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RESEARCH ARTICLE

DETAILED LOSES OF INTERNAL CAPACITOR

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ABSTRACT

This paper presents a review on the detailed capacitor model and it includes theoretical literature and suggestions how to measure capacitors properties at the laboratory. Theoretical part gives idea about how the capacitors work, its charging and discharging, its non-linear behaviors and capacitor types. Non-linear behaviors are presented and explained in details how to calculate them theoretically. Besides this the paper suggest some methods to measure dielectric absorption and Equivalent series resistance (ESR) at the laboratory and gives and a simple alternative technique to measure ESR. The method uses a switching DC-DC boost regulator to measure the ESR. This method is very simple in technique, consumes very little time and requires only simple instruments.

Conclusions: This project contains research about capacitor detail and its application in power electronics. With detail, we will see the capacitors behave and internal circuit characteristic design with mathematical calculation especially with ESR. The first part of this paper show the main capacitor internal circuit component design and behave in power electronic circuit charging, discharging, and internal electric field. The paper shown test of the ESR effect on the internal circuit of the capacitor circuit and analysis of modelling design with effect of the losses on the output of the DC-DC converter represented as increasing or decreasing ripple voltage and current with capacitor value. In general, the Equivalent Series Resistance (ESR) is termed as real resistive capacitor component. The capacitor ESR depends on the capacitor type and design. It will change by changing the frequency and temperature according to the company data sheet. The capacitor ESR has effect on the output ripple voltage, and current of DC-DC boost converter. It will increase or decrease according to the value of the capacitor. The ripple output voltage decreases by increasing the value of capacitor. The electronic companies try to design the capacitor as ideal as possible with less losses, by changing the internal design, and searching for new material that has less losses and perfect performance.

INTRODUCTION

Capacitance is the ability of a circuit or device to store electrical charge. a component specifically designed to have this capacity or capacitance is called a capacitor.Capacitor will charge by the source, store the energy and it will return back almost all energy back to the circuit rather than lose it in wasted heat, which the resistance does. Capacitance consists the two or more conductive metal in parallel, which are not connecting or touching each other. The plates are separated electrically by insulating material (flex mica, plastic). The insulting material between the plates named Dielectric as shown in figure (1) [1].

The unit of capacitance is farad (F). a capacitor with a capacity of 1 F can store 1 coulomb of electrical charge, which is $6.24*10^{18}$ electrons if 1 volt is applied across the capacitor plates. Capacitor is wholly characterized by a constant capacitance *C*, defined as the ratio of charge $\pm Q$ on each conductor it has the voltage *V* between them Eq (1)

$$C = \frac{dQ}{dV} \quad (1)$$

Theory and model

(a) Parall palte conductor model: This capacitor model has parallel plates Fig (2) and its capacitance is related with proportional area a, and inversely with distance between the plates or dielectric electric thickness d. Their relation gives us the capacitance value Eq(2)[2]

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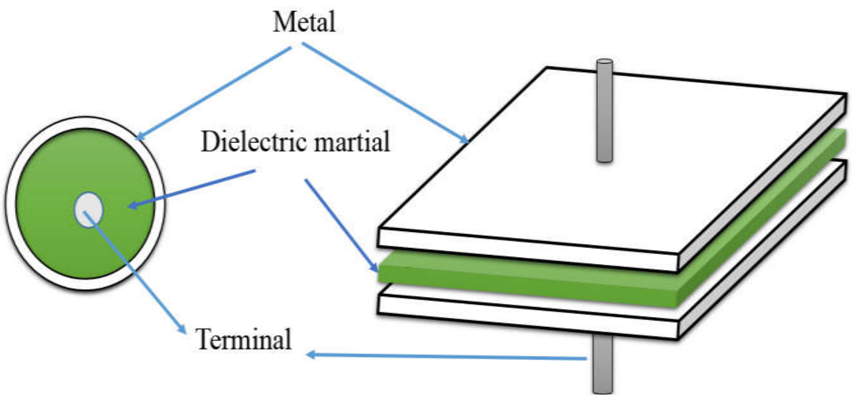


Fig.1. Capacitance material

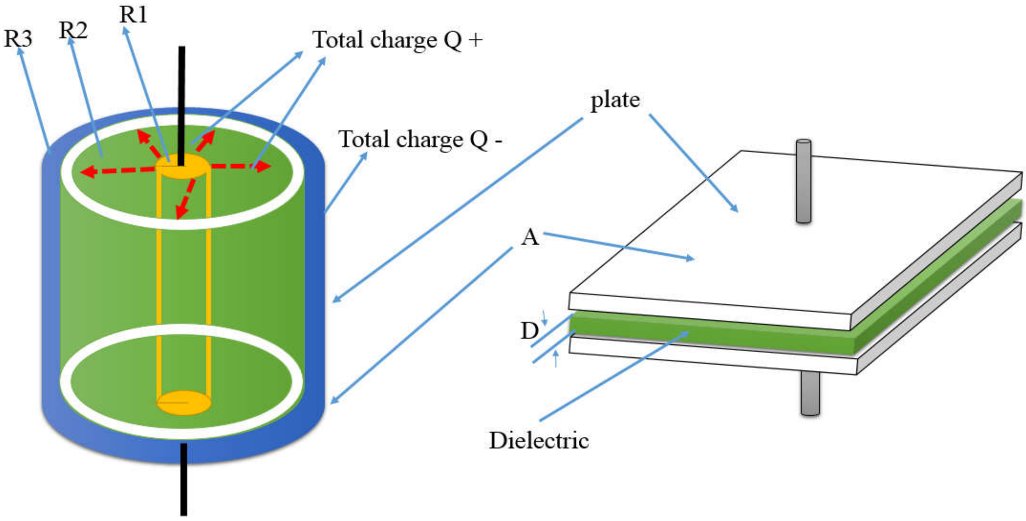


Fig.2. Capacitance plates

$$C = k*(A/d) \qquad \text{.......................... (2)}$$

The plate conductivity in capacitance is separated by Air or one of the different type's insulated materials. Well different materials have their own characteristics and permittivity. This parallel plate model can be an example for us to understand the other types of geometries. Here is the permittivity relation for other insulting materials rather than free-space: Eq(3)

$$\varepsilon = \varepsilon_0 * \varepsilon_r \qquad \text{.............................(3)}$$

Than the capacitance becomes: Eq(4)

$$Capaci\tan ce, C = \frac{\varepsilon_0 * \varepsilon_r * A}{d} \qquad \text{.............................(4)}$$

The charge on the plates of the capacitor is given as: Eq(5)

Q = C*V …………………………….(5)

Capacitance Electric Field: After an external influence (source) is applied to the capacitor, the charge moves between capacitor conductors. On the other hand the charge will find its equilibrium position after the source is removed and the charge is allowed to release Fig(3) To find the work, which is done, we have to first define the energy that is stored. Eq(6) [2]

$$W = \int_0^Q V\,dq = \int_0^Q \frac{q}{C}dq = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2 = \frac{1}{2}VQ \qquad \text{.................................(6)}$$

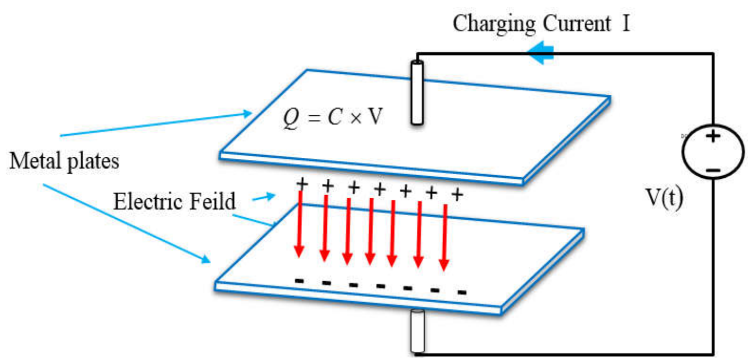


Fig.3. Capacitance electric field

The power flows into the capacitor or out of capacitor when the voltage $V(t)$ applied is changing in time. The power can be found by taking the derivative of the stored energy Eq(7)

$$P = \frac{\partial W}{\partial t} = \frac{\partial}{\partial t}(\frac{1}{2}CV^2) = CV(t)\frac{\partial V}{\partial t} \quad \text{.....(7)}$$

Impedance and reactance: Ac circuits have capacitive reactance is only the opposition current flow in the circuit. Where the resistance is ohm represent by X to make it different to pure resistive value. Xc is the symbolor capacitive reactance for capacitive in AC circuit. In simple way we can say that Xc is the resistance that varies with (f) frequency and it's depend on value of capacitance in F farad Eq(8) in Ac circuit.

$$X_C = \frac{1}{wC} = \frac{1}{2\pi fC} \quad \text{.....(8)}$$

Impedance Eq(9) (inductive or capacitive) describes the phase shift and ratio of amplitude between current varying and voltage varying in sinusoidal waveform at given frequency f.

$$Z = \frac{1}{jwC} = -\frac{j}{2\pi fC} \quad \text{.....(9)}$$

DC charging and Discharging Capacitor: It takes a certain time to charge and discharge the capacitor with the energy. Time for charging and discharge in capacitance depend on resistance value in RC circuit and the capacitance that we have in witch can represent by time constant(τ) Eq(10). If the capacitor is connected to a resistance in series circuit RC, the current through the resistance will charge the capacitance in during time τ until the capacitor is filled with supply voltage. Transient response, which is about 5 time constant (5τ) is the time required to fill the capacitor with the supply voltage.

$$\tau = R \times C \quad \text{..... (10)}$$

This Fig (4) shown that resistance R, and capacitance C connected in series named RC circuit connected to the voltage supply DC battery (Vs) and controlled with the mechanical switch-t and V-t curves are showed in the Fig (5) above where the switch was closed and capacitor started to charge up.

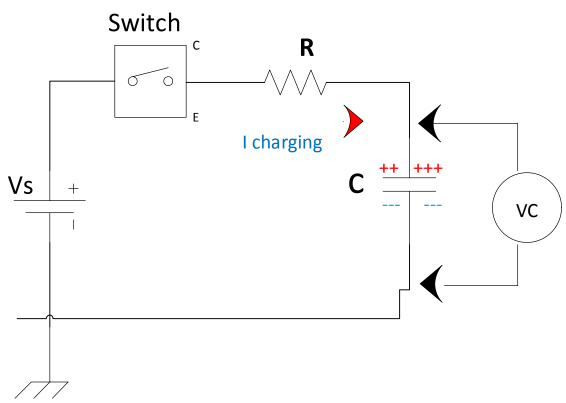


Fig. 4. RC series circuit

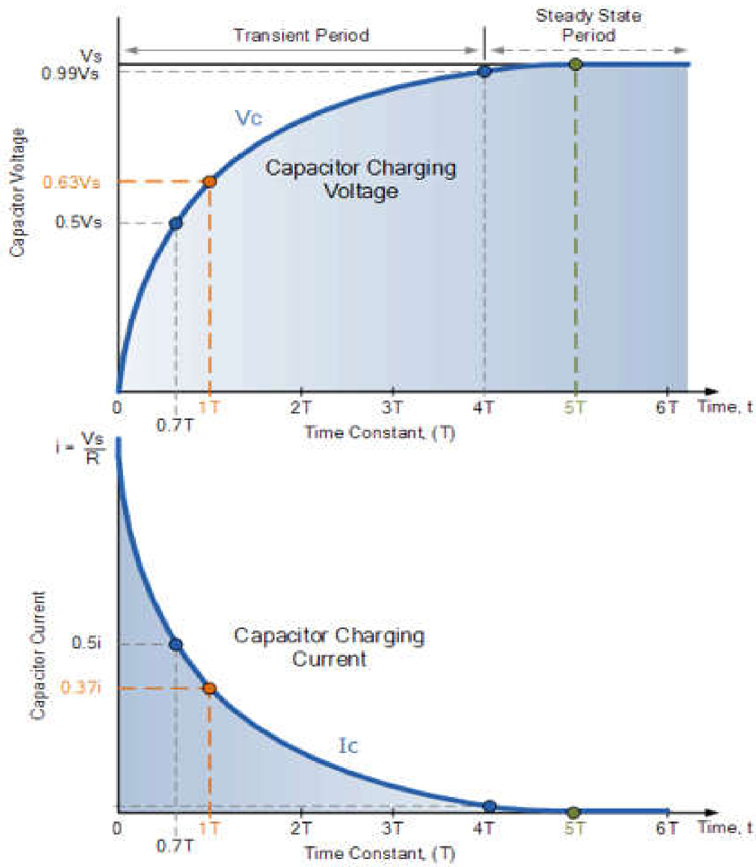


Fig. 5. Capacitance in chagrining mode [2]

The charging rate is faster at the beginning and it is followed with the slower rate afterwards. As it shown in the figure, the capacitor was able charge %63 of the input voltage in 1 time constant. The different between source voltage and the capacitor voltage decreases, same as circuit current. After 5τcapacitor manages to fully charge itself. (It can never be charged 100%) Capacitor voltage (Vc) is represented in below at any instant time during the charging period Eq(11)

$$V_C = V_S(1 - e^{-t/RC}) \quad \text{..(11)}$$

If we have short circuit applied to the circuit Fig (6) by removing the battery and mechanical switch is closed again, the capacitor will start to discharge itself through the resistor as now we have RC discharging circuit. The voltage across the capacitor will go to zero as it shown in the Fig (7) the discharging curve is sharper at starting point because the discharging rate is higher. When the discharge continues, the rate slows down due to Vc goes down and so the discharging current. The capacitor manages to "fully discharge" itself in 5 time constant (5 τ) as it was with the charging. Capacitor voltage (Vc) is represented in below at any instant time during the discharging period Eq(12)[2]

$$V_C = V_S \times e^{-t/RC} \quad \text{(12)}$$

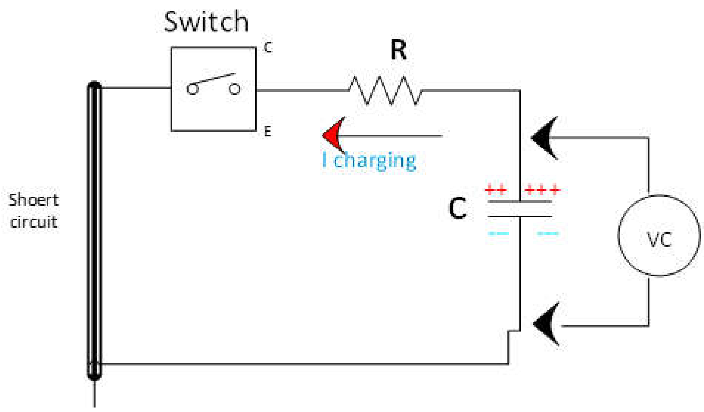


Fig .6. Voltage source in short circuited

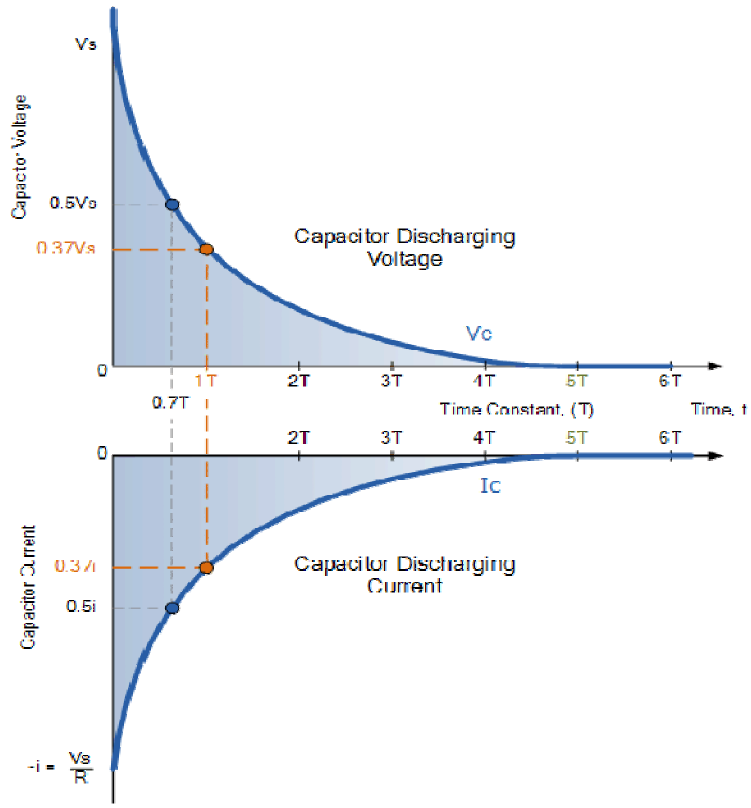


Fig. 7. Capacitance discharging mode

EQUIVALENT series resistance (ESR)

Complex impedance consists of two parts at a certain Fig (8) frequency, the real part and the imaginary part. The impedance Eq (13) acts like a combination of resistance Rs and reactance Xs where ESR equals to real part of Z Eq(14)

Z= Rs+ JXs ……………………………….(13)

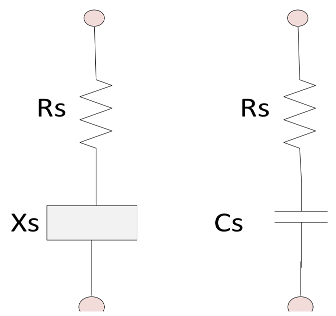


Fig. 8. ESR resistance in series

$$ESR = Rs = real\ part\ of\ Z \qquad \ldots(14)$$

First we have to define dissipation to calculate main losses in a capacitor in ESR.Eq (15), (16)

$$D = \frac{energy\ lost}{energy\ stored} = \frac{\mathrm{Re}(Z)}{-\mathrm{Im}(Z)} = Dissipation\ factor \qquad \ldots(15)$$

$$D = \frac{energy\ lost}{energy\ stored} = \frac{\mathrm{Re}(Z)}{-\mathrm{Im}(Z)} = Dissipation\ factor \ (15)$$

$$D = \frac{R_S}{-X_S} = R_s wC = (ESR)wC \quad (16)$$

Main loss sources in the actual Capacitance Actual Series Resistance There is some small amount of loss in leads and plates due to resistance of conductors Eq (17)

$$D_1 = wR_{as}C \qquad \text{.............................(17)}$$

Leakage resistance there is a resistance in the capacitor due to leakage current. This resistance is high and we call it R_L. This resistance is parallel resistance to the capacitor and highest for plastic capacitors. The leakage current causes Eq(18)

$$D_2 = \frac{1}{wR_L C} \qquad \text{..............................(18)}$$

In addition, it is generally negligible at high frequencies. Dielectric loss Fig (9) occurs because of the interfacial polarization and phenomena molecular polarization * absorption in dielectric*!where its acts as parallel resistance or series resistance that will pass the Dc. In illustration dielectric resistance R_D is a parallel resistance, which is variable with frequency, with DC blocked by large series capacitance (C_B) Fig (11) where All capacitance losses

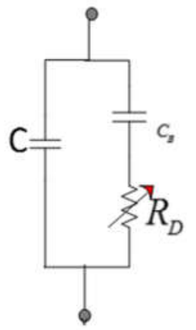


Fig. 9 Dielectric loss

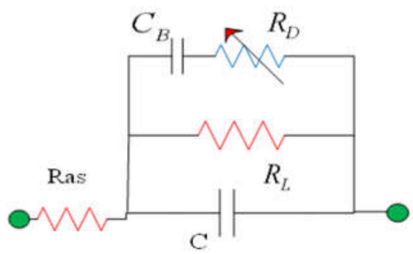


Fig. 10. All capacitance

In this case D_3 will be: Eq(19)

$$D_3 = \frac{1}{WR_D C} \qquad \text{........................... (19)}$$

All the source of in figure we have dissipation factor Eg(20),(21) Fig (11)

$$D_{eq} = D_1 + D_2 + D_3 \qquad \text{...........................(20)}$$

$$D_{eq} = D_1 + D_2 + D_3 = wR_{as}C + \frac{1}{wR_L C} + \frac{1}{wR_D C} \qquad \text{............................(21)}$$

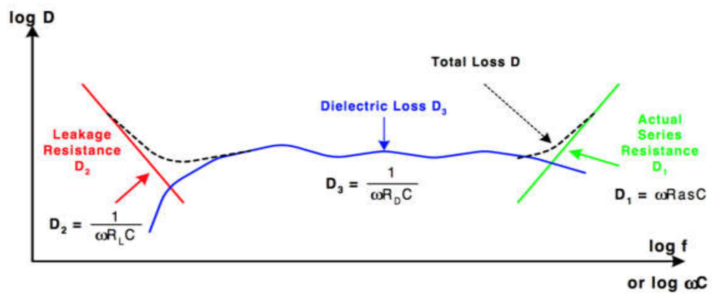


Fig. 11. General plot of the combination series and parallel In capacitance measurement

To find the ESR, we should measure the RsEq(22)which is the real part of the impedance or we would measure C and D and calculate the ESR Eq(23)

$$R_s = ESR = \frac{D}{wC} + \frac{1}{w^2C^2R_L} + \frac{1}{w^2C^2R_D} \qquad \text{..........................(22)}$$

$$ESR = R_{as} + \frac{1}{w^2C^2R_L} + \frac{1}{w^2C^2R_D} \qquad \text{.............................(23)}$$

Thus always $ESR > R_{as}$

Generally, Ras is much less than ESR but in high frequency with high capacitance value, R_{as} can be the largest part of the D as it shown in the figure. At low frequency it is the small part of D with ESR

Table. 1 percentage absorption for different dielectric material [1]

Dielectric Material	PERCENTAGE DIELECTRIC ABSORPTION (Typical %)
PARYLENE	0.1 - 0.25
POLYCARBONATE	0.1 - 0.25
TEFLON	0.02
POLYSTYRENE	0.02 - 0.05
POLYESTER	0.3
MICA	0.7 (varies)

Non- ideal behaviors of capacitors

Dielectric Absorption

Dielectric absorption is an important parameter in a capacitor. It is a property of the dielectric material and explained as a tendency of a capacitor to recharge itself a small amount even it is short circuited for a short time. It prevents the capacitor to discharge completely. It occurs when the capacitor remains charged for a while and shorted. Than the capacitor will recharge itself slowly. This recovery will be around 0.01% to 10% of its value. The dielectric absorption is not considered in the ceramic capacitors but it occurs primarily in the film capacitors. In addition, it can also be a consideration for low voltage ceramic capacitors than the larger ones. The amount of the dielectric absorption is highly dependent on the dielectric material. [3]

Dielectric absorption can be measured by following these steps: table (1)

- For 4 - 24 hours' capacitor has to be short-circuited.
- Charge it to a rated voltage.
- Discharge it for 5 - 10 seconds through a 5 Ohms resistor.
- Use a millimeter with an impedance of 10^{10} to measure the maximum recovery voltage in 1-10 minutes.
- Absorption recovery voltage will be calculated as a percentage of the charging voltage.

Ripple current

Ripple current defines AC portion of the current signal in a device. Even it refers to an AC portion of the applied signal, it is defined as a little variation of DC signals. It causes heat in the capacitor. Although the EIA has standards for calculating ripple current ratings, Ripple current ratings for capacitors are arbitrary. The method of calculating the ratings varies from one manufacturer to another. It is possible to derive a general formula for ripple current capability by using the elementary physics. The power generated in a capacitor or rate of heat generation Eq(24)

$$P_{gen} = I_{rms}^2 \times ESR \qquad \text{…………………………… (24)}$$

The rate of heat removal P_{rem} from the capacitor Eq(25)

$$P_{rem} = \Delta T / R_{th} \qquad \text{…………………………..(25)}$$

At steady state, two expressions are equal and we can solve for the temperature rise due to the ripple current heating ΔT Eq(26)

$$\Delta T = I_{rms}^2 \times ESR \times R_{th} \qquad \text{…………………………..(26)}$$

Ripple current an effect on the capacitor to raise its core temperature. It is necessary to define the maximum $\Delta T_{\max}$ to calculate rms ripple current. When we define $\Delta T_{\max}$, the maximum power becomes Eq(27) [5]

$$P_{\max} = \frac{\Delta T_{\max}}{R_{th}} \qquad \text{…………………………...(27)}$$

To find the maximum allowable rms ripple current Eq(28) we combine Eq(26)and (27)

$$I_{\max} = \sqrt{\frac{P_{\max}}{ESR}} \quad \text{...(28)}$$

AC ripple current will generate AC component of voltage across the capacitor. The rms AC voltage can be calculated from Ohm's law Eq(29)

$$E_{rms} = Z \times I_{rms} \quad \text{...(29)}$$

This can be converted to a peak AC voltage Eq(30)[5]

$$E_{peak} = \sqrt{2} \times E_{rms} \quad \text{...(30)}$$

Different ripple current observations for different types of capacitors

- Tantalum electrolytic capacitors with solid manganese dioxide electrolyte have ripple current limitation and they have the highest ESR ratings among capacitors. Shorts and burning parts can occur by exceeding the ripple limits.
- Aluminum electrolytic capacitors suffer a shortening of life expectancy at higher ripple currents. Exceeding the rated value of the capacitor may end up with explosive failure.
- Ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.
- Film capacitors have very low ESR ratings but exceeding rated ripple current can cause some failures.

Leakage current

In a capacitor there is always a small current flowing through the dielectric material. It is because the dielectric used in the capacitor is not a perfect isolator. The powerful electric field on the plates causes this leakage current when it is applied a constant supply voltage. This DC current is in nano-amper (nA) level and named leakage current of the capacitor. Leakage current occurs on the edge of the plates and it can discharge the whole capacitor in some time if there is no power supply connected.The problem usually seen in the vacuum tube circuits and specifically where the oiled paper and foil capacitors are used. Insulation resistance R_L refers to the leakage current Fig (13) in a film or foil capacitors shown in the figure as a resistance.

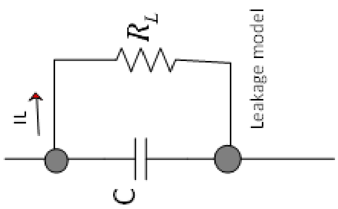


Fig. 12. Leakage current

We can also say that Electrolytic-type capacitors have high capacitance but they also have high leakage current because of their poor isolation resistance. For this reason, they are not used for storage or coupling applications. In addition, the leakage current of the aluminum electrolytic capacitors increases with the temperature

Measurement Technique of Capacitor (esr)

This technique aims to measure the Equivalent Series Resistance (ESR) simply using DC-DC boost regulator. The technique is really low time consuming and requires simple circuit. It is very important to measure ESR for a capacitor since it is really beneficial use to find solutions for stability issues.

General Method

This method is actually the pole-zero analysis method. External resistance is required to chosen so that the pole that is created by external resister and the capacitor is in a minimum separation 2 decade with the zero generated. There is no limitation for choosing the external resistance. There can be only some limitations because of the oscilloscopes probe related to attenuation of the signal generation at high frequency. It is necessary to the pole where the phase difference is 45 degrees after the RC network is settled. The 45 degrees' difference is between input and output. Now we will increase the frequency until it starts decreasing. The zero is founded when the difference becomes 45 degrees again while decreasing.

The relation between R_{ESR} Eq(31) and frequency at the point zero is founded is:

$$R_s = 1/(2 \times \pi \times f \times C) \quad \text{………………………..(31)}$$

There are some other methods to find the R_{ESR} which measures voltage and current during the charging of the capacitor and discharging the charged capacitor simultaneously.

Proposed Method

This method is really easy to apply and it is not time consuming to follow and finish the procedure. A simple oscilloscope is required to apply the method. Six simple steps form the method:

- Connect any boost regulator in a board where the capacitor under test is connected at the output node. The cap must be placed very close to the Schottky diode (or V_{OUT} pin for synchronous booster). Reference IC: MPS1518
- Check the inductor current wave (DC coupled) and V_{OUT} Node Voltage (AC coupled, 50mV/ DIV)
- Check for sharp V_{OUT} node voltage change during
- TON-TOFF transition
- Find del V = V_{OUT} (just after transition) - V_{OUT} (just before transition)
- Find I_{PK} = peak value of inductor current (right at the moment of transition)
- $R_{ESR} = (del\ V)/I_{PK}$

Advantages of Proposed Method

This method has several useful advantages over the general technique

- It is easy to apply and test
- Very little time consuming to perform
- No error correction is necessary
- There is no boundary limitation of ESR

RESULT OF CAPCITOR EXPREMINATAL

Test capacitor with (BOOST CONVERTER)

From the measture discussion methods by putting the capacitor in boost circuit as in Fig (13) the schematic view of the booster. NFET controls the SW node to charge during T-ON

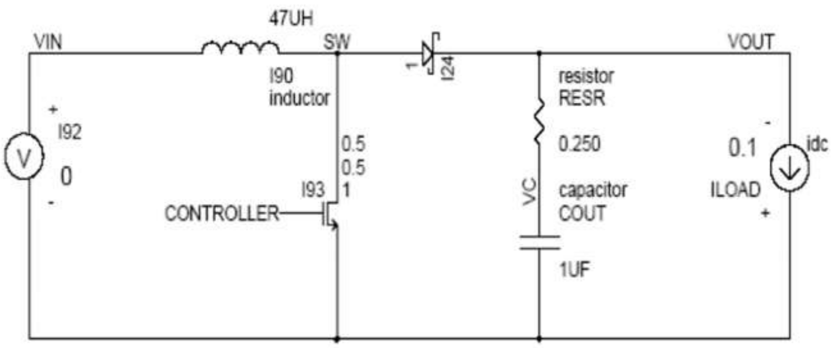


Fig. 13. booster circuit diagram

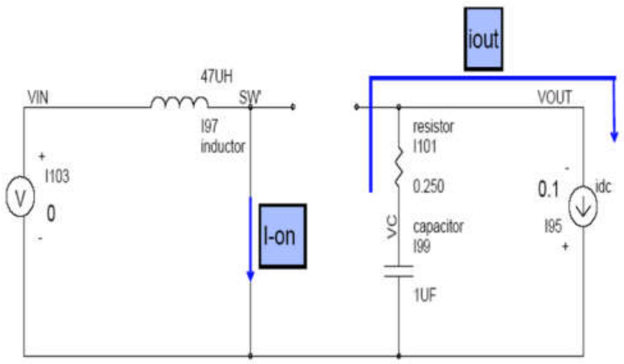


Fig. 14. Current path T-On

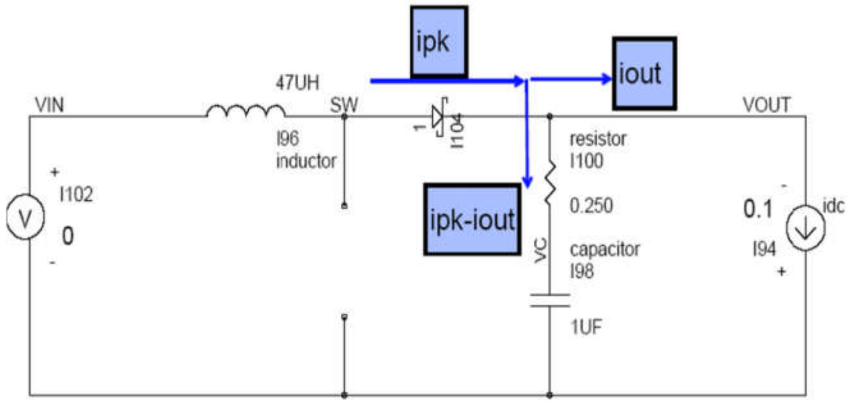


Fig. 15. Current path T-OFF

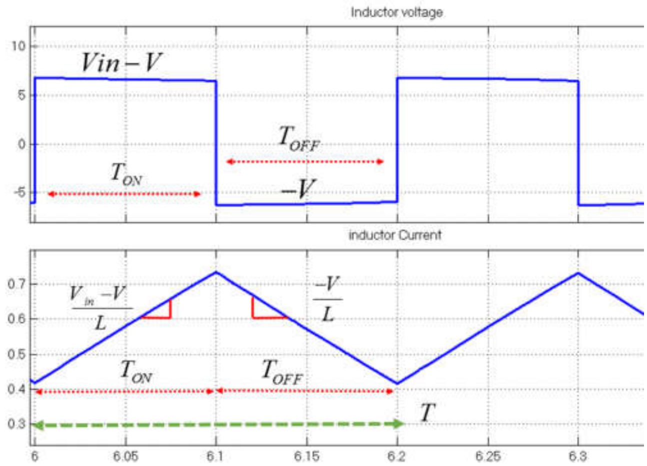


Fig. 16. Current path during the T-ON phase

By solving the Kirchhoff's voltage law around outer loop during the charging phase gives Eq(32)

$$V_{C1} = V_{OUT1} + I_{OUT} \times R_{ESR} \quad \text{……………………(32)}$$

BOOST PHASE: TOFF Applying again the Kirchhoff's voltage law around outer loop gives Eq(33)

$$V_{C2} = V_{OUT2} - (I_{PK} - I_{OUT}) \times R_{ESR} \quad \text{……………………..(33)}$$

Eq(32) is for T-ON and Eq(33) is for T-OFF. It is necessary to those two equations and at the T-ON, T-OFF phase transition boundary we have Eq(34) Fig (15) (16)

$$V_{C1} = V_{C2} \quad \text{……………………(34)}$$

Because voltage across the capacitor doesn't change momentarily. Using the Eq(34) and combining with the Eq(34) we get Eq(35) [3]

$$V_{OUT2} - V_{OUT1} = I_{PK} \times R_{ESR} \quad \text{……………………………..(35)}$$

At the end we finalize with the R_{ESR} Eq(36), (37)

$$R_{ESR} = (del\ V) / I_{PK} \quad \text{………………………………(36)}$$

Where

$$del\ V = V_{OUT2} - V_{OUT1} \quad \text{……………………………..(37)}$$

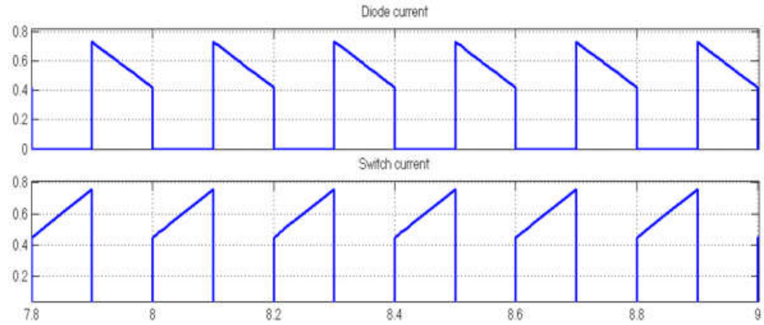


Fig. 17. Current path during the T-OFF phase Diode

Other experiment shown as in Figure (18) the output of the boost converter capacitor current with load current as in Fig (18) [7]

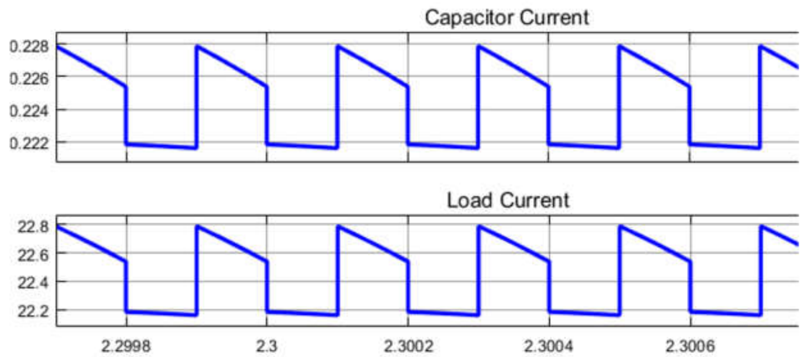


Fig. 18. Load current with capacitor current

Type of capcitor in power electronics

This type of capacitor is an example from two different companies (kemet and TDK), both of them using almost the same information, but with diffrent internal circuit design, dielectric material, and shape [4]

Table 2. Type of capacitor with internal circuit

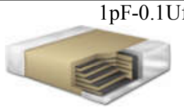
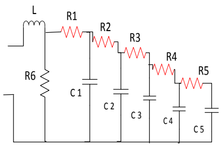
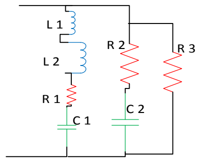
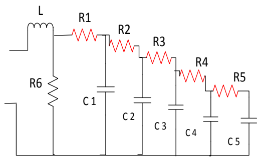
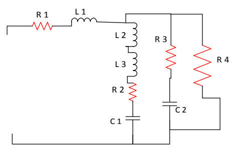
Type	Electrolytic Aluminum	Ceramic	Tantalum	Polymer
Range	100uF-10000uF	1pF-0.1Uf	0.1uF-100uF	10-1000uF
Figure				
Internal Constriction				
How it is made	1- Etched foil with liquid Electrolyte 2- Placed in a can with a seal/vent	1- Alternating layers of electrodes covered with ceramic dielectric	1- Tantalum Anode pressed around a tantalum wire 2- Oxide grown on surface 3- Cathode it formed by dipping and heat conversion Monomer to MnO2 with 4- Epoxy encapsulated	1-Tantalum Anode pressed around a tantalum wire 2- Oxide grown on surface 3- Cathode formed by dipping into Monomer and cured at room temperature 4- Epoxy encapsulated
Advantages	1-Low cost materials. 2-High capacitance available value 3-Long history many manufacturers choose from	1- Low cost materials 2- Reliable and rugged 3- Notarized	1- Lots of capacitance in a small package 2- Easy to control 3- Numerousmanufacturers	1- New technology for design 2- High capacitance per unit volume 3- There is no any voltage coefficient
disadvantage	1- Large swings ESR and ESL with temperature. 2-eventually degrade over the life of the product. 3- Have large DC leakage current	1- Power supply not stable with ceramic output capacitor 2- Difficult to control 3- Coefficient voltage And temperature reduce capacitance value	1- High cost 2- Limited inrush surge current capability 3- Limited voltage range 50V rating max	1- High cost 2- Voltage capability surges depend on the chemistry 3- Tend to be from a single supplier
ESR - ESL	High	Low	Low	Low

Table 3:Boost circuit data circuits

Variables	Values of Boost DCM	SI unit
Capacitance	600E-6	F
Inductance	400E-3	H
Load resistance	100	Ω
ESL (RL)	0.5	Ω
ESR	1	Ω
Input voltage	12	V
Amplitude voltage source	1	V
Period	2E-4	sec
Pulse Width (D)	30	%
Phase delay	0	sec

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