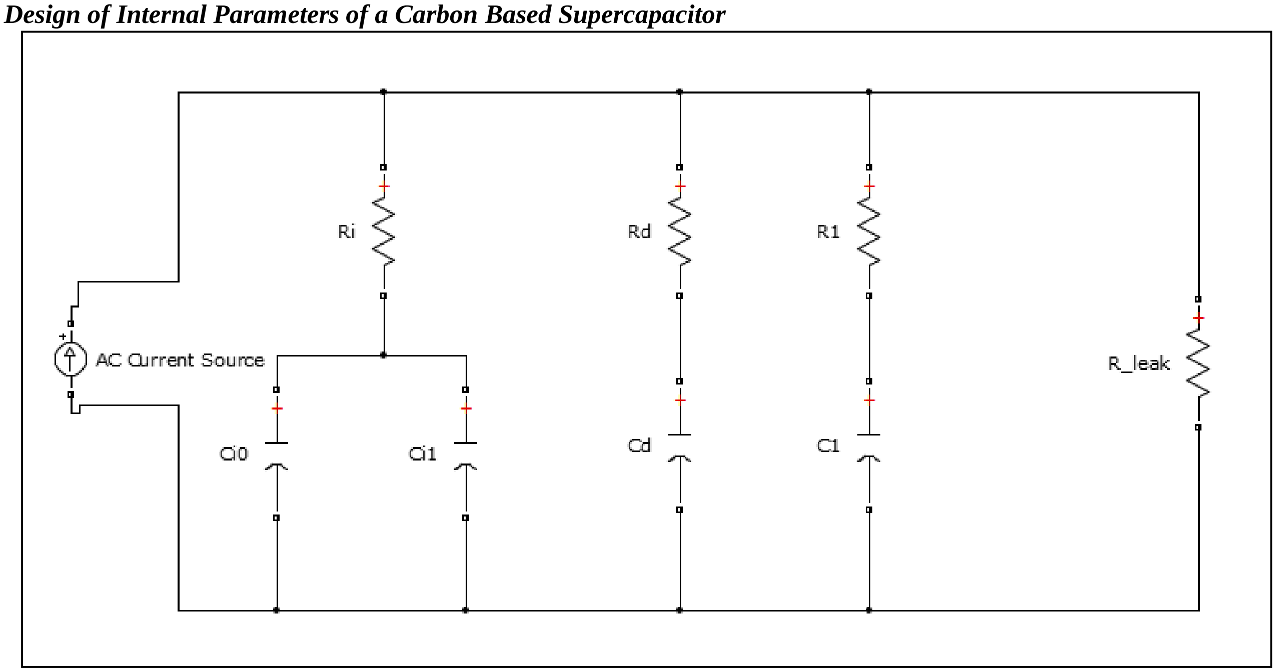


Fig. 1: Topology of the 100-kVA UPS

Fig. 1 shows a simplified electrical diagram of the UPS under consideration. Its topology is an Online/Double-Conversion system [3]. Before adding the supercapacitors (without the dotted part), in the case of interruption of the power grid from “Input1,” the battery supplies immediately the full power to the inverter during short and long outages. The period of backup time is 10 min which is enough for the generator to start up and to reach its rated operation [3].

B. Design of Internal Parameters of a Carbon Based Supercapacitor



1) Calculations

To study the internal parameter, behavior of supercapacitor is required. For this reason simple resistive capacitive model (series RC circuit) is used. In this paper carbon based super capacitor is used. These capacitors are low voltage device with a rated voltage of 2.4 V with capacitance value of 540 F. Higher voltages can be achieved by connecting many cells in series connection like batteries. An equivalent circuit describes the terminal behavior of a supercapacitor. In this paper the measured voltage of a 540 F supercapacitor charged up to the rated voltage with a constant current of 2 A, and discharged after some time with the same magnitude of constant current[2]. For a simple model and the experience from measurements, a model consisting of three RC branches is proposed. This provides three different time constants to model the different charge transfers, which provides sufficient accuracy to describe the terminal behavior of the super capacitor for the desired span of 30 minutes.

In this paper to show the voltage dependence of the capacitance, the first branch is modeled as a voltage dependent differential capacitor Cdlff. The differential capacitor consists of a fixed capacitance Ci0 and a voltage dependent capacitor Cil* V. A resistor, parallel to the terminals, is added to represent the self-discharge property. The proposed equivalent circuit is shown in Fig.3. The first or immediate branch, with the elements Ri, Ci0 and the voltage dependent capacitance Cil in [F/V], dominates the immediate behavior of the super capacitor in the time range of seconds in response to a charge action. The second or delayed branch, with parameters Rd and Cd, dominates the behavior in the range of minutes. Finally, the third or long term branch, with parameters R1 and Cl, determines the behavior for times longer than 10 minutes [2]. The relation between voltage and capacitance is described following: Where, Q is the stored charge and V the capacitor voltage. The same definition of C applies if the charge Q is the total charge in the device or an incremental charge ΔQ resulting from an incremental change ΔV in voltage. This definition is not valid for voltage dependent capacitance. Cdiff (V) = Where, dQ an incremental change in charge at a certain capacitor voltage V that produces an incremental change in voltage dQ. The internal parameters of the super capacitor model with three RC branches that have heard time constants can be identified carrying out a single fast current controlled charge.

2) Calculation of Immediate Branch Parameters [2]:

At n=0:
At that time V0 = 0 V.
Q0 = 0 Current source is switched on (I = Ich)
At n=1:
t1 = 9 sec t1 is given at the at which current source is rises to the sat value Ich in 9 sec,
At that time measure V1. V1=1.29 V
. After small time t1

$$R_{1}=\frac{V1}{Ich} = 0.645.$$

At n=2:
At when V2=V1+ΔV ΔV chosen to be 500 mV.
Measure t2 . t2=62 sec, Δt = t2-t1 = 53 sec.

$$Ci0={=Ich}\frac{\Delta t}{\Delta V} = 212F.$$

n=3:
Reached when V3 = V rated. V3 = 2.4 V.
Measure t3. t3 = 210 sec.
Now current source is turned off (Ich = 0)
At n=4:
t4 = t3 + 9 sec. 9 sec is given by fall time of the current.
At that time measure V4. V4 = 1.828 V.
Total charge supplied to the supercapacitor: Qtot = Ich * (t4 - t1) = 420 coulomb.
Now we calculate Cq = Qtot/V4 = 229.75 F

$$Ci1=\frac{2}{V4} * \left(\frac{Ich*(t4-t1)}{V4} - Ci0\right) = 19.43F$$

3) Calculation of Delayed Branch Parameters: [2]

At n=5:
At when V5 = V4 –ΔV. ΔV is chosen to be500 mV. V5 = 1.328 V.
Measure t5. t5 = 303 sec. Δt = t5-t4 = 84 sec.
As ΔV is small and Cd is assumed discharged
Itr =(V4-ΔV/2)/Rd. (Ri is neglected because Ri<<Rd) Relating the transfer current
Itr = Cdiff *ΔV/Δt. Here, Cdiff = Ci0 + (Ci1*V) = 258.63 F.
Now,

$$R_{d}=\frac{(V4-\left(\frac{\Delta V}{2}\right)*\Delta t)}{Cdiff*\Delta V} = 1.025 ohms.$$

At n=6:
$t_6 = t_5 + 3(R_d * C_d)$ Typically $R_d * C_d = 20$ sec. $t_6 = 303$ sec
Measure V6. V6 = 1.164 V.

$$Cd=\frac{Qtot}{V6} - \left(Ci0 + \frac{Ci1}{2} * V6\right) = 137.5F$$

4) Calculation of Long Term Branch Parameters: [2]

At n=7:

At when V7 = V6 –ΔV. V7 = 0.664 V.
Measure Δt = 73 sec. As ΔV is small and Cl is assumed discharge, Itr is virtually constant and given by: Itr = (V6-ΔV/2)/Rl. (Ri and Rd neglected becauseRi << Rd << Rl)
Because Rd is much larger than Ri, the transfer current I,
At this initial instant is supplied mainly from the immediate branch: Itr = Cdiff*ΔV/Δt.

$$R_{1}=\frac{(V6-\frac{\Delta V}{2}*\Delta t)}{Cdiff*\Delta t} = 5.9\,ohms.$$

At n=8:
t8 = 30 min: At t, it is assumed that the charge redistribution to the long term branch has ended and the three equivalent capacitors have the same voltage. Measure V8. V8 = 0.60 V.
The long term capacitor (Cl) is calculated using the charge balance:

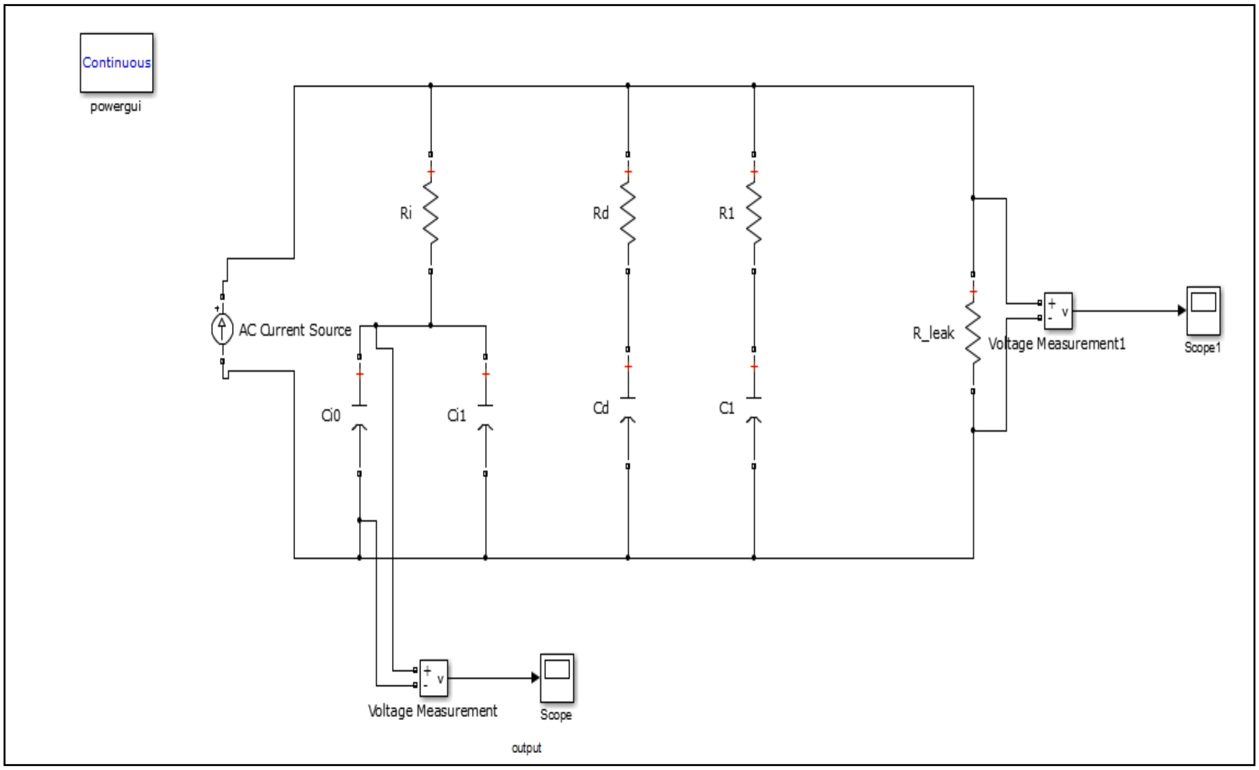
$$Cl=\frac{Qtot}{V8}-\left(Ci0+\frac{Ci1}{2}*V8\right)-Cd=344.66F.$$

With the following equations and the procedure for parameter calculation, the parameters values may now be are as shown below in the table (average results of the parameters measurements).

Table.1 Internal Parameters of Super Capacitor

Parameters	540 F Super capacitor
R_i	0.645 Ω
C_{i0}	212 F
C_{i1}	19.43 F
R_d	1.025 Ω
C_d	137.51 F
R_l	5.9 Ω
C_l	344.66 F
R_{leak}	1.6 KΩ

III. MATLAB/SIMULINK MODEL



Output:

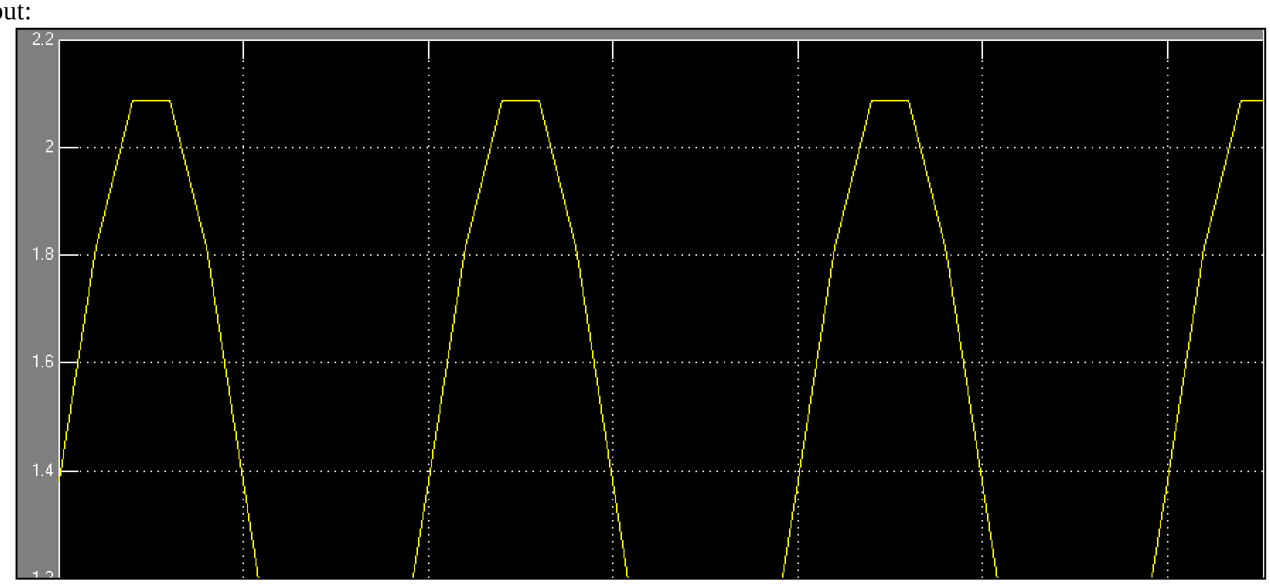


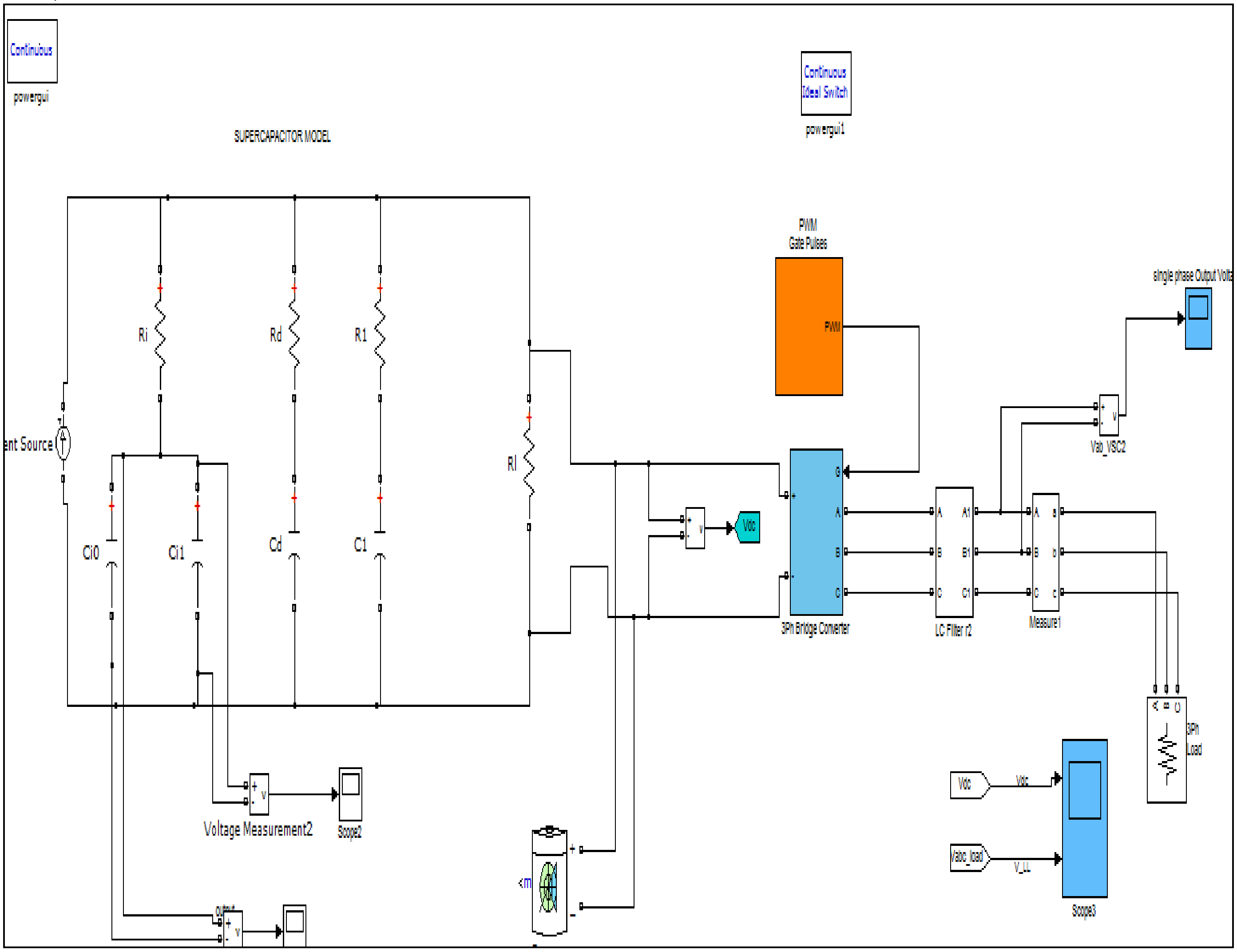
Fig. 2: Supercapacitor charging and discharging output

A. Design Structure of Supercapacitor/Battery Combination for Specific Load

The performance of a battery–supercapacitor hybrid (combination) power source under pulsed load conditions is analytically described using simplified models. We show that peak power can be greatly enhanced, internal losses can be considerably reduced, and that discharge life of the battery is extended hence increasing the reliability of the battery. The parallel hybrid power sources that combine advanced batteries with supercapacitors can overcome the power deficiency at lower cost factor.

B. Battery/Supercapacitor Hybrid Combination for Single Phase Load

1) MATLAB/SIMULINK Model



A Hybrid combination of battery/supercapacitor is combined and further given to the inverter to get the desired output of 220 volts. The purpose of the combination between Supercapacitors and the battery is to make the Supercapacitors supply the power transients and to smooth the high-power demands applied to the battery during autonomous operation.

Output:

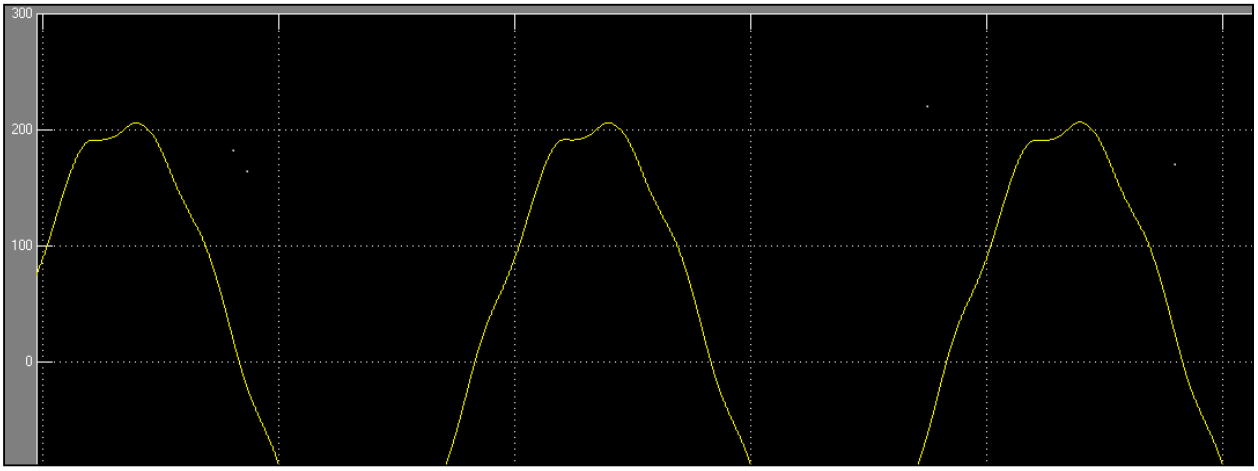


Fig. 4: Output for hybrid combination

IV. CONCLUSION

In this paper, the design of a control system that optimizes the battery-supercapacitors combination in a 100-kVA rated UPS has been presented. The advantage of having a hybrid energy source for the UPS has been shown. The importance of supercapacitors in peak-power smoothing has been elaborated. The supercapacitors overcome the power surges and reduces high-power demands away from the battery during the backup time. They also ensure the supply of full load power during outages lasting less than 10 s. In this paper we have also presented theoretically as well as a MATLAB/SIMULINK model of supercapacitors with design equations showing voltage v/s time output.

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