CHAPTER 6

CHARGERS AND VOLTAGE REGULATORS

Voltage regulator circuits are essential elements in solar photovoltaic systems utilizing batteries for energy storage. The voltage regulator1s function is to regulate the current from the solar panel array to the battery to provide optimum current control during charge.

The output of the voltage regulator must have the same electrical characteristics as a good battery charger. Voltage regulators can vary from a simple, manually controlled resistor between the battery and the photovoltaic panel array to complex, temperature compensating electronic circuits. Cost vs. performance trade-offs must account for concerns such as battery life and capacity, efficiency, power density, reliability, maintainability, size and weight

Without a voltage regulator, proper charge conditions for the battery cannot be achieved readily. If the solar array is sized to provide sufficient current to charge the battery fully on a daily basis, severe overcharging could occur without some means to regulate the current when only a partial recharge is required. Excessive overcharge would reduce battery life and increase system cost by requiring more frequent battery replacements.

Conversely, if a solar panel array is sized only to provide a maintenance of finishing charge current. the charge time following a deep discharge might be too long to recharge a battery in the specified time. chapter will review the main characteristics of four different types of voltage regulators as a guide for selecting the best type for a given application. Detailed design information will be referenced, and sufficient circuit examples will be given to illustrate design principles.

BASIC VOLTAGF REGULATOR

Every voltage regulator consists of four basic elements:

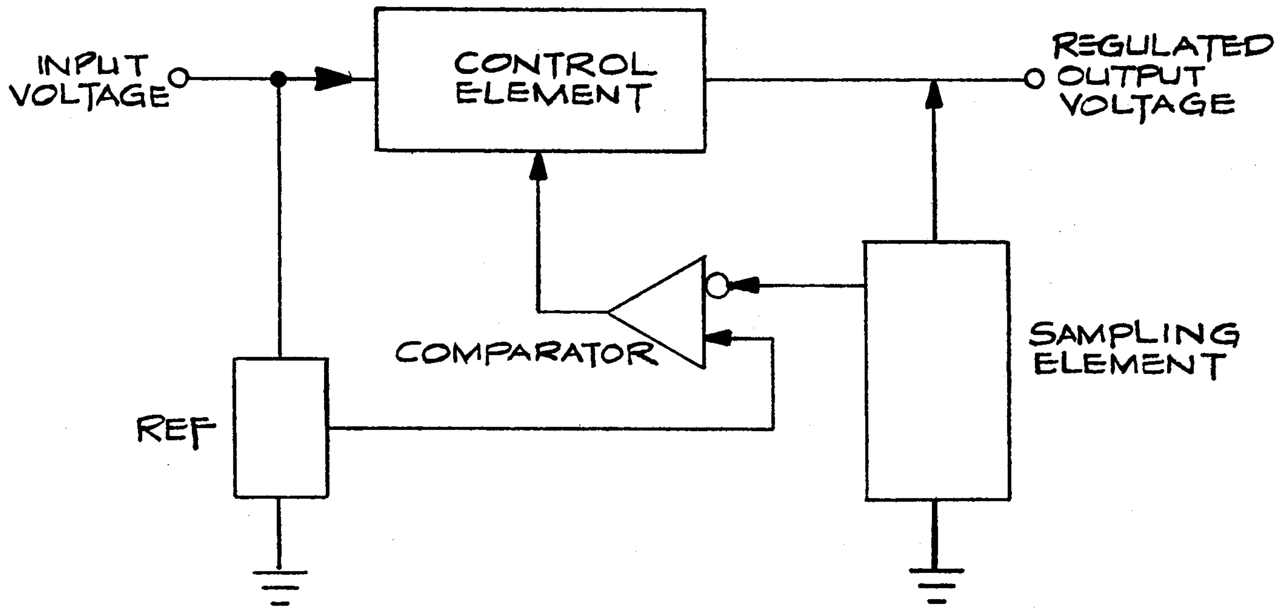
1 a stable reference voltage;

2 a voltage sampling element;

3 a voltage comparator, and

4 a power dissipating control device.

This basic system is shown in the block diagram of Figure 6-1.



Fi gure 6-1

Basic Regulator Block Diagram 1

(Courtesy of Texas Instruments. Inc.

The voltage sampling element translates the output voltage down to a level that will be equal to the reference voltage for a particular output voltage. Then, as the output voltage varies, the sampled voltage changes to a value more or less than the reference voltage. The voltage difference is sensed by the comparator element which generates an error signal. This signal is amplified and directs the power dissipating control element to perform the desired regulation function. The control element has normally one of four types of circuitry:

- Series pass
- Shunt
- Series switching
- Shunt switching

Voltage regulators obtain their names from the type of circuitry in the control element. Figure 6-2 shows schematic configurations for each of the four control circuits.

[Figure 6-2 is shown on the following page]

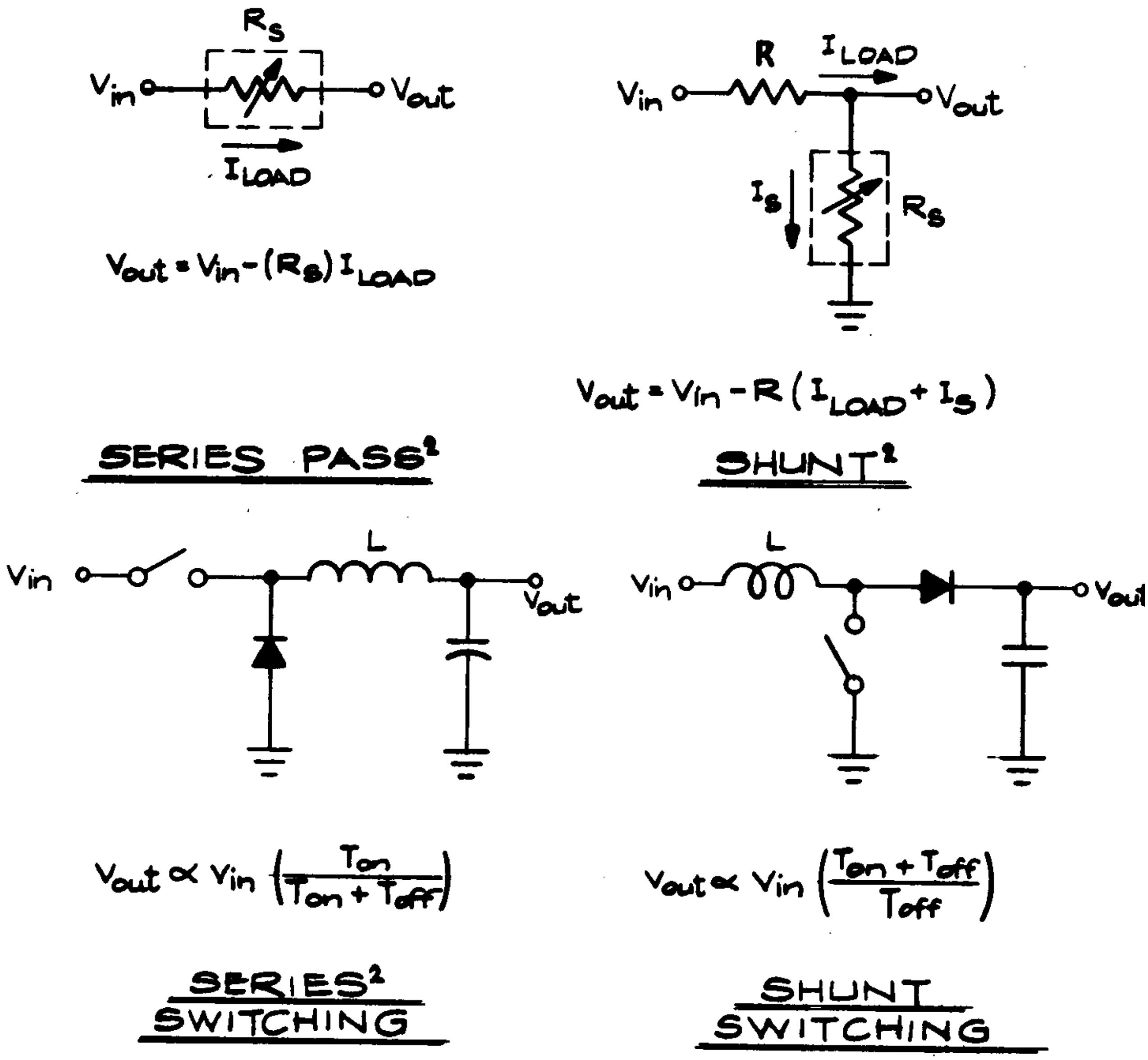


Figure 6-2

Control Element Configurations[2]

(Courtesy of Texas Instruments, Inc.

In photovoltaic system applications, the regulator-PV (Photovoltaic) array acts like a constant current source limited by the array short circuit current when the battery capacity is low. As the battery approaches full capacity, the regulator/array system behaves as a constant voltage source. The regulator can be designed to turn itself
off when full capacity is reached. In fact, with the appropriate control circuitry, almost any charge current vs. time curve can be approximated by the regulator. Figure 6-3A shows the more desirable charge current vs. time patterns and their corresponding battery voltage vs. time response.

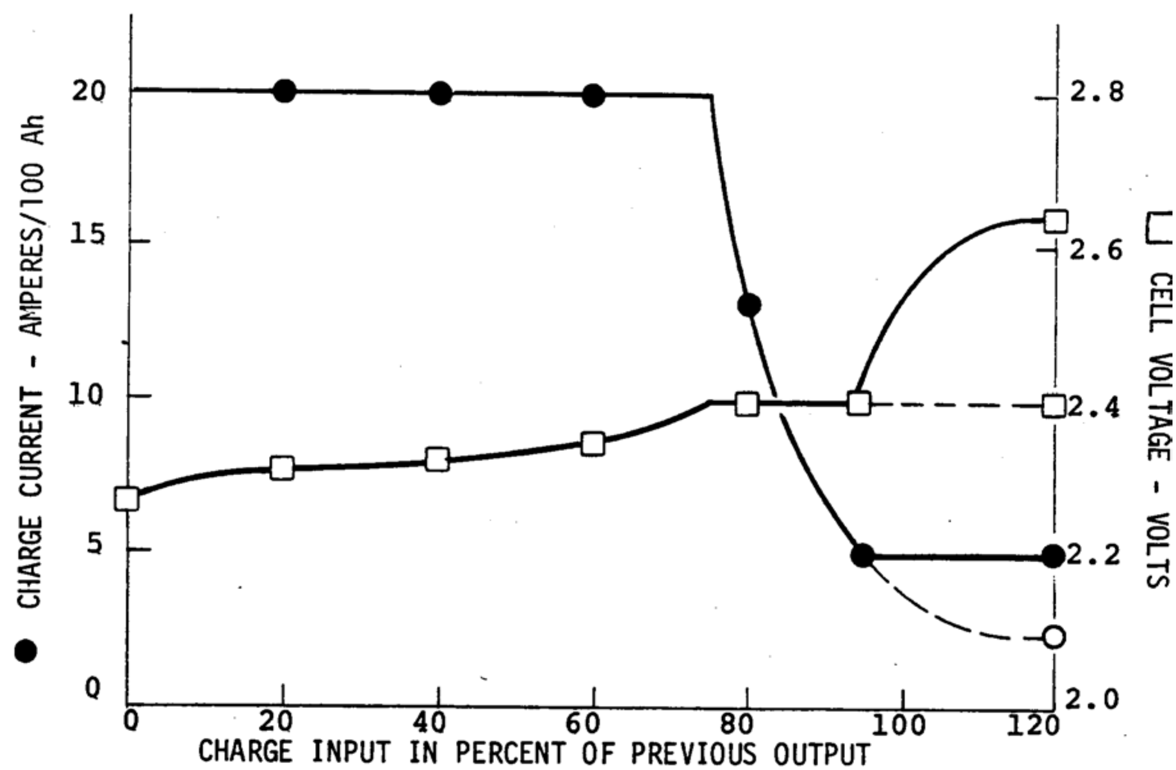
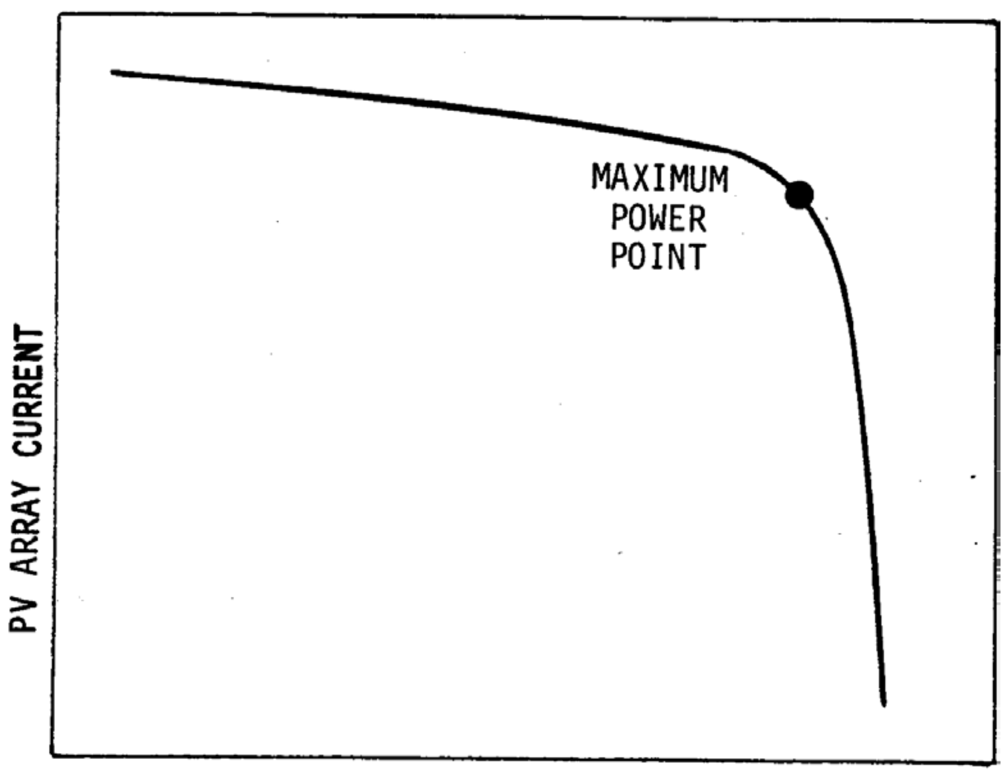


Figure 6-3A Cell Voltage and Current During Charge

In these charge patterns, the initial current remains constant until the average cell voltage reaches the gassing voltage where appreciable electrolysis of water begins. The current then decays at this constant voltage, Vgas, until charge is terminated (dotted lines of Figure 6-3A) or until the predetermined finishing rate is reached. At this point the voltage may be decontrolled and the current maintained constant for a predetermined time before terminating the charge. In this case (solid lines of Figure 6-3A), the average cell charging voltage can rise to a value of 2.65 volts per cell, or greater depending on the finishing rate and battery type .

Figure 6-3b shows a graph of the photovoltaic array current



PV ARRAY VOLTAGE

Figure 6-3B Typical Solar Array Current vs. Voltage Output

It is desirable to size and operate the PV array as close as possible to the maximum power point to minimize the cost and size of the array. If the operating point is chosen at a voltage much lower than the maximum power point (Figure 6-3B), the PV array will be operating at very low efficiency at the. end of charge. Conversely, if the operating point is chosen much greater than the maximum power point, there is a danger that the insufficient current will be available near the end of charge. This would have the effect of extending the time required to fully charge the battery. The voltage regulator in general should approximate the characteristics of a constant voltage/constant current dc power supply. During the initial portion of the charge, the current would remain limited by the output of the array. When the battery gassing point is reached, the regulator should reduce the current to the battery so that the gassing voltage is maintained until near the end of charge.

The gassing voltage changes with temperature. See Table 6-1 for values from +50 to -20°C (+1 22 to -40 F) . The regulator must compensate for this change in gassing voltage with temperature to avoid overcharging at high temperature and undercharging at low temperature. If a reference voltage is made constant over the operating temperature range by use of precision voltage reference chip or a precision Zener diode (less than 10 PPM/°C (5.6 PPM/°F variation)), a thermister can be used in the sampling network to compensate for temperature variations in battery voltage.

Precision resistors are used in the sampling network for accuracy. Thermistors are available with both negative and positive coefficients, thus permitting several sampling network configurations.

A blockfng diode should be placed between the PV panel array and the regulator to prevent the battery from discharging through the array in time of total darkness and zero panel output.

The major features of the four types of voltage regulator control circuits can now be reviewed to make comparisons in their performance.

SERIES PASS VOLTAGE REGULATOR

A typical series pass voltage regulator circuit is shown in Figure 6-4 on the following page.

A variable input dc voltage is translated into a lower constant voltage by the series-pass element which consists of one or more transistors in parallel. As the source voltage varies, the effective resistance of the series element is increased or decreased, so that it absorbs the change in source voltage. Control of the series-pass transistor(s) is accomplished by the negative feedback loop consisting of the resistor sampling network, the difference amplifier, and the voltage amplifier and level shifter.

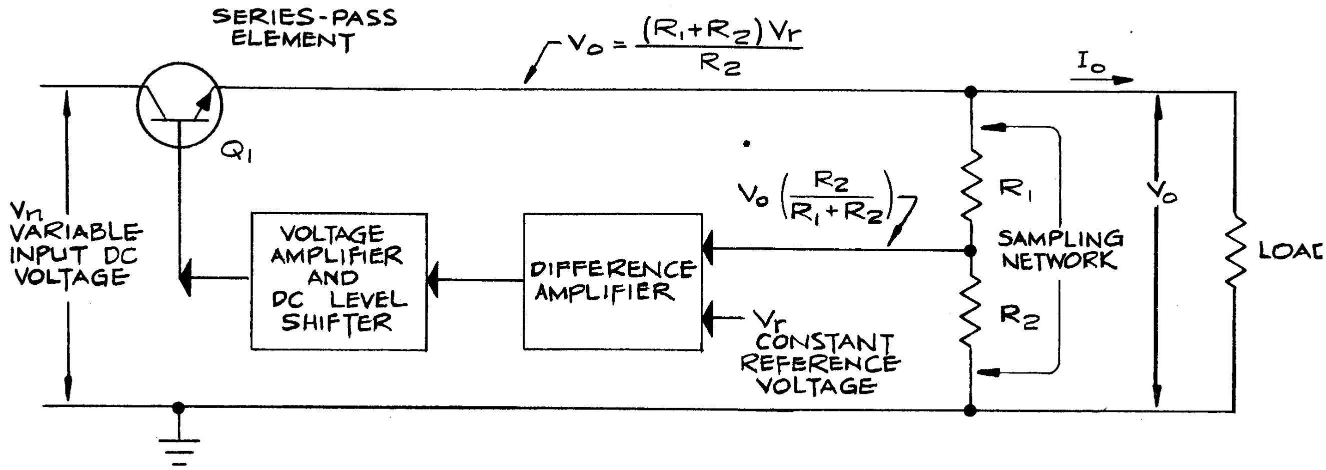


Figure 6-4 Basic Series - Pass Voltage Regulator. Q_1 is an Electronically Controlled Variable Resistance in Series with the Load.[3]

(Courtesy of Hayden Book Company, Inc.)

The sampled output voltage $V_o\left(\frac{R_2}{R_1 + R_2}\right)$ is compared to the constant reference voltage, Vr. An error is generated by the difference amplifier that is proportional to the difference between the sampled output voltage and Vr. This error voltage is amplified and level shifted to drive the series-pass transistor. A small increase in output voltage causes an increase in the series-pass element impedance to maintain a constant output voltage. Likewise, a small decrease in output voltage will cause the impedance of the series-pass transistor to decrease. The negative feedback loop always maintains the sampled output voltage $V_o\left(\frac{R_2}{R_1 + R_2}\right)$ very nearly equal to Vr.

With the use of several parallel series-pass transistors, the series- pass regulator can handle up to 2000 watts of power. Above that power level, unequal current sharing by the series-pass transistors and voltage drops across interconnecting wiring limit the applicability of this design.

SHUNT REGULATORS

The basic shunt regulator, shown in Figure 6-5, converts a variable higher voltage dc to a constant lower voltage dc by using a shunt element. consisting of one or more parallel transistors, as a variable resistance device. As the input rises or falls~ the effective resistance of the shunt element is increased or decreased, thereby shunting more or less of the current away from the load. The shunt is controlled to provide a constant output voltage by the negative feedback loop composed of the resistor sampling chain, the difference amplifier, and the voltage amplifier, level-shifter element.

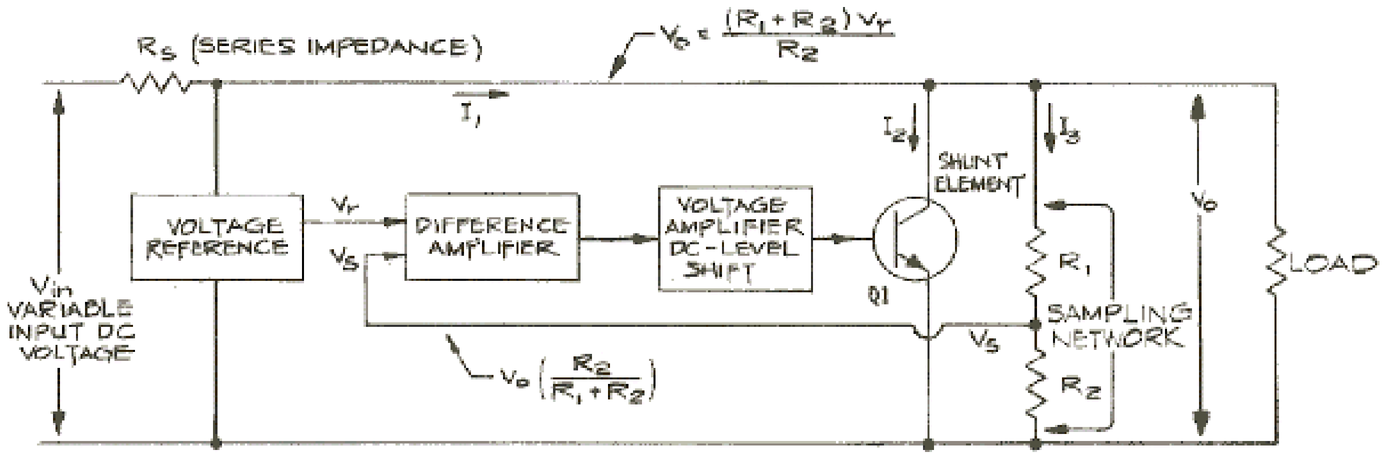


Figure 6-5 Basic Shunt Regulator

A fraction of the output voltage $\frac{R_2}{R_1 + R_2}$ X V_0 is sampled and compared to a constant reference voltage, V_r. The difference amplifier yields a voltage proportional to the difference between Vr and the output sample. The amplified difference voltage is further amplified and the dc level shifted to drive the input terminal of the shunt element. Voltage polarities are such that a small increase or decrease in output voltage resulting from line or load changes causes the correct decrease or increase, respectively, in shunt element impedance to keep the output constant. The output adjusts itself so that the sampled fraction is very nearly equal to the reference voltage.

Even though it is usually less efficient than the series-pass regulator, a shunt regulator may prove to be the best choice for a specific application. It is less sensitive to input voltage transients, does not reflect load current transients back to the source, and is inherently short circuit proof.

Shunt regulators can be used in a master-slave arrangement for increased power handling up to 1000 watts. A master shunt regulator operates normally except that it also drives other paralleled shunting devices (slaves) which are mounted on their own heat sinks. In this way, the master controls the slave and the power can be more easily dissipated.

Equal current sharing in the power transistors can become a problem, and the betas of large power handling devices must be closely matched The power dissipated by each succeeding slave decreases due to voltage drop losses in the interconnecting wiring.

These two problems limit shunt regulators to less than 1000 watts.

SWITCHING REGULATORS

Switching regulators are used where large input-to-output differential voltages may exist, or where high load current requirements are necessary. Their use is particularly suited for high power applications, and systems where efficiency is important. Two basic switching regulators are shown in Figure 6-6.

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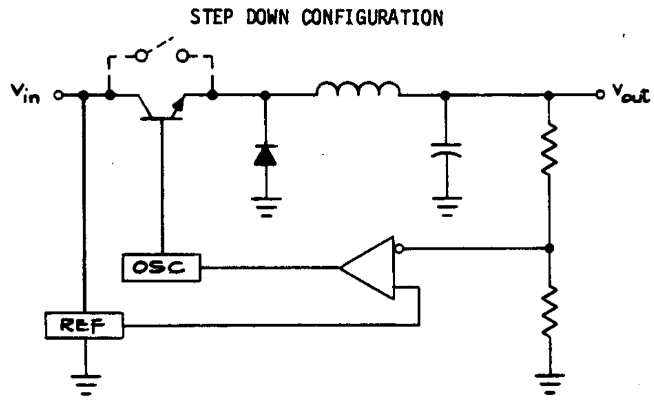

(Courtesy of Texas Instruments, Inc.)

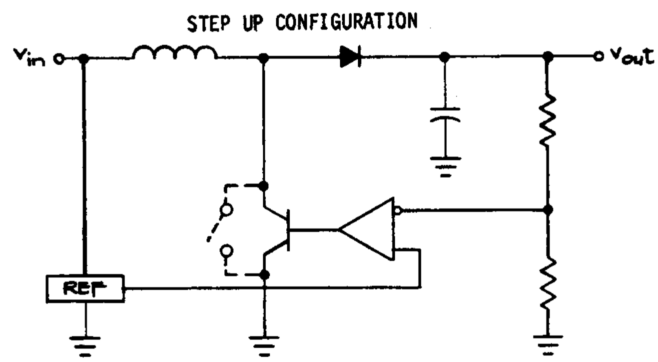

Figure 6-6 Basic Switching Regulators[4]

In a switching regulator, an active device (such as a switching transistor) is used to chop the input voltage or current to meet the load requirements. This is accomplished by varying the duty cycle of the switching transistors. This can be accomplished in three ways:

1 Varying the frequency with a constant "on" time

2 Varying the frequency with a constant "off" time

3 Varying the "on" and "off" times wi th a constant frequency

<u>Method No.1</u> simplifies regulator design, because the energy stored in the inductor during the Ilonll time is fixed and determines the power deliverable to the load.

The calculation of inductor size is relatively easy, since the operating window of the inductor is well-defined. The operating frequency of the regulator varies with the load.

An LC filter normally averages the regulator output voltage as perceived by the load. The switching power transistor is operated in the saturated mode where it is either "on[t1] or "off".

Method No. 2 will provide operation at a well-defined minimum frequency under full-load conditions. It also reduces the ripple current and maintains the same average current under increased loading, by allowing a dc current to flow in the inductor. However, precautions should be taken concerning the problem of inductor saturation.

Method No. 3 is usually taken because it is easier to filter the noise or EMI (electromagnetic interference) generated by the switching regulator when it is at a fixed frequency. This approach also results in a dc inductor current (for increased loads) to maintain the required current transferred with minimal ripple.

In designing switching regulators, one may select discrete components or use one of several monolithic switching regulator circuits that are currently available. In low power applications, the complete regulator is included on a single IC (integrated circuit) chip; by adding larger external power elements (such as a switching transistor, a free-wheeling diode, and necessary driver components to adequately drive the transistor), many kilowatts of power can be regulated by the IC chips. Supervisory IC chips are also available for almost all of the control loqic. such as Qvervoltage protection, undervoltage protection, current limiting, and current sensing.

STEP-DOWN SERIES-SWITCH CONVERTER/REGULATOR

The switching operation of a basic step-down converter is shown in Figure 6-7. A low impedance transistor is opened and closed periodically between the input and the output.

Since the collector-emitter voltage drop of the transistor when it is in the saturated "on" state (normally closed) is very small compared to the system output voltage, it will be assumed to be zero. Then the out will periodically vary between zero volts and the input voltage, with the average value of this being V_o - V_{in} *(T_{on}/T) where T_{on} is the time that the transistor switch is "on" and T is the switching period. The ripple voltage still has a peak-to-peak value of V_{in}. However, adding the L_1C_1 filter reduces the ripple to an acceptable level. The filter components required become smaller as the switching frequencies increase to the 20-50 kHz range.

The switching duty cycle, defined as T_{on}/T, means that by varying the duty cycle. any output voltage lower than the input can be obtained. Efficiency is high, since the only losses in the converter occur in the switching transistor when it is “on”. These losses are insignificant because the voltaqe drop across the transistor when it is "on" is at V_{ce} (SAT) or approximately 1 volt. There is no power dissipation when the transistor is "off" because no current flows through it.

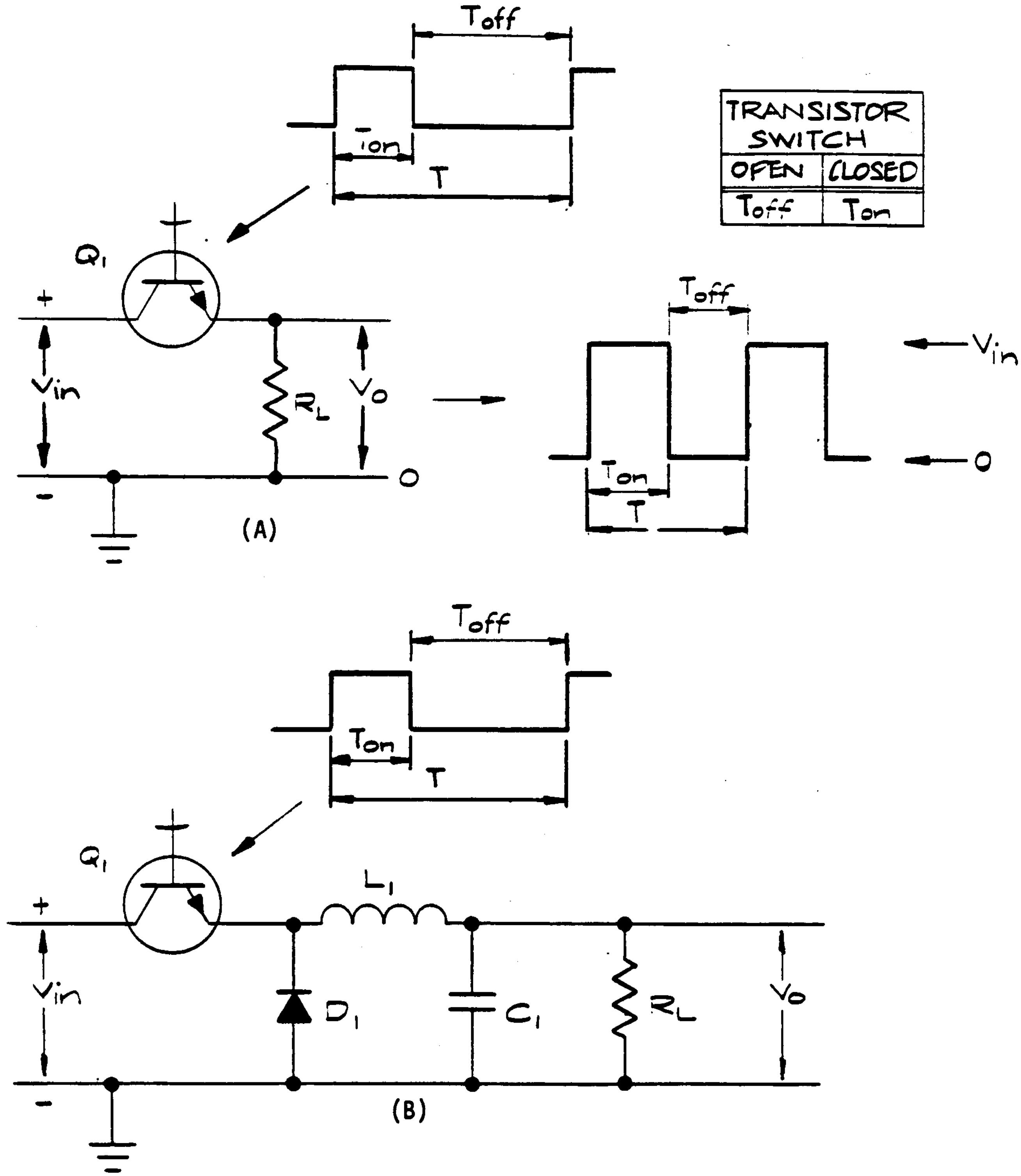

Figure 6-7 (A) SWITCHING VOLTAGE CONVERTER AVERAGE OUTPUT VOLTAGE AT Vo = Vin (T_{on}/T). [5]

(B) SWITCHING VOLTAGE CONVERTER WITh LC FILTER AND DIODE FOR ELIMINATING RIPPLE. [5]

(Courtesy of Hayden Book Company, Inc.)

When the transistor switch turns "off", the; input side of L_l goes negative because current cannot change instantaneously through an inductor. Diode D_l starts conducting when its cathode potential becomes sufficient1y negative to cause the diode to become forward biased. When the transistor is "off", load current is supplied by both L_l and Q_l in parallel.

If L_l is made large enough, then the current in L_l will change very little from the transistor on to off time and will be equal to the dc output current V_0/RL_L. When the transistor turns "on" again, diode D_l i.s reverse biased and stops conducting. Load current is then supplied by the source through the transistor. The series-switching converter behaves like a step-down transformer where the input source voltage V_{in} at an average current of I_l (T_{on}/T) is transformed to a lower voltage $Vo = Vin (T_{on}/T)$ at a stepped up average current I_O**.** This, of course, is with transistor and diode losses neglected so input power equals output power.

The converter of Figure 6-7 can be transformed into a voltage regulator by adding an output voltage sampling resistor network, a difference amplifier, a stable voltage reference, and a dc voltage controlled pulse-width modulator.

The negative feedback circuit changes the pulse width or duty cycle to maintain a constant output. Changes in the load or input voltage are compensated by varying the duty cycle of the transistor switch without increasing the interval power dissipated in the switching regulator.

Present practice is to switch at the 20 kHz rate; however, the switching frequency may range from 3-100 kHz. The higher frequencies result in smaller filter inductors and capacitors which in turn reduces the size and weight of the regulator for the same power output. Higher frequencies also result in larger switching losses and hence lower
efficiencies.

STEP-UP SHUNT SWITCH CONVERTER/REGULATOR

Unlike the step-down switching converter which can only produce a voltage less than the input voltage, the step-up switching converter is capable of producing a higher voltage than the input. It can be used wherever a higher voltage than the existing source is required. There is no dc isolation, however, from the negative terminal of the source .

Figure 6-8A illustrates the basic step-up switching converter and its wave form. Transistor Q1 is switched "on" and "off". It is "on" for T_{on} and "off" for T_{off} with a period T. Placing diode D_1, filter capacitor C_O and load R_O as shown, the output voltage can be stepped up to $V_0 = V_{IN} / ((1-T_{ON})/T)$

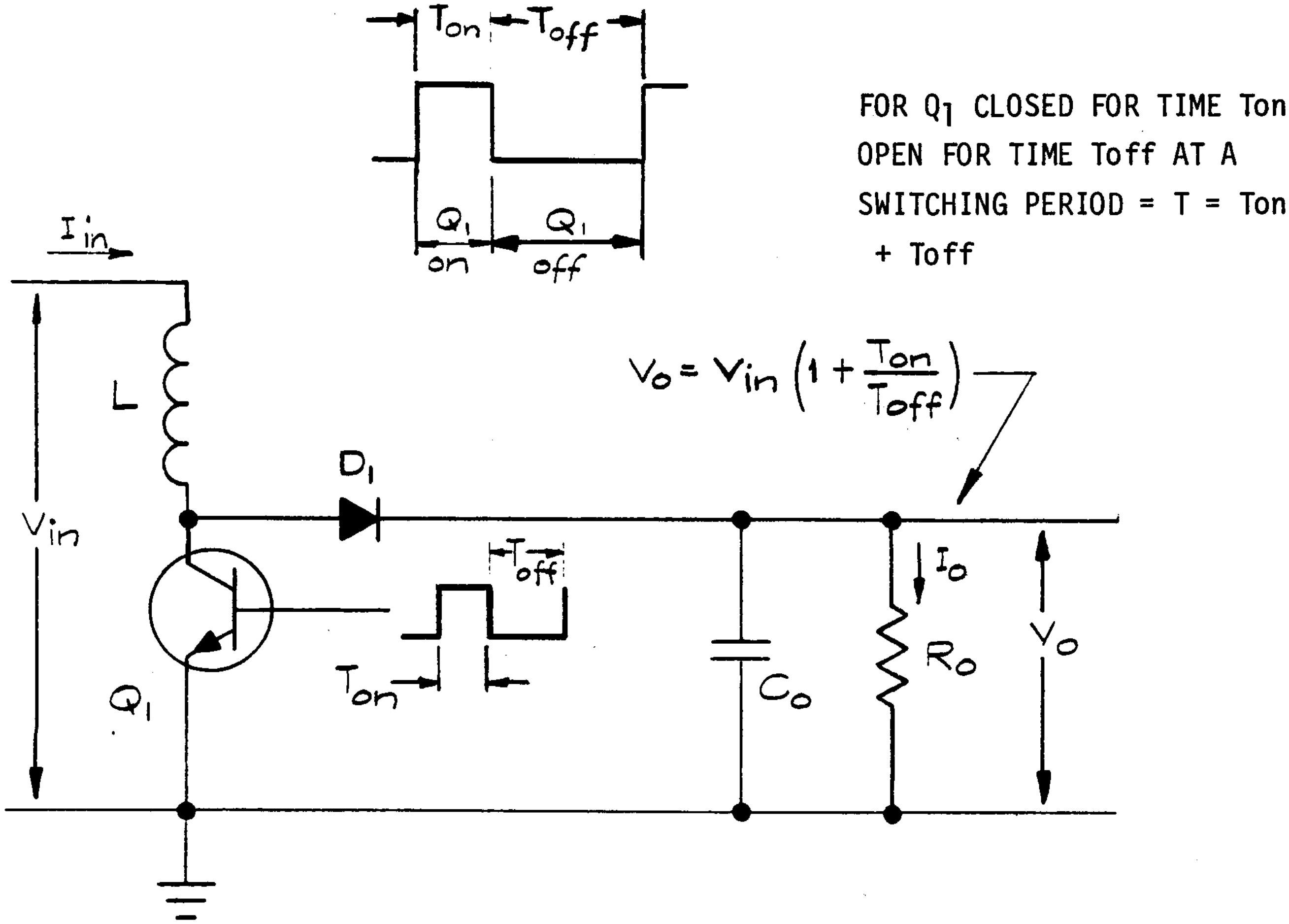

Figure 6-8A

A Shunt Switch Voltage Step-Up Converter

As transistor Q_1 is turned "on", energy from the source is stored in inductor L. Diode D_1 is reverse biased, and capacitor C_0 supplies the load current I_O thereby partially depleting its stored energy (1/2 $C_0V_0^2$). When Q_1 turns "off", an inductive voltage step (V_0 -Vin) is generated across inductor L, forcing the Q_1 side of diode inductor L positive with respect to the input. This forward biased diode D_1 now transfers the current that had been flowing through inductor L and transistor Q_1 to filter capacitor C_0 and load R_0.

When Q_1 is turned "off", the energy stored in inductor L during T_{on} (1/2 LI^2_{peak}) is transferred to load R_0 and filter capacitor C_0 to restore the energy lost while supplying load % during T_{on}.

The duty cycle T_{on}/T controls the amplitude of the inductive voltage. As T_{on} increases, more energy is stored in inductor L. Therefore, the inductive voltage pulse across inductor L during T_{0ff} must be higher if all the stored energy is to be transferred out during T_{0ff}.

Assuming no power losses during switching, the step-up converter acts like a step-up voltage transformer where the input voltage V_{in} at a dc current I_{in} is stepped up to a higher voltage.

By adding a negative feedback circuit consisting of a voltage sampling resistor network, a constant voltage reference, a difference amplifier, and a dc voltage-controlled variable-width pulse generator, the step-up converter can be transformed into a voltage regulator.

The basic circuit and its corresponding wave form is shown in Figure 6-8B.

From Figure 6-88, it can be seen that the duty cycle T_{on}/T is automatically adjusted to maintain a constant output voltage with variations in input voltage. As V_{in} increases, the duty cycle decreases; conversely, a decrease in V_{in} causes an increase in duty cycle.

This circuit will also regulate changes in output load current in the same manner,

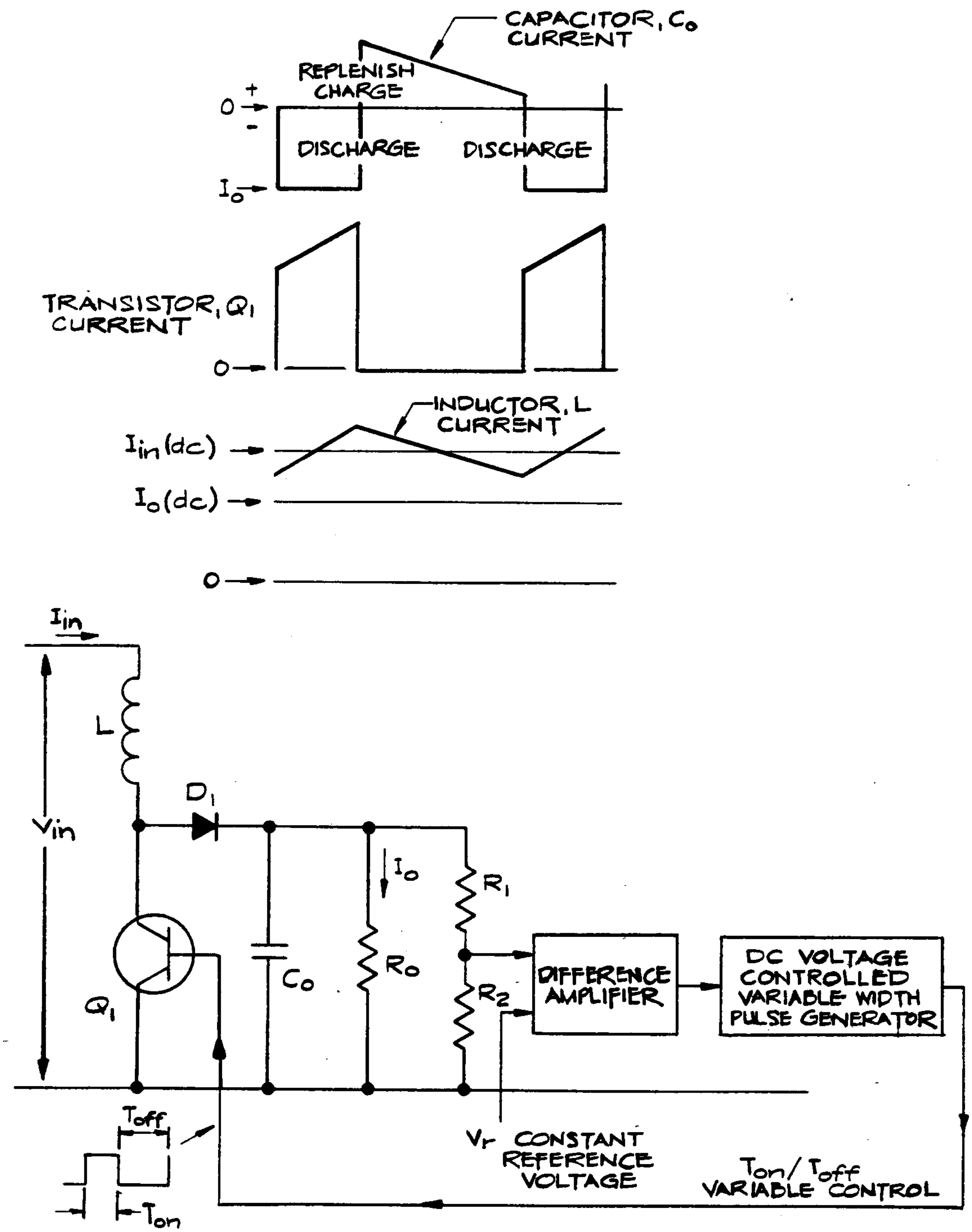

Figure 6-8B

Addition of a Feedback Loop to Build a Step'-Up Switching Converter6

(Courtesy of Hayden Book Company, Inc.)

COMPARISON OF VOLTAGE REGULATORS

Four different voltage regulators have been described. Each uses a different means of control and will exhibit unique advantages and disadvantages. In this section, a comparison of some of these characteristics will be made to aid the solar PV system designer in selecting the regulator best suited for his needs. Battery l.ife is extended by using the proper charging profile and having adequate battery voltage temperature compensation. Each type regulator can accomplish this goal with appropriate contro1 1ogic but may vary in degree of success. Comparisons are made therefore of each regulator under the headings "Reliability", "Control", “Heatsink”, "Power Handling Capability", and “Cost". The switching type voltage regulators are also compared in terms of operation frequency, EMI problems and stability.

Finally, recommendations are made for the usage of each type in solar PV applications.

SERIES-PASS VOLTAGE REGULATOR

Efficiency

The series-pass element continuously dissipates power, making this type of regulator one of the least efficient. Regulator efficiency increases as the input voltage decreases, or as the output voltage increases according to:

$$E = \frac{P_{out}}{P_{out} + P_{reg}} = \frac{V_O I_O}{V_O I_O + (V_{IN} - V_O) I_O} = \frac{V_O}{V_{IN}}$$

Maximum efficiency occurs when the pass transistor operates near saturation.

Reliability

Because of the low complexity of the circuit, a higher reliability can be attained than for other types of regulators.

Control Logic

Control logic can be implemented for temperature compensation, charging control and low voltage protection. The control element can be operated anywhere from near saturation to “off”.

Heatsink Requirements

A fairly large heatsink is required to dissipate all the power in the pass transistor, which contributes much to the weight and size of the regulator. If the heat dissipated by the regulator could somehow be recovered, then the size and weight could be reduced through use of a smaller heatsink.

Power Hand1ing Limitations Switching transistors can be paralleled to handle larger loads up to 2000 watts, after which, unequal current sharing and base drive deficiencies become predominant limiting factors.

Cost

The cost of the series-pass voltage regulator is relatively low. Cheap silicon transistors can be used. Darlington transistors, used as the pass element, are not recommended because of the larger voltage drop and resulting power loss.

Recomnended Use

The series-pass voltage regulator can be used in high voltage systems because of its increased efficiency at those levels Although it continuously dissipates power, the level of power dissipation is much less than the shunt voltage regulator, which dissipates almost all of the power when the battery capacity is reached. The series-pass voltage regulator can be used in the l kw to 2 kw power range, whereas the shunt regulator is only adequate to l kw. The series-pass regulator (rather than a switching regulator) can also be used where high reliability and lower cost are required, because of circuit simplicity. This type of regulator is more suited to battery storage systems requiring continuous float charging than a shunt regulator, for example, because less power would be dissipated by the voltage regulator during float.

SHUNT VOLTAGE REGULATOR

Efficiency

The shunt regulator dissipates nearly all of the solar power when the battery approaches 100 percent capacity, and essentially none of the power when the battery capacity is low.

This raises the overall daily efficiency of the shunt voltage regulator, because power will not be dissipated by the regulator until the battery nears 100 percent capacity. Therefore, minimum efficiency occurs when the battery reaches full charge.

Reliabi1ity

The basic shunt voltage regulator circuitry is not complex, and therefore is relatively reliable.

Control Logic

Control logic can be implemented for temperature compensation, charging control, or low voltage alarms.

Heatsink Requirements

The large power dissipation required during full charge requires a fairly large heatsink.

Power Handling Limitations

Power handling transistors can be paralleled to attain higher power levels; however, unequal current sharing between transistors and large base drives becomes a problem beyond 800 to 900 watts.

Cost

The cost of the shunt voltage regulator is relatively low. Cheap silicon power transistors and power Darlington transistors can be used as the control element.

Recommended Use

The shunt regulator is limited to systems of 1000 watts or less because of the problem of paralleling many power transistors. In this power range, the shunt regulator is rather well suited for medium to deep discharge battery storage systems because of its near 100

percent efficiency when the battery is less than full capacity. It would not be recommended for battery backup systems where the batteries would be float charged 100 percent of the time to compensate for the battery stand loss (the regulator would be very inefficient). The shunt regulator is limited in system battery voltage to 48-60 volt dc.

Beyond that, the breakdown voltages of the power transistor could be exceeded, accompanied by the destruction of the transistor. The shunt regulator is also low in cost and has better reliability than, for example the switching regulator.

STEP-DOWN SERIES SWITCH REGULATOR

Efficiency

The efficiency of the series switch regulator varies from 70 to 97 percent, with the value dependent upon the ac and dc losses in the switching transistor and diode. The efficiency can be approximated by $V_O/(V_O+2)$ where 2 rep resents the combined dc and ac vo1tage drops. The efficiency increases with an increase in output voltage.

Re1iabi1ity

Because of the complexity of the circuitry, it is less reliable than the series-pass or shunt voltage regulators.

Control Logic

Control logic can be implemented for temperature compensation, charging control, low voltage protection and maximizing array power.

Heatsink Requirements

The high efficiency of the circuitry means that a smaller heatsink may be used

Power Handling Limitations

The step-down voltage regulator provides regulation for systems between 1000 and 5,000 watts.

Cost

The cost of this type of regulator is much higher than the cost of the series-pass or shunt voltage regulators, because of the complexity of the circuitry. It can use low cost silicon power transistors with the appropriate drive circuitry at lower frequencies, but at higher frequencies, it is necessary to use faster silicon power transistors or the more expensive power FET transistors, which use a greatly simplified drive circuit.

Frequency Operation

Operation is possible at frequencies between 5 kHz and 100 kHz, with the most typical application at 20 kHz. At this frequency, the size of the inductor and output filter capacitor can be reduced, which will enable the reduction of the overall size and weight of the voltage regulator.

EMI Problems

There are numerous EMI problems associated with a switching regulator, such as environmental contamination and the problem of internal noise and crosstalk which can affect proper regulator operation.

Stabi1ity

Since the switching regulator is a negative impedance with regard to the PV array, and since the maximum power point of the array can vary, the regulator must be designed to be stable under its intended operating range. Otherwise. it will tend to oscillate.

Recommended Use

The step-down regulator is better suited for systems of 1000-15,000 watts, with emphasis on the larger systems. Because of its high efficiency, it can handle the higher power that the series-pass and shunt regulators cannot. It should be used where system efficiency

s of prime concern, since efficiencies of 98 percent can be attained with proper design. It is also better suited to higher voltage systems since efficiency increases with output voltage.

STEP-UP SHUNT SWITCHING REGULATOR

Efficiency

The efficiency of the step-up regulator can vary from 70 percent to 95 percent, depending on the dc and ac losses in the switching transistor and diode. The efficiency is limited by the input voltage (Vin) according to $V/(V_{IN}+2)$ and is usually from 1 to 5 percent less than the step-down regulator.

Reliabi1ity

The reliability is less than the series-pass or the shunt voltage regulator due to the overall circuit complexity.

Heatsink Requirements

The generally high efficiency of this voltage regulator permits the use of smaller heatsinks than either the series- pass or shunt voltage regulators.

Power Handling Limitations

Because of the high input current and power transistor limitations, it would be economically impractical to consider this type of regulator for power levels greater than lkw.

Cost

Because of the complexity of the circuitry, the cost of this regulator is high.
Cheap silicon power transistors with the appropriate drive circuitry or the more expensive (in 1981) power **FET** transistors with their simplified drive circuitry requirements can be used as the switching element.

Frequency Operation

The operating frequency of the step-up regulator can vary from 5 Khz to 100 kHz, but 20 kHz is usually typical. Operating the device at higher frequencies reduces the size of both the inductor and output filter capacitor. Since these components are the largest in the regulator, a reduction in their size means a big reduction in the size and weight of the device.

EMI Problems

The step-up voltage regulator generates lower EMI levels than the step-down voltage regulator.

Stability

Since the switching regulator is a negative impedance with respect to the PV array, and since the maximum power point of the array can vary, the regulator must be designed to be stable under its entire operating range. Otherwise, it will tend to oscillate.

Recommended Use

Recommended use of the step-up regulator is similar to that for the step-down regulator except that its efficiency is 1 to 5 percent less, and it will generate less EMI.

COST/PERFORMANCE TRADE-OFFS

A comparison of the four types of voltage regulators, showing the normalized cost to performance trade-offs, is provided in Table 6-5. The ratings are based upon a current price schedule and the complexity which the designer includes in the intended system.

The efficiency was calculated with respect to a 14 volt dc output voltage.

With the cost of each regulator having been determined on a relative basis, the actual cost of a commercially available shunt regulator system can be applied, giving an approximate indication of the cost of each type of regulator.

It is not possible to cost each regulator component on an individual basis because of the price differentials involved between components on a quantity and quality basis, and the variations in designs.

TABLE 6-1 - NORMALIZED COST/PERFORMANCE TRADE-OFFS

	STEP-DOWN REGULATOR	STEP-UP REGULATOR	SERIES-PASS REGULATOR	SHUNT REGULATOR
EFFICIENCY (%)	1.0	0.95	0.67	0.67
POWER DENSITY	0.25-1.0	0.25-0.90	0.25	0.25
COST	2.5	2.5	1.0	1.0
RELIABILITY	0.7	0.7	1.0	1.0
COMPLEXITY	3.3	3.3	1.0	1.0
SIZE	1.0	1.3	3.3	3.3
WEIGHT	1.0	1.0	5.0	5.0

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