Micro Controller Based Energy Efficient Four Steps Charging of a Capacitor Using a Buck Converter with Consecutive Changes of its Duty Ratio

Mohammad Sehon Pasha[1], G.C.Prabhakar[2]

M.Tech Scholar, EEE Dept, VNR VJIET, Telangana, India

Assistant Professor, EEE Dept, VNR VJIET, Telangana, India

Abstract: *Since the discovery of Electricity, we have sought effective methods to store that energy for use on demand. Energy efficiency is "using less energy to provide the same service". A capacitor can store maximum energy with respect to input by using direct charging method. In this paper four steps charging of capacitor by consecutively changing the duty cycle of Buck converter. In four step charging, dissipation energy is reduced to one 4th when compared with the conventional direct charging. The reduced dissipated energy is verified by MATLAB simulations and by breadboard experiment with help of Micro controller, which an energy reduction of one fourth is confirmed from the measured power supply currents in four step charging.*

Keywords — *Adiabatic circuit, conventional direct charging method, step wise charging, duty ratio.*

I. Introduction

In engineering field, Energy efficient circuit topic is widely discussed. Adiabatic charging is promising method because it does not dissipate energy. Energy dissipated in capacitor, when charging with constant voltage is $SV^2/2$ where S is capacitance and V is Supply voltage. There is no energy dissipation in adiabatic charging, even if resistance in circuit because moving of change is between voltages is infinitesimally different.

We have two methods of adiabatic charging, One is step wise charging with switched capacitor circuit [1],[2] two is LC resonant circuit with Inductor and load capacitor. For reducing Energy dissipation this two are promising methods.

Now- a- days, another method for stepwise charging of capacitors using inductor current controlled by changing the duty ratio of the switching transistors stepwise. Advantage of this circuit is it does not have tank capacitors and that it does not have to match the load capacitor in LC resonant circuit. The circuit can also open up important applications, energy storage to super capacitors. With adiabatic circuit, we can store energy in electrostatic of capacitor, recover it without dissipation of energy at resistor. Super capacitors are important because they can utilize the output voltage from renewable sources of energy, like wind and solar power. They play an important role in smart grid technology because they are able to store energy when the electricity supply is larger than the electricity demand and release the energy when the demand is larger than the supply.

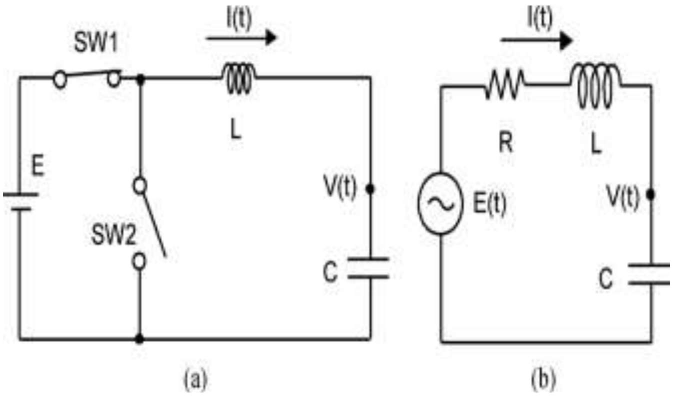


Fig : The DC-DC converter circuits

II.DOWN CONVERSION OPERATION ON LC CIRCUITS

To understand the four steps charging of a capacitor, the conversion operation of a Buck converter with an LC circuit is reviewed first. The circuit is shown in Fig. 1(a). The circuit generates a converted voltage corresponds to the duty ratio by switching S1 and S2 respectively. The switches S1 and S2 are composed of pMOSFET and nMOSFET transistors with resistance R , respectively. Buck converter is equivalent to basic LCR circuit with periodic power supply voltage V(t).

III.STEPWISE CHARGING OF A CAPACITOR

Charging means storing energy in the form of Electric field between the plates of capacitor is charging. Returning this energy to circuit when required is discharging. Corresponding to the duty ratio E,Buck converter generates a constant voltage EV Capacitor charged with voltage EV not by supply voltage V. Now Effective supply voltage EV, by this feature, we can change the duty ratio consecutively and charge the capacitor step wise. The energy dissipation is reduces in charging process of the capacitor by stepwise charging or four steps method than conventional direct charging.

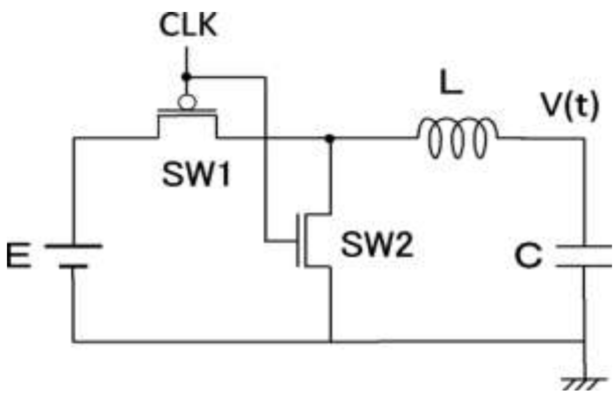


Fig.3. Simulated DC-DC converter circuit with MOS transistor switches.

A. Energy Dissipation in the Charging Process Using a DC-DC Converter:

When capacitor with is charged with Buck converter with the duty ratio E.

Energy dissipation is:

$$\frac{S(EV)^2}{2} = \frac{SE^2V^2}{2}$$

Charging of capacitor from 0V to EV. Energy dissipation when charging a capacitor from 0V to EV under supply voltage V is:

$$E(1\text{-}E/2)SV^2$$

Storage of energy in capacitor is: $S(EV)^2/2$.

We verify by using **MATLAB** Simulations

The final voltage of the capacitor is 1.59 V and the current oscillates between -14.5 mA and 16.5 mA. These values are consistent with the theoretical values of the voltage EV=1.6V and the current $\pm$ E (1-E)TE/2L=$\pm$ 16 mA.

Table I shows measurement results of the consumed power in MATLAB simulations. The D_A is a averaged power consumption over simulation time of 0–1000μs. The D_A is the averaged power consumption over a simulation time of 900–1000μs. The D_B can be regarded as consumed power in resister R, because it is dissipated power after the circuit has reached steady state. Therefore, it gives the consumed power for charging the capacitor, which is injected energy. $V_{inj}=E^2SV^2$ from power for charging the capacitor, which leads to energy of 2.55μJ. Half of the E^2SV^2 is stored in capacitor and remaining half is dissipated in charging process at register as heat in Joule. This value nearly matches the theoretical value of 2.55 E^2SV^2=2.56μJ. Results show that the capacitor is charged under effective power supply voltage of EV=1.6V.

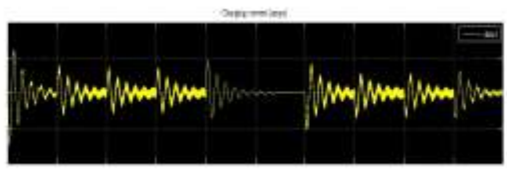
B. Four Steps Charging of a Capacitor

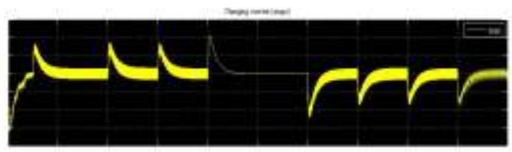
The proposed stepwise charging of a capacitor is to decrease the energy dissipation in the charging process. In this approach, the duty ratio E of the Buck converter is consecutively changed in N steps as E=i/N (i=1,2,3,4…..N).In this section stepwise is verified using MATLAB simulation for N=4.

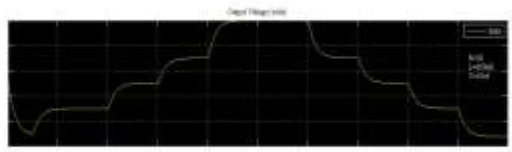
Components with values of L is 1,10, and 20μH with C=1.0μF and T=0.1μs. Duty ratio consecutively changed to 0.2,0.4,0.6, and 0.8. Capacitors voltage increases stepwise to 0.4, 0.8, 1.2, and 1.6 V, which is consistent with EV. Current reaches steady state after a initial large flow. Steady state current then oscillates in between two values, then oscillation amplitude decreases when L increases. Fig. 7 is the magnification of Fig. 6 at around t=154μs. In this case of L=1.0μH, current oscillates linearly between-24 and 23 mA. For L=10 and 20μH, it oscillates between-2.4 and 2.4 mA and between-1.2 and 1.2 mA, respectively. Theoretical values, E(1-E)TV/2L , are 24, 2.4, and 1.2 mA, which are consistent with the MATLAB simulation results.

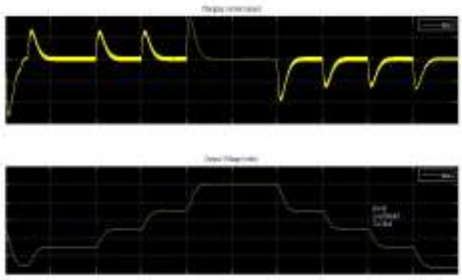
MATLAB RESULTS:

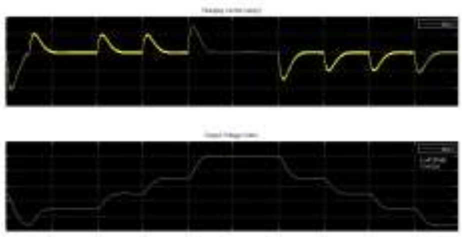
Simulated waveforms of Charging Current and Output Voltage for different R,L,C Values











V. ENERGY DISSIPATION IN STEPWISE CHARGING

We discussed the energy dissipation of step wise charging. Here, set L to 800 µH in order to clarify the energy dissipation in charging process of capacitor. This compresses the contribution of steady state currents to dissipated energy because the currents in steady state are nearly zero. The Joule heat can be decreased by making it small at the steady state. By setting to 800 we can set to 1, 20, 40, and50 to investigate the stepwise charging or four steps in detail. In the following MATLAB simulations T=1.0 µs.

The MATLAB simulation results for C=1µF. Time period for each charging step is 1ms. Average voltage slightly changes by stepwise. The voltage oscillates up to it converges the step value. The current is also oscillates with accordance of I=S dv/dt , meaning that voltage increases more than expected step voltage due to of its oscillation. In general of, a voltage increase up to final step is not a desirable because of the overshoot degrades of reliability of a device. Then, we can decrease the voltage overshoot caused by the oscillation. The oscillation occurs because of k_1 and k_2 in (5) are typical. The k_1 and k_2 oscillation does not occur if they are real. In order to make the real numbers, value of R^2-4L/S should be positive, so value must be increased.

The MATLAB simulation results for S=50µF. Time period for each charging step is 10ms. In this process, the oscillation and overshoot completely disappear. Current increases by largely at beginning and then decreases by monotonically. This type of behaviour is similar to conventional RC charging circuit. The disappearance of oscillation should be satisfy R^2-4L/S for S=50µF .Therefore, R is estimated to 8Ω.

The value is consistent with resistance of switching transistor. In a steady state at t=19ms, the change of current is linearly between-0.3 and 0.3 mA and is also consistent.

Now, we discuss the dissipated energy. Then, we give a brief review on dissipation of energy in four steps charging or stepwise charging. Then duty ratioE is changed in the step E=i/N (i=1,2,...N). During the 4th step of charging, the capacitor is charged from the voltage (i-1)V/4 to iV/4 under the voltage of iV/4 , then the energy dissipation $X_{diss,}$ is given as
Summing-up Xdiss for i from1to4 ,we obtain the total energy dissipation as (9)

$$X(dissp) = \frac{5V^2}{8} \quad (9)$$

The energy dissipation is reduced to1/4th in four step charging when compared with conventional direct charging method.The conventional direct charging corresponds to N=4. The energy store in the capacitor in the 4th step is

$$X(store)=\frac{(2i-1)5E^2}{32}$$

When capacitor is charged to the voltage V, the total energy stored is Estore= given in (11)

$$X(store)=\sum_{i=1}^{4} X,i = \frac{5V^2}{2}$$

The MATLAB simulated values for E=0.4,0.6,and0.8. Then,the values for charging the capacitor are similarly calculated as 6392, 9604, and 12808 nJ for E= 0.4, 0.6, and 0.8, respectively. The theoretical EVΔZ values are 6402, 9604, and 12806 nJ, which are consistent with simulated Matlab values. We consider energy efficiency of four steps charging process. The total X for charging the capacitor is the sum of 3192,6394,9607,and12809nJ,which is 32002 nJ. Electrostatic energy of capacitor is SV2/4, which is calculated as 22µF.(1.6)2/2=25608nJ.The energy dissipation is the difference between the total for charging capacitor and capacitor's electrostatic energy.

Then, the energy dissipation is 32002-25608=6394 nJ .In conventional method constant voltage charging, energy dissipation is equal to25608 nJ (=SV2/2). Then, the energy dissipated decreased to 6394/25608=24.96%, which is the consistent with theoretical value of one fourth for four step charging. We can confirm the energy dissipated decreased to one fourth when S=40µF and S=50µF .

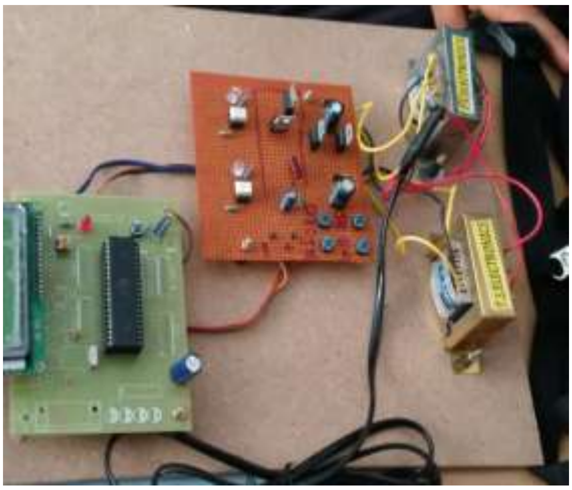
The Matlab simulated power consumptions are 13µW and108µW at 4 MHz for circuits by using power supply voltages of 1.8V and 3.3V respectively. The total power consumption is 121µW,which includes the power consumption caused by the gate capacitances of the switch transistorsThe saved energy for four step charging to direct one step charging is (SV2/2)(3/4)=75µJ.A switching loss of 182nJ is negligible, as it is about 1/400 to the saved energy of 75µJ .If the switch sizes are same, these ratio does not change because of save energy and the charging time are proportional to capacitance(S).

VI. EXPERIMENTS USING BREADBOARD CIRCUIT WITH MICRO CONTROLLER:

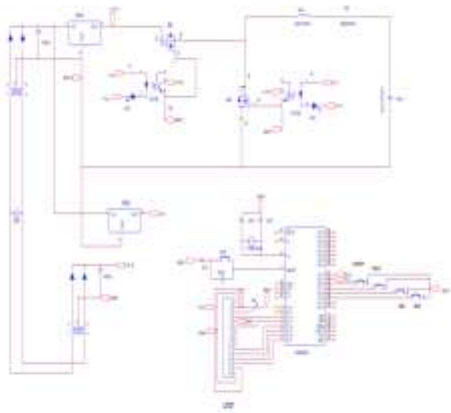
We can show the reduction of dissipated energy through breadboard experiment by the help of micro controller. The breadboard is shown in Fig. 9. The circuit parameters are V=12v,L=500µH (micro inductor), S=100µF and T=10µs . Analogy Devices' AT89S521 is used for two switches. Duty ratio is changed in four steps and eight steps charging. Capacitor is charged stepwise from 0 V to 12 V by changing E and discharged stepwise from 12 V to 0 V by changing inversely also. Observed waveforms are shown in Figs. 10 and 11 for the four steps and eight steps charging process.

Measured data of output voltages and average currents are shown in Table III. Then average currents in "Stepwise Charging or Four steps charging" column are averages of currents after circuit has reached steady state in every stage of stepwise charging. Then the averaged currents in the "Char/Discharge" are the averages of currents over total time of the stepwise charging and the stepwise discharging. The "Char/DischarGE" includes the steady state currents. Therefore, the difference between "Char/Discharge" and "Stepwise Charging" gives the consumed currents corresponding to the energy dissipation when charging the capacitor.

HARDWARE KIT:



INTERNAL DIAGRAM OF HARDWARE:



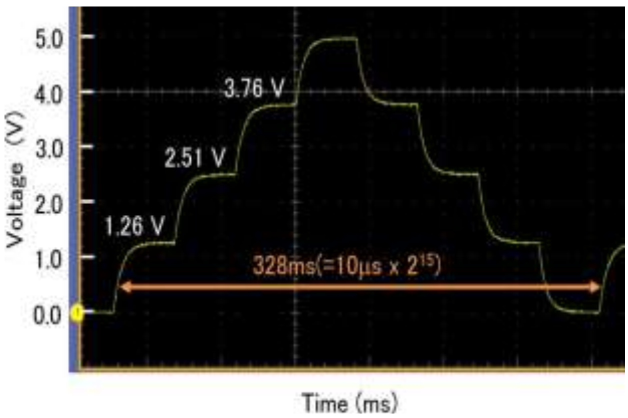


Fig.10. Four step charging and discharging for L=500µH and C=500µF

MEASUREMENT RESULTS:

	α	Four step Output Voltage	Four step Average Current	Eight step Output Voltage	Eight step Average Current
Stepwise Charging	0.125	—	—	0.63 V	0.14 mA
	0.250	1.26 V	0.40 mA	1.25 V	0.40 mA
	0.375	—	—	1.88 V	0.61 mA
	0.500	2.51 V	0.70 mA	2.51 V	0.69 mA
	0.625	—	—	3.14 V	0.62 mA
	0.750	3.76 V	0.40 mA	3.76 V	0.42 mA
	0.875	—	—	4.40 V	0.14 mA
Stepwise Char/Dischar			0.80 mA		0.60 mA
Direct Char/Dischar			1.60 mA		1.60 mA

VII. CONCLUSION

We propose the four steps charging of a capacitor using a Buck converter by changing the duty ratio successively. The energy dissipation is reduced to one 4th in 4 steps charging. When compared with conventional direct charging. The reduction in dissipated energy was confirmed experimentally using discrete IC circuits built on a breadboard for four and eight step charging.

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