A Novel DC-DC Buck Converter Solely Powered by Supercapacitors for Efficiently Powering the Hand-Held Devices

Aditya Sankar Sengupta[1*], Saraju P. Mohanty [2], Bidyut K. Bhattacharyya [3]

[1] Department of Electrical Engineering, NIT Agartala, Jirania, Agartala, India
[2] Department of Computer Science and Engineering, University of North Texas, Denton, USA
[3] Department of Electronics and Communication Engineering, NIT Agartala, Jirania, Agartala, India
[*]aditya.nitagt@gmail.com

Abstract: In this paper closed loop feed-forward DC-DC converter has been designed which operates solely on two supercapacitor modules. This is an innovative new design where the challenge was to maintain the constant output voltage when the input voltage of the converter is decaying continuously as a function of time as long as the output load draws current. The second innovation is the selection of all the components that are required to design the regulated output DC-DC converter, even though the parameters like the supply voltages for the components have been falling continuously as a function of time since the supercapacitor modules are providing these supply voltages. The design is also robust enough to withstand certain fluctuations in the output current ranging between 200mA to 950mA and yet maintain a regulated output voltage. In this paper we have successfully demonstrated that one can design a DC-DC converter powered by supercapacitors, to generate a constant voltage and desired output current while all the components required to make that DC-DC converter remain operational although the input voltage of the supercapacitors are dropping constantly, due to output drawing current. The operating frequency i.e. the switching frequency ranges from 1.5 KHz to 3.5 KHz.

1. Introduction

With the advancement in technology, hand-held applications like mobile phones have become a part of our day to day life. Although the pivotal role of supplying power to these hand held devices is done by battery. Higher the specification of hand-held device, higher is the battery capacity required for these hand held applications to operate. Higher the battery capacity longer is the time needed to charge the hand held device.

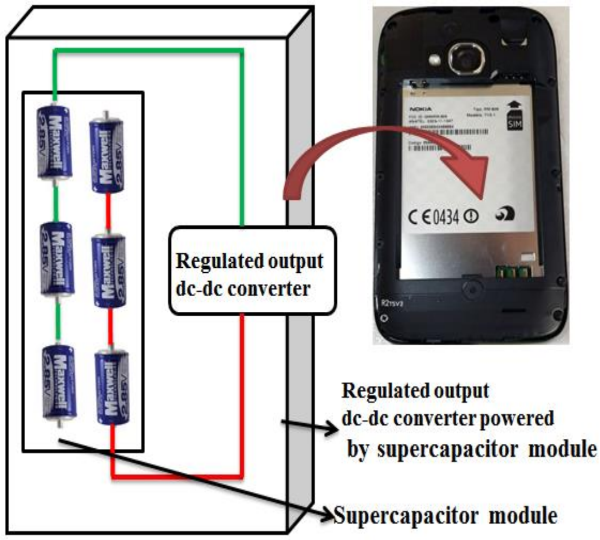

Fig. 1. *Application Perspective: Regulated output Dc-Dc converter powered by supercapacitor module to replace battery in mobile phones*

Many a times the battery capacity is not sufficient to meet the power demanded by these hand-held devices, as a result of which the battery discharges quickly and the operating time period of the hand-held device decrease which is a pressing issue of battery technology. Another important issue that needs to be addressed is the battery charging time. Higher the battery capacity, longer is the time needed to charge the battery of the hand-held device. Also battery is not environment friendly. Thus, the idea about an alternative for battery was thought of that has shorter charging time compared to battery and also is environment friendly which could meet the power requirement for hand held devices. Eventually the idea formed which is to use supercapacitors as sole power source for hand held applications. In the recent researches and industrial applications supercapacitors are used along with battery as a hybrid energy storage system [1, 2].

In this work a buck converter topology solely powered by two supercapacitor modules has been shown. These two supercapacitor modules supply input power to the buck converter and to all its components. That includes the power given to input dependent control loop. This buck topology is designed to deliver a maximum output current of 950mA, with an assumption that the output current fluctuations are occurring at frequencies less than the switching frequency of the buck converter. Use of separate circuit for load regulation [3] has been avoided. Out of the two supercapacitor modules one is supplying positive voltage and the other one supplying negative voltage. The two supercapacitor modules each of which is constituted of three supercapacitor cells has been used instead of using two supercapacitors in order to get the higher input voltage [4]. This novel buck converter topology powered by supercapacitor modules should yield a constant output even though the positive and the negative voltages supplied by the supercapacitor modules are decaying over time. Rate of change of voltage decay across the supercapacitor depends on the total power consumed due to the output current drawn by the device and the power drawn by the components. Therefore this is the only circuit that is solely powered by two supercapacitor modules. In the work done in this paper, all the electronic components are also working by drawing power from these two supercapacitor modules, while the voltage across the supercapacitor modules are decaying with time. This has been done by wisely and appropriately selecting components which can work for wide voltage ranges. For these components it must be made sure that they are capable of operating up to a certain minimum voltage for a certain junction temperature, depending on the manufacturing specifications. It may happen that, these components are encapsulated inside some moulded plastics, which may increase the junction temperature and then the part may require higher voltages to operate which goes to imply that power consumption will increase due to which the voltage of supercapacitor modules will decay faster. This will result in decrease of the period of operation of the hand-held electronic gadget operating solely on supercapacitors.

The whole paper is organized in the following sections. In section 2 we have discussed about supercapacitor, in section 3 novelty of our work has been discussed, in section 4 prior and related works have been reviewed. In section 5 triangular wave generator circuit has been explained. In section 6 and section 7 we will discuss how we have developed this converter without any additional power supply except two supercapacitor modules. Section 8 shows the experimental result and analysis based on these results including the comparative studies done by other authors and differences from our work. Finally we will have a conclusion as section 9 followed by references.

2. Supercapacitor as Efficient Energy Storage - A Broad Perspective

A supercapacitor also known as electric double-layer capacitor (EDLC) has much higher capacitance than conventional capacitor. Supercapacitors are built to store ten to one hundred times more energy per unit volume or mass compared to electrolytic capacitors and have high energy and power densities. Supercapacitors use double-layer effect for storing energy. A supercapacitor consists of two electrodes that are separated by an ion-permeable membrane called separator and an electrolyte providing ionic connection between both the electrodes. The purpose of ion-permeable membrane is to prevent electric contact between the electrodes and still allow the flow of ions between the electrodes. When a voltage is applied across the supercapacitor cell, the electrodes get polarised and the ions in the electrolyte form electric double layers of opposite polarity at both the electrodes. And electric energy is stored in these supercapacitors by virtue of this phenomenon.

Supercapacitor has small Equivalent Series Resistance (ESR). Therefore it can deliver high current and can also be charged in small time depending on the thermal performance [5] of those supercapacitors. These thermal performances are characterized by 'θ_{ja}', which is called the difference in junction temperature for unit power. These supercapacitors are capable of storing high energy [6, 7] at low voltages. Usually the ESR can be as low as 2mΩ to 300mΩ.

In many applications supercapacitors are used along with batteries and in many cases supercapacitors are preferred over batteries since supercapacitors have high power density and the charging time of supercapacitors is much shorter compared to conventional battery. Apart from having much higher life cycles compared to battery, supercapacitors are environment friendly

3. Novel Contributions Of This Paper

A novel buck converter topology and its design has been shown. This is, at first being powered by two different voltage sources of same specification. One of which will be supplying positive voltage and the other one supplying negative voltage. This design of the buck converter circuit generates a constant output voltage independent of any fluctuations or changes at the input voltage. These two voltage sources power up the entire circuit that includes the various Integrated Circuit (IC) components and also the output load. This buck topology is an interesting and an innovative novel design. The design is such that the output load and all the components of the circuit collectively draw equal power from these two input voltage sources. That means at any given input voltage of the power supply, when the design is working, each power supply delivers almost equal current. This is something unique and has been developed for the first time in any supercapacitor development. This is a new buck topology design, which draws equal current from both the power supplies and can be used for delivering low or medium power in a load. This buck converter design is such that a fluctuating power source with fluctuating voltage will generate a constant regulated output voltage at some nominal current values, which can be in the range of 200mA to 950mA.

The method that we have developed here is novel because it takes care of various design parameters, first by using power supply and then replacing them with two modules of supercapacitors.

After the circuit is being tested using two power supplies, the two voltage sources were replaced by two individually packed supercapacitor modules of voltage specification same as power supply. One of the modules is supplying positive voltage and the other one is supplying negative voltage hence resulting in a novel buck converter design which is solely powered by supercapacitors/ supercapacitor modules and no extra power source is required. Due to the innovative design technique the output load of the buck converter circuit together with the different components in the circuit will draw equal power from the two supercapacitor modules. Due to this the rate change of voltage or the voltage drop across these two supercapacitor modules will be same. Depending on this rate of change of voltage the duty ratio and amplitude of the switching pulse will also change proportionately. This will generate a constant output voltage. Such an analogue buck circuit that is solely powered by supercapacitor modules has been demonstrated for first time. This can help to power any medium to low power applications/electronics gadgets at a constant output voltage without any wall power or extra power source from battery. Another novelty of this 'buck converter deign powered by supercapacitors' is that the design is capable of withstanding minor output current fluctuations in the range of 200mA to 950mA without using separate circuit for load regulation which increases efficiency. Moreover this novel buck converter topology has been designed using no-ideal components and taking into account the losses in these components. This battery less circuit topology in which supercapacitors are used to supply a constant voltage for medium to low power application electronics gadgets is a new innovation and brings out the novelty in this work. Majority of the supercapacitor based applications require an extra power source like fuel cell / battery etc and mostly concentrate on bidirectional power flow between supercapacitor and fuel cell / battery by using a bidirectional DC-DC converter.

The DC-DC converter that we build can make the mobile phone operate by maintaining device operating voltage close to 3.9V, particularly for all mobile phones usually operating on battery having a capacity up to 4500mAhr. We have tested in the laboratory and replace the battery with supercapacitor modules, and found it works.

The total number of supercapacitors used is 6 (3/module) each of which has a capacitance of 3400F and can be charged up to 2.85V [8]. Each of the two supercapacitor modules is built to supply 8.55V with an effective capacitance of 1133.33F.

4. Prior Related Research

In recent work, done by Suman K. Mandal et.al [9] on 'intell Batt' has an impact on extending the usable time of the battery by managing every cell which is inside the battery. This novel work [9] can also be implemented as if each supercapacitor of the supercapacitor module is behaving like an individual cell. And the entire supercapacitor module is like a battery with many cells. This is the way of using the supercapacitors by which one can reduce the time to charge and also enhance the life time of the supercapacitors by managing the optimum discharge rate of those individual supercapacitors using microcontroller. In Haswell chip design [10] Intel Integrated Voltage regulator module is used which is basically a sophisticated DC-DC converter inside the chip. The input voltage for this DC-DC converter ranges from 12V to 3.3V DC power and this input voltage is stepped down to the desired voltage which ranges from 1V to 2V. This was required to enhance Intel's 22nm process. The same can be done in our DC-DC converter module, but leakage current will drain the supercapacitors faster. This can be prevented by the method describe in [11] by Elias Kougianos et.al. In that paper they have reduced the leakage current of the components using high k materials

A DC-DC converter powered by supercapacitor has been discussed in [4] in which the DC-DC converter is powered by battery along with supercapacitor for operating and controlling hybrid vehicle. Various literatures about the charging method of the supercapacitors [7, 12] have been reviewed. Whereas, the decaying input voltage supplied by the supercapacitor to the buck converter remains one of the most important challenges in engineering design and on its methodology for the generation of constant output voltage. A control circuit [13] is always essential for a buck converter to yield a constant output. The work in [14] portrays the use of supercapacitors to power an electric lamp and the glow of lamp decays with the decay of voltage across the supercapacitor and is completely different from our work which requires a regulated output voltage. The supercapacitor can be used in various electronic devices. If the devices work at a very low power like1µWatt or even less for which the operating voltage ranges from 0.8V to 1V then a supercapacitor can be used which can be charged close to 1V. These supercapacitors can deliver the power to that low power device till it drops to 0.8V. Since power is very low (in the range of 1µW), so, the voltage of the supercapacitor will take huge period of time in order to drop below 0.8V. Thus this can be used for keeping the memory cells alive for EPROM. The battery base cache, which is normally seen inside the computer, can be replaced by supercapacitor [15]. The majority of the applications of the supercapacitor is to deliver the surge current, when the system requires sudden current and no DC-DC converters was ever built for this purpose. This phenomenon where supercapacitor is used to deliver the surge current can be seen when one turns on the power in the car to start the car [16].

Different control circuit strategies have been discussed in [17, 18], but the issue remains which is basically to eliminate that extra power source from the design. The issues related to the additional components requirement for various control circuits design will increase power consumption. This is just to design a control loop for generating a regulated output voltage. This control loop includes a separate circuit which is required for generation of input voltage dependent repeating unipolar triangular wave [19] or saw-tooth wave and the generation of fixed reference voltage for the pulse width modulation (PWM). This control circuit requires analogue components like op-amp that also adds to the power loss in the circuit and reduces the efficiency of the design. Digital and analogue ICs are also available off-the-shelves, which can be used for generation of saw tooth [20] and/or triangular wave [21]. Among various articles and literature about generating saw tooth wave there is a literature showing a circuit that deals with generating saw tooth wave in the rage of 100 kHz [22] and depends on the input voltage. In [22] a clock pulse is used to switch the MOSFET on and off. A capacitor is connected to that MOSFET. The MOSFET switching causes the continuous charging and discharging of the capacitor connected to it, and this periodic charging and discharging waveform of the capacitor takes the shape of a periodic saw-tooth wave form. This clock circuit, as described in [22] requires another power source for its operation. If the frequency is in the range of 2 kHz, it was found that a delay was introduced on every saw tooth wave. That will definitely make the circuit to generate wrong or unregulated output voltage. Such kind of circuit failure is highly undesirable. In article [23] switching pulses of varying duty ratio has been generated by comparing the inductor current of the DC-DC converter and the output current. In the work done in [24] inductor current was compared with current going through the filter capacitor, which is located at the output for generating the desired switching pulse. In continuous conduction mode (CCM) the inductor current looks like a triangular waveform [25, 26]. The slope and the peak of this inductor current waveform changes with the change in input voltage. This technique cannot be used in our case here, because of issues like the DC-DC converter suddenly beginning to operate in DCM (discontinuous conduction mode) mode [27]. In this paper perturbation is being used in the circuit parameters, which causes various circuit failures. Many current controlled 'control topologies' [28, 29] for buck converter have been discussed but either separate circuit or external chips are required to sense the current at various points in the circuit. These 'current sensing' circuits also require external power sources like battery for their operation. Hence the use of such circuitry is undesirable and cannot be used in our work. So, it is unlikely that we will be using such a technique to regulate the output voltage where we need to use of external power source for operation of components of the circuit. For digital control topologies of a given buck converter [23, 30], at times sensing of current through inductor becomes essential, also an analogue to digital converter (ADC) is required or needed. The current sensing circuit together with ADC require additional power source other than the power source for the buck converter. This additional power supply has to be eliminated for reducing power loss and increasing circuit efficiency. In general no such work has been done, where charged supercapacitors have been used for operating an analogue circuit without any additional power supply. Therefore, this work is very different and unique than whatever has been found by reviewing various literatures.

5. Circuit for Triangular Wave Generation

Fig. 2 shows the triangular wave generator circuit. The value of 'V_{tr}' should be equal to 'V_{in}' for ideal op-amp. In real life there are some losses inside the op-amp which causes the 'V_{tr}' to be less than 'V_{in}'. For a non-ideal op-amp 'V_{tr}' is nearly equal to (V_{in}-1.6) Volt. The op-amps selected from the data book, from the component supplier, have wide supply voltage and input voltage ranges. This is required because due to wide input voltage range of buck converter the peak of triangular waveform will also change over a wide range. Due to this the PWM would vary accordingly. In Fig. 2, the values selected of 'R' and 'C1' are chosen such that the voltage waveform at the point 'T1' almost takes the shape of bipolar periodic triangular wave. The frequency of the triangular wave is determined only by the values of 'R' and 'C1'.

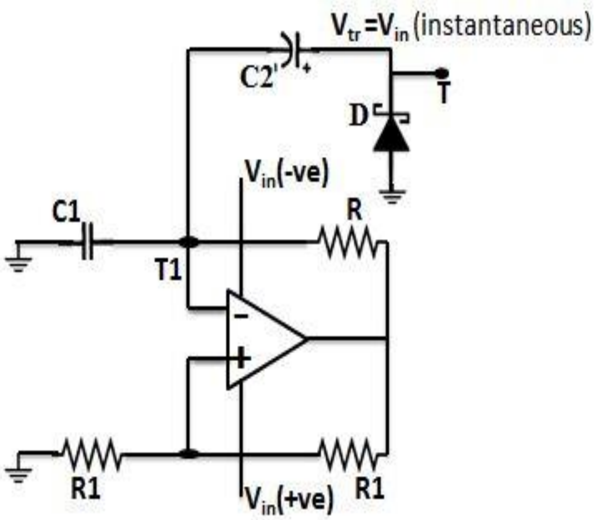

***Fig. 2**. Circuit generating repeating triangular wave.*

This in turn is the switching frequency 'f_s' for the buck converter. The selected op-amp is also capable of functioning for a wide range of power supply and input voltages. Reducing the values of 'C1' and 'R' increases the frequency of the wave. This portion of circuit in Fig. 2 comprising of diode 'D' and a capacitor 'C2' is a clamper circuit which clamps the signal up at point 'T1'. This gives us a repeating unipolar triangular wave at point 'T'. The diode 'D' is a schottky diode. The reverse voltage drop for schottky diode is negligible. The power loss for a schottky diode is also low. Thus from circuit as shown in Fig. 2, one can generate a repeating unipolar triangular wave having frequencies in the range of few KHz. Considering present market conditions, the components available can generate the triangular wave form ranging from 1.5KHz to 3.5KHz. So we have to work using only those available components.

6. Proposed Novel DC-DC Buck Converter

6.1. Conventional Buck Circuit

In Fig.3(a), we have shown a conventional buck converter circuit. In this circuit ESR (the equivalent series resistance) for inductor 'L' and capacitor 'C' have been incorporated. The voltage 'V_i' denotes the input voltage and the voltage 'V_o' is the output voltage of the buck converter. In Fig.1, 'V_{tr}' shown at the input of the comparator, denotes the unipolar triangular waveform which is required for generation of switching pulse, when it is compared with a given reference voltage 'V_{ref}'. It is important to mention that for a certain load 'R_L' drawing a constant current 'Io' the magnitude of output voltage does not solely dependent on the duty cycle of the said switching pulse. In general the output voltage for a buck converter circuit depends on duty cycle 'D' and also on the amplitude 'V_g' of the switching pulse which is shown in Fig.3. The amplitude of the switching pulse depends on the positive and also on the negative supply voltages 'V_{cc}(+ve)' and 'V_{cc}(-ve)' respectively. These voltages are applied to the comparator. The duty ratio 'D' depends on the value of 'V_{ref}' and 'V_{tr}'. Taking into account the losses inside the op-amp, which is used as a comparator for generation of the desired switching pulse, the amplitude of 'V_g' should be a function of the magnitude of 'V_{cc}' and the loss occurring in the op-amp used as comparator. Given 'Ton' represents the on time for the switching pulse, which is the output of the comparator and 'T_{total}' denotes its total time period, then the relation between 'Ton', 'T_{total}', 'D', 'V_{tr}' and 'V_{ref}' are given below and shown in (1). This equation is derived using equations of straight line.

$$D = \frac{T_{on}}{T_{total}} = \frac{V_{ref}}{V_{tr}} \tag{1}$$

6.2. Input Voltage Based PWM Controlled Buck Circuit

In this case the buck converter circuit shown in Fig. 3(b) is being powered by two power supplies. Each of these power supplies is supplying an input voltage 'V_i'. These power supplies are supplying both positive and negative voltages. The op-amp is powered by these two power supplies. 'S1'and 'S3'are two MOSFET, 'S2' is a schottky diode. 'A1' and 'A3' are two op-amps of identical specification. 'A1' is used in generating triangular wave while ‘A3’ is used for generating reference voltage for PWM ‘A2’ is also an op-amp which is being used as comparator. ‘C’ and ‘L’ denotes the capacitance and inductance respectively, R_C and R_L are their equivalent series resistances (ESR) respectively. ‘D1’,‘D2’,‘D3’ and ‘D4’ are all schottky diodes and they are identical in nature. Resistances ‘R1’ and ‘R2’ and capacitor ‘C1’ are required in order to build an the relaxation oscillators for the generation of bipolar triangular waveform which is then clamped up to generate unipolar triangular waveform by the clamper circuit made of schottky diode ‘D2’and capacitance ‘C2’.

‘Z2’ represents the zener diode. ‘R_o’ is the load resistance. The output voltage and current are represented by ‘V_o’ and ‘I_o’ respectively. The output of op-amp A1, which is the relaxation oscillator, is bipolar in nature. This output is fed to the voltage doubler circuit (bordered by blue lines, see Fig.4). This output voltage doubler circuit generates a dc voltage which has an average value equal to ‘$2V_i$’. This voltage acts as the input for the buck converter. Since input to the buck converter gets doubled, so theoretically the reference voltage for PWM should be halved. Therefore, the value of the reference voltage for the PWM is close to ‘$V_o/2$’ which is generated from ‘$2V_i$’ by using a voltage regulator circuit. This regulator circuit is composed of op-amp ‘A3’, zener diode ‘Z2’, MOSFET ‘S3’ and the resistances ‘R3’ and ‘R4’. The Fig.4, shows the input to the closed loop feed forward buck converter is doubled. Also the reference voltage for PWM is halved accordingly.

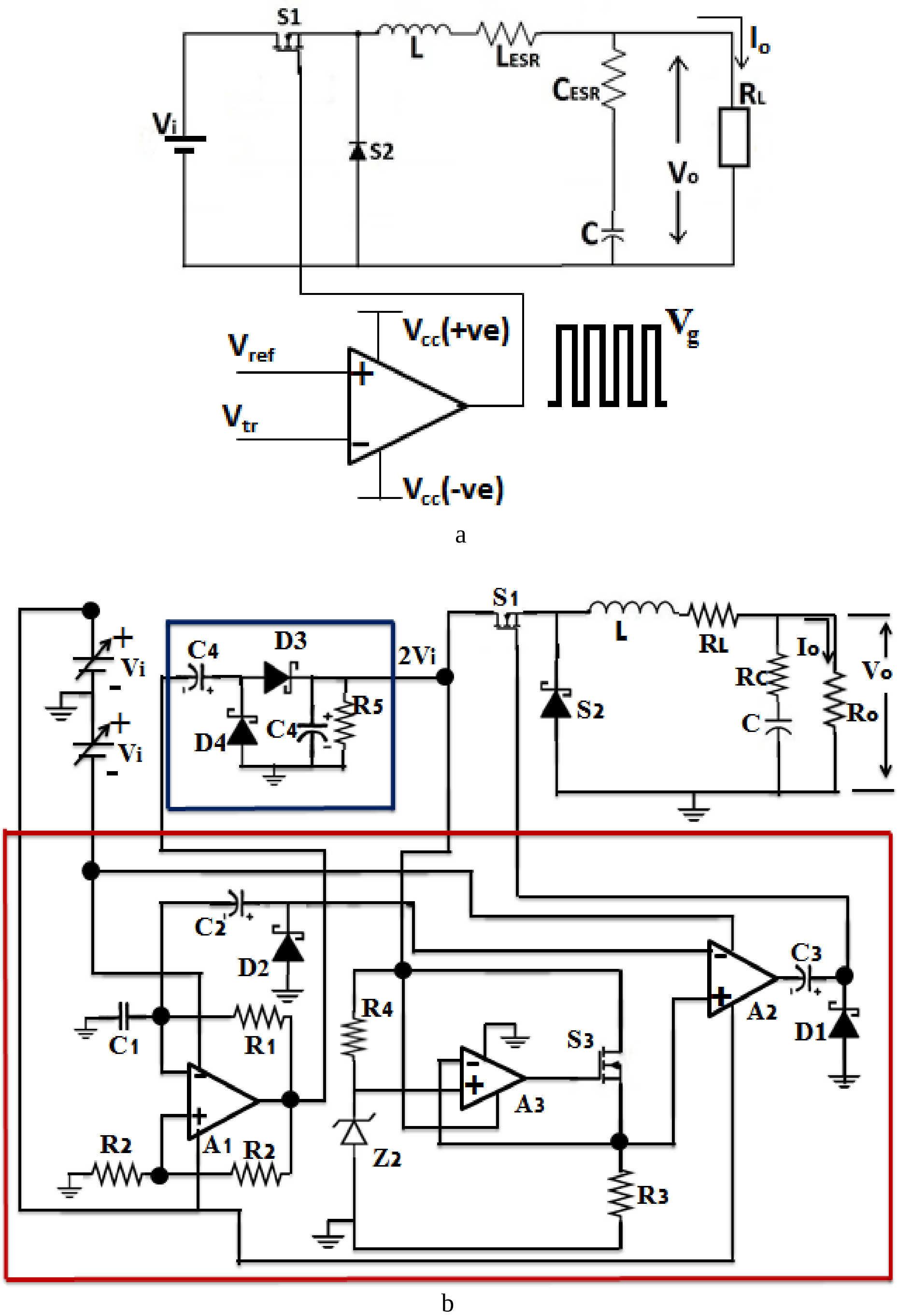

Fig. 3. Buck Converter.
(a) A Conventional Dc -Dc Buck circuit, (b) Voltage controlled regulated output Buck converter circuit.

Theoretically and mathematically if the input '2V_i' and reference voltage for the PWM is close to '$V_o/2$', then the desired time variant duty ratio can be generated for obtaining a constant output from the buck converter irrespective of changing input voltage 'V_i' of the power supplies . This output voltage does not depend on the decay or fluctuations in input voltage. This design reduces the total power consumption since in this design we half the reference voltage in the PWM control circuit instead of using a voltage divider to half the input voltage.

The portion of the circuit inside the red line border, as shown in Fig. 3(b), is the control loop for the generation of PWM. This PWM generates a switching pulse of desired amplitude and duty ratio. For a certain input voltage 'V_i' the desired ratio is close or equal to '$V_o/2V_i$'and the desired amplitude of the signal is (2V_i-1.6) Volt. The positive power supply 'V_i' is connected to the positive supply terminals of the op-amps 'A1' and 'A2' while the negative power supply 'V_i' is connected to the negative supply terminals of the op-amps 'A1' and 'A2'. The op-amp 'A3' is powered by the output of the voltage doubler circuit. This is supplied by the output of the op-amp 'A1'. Now, if the two voltage sources in the Fig. 3(b) are replaced by two modules of super-capacitors, then the voltage of these two super-capacitors modules will decay at the same rate. That is due to equal power being drawn by the circuit form these modules. It needs mention here all the components, as shown in Fig. 3(b) are functioning on the power which is solely supplied by the two voltage sources ('±V_i' each). Schottky diodes are used in its circuit have negligible reverse voltage drop and this diode consumes very low power. Incorporating all the losses in the components, we have found that, this buck converter circuit that we have designed will successfully work for a minimum input voltage of $V_i = (V_o+1.1)$V, where 'V_o' is the required output voltage.

7. Proposed Buck Converter Topology Solely Powered By Supercapacitor Modules

The circuit shown in Fig.4, which is build using supercacitor modules as its sole power source is almost similar to Fig. 3(b).

7.1. Circuit Design

The circuit shown in in Fig. 4 is a buck converter circuit which is solely powered by two supercapacitor modules, one of which is supplying a positive voltage and the other one is supplying a negative voltage. Each of the two supercapacitors modules, shown in Fig. 5, is supplying voltage 'V_i' and has capacitance 'Cs' are the input and only power sources for the entire Fig. 5 circuit. 'A1', 'A2' and 'A3' are op-amps are chosen from the vendors having the same specification, 'S1' and 'S3' are two different MOSFETS, 'S2', 'D1', 'D2', 'D3' and 'D4' are schottky diodes and they are also chosen to have the same electrical specifications, 'R1', 'R2', 'R3', 'R4' and 'R5' are different resistances used in the circuit, 'C2', 'C3 and 'C4' are capacitors of same capacitance, 'C5' is a different capacitance, 'Z1', 'Z2' are zener diodes of identical specifications, 'L' and 'C' are the inductance and capacitance of the buck converter and 'Io' is the output current drawn by the device 'Div' from the output of the buck converter at an output voltage 'V_o' . 'Z1' and 'Z2' are zener diodes having identical specifications. In Fig. 5 the green coloured connections are supplying positive voltage to the components from the supercapacitor module. While the red coloured lines are the connections which are supplying negative voltage to the various components from the supercapacitor module. This circuit shown in Fig.4 has been designed in such a way that the voltage across these two supercapacitor modules will change equally when all the components and the output load starts drawing current or

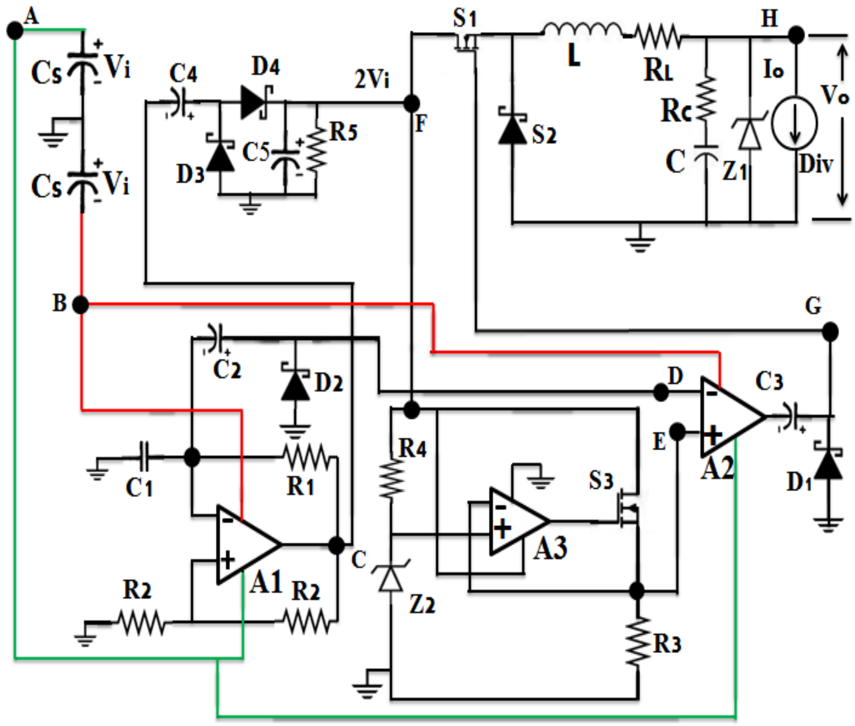

Fig. 4. *Buck converter circuit powered only by supercapacitor modules.*

power.

7.2. Circuit Operation

The circuit shown in Fig. 4 has been designed in such a way that both the amplitude and duty ratio of switching pulse depends upon the voltage of the supercapacitor modules. The purpose of zener diode ‘Z2’ is to maintain a desired reference voltage for pulse width modulation (PWM) throughout the entire period of circuit operation. According to circuit design, so long the amplitude and duty ratio of switching pulse are collectively sufficient to drive the MOSFET ‘S1’ of Fig.4, the voltage of supercapacitor modules will decay due to the collective power drawn by the device at the output and components of the circuit in Fig.5 from these supercapacitor modules. As the input voltage of the supercapacitor modules drop as a function of time, the corresponding peak of the triangular wave for PWM will decrease accordingly and proportionately due to which the duty ratio and the amplitude of switching pulse will also change accordingly as required. As a result of which the output voltage will remain regulated to the desired value. But, when the amplitude and duty ratio of switching pulse are collectively not sufficient to drive the MOSFET ‘S1’ of Fig.4, this circuit will cease to operate resulting in the output voltage to steeply fall to zero and the voltage of supercapacitor modules will decay only due to the power drawn by the components from them.

The purpose of having the diode ‘Z1’ is to get rid of any undesired voltage overshoot at the output.

8. Experimental Results

The values and specifications of all the components used in Fig. 4 are given in table 1.

These components have been chosen to work for the desired voltage ranges and for a frequency of 1.703KHz.

In Fig. 5(a) the black dashed line indicates the voltage across the supercapacitor module supplying positive voltage as a function of time, when the output is drawing a constant 500mA current. The black solid line is the current of this supercapacitor module as a function of time corresponding to its voltage. The node “A” as shown in Fig.4 is where the current and voltage are plotted in this figure, which corresponds to the positive side of the super-capacitor module.

Fig. 5(b) shows the supercapacitor module voltage and current obtained at the node ‘B’ of Fig.4. The black dashed line is the voltage across the supercapacitor module supplying negative voltage while the black solid line is its respective current.

In the Fig. 6(a) the peak value of triangular wave is shown by black dashed line and the reference voltage for PWM with respect to time is shown by the black solid line. The peak value of triangular wave is changing with time as the input voltage across the super-capacitor modules are changing. The peak value of triangular wave with respect to time and the reference voltage for PWM are obtained at

Table 1 This table shows the components used in Fig. 4 and their part numbers and manufacturers

COMPONENT NAME	MANUFACTURER	COMPONENT Number
S1	Vishay Siliconix	MOSFET Si2308BDS
S2, D1, D2, D3,D4	Vishay General Semiconductor	Schottky Diode 1N5819
S3	On Semiconductor	MOSFET 2N7000
A1, A2, A3	Texas Instruments	LM358P, Op-Amp
Z1, Z2	Fairchild Semiconductor	1N4730A, Zener Diode
C1		0.3µF
R1		820Ω
R2		10KΩ
R3		1MΩ
R4		1KΩ
C2, C3, C4		1µF
C5		10µF
R5		3.3MΩ
Supercapacitor (C_s, V_i)	Maxwell Supercapacitors	(1133.33F, 8.55V), each cell is BCAP3400
L		1mH
C		1mF
I_o		500mA output current

node ‘D’ and ‘E’ respectively of the circuit which is shown in Fig.4.

In Fig. 6(b) the changing duty ratio of the switching pulse with respect to and is shown by the black solid curve. The corresponding black dashed curve indicates the amplitude of switching pulse with respect to time. These curves are obtained at time is obtained at node ‘G’ of Fig. 4

The black solid line, in Fig. 6(c) represents the output voltage of buck converter and this is obtained at the node ‘H’ of Fig.4. The black dashed curve, in the same figure, represents the input to the same circuit at the node ‘F’ as a function of time.

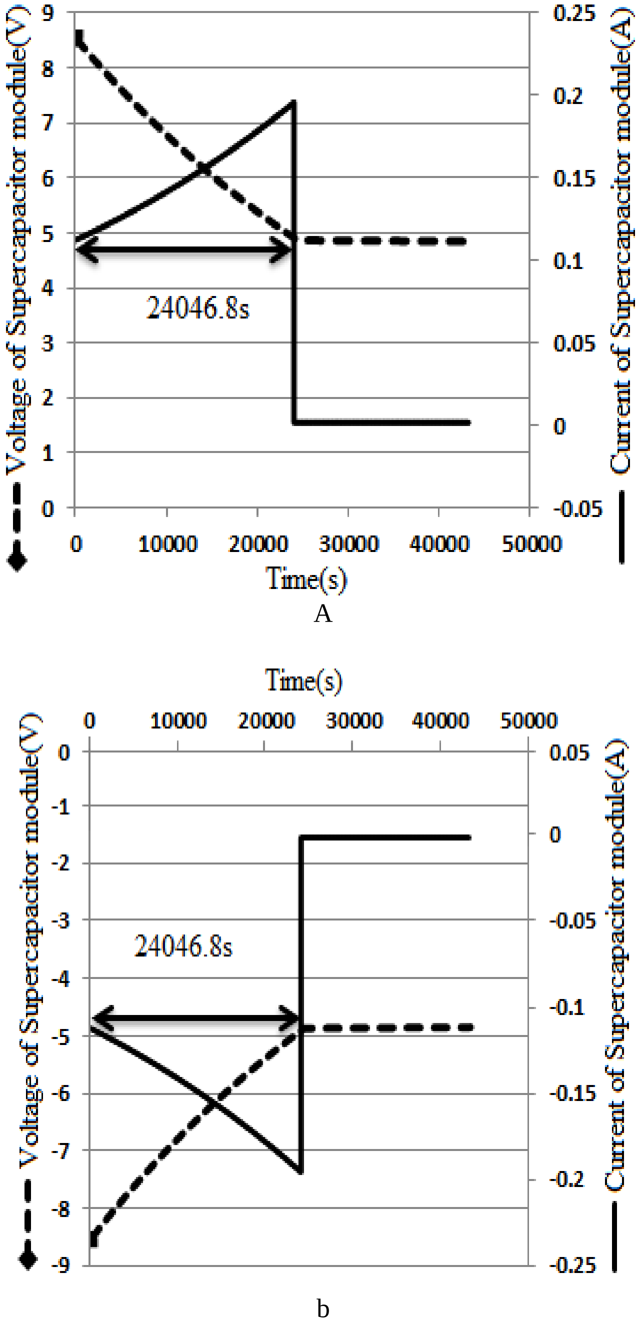

Fig. 5. *Voltage and current profile of supercapacitor module*

(a) Supplying positive voltage, (b) Supplying negative voltage.

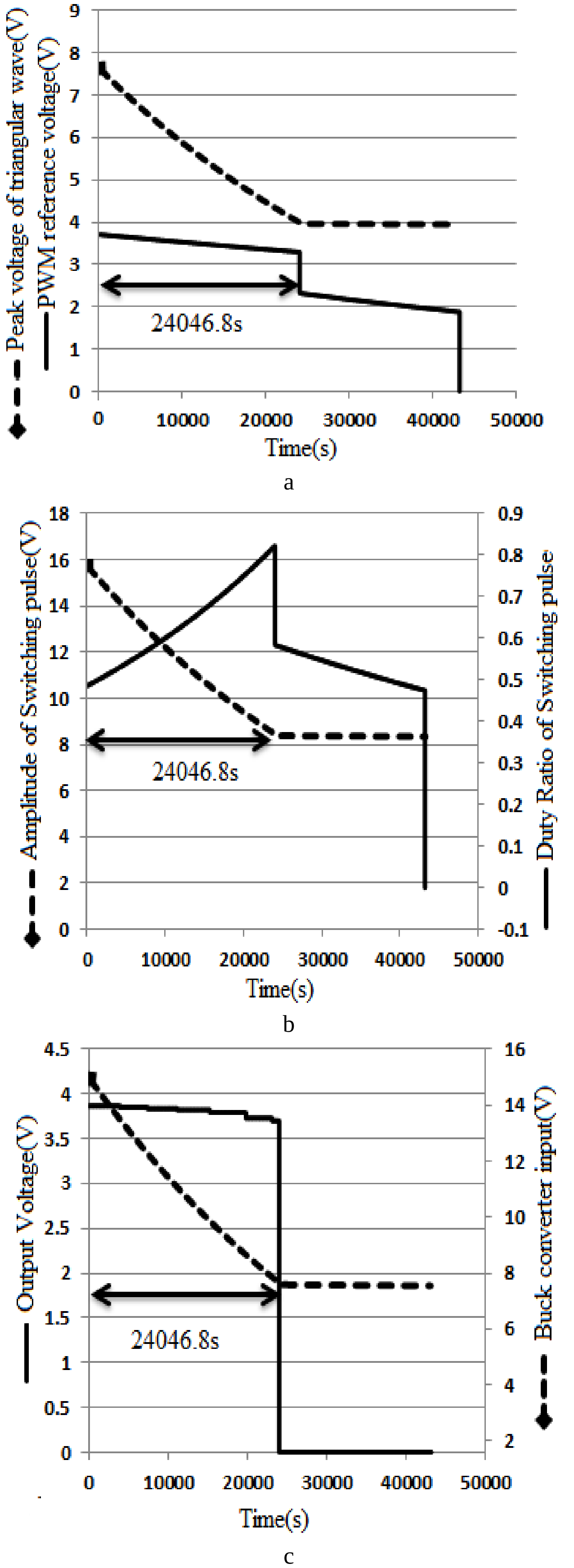

Fig. 6. *Different circuit parameters with respect to time*

(a) Peak voltage of triangular wave and PWM reference voltage, (b) Switching pulse amplitude and duty ratio,

(c) Output Voltage and final input voltage for buck converter

8.1. Analysis

With reference to the components listed in table 1, MOSFETs 'Si2308BDS' and '2N7000' have been used as they do not need any extra driver circuit for their switching. These MOSFETs have been specifically designed to be used in DC-DC converters only. Not requiring driver circuit reduces power consumption, which is helpful for our circuits, because our power is limited and is only stored in supercapacitors. Op-amp LM358 has been used in voltage regulator for generating reference voltage for PWM and also as comparator for generating the switching pulse of desired amplitude and duty ratio.

Fig. 5(a) and Fig. 5(b) are two graphs showing the voltage and current profiles of the two supercapacitor modules. These two graphs appear to be the mirror images of each other if placed parallel to time axis. The right components choice will make these two curves into exact mirror image curve for one another. This is an important design criterion, which if not met, then two supercapacitors will decay at different rates and the problem will get more complex. More research can be done on various control circuit designs, but in all cases extra components will consume additional power. What this means is, the control circuit will also require the similar components which may be hard to achieve without extra battery or power supply. This is the same problem as getting perfectly all matched electronics components, to start with, for equal power to be drawn from these two supercapacitor modules. In both the figures namely Fig.5(a) and Fig.5(b) it has been observed that the voltage across supercapacitor modules are decaying exponentially for 24046.8 sec (~6.68hours), given the output is pumping constant current,500mA. Fig. 5(a) and Fig. 5(b) both show that after 24046.8 sec the voltage remain almost constant at 4.8Volt and the current drops. This is because after 24046.8 sec (~6.68 hr) either the reference voltage at the op-amp acting as comparator 'A2' in Fig. 4, becomes higher than the peak of the triangular wave form or the amplitude of switching pulse is not sufficient to drive MOSFET 'S1'. In such cases the MOSFET 'S1' switches to off condition and the output voltage falls to zero as shown in Fig. 6(c). So, the buck converter goes in off mode condition and thereby stops drawing power from the supercapacitor modules. It is important to note that the system still draws the power from supercapacitor even after 24046.8 seconds which is due to the power drawn by various other components in the circuit as shown in Fig. 4. It is also to be noted that we have effectively used only a fraction of total power available in the supercapacitors since we started with the supercapacitor modules charged to 8.55 volts and our PWM control circuit quit working at the end of around 4.9 volts.

Referring to Fig. 6(a), it may be noted that the reference voltage for PWM is nearly equal to the output voltage. Theoretically it should be one half the value of the output voltage. This is because practically higher duty ratio was needed to get the 3.8V output voltage corresponding to an output current draw which is as high as 500mA.

From Fig. 6(c) it can be seen that the voltage drops steeply after 24046.8sec. This might be due to the fact that at the end of 24046.8sec peak voltage value of triangular wave may fall below the reference voltage for PWM. Even if this phenomenon does not happen, still the amplitude of switching pulse after the end of 24046.8sec is not high enough to drive the MOSFET 'S1' of the circuit shown in Fig.4 even if the desired duty ratio is provided by the switching pulse. As a result of which the circuit shown in Fig.5 goes to off condition after 24046.8sec. Therefore the output voltage steeply falls to zero. All this is evident form the graphs shown in Fig. 6(a), Fig. 6(b) and Fig. 6(c).

It can also be inferred from Fig. 5(a), Fig. 5(b), Fig. 6(a), Fig. 6(b) and Fig. 6(c) that, so long the duty ratio and amplitude of switching pulse are collectively sufficient to drive the MOSFET 'S1' of Fig.4, the output voltage will be regulated to the desired value irrespective of decaying input voltage.

Referring to Fig. 4, where 'V_i' is the input voltage supplied by each of the supercapacitor modules and 'V_g' is the amplitude of switching pulse, 'V_{tr}' is the peak of the triangular wave, 'V_{ref}' is the reference voltage, 'D' denotes duty ratio, 'V_o' is the output voltage and 't' is time, the relations between the different parameters that have been established from the experimental results are given below:

$$V_g(t) = 2V_i(t) - 1.362 \quad (2)$$

$$D(t) = \frac{V_{ref}(t)}{V_{tr}(t)}, \text{ for } t<=24046.8s \quad (3)$$

$$V_{tr}(t) = V_i(t) - 0.95 \quad (4)$$

$$V_o(t) = f^n\{V_i(t), V_g(t), D(t)\} \quad (5)$$

f^n denotes 'function of'.

8.2. Comparative works

The work done in this paper is the first of its kind where two supercapacitor modules were build and are used as the sole power sources for a buck converter for the generation of a regulated output voltage power supply. This circuit has been designed and the targeted market is for hand-held devices which will only operate with Super-Capacitors instead of a battery. Similar work where supercapacitors are used as a sole power source for electronic circuits was not found in the literature. All the works referred to or compared with requires battery or

Table 2 Comparative works

	Vsc	Csc	Extra power source	Output
This work	8.55V	1133.33F	Not required	3.86V to 3.6V
[4]	27V	260F	48V battery module	38V to 54V dc bus voltage
[31]	16V	58F	12V 14Amp-hour battery	48V

power from wall or solar cells or fuel cells apart from supercapacitors. The works done in [4, 14, 31] bear the closest (even though they used external power supply) similarity to the work done in this paper. In [4] a super-capacitor module of 27V and 260F is used having a 48V battery module to power a DC-DC converter in case of hybrid vehicle applications. It may be noted here that this battery is an extra power source in the circuit other than the super-capacitor. The super-capacitor provided the transient demand of current while one starts the car using a chock coil or for automatic ignition system. In our work, the buck converter design does not require any extra power source not even for the initial starting of circuit. Comparison of Fig.5 of our work with Fig.13 and fig.15 of [4] clearly shows that the voltage and current profiles of supercapacitor module is completely different in both the cases. The DC bus voltage for [4] ranges between 54V and 38V. In our case the output of the buck converter circuit ranges from 3.86V to 3.6V. Regarding the work done in [31] a super-capacitor and a batter is used for storing energy for a PV base DC grid. In this system, the DC-DC converter is being used for transferring power from PV system to super-capacitor module, battery and to a DC grid. This method employs very different and alternate kind of switching techniques. Moreover, the supply voltages required for the different components needed to run the DC-DC converters were not mentioned in this work [31] and also not shown clearly.

In our case coloured lines have been used in Fig.4 to clearly show and to indicate the connections supplying negative and positive voltages to all the components like the op-amps in the PWM control circuit from the two supercapacitor modules that are powering the entire circuit shown in Fig.4. Therefore, the two super-capacitor modules are the sole power sources in the circuit shown in Fig.5 which by itself brings out innovation and novelty in the circuit design. Such a circuit has been developed for the first time. Moreover the output voltages level for the DC-DC converter in [31] differs from the constant output DC-DC buck converter circuit solely powered by super-capacitor modules. Comparative result of the work done here and the works referred to in [4, 31] is shown in table 2. In this table ‘Csc’ denotes capacitance of value of the super-capacitor module and ‘Vsc’ is the voltage rating of the super-capacitor modules.

9. Conclusion

As per any and every conventional buck converter circuit topology, the buck converter circuit cannot adapt to the changes in input voltage or output current. Any change in input voltage or output current will cause significant change in output voltage. Also the supply voltage fluctuations for the op-amp which is acting as a comparator for generating PWM is not accounted for in any design that one can find in literature. Also, the complex relationship between the supply voltage of the op-amp acting as comparator and the amplitude of switching pulse which is responsible for triggering the MOSFET has never been established in any literature. In this work all the above issues were taken care while making a final design of the buck converter circuit which is describe in Fig. 4. This is powered by two super-capacitor modules only and no extra power supply is added in the circuit. The two supercapacitor modules are the sole power sources in the circuit one of them supply positive voltage to all the components like op-amps and these connections are marked by green, while the other super-capacitor module provides the negative voltage supply to all the components and the connections are marked by red. The biggest win and the innovation in this work is to manage all components to run and function properly even though the input voltage decreases monotonically with time with an objective that the output voltage has to remain constant. This is achieved in our Buck converter design, first by testing a circuit using a real power supply to understand all the components and how they will function when output draws current, in our case about 500mA. Then the power supply was replaced with the super-capacitors modules, which is capable of producing both positive and negative voltage. We have observed that the output voltage remain constant up to 24046.8sec (~ 6.68 hr). It has also been observed that maximum part of energy stored in the supercapacitor modules have been utilised in time period of approximately 6.68 hour, yet some part of the supercapacitor’s energy could not be used. In future we will be devising some other circuit topology that may be capable of utilizing the entire energy stored in the supercapacitors

10. References

[1] Jing, W., Lai, C. H., Wallace, H. S., et al.: ‘Battery-Supercapacitor Hybrid Energy Storage System in Standalone DC Microgrids: A Review’, IET Power Generation, 2017, 11, (4), pp. 461-469.

[2] Hu, A. P., You, Y. W., Chen, F. Y. B., et al.: ‘Wireless Power Supply for ICP Devices With Hybrid Supercapacitor and Battery Storage’, IEEE Journal Of Emerging And Selected Topics In Power Electronics, 2016, 4, (1), pp. 273-279.

[3] Chen, J. J., Hsu, J. H., Hwang, Y. S., et al.: ‘A DC–DC Buck Converter With Load-Regulation Improvement Using Dual-Path-Feedback Techniques’, Analog Integrated Circuits and Signal Processing, 2014, 79, (1), pp. 149-159.

[4] Camara, M. B., Gualous, H., Gustin, F., et al.: ‘DC/DC Converter Design For Supercapacitor And Battery Power Management In Hybrid Vehicle Applications—Polynomial Control Strategy’, IEEE Transactions On Industrial Electronics, 2010, 57, (2), pp. 587-597.

[5] Miller, J. M: Electrical and Thermal Performance of the Carbon-carbon Ultracapacitor Under Constant Power Conditions’. IEEE Vehicle Power and Propulsion Conference, 2007

[6] Rufer, A., Barrade, P: ‘A Supercapacitor-Based Energy-Storage System For Elevators With Soft Commutated Interface’, IEEE Transactions On Industry Applications, 2002, 38, (5), pp. 1151-1159.

[7] Simjee, F. I., Chou, P. H: ‘Efficient Charging Of Supercapacitors For Extended Lifetime Of Wireless

Sensor Node', IEEE Transactions On Power Electronics, 2008, 23, (3), pp. 1526-1536.

[8] 'Maxwell Technologies. Datasheet K2 Ultracapacitors - 2.85V/3400F', http://www.maxwell.com/images/documents/K2_2_85V_DS_3000619EN_3_.pdf.

[9] Mandal, S. K., Bhijwani, P. S., Mohanty, S. P., et al.: 'IntellBatt: Towards Smarter Battery Designs', ACM/IEEE Design Automation Conference, 2008.

[10] 'Merritt R. (2013) Intel Haswell packs integrated voltage regulator', http://www.eetimes.com/doc_id=1263259, accessed 24 May 2017.

[11] Kougianos, E., Mohanty, S. P: 'A comparative study on gate leakage and performance of high-# nano-CMOS logic gates', International Journal of Electronics, 2010, 97, (9), pp. 985-1005.

[12] Maxwell Technologies, Inc. Charging Of Ultracapacitors. Application Note, Document 1008981 Rev 1.

[13] Camara, M. B., Gualous, H., Gustin, F., et al.: 'Design And New Control Of DC/DC Converters To Share Energy Between Supercapacitors And Batteries In Hybrid Vehicles', IEEE Transactions On Vehicular Technology, 2008, 57, (5), pp. 2721-2735.

[14] 'Khare E. (2013). Teenage Girl Invents World's Fastest Mobile Phone Battery Charger', http://www.ibtimes.co.uk/eesha-khare-mobile-phone-charger-google-471247.

[15] 'Maxwell Technologies. Ultracapacitor Flash Memory Application', http://www.maxwell.com/images/documents/Flash_Memory_Application%20Brief_3000690_EN_1.pdf.

[16] Burke, A., Zhao, H: 'Applications of Supercapacitors in Electric and Hybrid Vehicles', 5th European Symposium on Supercapacitor and Hybrid Solutions (ESSCAP), 2015.

[17] Zheng, Y., Chen, H., Leung, K. N.: 'A Fast-Response Pseudo-PWM Buck Converter With PLL-Based Hysteresis Control', IEEE Transactions On Very Large Scale Integration (VLSI) Systems, 2012, 20, (7), pp. 1167-1174.

[18] Tsai, C. H., Chen, B. M., Li, H. L.: 'Switching Frequency Stabilization Techniques For Adaptive On-Time Controlled Buck Converter With Adaptive Voltage Positioning Mechanism', IEEE Transactions On Power Electronics, 2016, 31, (1), pp. 443-451.

[19] Wu, S., Kobori, Y., Kobayashi, H: 'Dynamic Performance Improvement Of DC-DC Buck Converter By Slope Adjustable Triangular Wave Generator', International Soc Design Conference (ISOCC), 2014.

[20] 'Yates A. (2008) Discrete Sawtooth Oscillators. Alan Yates' Laboratory', http://www.vk2zay.net/article/196

[21] 'MAX038. (2007) High-Frequency Waveform Generator', https://www.maximintegrated.com/en/products/digital/clock-generation-distribution/silicon-crystal oscillators/MAX038.html.

[22] Kazimierczuk, M. K., Edström, A. J. : 'Open-Loop Peak Voltage Feedforward Control Of PWM Buck Converter', IEEE Transactions On Circuits And Systems—I: Fundamental Theory And Applications, 2000, 47, (5), pp. 740-746.

[23] Cheng, K. Y., Yu. F., Lee, F. C., et al.: 'Digital Enhanced V2-Type Constant On-Time Control Using Inductor Current Ramp Estimation For A Buck Converter With Low-ESR Capacitors', IEEE Transactions On Power Electronics, 2013, 28, (3), pp. 1241-1252.

[24] Sha, J., Xu, D., Chen, Y., et al.: 'A Peak-Capacitor-Current Pulse-Train-Controlled Buck Converter With Fast Transient Response And A Wide Load Range', IEEE Transactions On Industrial Electronics, 2010, 63, (3), pp. 1528-1538

[25] Smithson, S. C., Williamson, S. S.: 'Unified State-Space Model Of Constant-Frequency Current-Mode Controlled Power Converters In Continuous Conduction Mode', IEEE Transactions On Industrial Electronics, 2015, 62, (7), pp. 4514 - 4524 .

[26] Zhou, G., Xu, J., Wang, J.: 'Constant-Frequency Peak-Ripple-Based Control Of Buck Converter In CCM: Review, Unification, And Duality', IEEE Transactions On Industrial Electronics, 2014, 61, (3), pp. 1280-1291.

[27] Xu, J., Qin, M.: 'Multi-Pulse Train Control Technique For Buck Converter In Discontinuous Conduction Mode', IET Power Electronics, 2010, 3, (3), pp. 391-399.

[28] Cortés, J., Šviković, V., Alou, P., et al.: 'Accurate Analysis Of Subharmonic Oscillations Of V^2 And V^2Ic Controls Applied To Buck Converter', IEEE Transactions On Power Electronics, 2015, 30, (2), pp. 1005-1018.

[29] Šviković, V., Cortes, J. J., Alou, P., et al.: 'Multiphase Current Controlled Buck Converter With Energy Recycling Output Impedance Correction Circuit (OICC)', IEEE Transactions On Power Electronics, 2015, 30, (9). pp. 5207-5222.

[30] Chattopadhyay, S., Das, S.: 'A Digital Current-Mode Control Technique For DC–DC Converters', IEEE Transactions On Power Electronics, 2006, 21, (6), pp. 1718-1726.

[31] Kollimalla, S. K., Mishra, M.K., Narasamma, N. L.: 'Design And Analysis Of Novel Control Strategy For Battery And Supercapacitor Storage System', IEEE Transactions On Sustainable Energy, 2014, 5, (4), pp. 1137-1144.