Efficiency Improvement of LDO Output Based Linear Regulator With Supercapacitor Energy Recovery – A versatile new technique with an example of a 5V to 1.5V version

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Abstract

Supercapacitors are used in various industrial applications , and the supercapacitors technology is gradually progressing into a mature state. Common applications of supercapacitors are in electric vehicles, hybrid electric vehicles, uninterruptible power supply (UPS) and in portable devices such as cellular phones and laptops. The capacitance values range from fractional Farads to few thousand Farads and their continuos DC voltage ratings are from 2V to 6V.

At University of Waikato, a team works on using supercapacitors for improving the efficiency of linear voltage regulators. In particular, this patented technique aims at combining off the shelfs LDO ICs and a supercapacitor array for improving end to end efficiency of linear regulator.

My work is aimed at developing the theoretical background and designing prototype circuitry for a voltage regulator for the case of unregulated input supply is more than 3 times of the minimum input voltage requirement of the LDO which is applicable for a 5V to 1.5V regulator. Experimental results are indicated with future suggestions for improvement.

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Chapter 1 – Introduction

1.1 Background

With the high demand of worldwide portable electronic products such as notebooks, PDAs, camcorders, digital cameras, mobile phones and laptops, its boosts the needs for a compact, lightweight and powerful energy storage than ever. In these circumstances, time is very high. This is due to incorporation of more features required in mobile electronics product and also for a wireless network application. The manufacturers of these portable products have spent a lot of time and money towards research to optimize power usage and efficiency; including power management circuits and new battery technologies. The optimization in these two areas must be parallel with the environmental impact of the product as well.

1.2 DC-DC Converter

DC-DC converter is an electronic circuit that converts a source of direct current (DC) from one voltage level to another level, either lower or higher voltage than the input. There are two types of dc-dc converters: linear and switching regulator. A linear regulator has more advantages compared with switching regulator in terms of cost and output noise but it comes with low efficiency. Table 1 below is the comparison of basic differences between linear regulator and switching regulator.

Table 1.1 : Comparison basic differences between linear and switching regulator

	Linear	Switching
Function	Only steps down; input voltage must be greater than output.	Steps up, steps down, or inverts
Efficiency	*Low to medium, but actual battery life depends on load current and battery voltage over time; high if V_{IN}-V_{OUT} difference is small.*	*High, except at very low load currents (μA), where switch-mode quiescent current is usually higher.*
Waste Heat	High, if average load and/or input/output voltage difference are high	Low, as components usually run cool for power levels below 10W
Complexity	Low, which usually requires only the regulator and low-value bypass capacitors	Medium to high, which usually requires inductor, diode, and filter caps in addition to the IC; for high-power circuits, external FETs are needed
Size	Small to medium in portable designs, but may be larger if heatsinking is needed	Larger than linear at low power, but smaller at power levels for which linear requires a heat sink
Total Cost	Low	Medium to high, largely due to external components
Ripple/Noise	Low; no ripple, low noise, better noise rejection.	Medium to high, due to ripple at switching rate

From the table above, generally linear regulators have more advantages than switching regulators in term of simplicity and cost but not efficiency. Due to this factor, a study has been carried out to increase the efficiency of LDO linear regulator. The efficiency of the LDO is increased using supercapacitor energy recovery technique that has been successfully developed in 12V to 5V regulator.

1.3 Supercapacitor

As we know, capacitors are to store energy and normally in the range of microfarad to picofarad. The technology of supercapacitors (also known as ultracapacitors) came into wide usage in the industry a decade ago. The supercapacitors value had increase up from few Farads until 5000 Farads. This makes supercapacitors store more energy than the normal capacitor. Due to very large capacitance value in supercapacitors, if ideal, they can be used as lossless voltage droppers in the series path of a linear regulator circuit, without blocking the circuit for a reasonably longer time.

1.4 Low Dropout (LDO) Regulator

Low dropout regulator is a linear regulator that can operate even when the difference between input and output voltage is small. The advantages of low dropout regulators are including lower minimum operating voltage, high efficiency, noise sensitive, fast transient load and lower heat dissipation. The application of LDO is suitable to be applied to this technique because the minimum input of the LDO will be 1.6V and the output of the LDO 1.5V. This means very low dropout between the input/output voltages that is only 100mV.

Chapter 2 – Literature Review

2.1 DC-DC Converter Fundamentals

In the world of electronics today, DC-DC converters are classified into two types: linear voltage regulators and switching voltage regulators; depending on the circuit implementation. Power losses are unavoidable in both types of voltage regulator and affect the lifetime of the battery; wasting about 10% to 40% of the total energy consumed by the system. Figure 2.1 indicates the typical current flow path and nontrivial power loss in the dc-dc converter results in a short battery life despite lower power dissipation of the digital system [1].

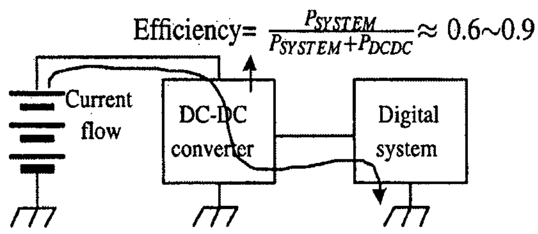

Figure 2. 1: Typical current flow path. Nontrivial power loss in the dc-dc converter results in a short battery life despite lower power dissipation of the digital system (Source: Yongseok et al [1])

It is known that switching regulators achieves better power efficiency than linear regulators, which have low efficiency due to the use of bulky heat sinks, cooling fans and isolation transformers. This makes linear regulators unfit for most modern compact electronic systems [2]. Linear voltage regulators can only step-down an input voltage to produce a lower output voltage and are available with either a fixed output voltage or a variable output voltage when using external biasing resistors. This is achievable by operating a bipolar transistor (current controlled, current source) or MOSFET (voltage controlled, current source) pass device in its linear operating mode. Control signal which drives the pass device is proportionally changed to maintain the required output voltage [3]. The advantage of a linear regulator is its simple implementation, minimal parts (just the IC in case of fixed output) and low output ripple. A linear regulator is suitable when the difference between input and output voltage is minimal and converter efficiency is not a concern [4]. Despite the increasing use of switching regulators, linear regulators continue to enjoy widespread use because they are easily implemented and have much better noise and drift characteristic than switching regulators. In addition, linear regulators do not radiate RF, function with standard magnetics, and are easily frequency compensated and have a fast respond.

Excess energy is dissipated as heat and because of this, linear regulators are associated with excessive dissipation, inefficiency, high operating temperature and the need for large heat sinks. The major disadvantage of linear regulators is low efficiency that can be overcome by minimizing the input-to-output voltage across the regulator. The smaller the difference between input and output, the lower the power loss. The minimum input/output voltage required to support regulation is called 'dropout voltage' [5]. One way to improve efficiency is to apply a very low frequency supercapacitor circulation technique at the input side of a LDO regulator IC as developed by Kularatna et al [6].

For low-power or high-current converters, a switching regulator is mostly used except when low noise or low cost is particularly important. Increasing the efficiency of switching regulators is a problem that has been addressed by several studies that focused on more efficient circuit configuration, circuit modification, investigation of sources of power loss in DC-DC converters, and developing dissipation models of input/output characteristics and converter parameters. A simulation developed by Simunic et al [7] for cycle-accurate simulation of performance and energy consumption in an embedded system with a DC-DC converter showed that the regulator consumed a significant fraction of the total energy consumption.

2.1.1 Modes of Operation of Switching Regulator

Within the switching regulator, there are two major operational modes for DC-DC converter: forward mode and flyback mode. The modes differ in the way the magnetic component operates and each mode has its advantages and disadvantages.

2.1.1.1 Forward Mode Converters

A forward mode converter is identified by the L-C filters on its output that creates a DC output voltage which is essential for the volt-time average of the L-C filter input AC rectangular waveform. This can be expressed as:

$$Vout \approx Vin * dutycycle \tag{1}$$

The switching power supply controller varies the duty cycle of the input regulator voltage waveform and thus control the signal's volt-time average. The buck or step-down converter is the simplest forward mode converter as shown in Figure 2.2.

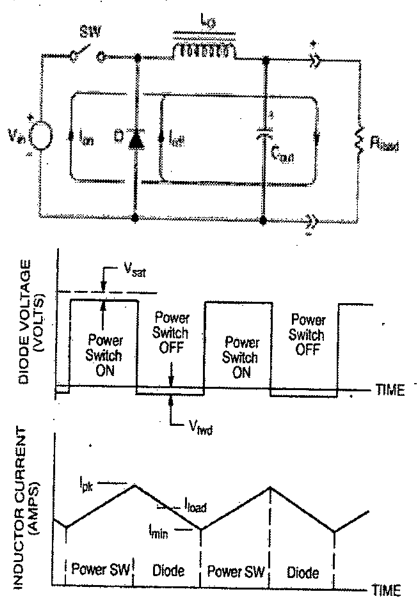

Figure 2. 2: Basic forward-mode converter and waveforms (Buck converter)

Its operation can be divided into two time periods, when the power is tuned on and turned off. When the switch is on, the input voltage is directly connected to the input of the L-C filter. Assuming the converter is in a steady-state, there is the output voltage on the filter's output. The inductor current begins a linear ramp from an initial current dictated by the remaining flux in the inductor. The inductor current is given by:

$$i_L(on) = \frac{(Vout - Vin)}{L}t + i_{init} \qquad 0 \le t \le t_{on} \qquad (2)$$

During this period, energy is stored as magnetic flux within the core of the inductor. When the switch is off, the core contains enough energy to supply the load during the following off period plus some reserve energy. The voltage on the input side of the inductor tries to fly below ground, but it clamped when the catch diode D become forward biased. The stored energy then continues flowing to the output through the catch diode and the inductor. The inductor current decreases from an initial value i_{pk} and is given by

$$i_L(off) = i_{pk} - \frac{Vout}{L}t \qquad 0 \le t \le t_{off} \qquad (3)$$

The off period continues until the controller turns the power switch back on and the cycle is repeated.

The buck converter is capable of over one kilowatt of output power but typically used for on-board regulator applications whose output power are less than 100 watts. Forward mode converter exhibits lower output peak-to-peak ripple voltage compare with the flyback converter. The disadvantage is that it is a step down topology only. Since it is not an isolated topology, for safety reason the forward converter cannot be used for input voltage greater than 42.5V DC [3].

2.1.1.2 Flyback Mode Converter

It is based on the same components as the forward mode converter but in a different arrangement. Consequently, it operates in a different way from the forward mode converter. The most elementary flyback mode converter, the boost or step-up converter is shown in Figure 2.3.

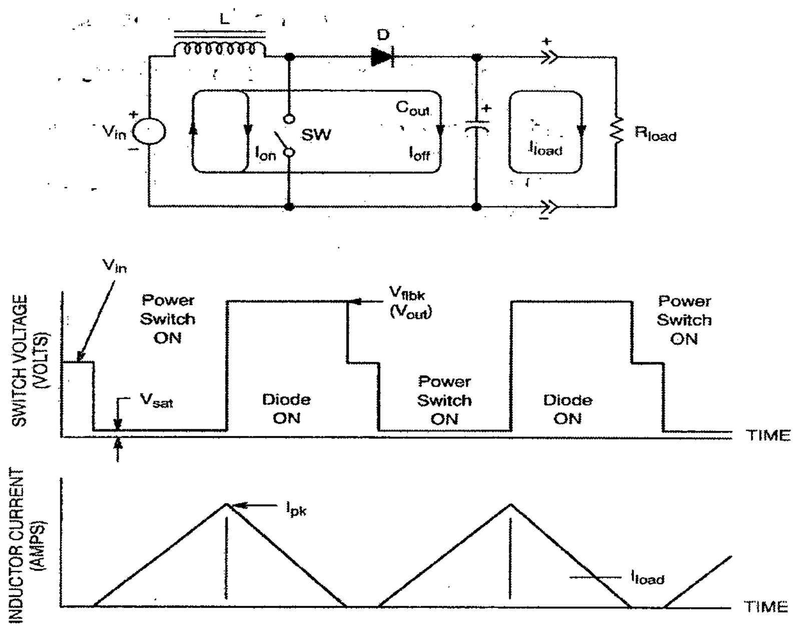

Figure 2. 3: Basic boost-mode converter with waveforms (Boost converter)

The operation is best understood by considering the `on' and `off' period separately. When the switch is on, the inductor is connected directly across the input voltage source. The inductor current then rises from zero and given by:

$$i_L(on) = \frac{Vin}{L} t \qquad 0 \le t \le t_{on} \qquad (4)$$

Energy is stored within the flux in the core of the inductor. The peak current i_{pk} occurs at the instant the power switch is turned off and is given by :

$$E_L = 0..5L * i_{pk}^2 \qquad (7)$$

The boost-mode inductor must store enough energy to supply the output load for the entire switching period (t_{on}+t_{off}), and typically limited to a 50 percent duty cycle. There must be a time period when the inductor is permitted to empty itself of its energy.

The boost converter is used in board-level (i.e non-isolated) step up application and its limited to less than 100-150 watts due to high peak currents. Being a non-isolated converter, it is limited also to input voltage less than 42.5V DC. Replacing the inductor with a transformer results in flyback converter, which may be step-up or step-down. The transformer also provides dielectric isolation from input to output [3].

2.1 2 DC-DC Converters & Associated Power Management

All electronic circuits required a clean and constant DC supply but in reality this energy source comes in terms of commercial AC supply, battery or combination of both. Sometimes the energy source maybe from other DC bus within the system or for a laptop it may be derived from the universal serial port (USB). During design stage of the system, the power supply should not be considered at the last stage. It is because for an excellent total system design exercise, power supply is the most important and vital part of the entire system beside consideration of the total weight and power management of the system.

Resources and limitations of components in the power supply and power management system are the most serious power supply design issues. Inadequate attention to all the possible worst case scenario at an early design stage such as limitation to allocate sufficient backup battery within the battery pack, unexpected surges and transient from the AC supply and fast load current transients by the load can create problems.

Nowadays, power management and digital control concepts were introduced in power supply and overall power management. There is four elements that must be fulfilled in the design of a low voltage power supply subsystem that is (i) isolation from mains, (ii) change of voltage level, (iii) conversion to a stable and precise DC value (DC-DC Converter) and (iv) energy storage [8].

Most of the digital systems today are equipped with the dc-dc converter to supply a multiple level of voltages from batteries to logic device as per Figure 2.5 below. DC-DC converter maintains the required voltage ranges regardless of the variation of the load current and at the same time the voltage drop of the battery. Even though the efficiency of DC-DC converter is changed by the output voltage level and the load current, this efficiency variation of dc-dc converters is simply ignored by the existing power management technique. Developing a true optimal power management is impossible without taking into consideration of these efficiency variations of the DC-DC converter [1].

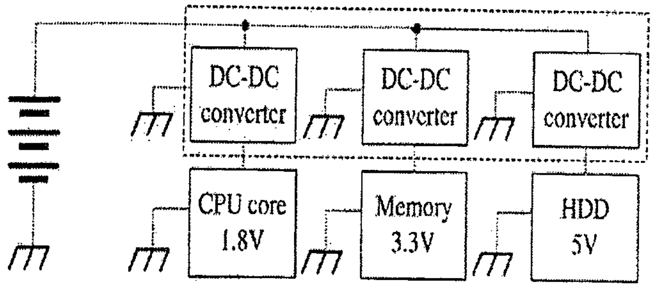

Figure 2. 5: DC-DC Converters generate different supply voltages for the CPU, memory and hard disc drive from a single battery (Source: Yongseok et al [1])

Until today, many proposed power management techniques are aiming to saving energy in the embedded system design. Also at the same time, not all of the proposals seriously take into consideration the efficiency of the dc-dc converter. The dc-dc converter's effect on the total energy consumption of the system can be ignored if the efficiency of a dc-dc converter was constant over its entire operating range. But in the real world, the efficiency of dc-dc converter has a close correlation with the level of output voltage and load current. Consequently, when a power management scheme such as dynamic voltage scaling (DVS) that is also known as the most effective and well-studied power management technique; involves varying the DC supply voltage in an embedded system. It is also essential to properly schedule the output voltage of the dc-dc converter to minimize the overall energy consumption of the system. As the output voltage and power efficiency are the key element of the switching regulator that is affected by the load current, an effective power management is capable to reducing the power consumption of a device to a large extend. But by doing this, it doesn't means that it also reduces the power consumption of the DC-DC converter at minimum level where is some cases operating very inefficiently, resulting in a poor battery enhancement. In addition to that, it is necessary to solve the problem of output voltage scaling of DC-DC converter and problem of voltage scaling that is applied to the devices other than dc-dc converter in an integrated way, so that the total energy consumption can be minimized entirely. There are two major problems arising from DC-DC converter-aware power management that is the converter-aware voltage scaling and the application-driven converter optimization [1].

The increasing demand of high power application such as fast processors and pulsed loads require a new dimension of performance from DC-DC converters. The requirement of high slew rate of load current with minimal output voltage deviation together with high conversion efficiency, small size and low cost are all contradictory requirements of a DC-DC converters design. In order to have a high slew rate, it needs a small filter inductance but this will create high current ripple which increase the conduction and switching losses. New approaches have been introduced by Osama Abdel-Rahman [9] to efficiently limit the voltage overshoot and undershoot during load transient and reducing the number of capacitors. It is achieved without compromise on the efficiency, cost or size of the DC-DC converter by allowing to optimize the power stage efficiency for the dc operation with less concern on dynamic performance. Additional switching circuits that utilizes the output capacitor current to detect load transient; is activated during load step up to deliver the shortage charge from the output capacitor, and also to pull out the extra charge from the output capacitor during load step down. Therefore, lower voltage deviation are achieved during the load transient.

Interleaved multiphase voltage regulator can reduce the input and output current ripples and have good distributed thermal capability which is regularly used in powering the central processing unit (CPU) of the desktop and laptop computer systems. In high slew transient, the voltage regulator current cannot catch up with the required load current immediately. The unbalanced current will be provided by filter and decoupling capacitor. Due to this, two transient voltage spikes occur in the voltage regulator output voltage. The first voltage spike is determined by ESR, ESL of capacitor and the second voltage spike is mainly determined by the energy stored in filter conductor related to the close-loop bandwidth. Large numbers of capacitor are mounted near to the processor on the motherboard in order to reduce the voltage spike for a lower ESRs and ESLs. Due to the limitation of space on the motherboard, it is difficult to add more capacitors for increasing the slew rate. Due to this, increased numbers of motherboard capacitors have limited effect on the voltage spike suppression and also to the existence of resistance and inductance of PCB traces and socket. The effective method to reduce the second voltage spike is to reduce the times delays in the controller, especially in large signal transients. There are three main delay times in a voltage regulator they are LC filter, compensation network and IC propagation delay times. The challenge is how to reduce those delay times in a simple way and to achieve tradeoffs between fast transient response and high efficiency. The voltage regulator equivalent inductance and its applied voltage is determined by the barrier of the output voltage regulator current slew rate. High switching frequency operation helps to reduce its LC for high bandwidth but also produce a higher switching loss.

Other studies have limiting the internal supply voltage spikes in the DC-DC converter by using a different spike reduction technique that have been presented by Rocha J et al [10]. The supply voltage spikes can be reduced in the resonant converter. This study is about original techniques that limit spikes in the internal supply voltage on a monolithic DC-DC converter. By applying monolithic

DC-DC converter for low power portable devices with a standard low voltage CMOS technology, it contributes to the saving on the production cost and higher reliability. Its also allows miniaturization by the integration of the two units in the same die that is the power management unit (PMU) that regulates the supply voltage for the second unit and a dedicated signal processor that performs the function required. The spikes mostly caused by the fast current variation in the path connecting the external power supply to the internal pads of the converter power block that includes the two parasitic inductances inbuilt in bond wires and in package pins. The small effect of relatively low values of the parasitic inductance cannot be ignored when switching high current at high switching frequency compared with the typical external inductance of DC-DC converter because these associated overvoltage frequently causes destruction, reliability problem and/or control malfunction.

The growth in portable devices has lead to the increasing level of integration in circuits, smaller in size and weight that integrate the power management unit (PMU) and signal processing unit that composed by analog and digital blocks in the same die that outlining the system-on-chip (SoC). In PMU with the step-down DC-DC converter, the components size of the off-chip LC filter should be small because the limited space on the printed circuit board (PCB) area. The reduction of inductor and capacitor value require a high switching frequency in order to maintain successful energy transferred from the battery to the load. At high switching frequency, DC-DC converter produces fast current variation in the path connecting external power source to the internal pads. When the switch is off, the fast current variation produces an internal supply voltage overshoot due to the parasitic inductances inbuilt in bond wires and the package pin on the serial path with the switches. Due to high switching frequency and high current, the effect of the low value of the parasitic inductances when compared with external inductor of the converter cannot be neglected since this is the main reason for spikes on internal supply voltage that cause overvoltage, which leads to device destruction, reliability problem or malfunction on the converter feedback control [10].

The class of resonant converters to reduce the supply voltage spike uses extra circuitry connected to the output load (load resonant) or to switches (switch-resonant) to force a sinusoidal shape of current and voltage in the switches. Beside to reduce the switching loss, the design of zero current switching (ZCS) or zero voltage switching (ZCS) is also to reduce supply voltage spike.

The increasing of interest on the green environment, pollution, global warming and energy conservation has triggered the research activity in the automotive sector to identify and develop alternatives to the internal combustion engine. Fuel cell vehicles (FCV) are among most interesting technical solution that are intensively studied today [11] and also an electric bus with supercapacitors as the only on-board power source that can realize fast and effective recuperation of energy in frequent braking and deceleration in the city. This bus is designed for operation over fixed routes no longer than 15km within the city [12]. Both technologies are using the bidirectional DC-DC converter that will be discussed separately based on the application of the converter. Basically, bidirectional converters are the combined configuration of battery charging circuits and DC-DC converter circuits. That allow power flow in either direction, i.e. towards battery or away from battery which been apply in DC UPS, battery charging circuits, stand by DC power supplies and also in aerospace applications [13].

The main functional electric scheme of the electric bus is shown in Figure 2.6 below.

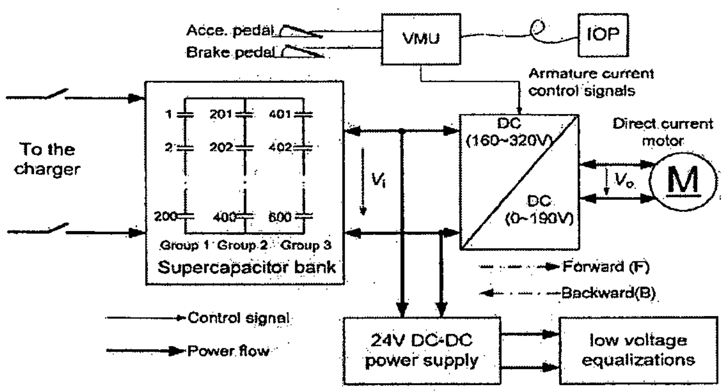

Figure 2. 6: Main functional electric scheme of electric bus (Source: Kong et al[12])

As we concentrate of the dc-dc converter part of the system, the DC motor is designed to work in two quadrants to realize regenerative braking and the DC-DC converter must be bidirectional. However, it is a difficult task to design a bidirectional dc-dc converter because of the wide voltage range and high current order of supercapacitor. For this system, the energy in the supercapacitor is transferred to the DC motor (motoring operation) through the DC-DC converter which is called the forward energy transmission. The recuperative braking energy of the DC motor is fed back to the supercapacitor bank in regenerative braking mode through the converter which is backward energy transmission. The converter exercises control of armature current with the signal from the vehicle management unit (VMU). VMU is the main controller in the electric bus and an input-output panel (IOP) to display all the information of the bus, the DC motor and the supercapacitor bank. Buck/Boost converter is used as a final choice for the DC-DC converter of this electric bus and the design specification is determined by the parameters of the supercapacitor bank and the DC motor[12].

In a new DC-DC converter structure for power flow management in fuel-cell electric vehicles that have fuel cell generator, batteries and supercapacitor, the batteries and supercapacitor guarantee load levelling, assuring braking energy recovery and good performance in transient operation. To this end, converters with bidirectional power flows are needed to connect the accumulator to the dc-link of the motor drive system, while a classical bidirectional DC-DC converter (typically with step-up function) is used to connect the fuel-cell generator. A possible connection that has been described by [14] is connected in parallel to provide voltage regulated dc power supply to the traction drive.

A new conversion solution proposed by [15] for interfacing fuel cell and supercapacitor with motor drive that only need two controllable power electronic switches to achieve 6 way power flow control and in other words, has halved the number of power electronic devices is needed to obtain the same performance in terms of power flow control with respect the solution described by [14].

2.2 Linear Regulator Advantages

The basic of linear regulator is as Figure 2.7 below. As we can observe from the figure below, linear regulator is nothing more than a electronically resistor in between the input and the regulated output. The resistance varies according to the load resulting in a constant output voltage. The capacitor is placed at the input of the linear regulator to help filter out the ripple. For example, if the input voltage is 24V, output voltage is 12V and load current is 10A, this regulator must dissipated heat energy of approximately 120W (12V voltage drop across variable resistor x 10A). This results in a mere 50% efficiency for the linear regulator for the linear regulator and a lot of wasted power which is normally transformed into heat.

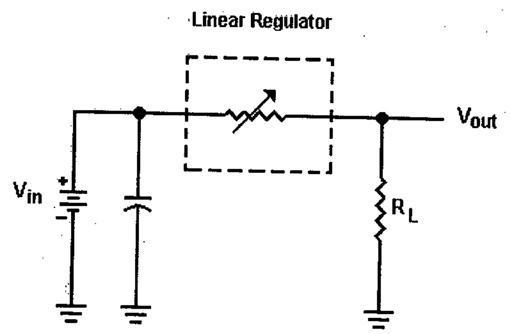

Figure 2. 7: Basic of linear regulator

Linear regulator is the basic building block of nearly every power supply used in electronics. The IC linear regulator is very easy to use that it is foolproof and the cheapest component is an electronic assembly. The operation of a linear regulator is to provides the constant DC output voltage and contains circuitry that holds the output voltage at the design value even when there is a change in the input voltage and load current (Input voltage and load current is also within the specified operating range). A modern linear regulator is developed using series MOSFETS (operates as a voltage controlled current source) to force a fixed voltage at the output terminal as in Figure 2.8.