Automation

The word ‘Automation’ is derived from greek words “Auto”(self) and “Matos” (moving). Automation therefore is the mechanism for systems that “move by itself”. However, apart from this original sense of the word, automated systems also achieve significantly superior performance than what is possible with manual systems, in terms of power, precision and speed of operation.

Definition: Automation is a set of technologies that results in operation of machines and systems without significant human intervention and achieves performance superior to manual operation.

Control

Definition: Control is a set of technologies that achieves desired patterns of variations of operational parameters and sequences for machines and systems by providing the input signals necessary.

Note:

Automation Systems may include Control Systems but the reverse is not true. Control Systems may be parts of Automation Systems.

The main function of control systems is to ensure that outputs follow the set points. However, Automation Systems may have much more functionality, such as computing set points for control systems, monitoring system performance, plant startup or shutdown, job and equipment scheduling etc.

Role of automation in industry

Manufacturing processes, basically, produce finished product from raw/unfinished material using energy, manpower and equipment and infrastructure. Since an industry is essentially a "systematic economic activity", the fundamental objective of any industry is to make profit.

Roughly speaking, Profit = (Price/unit – Cost/unit) x Production Volume

So, profit can be maximised by producing *good quality products, which may sell at higher price, in larger volumes with less production cost and time. Figure shows the major parameters that affect the cost/unt of a mass-manufactured industrial product.*

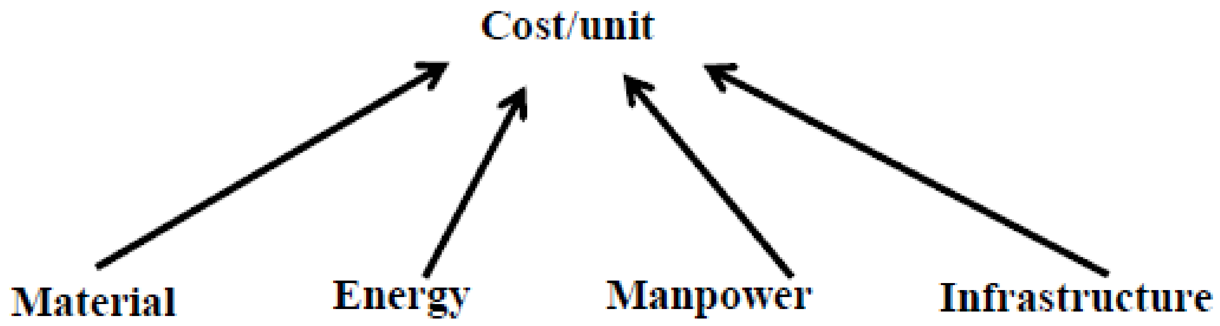
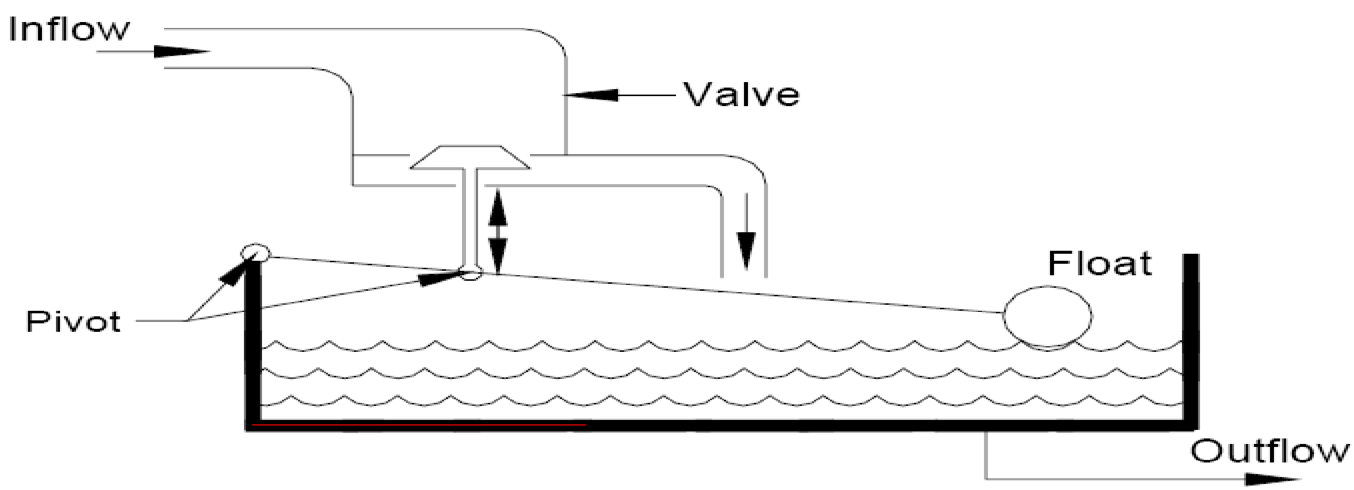
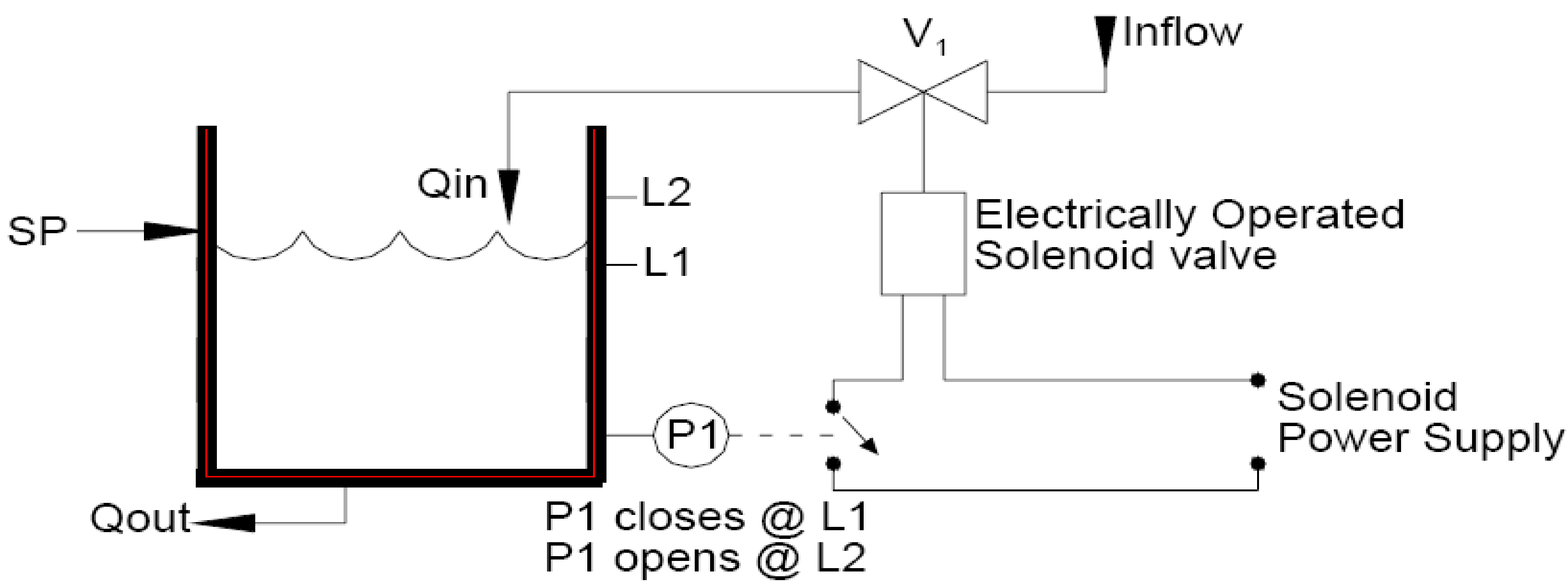


Fig. 1.2 The Components of per unit Manufacturing Cost

Simple ON/OFF Control System





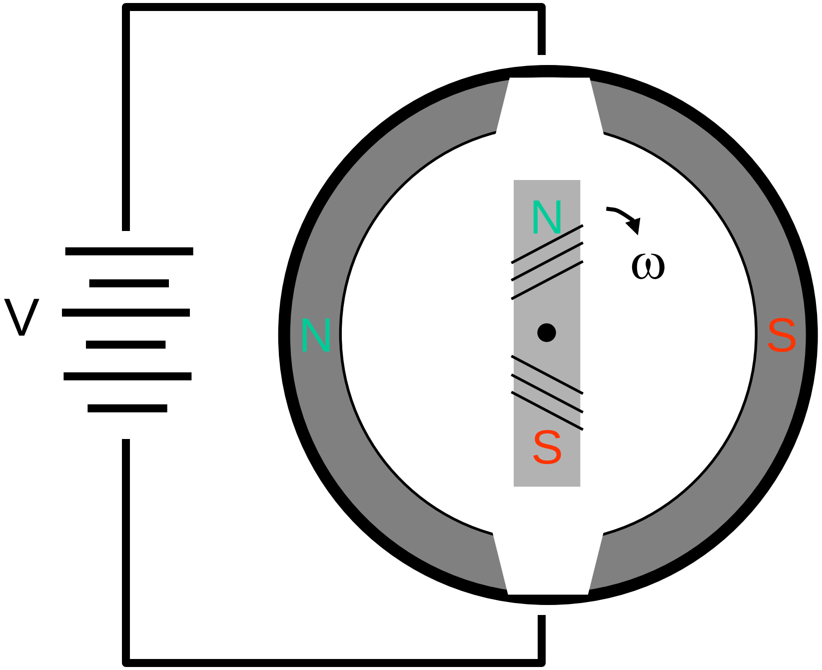
Control

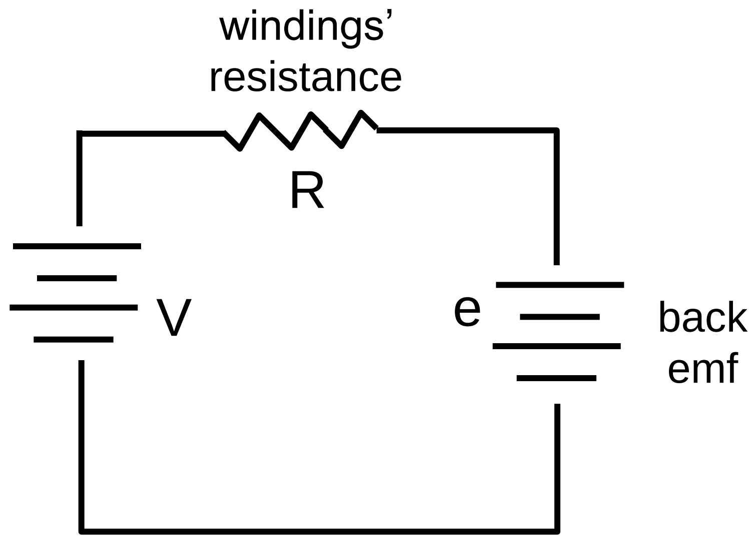
Control: getting motors to do what you want them to

What you want to control = what you can control

For DC motors:

speed **voltage**





e is a voltage generated by the rotor windings cutting the magnetic field

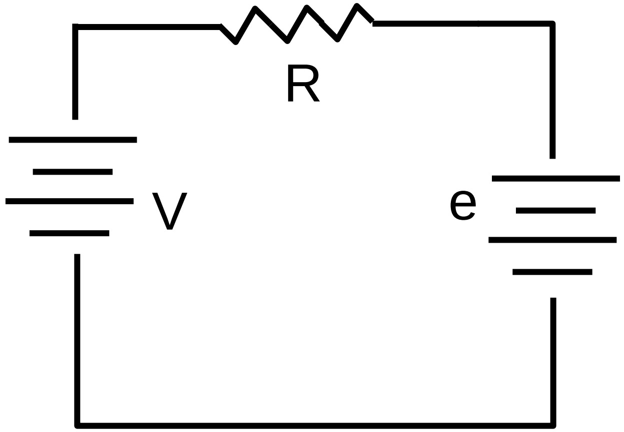
emf: electromagnetic force

Controlling speed with voltage

- The back emf depends only on the motor speed.
- The motor's torque depends only on the current, I.

$e = k_e \, \omega$

$\tau = k_\tau \, I$



DC motor model

Controlling speed with voltage

- The back emf depends only on the motor speed.
- The motor's torque depends only on the current, I.

$e = k_e \, \omega$

$\tau = k_\tau \, I$

$I_{stall} = V/R$

current when motor is stalled

speed = 0

torque = max

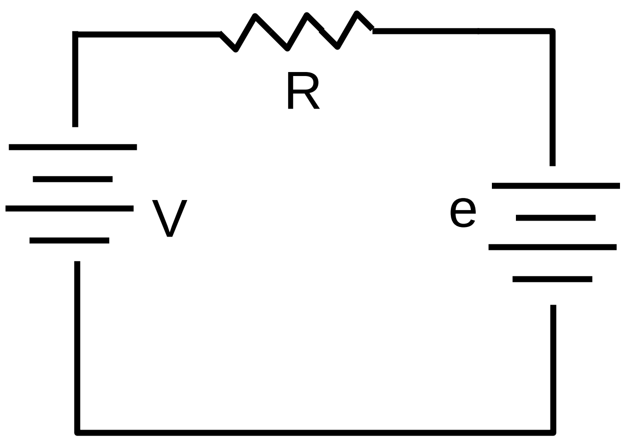
- Consider this circuit's V: $V = IR + e$

How is V related to ω?

$$V = \frac{\tau R}{k_\tau} + k_e \omega$$

– or –

$$\omega = -\frac{R}{k_\tau k_e}\tau + \frac{V}{k_e}$$



DC motor model

Speed is proportional to voltage.

Back to control

Basic input / output relationship:

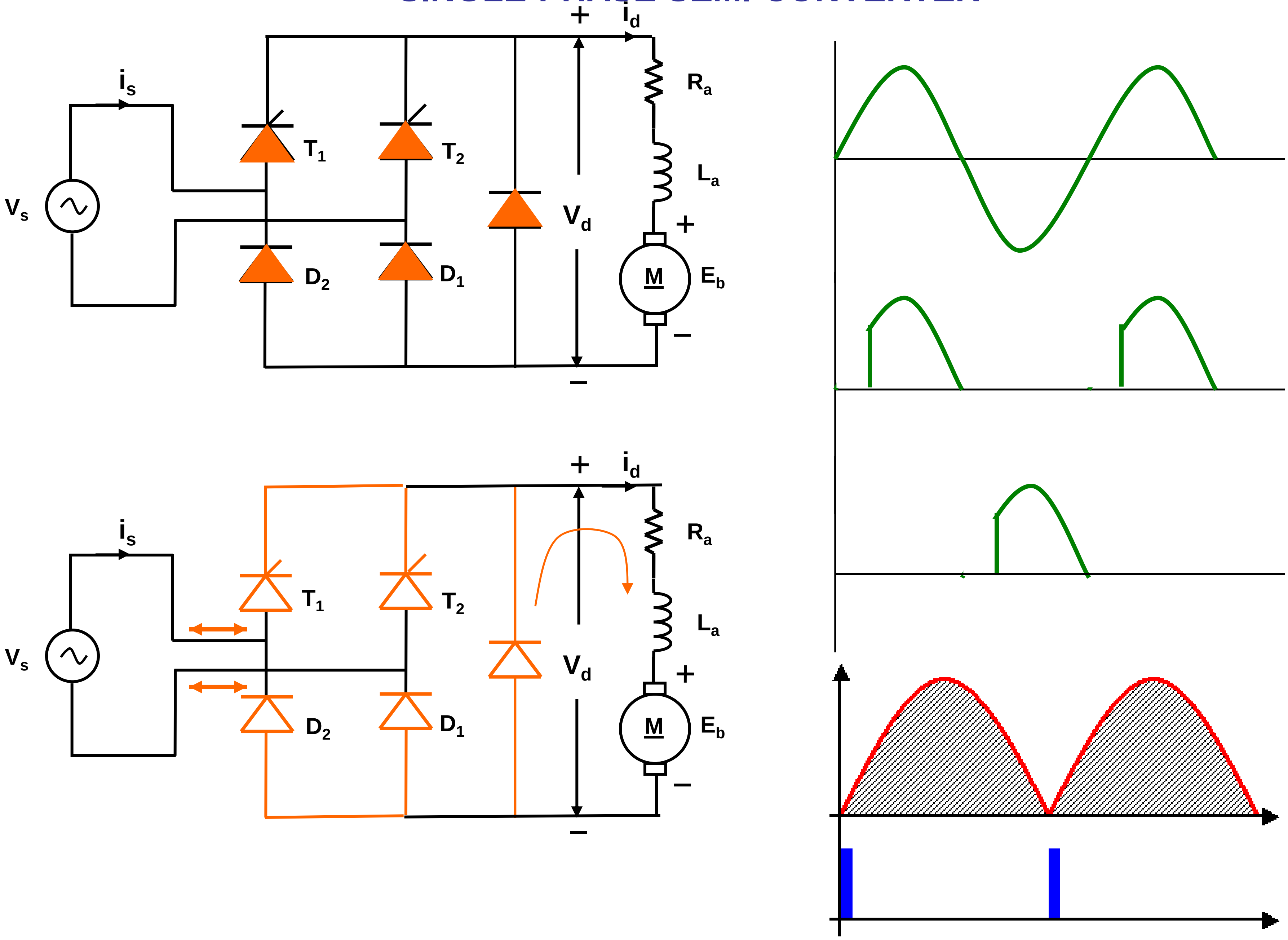
$$V = \frac{\tau R}{k_\tau} + k_e \omega$$

We can control the voltage applied V.

We want a particular motor speed ω .

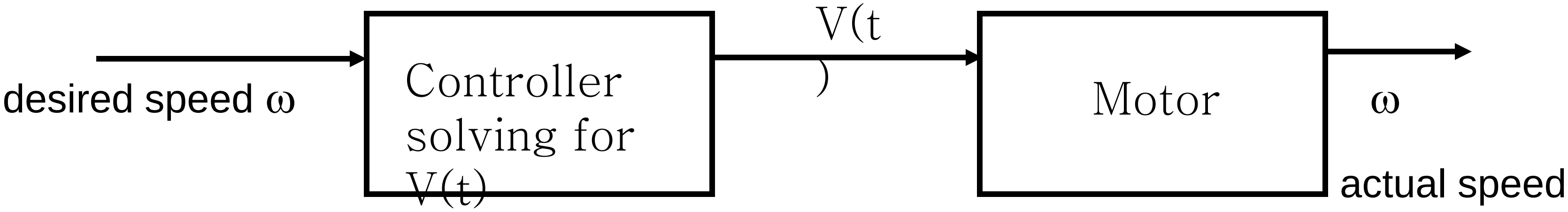
How to change the voltage?

SINGLE-PHASE SEMI-CONVERTER



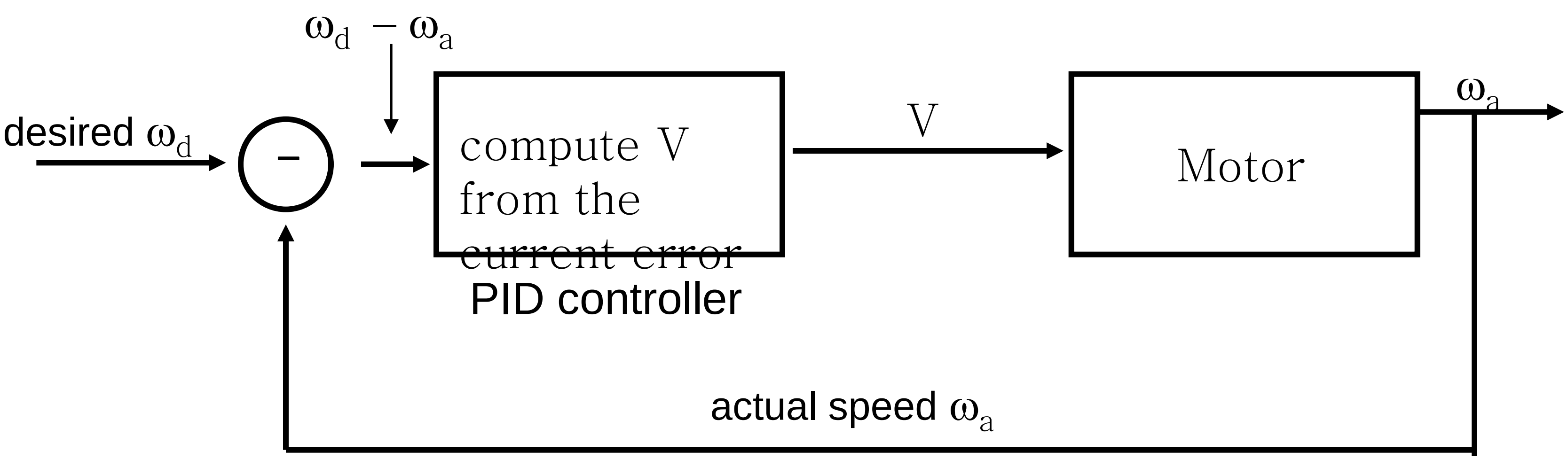
Open-loop vs. Close-loop Control

Open-loop Control:

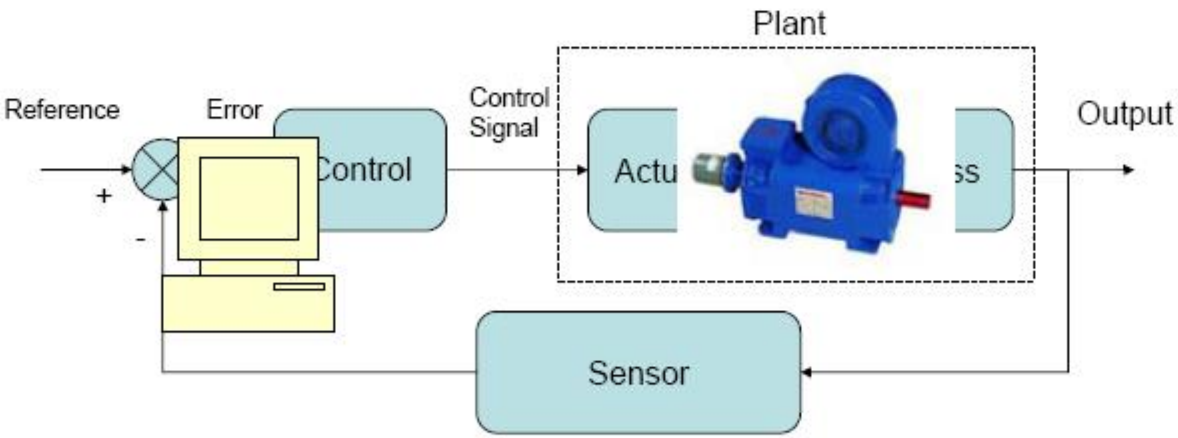


If desired speed $\omega_d \neq$ actual speed $\omega_{a,}$ So what?

Closed-loop Control: using feedback



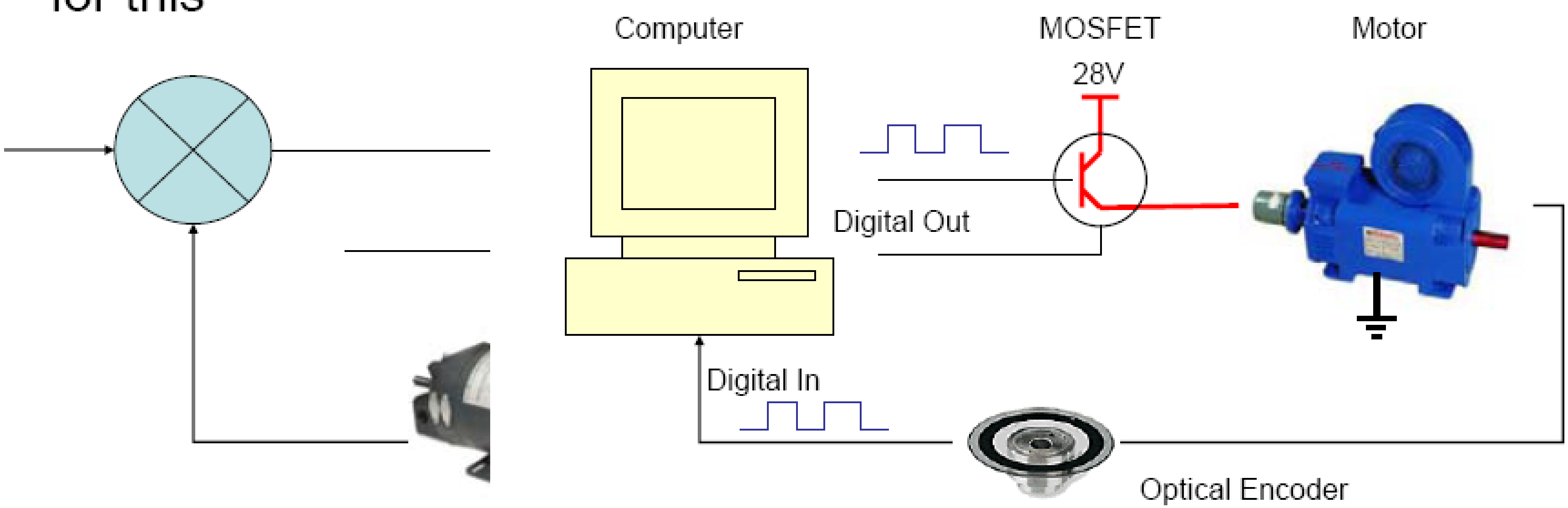
Speed control of dc motor



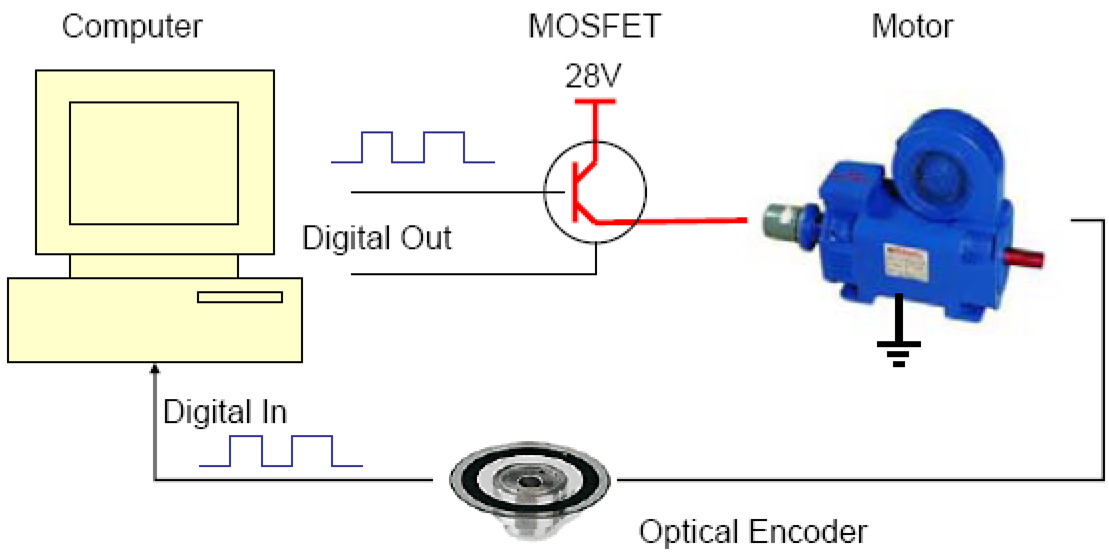
Reference
Sensor

computer
(μPs / μCs / DSPs / FPGA controllers)

- In fact, **we** don't even need a computer for this



Speed control of dc motor



- Computer options will depend on the application
  - Size
  - Power requirements
  - Speed of motion
  - Complexity of control paths
  - IO requirements
- Options include
  - Microprocessor
  - General Purpose Processor
  - ASIC/FPGA

computer

(µPs / µCs / DSPs / FPGA controllers)

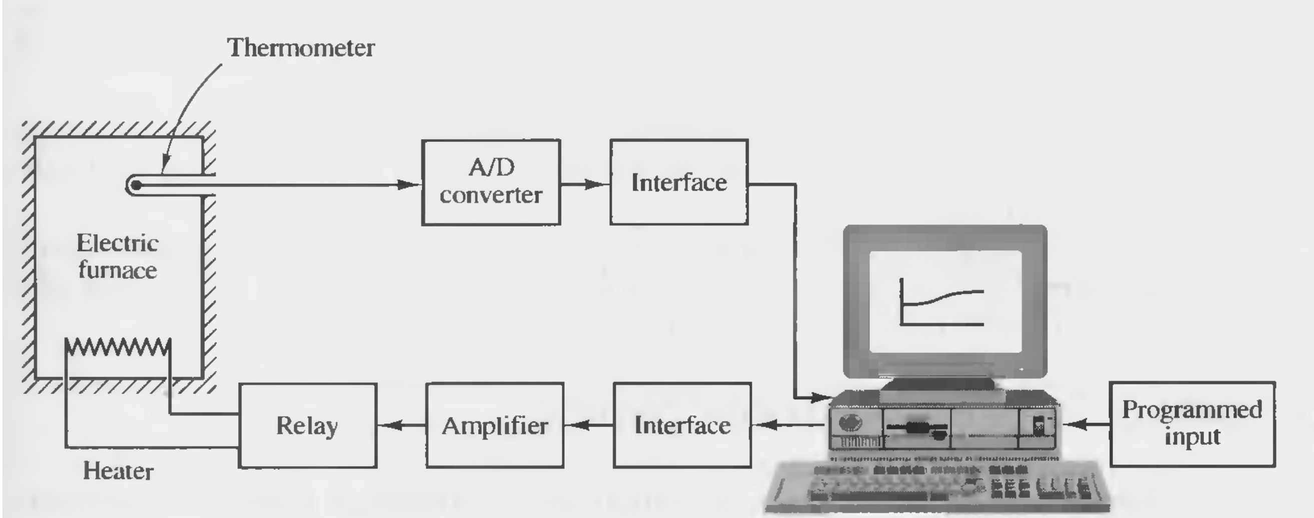
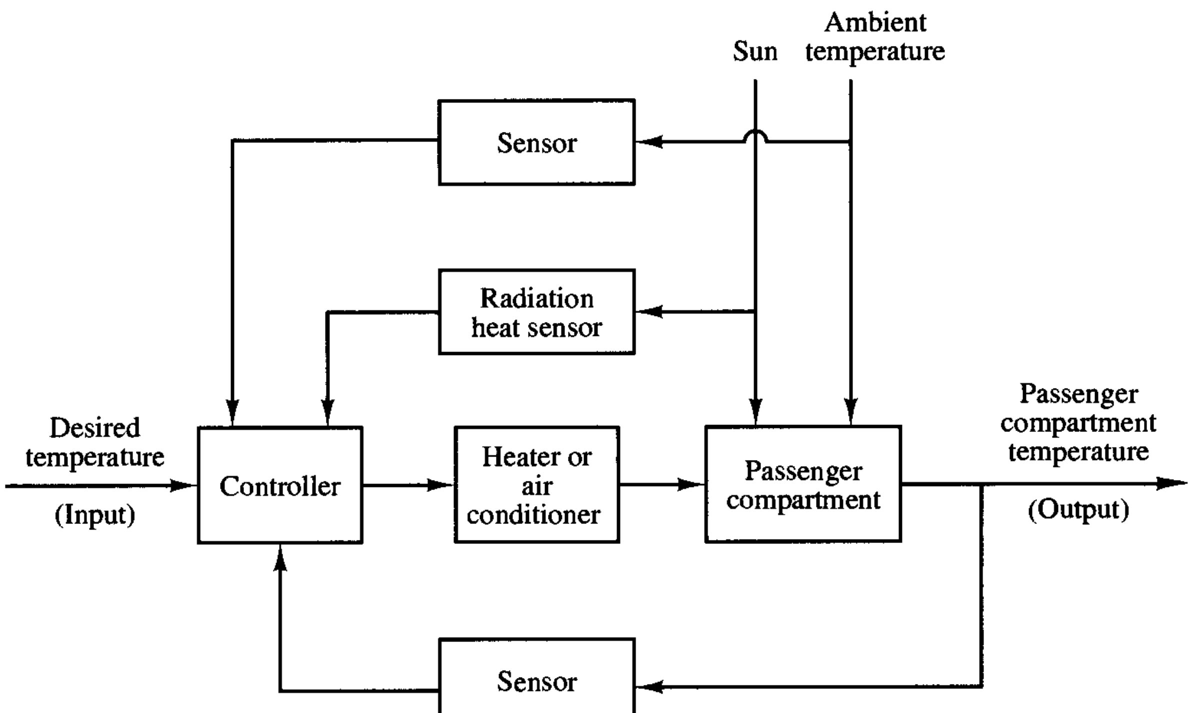
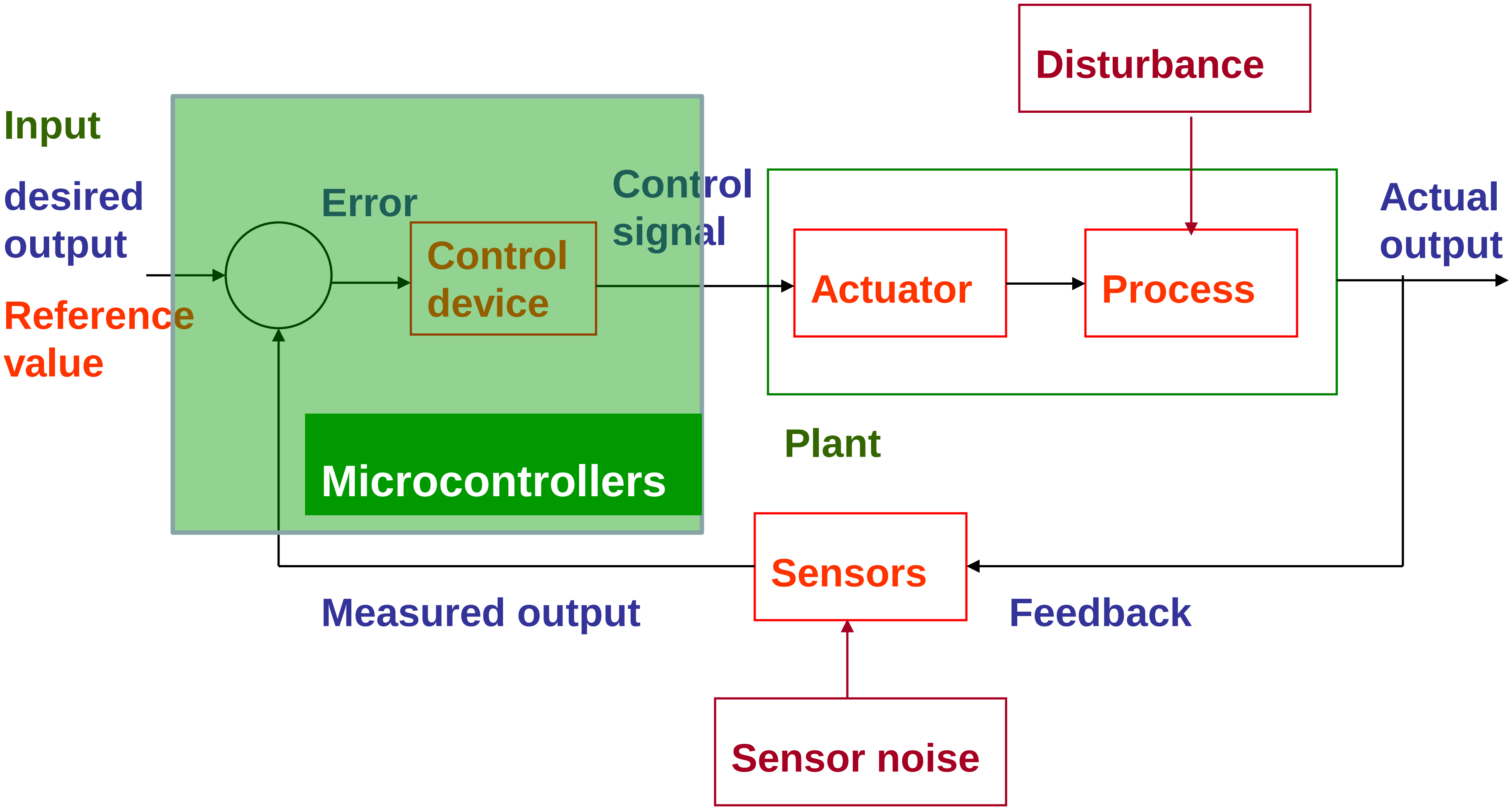


Figure 1–3
Temperature control system.



A basic closed-loop control system



Block diagrams show relationship between components.
They are helpful for visualizing system structure and the flow of information.

In modern control systems, the connection between sensors and actuators is invariably made via a computer (μPs / μCs / DSPs / FPGA controllers)of some sort.

Algorithms

Algorithms is the real *heart* of control engineering

i.e. the algorithms that connect the sensors to the actuators.

As a simple example from our everyday experience, consider the problem of playing tennis at top international level. One can readily accept that one needs good eye sight (sensors) and strong muscles (actuators) to play tennis at this level, but these attributes are not sufficient. Indeed eye-hand coordination (i.e. control) is also crucial to success.

Driving two wheelers

***If you can measure it, you can control it*.**

ANALOG CONTROLLERS

The purpose of the controller is to provide a signal that will cause the process to be modified in such a way as to keep the set point (reference) and the Process variable (actual output) equal.

Any change in set point or the loads on the process should cause a change in the controller's output to assure that the PV tracks the SP.

Types of Analog controllers:

(i) Simple ON/OFF Controller - cycling or chatter

(ii) Proportional controller (st. state error not zero)

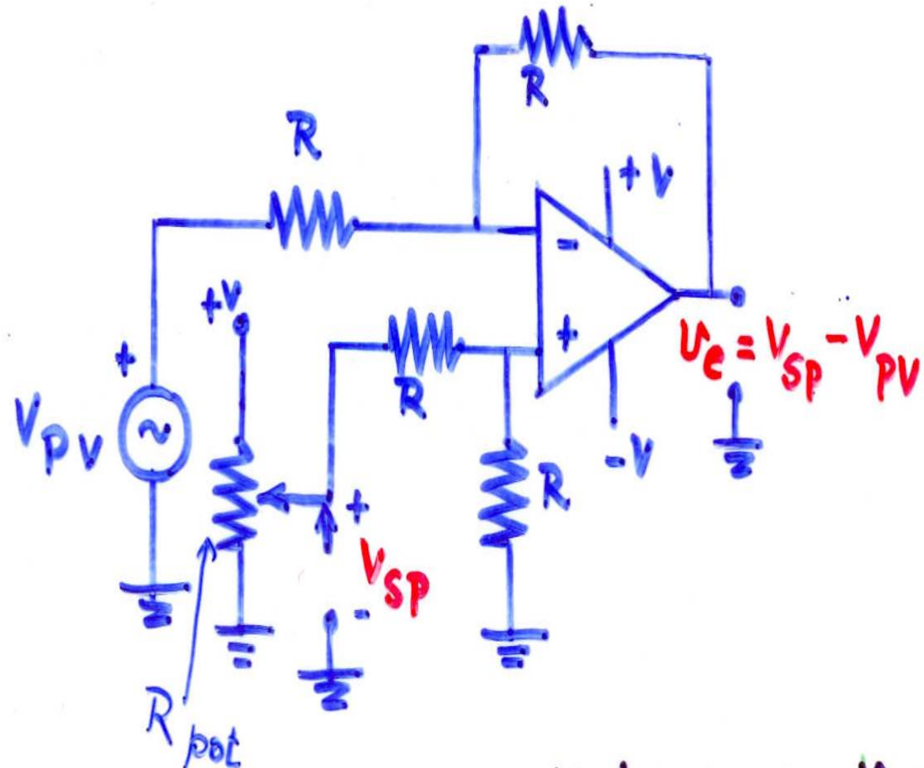
(iii) Proportional Integral controller (Sluggish Transient response)

(iv) P I D Controller (good transient & steady state control)

The most important block in an analog controller is ERROR AMPLIFIER

Configurations of Error Amplifier :

(i) Difference amplifier

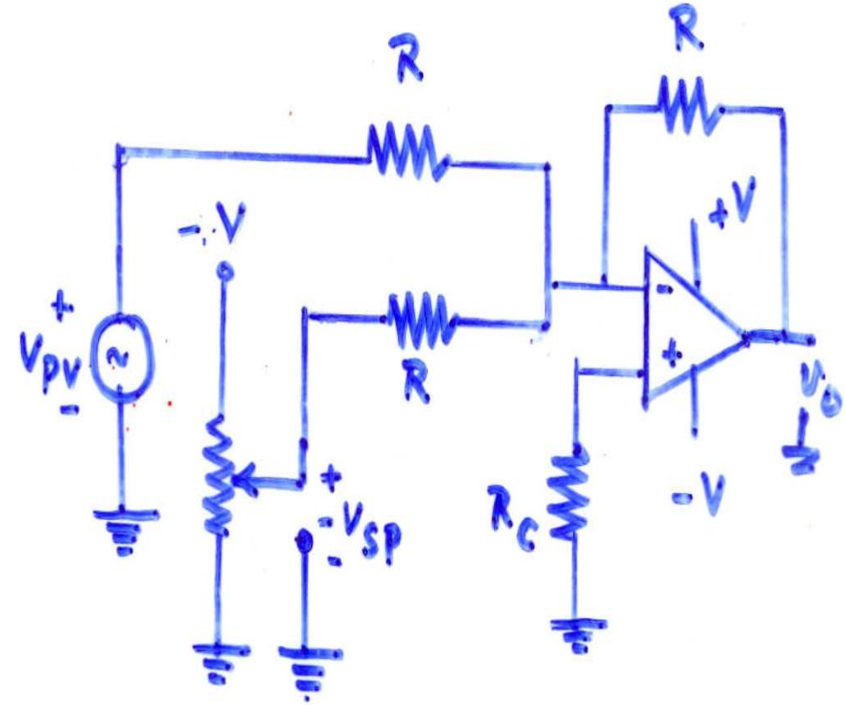


$$V_e = \frac{R}{R}(V_{SP} - V_{PV})$$
$$= V_{SP} - V_{PV}$$

Make sure that

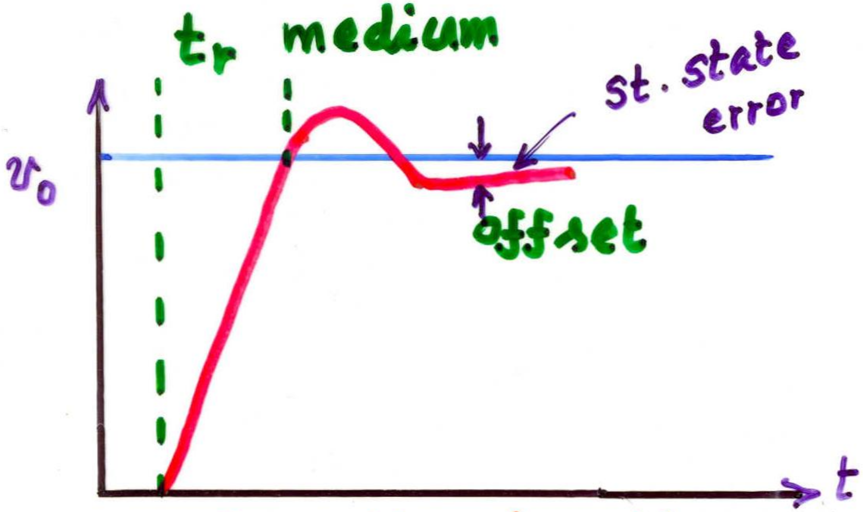
$R \gg R_{pot}$

(ii) Inverting Summer

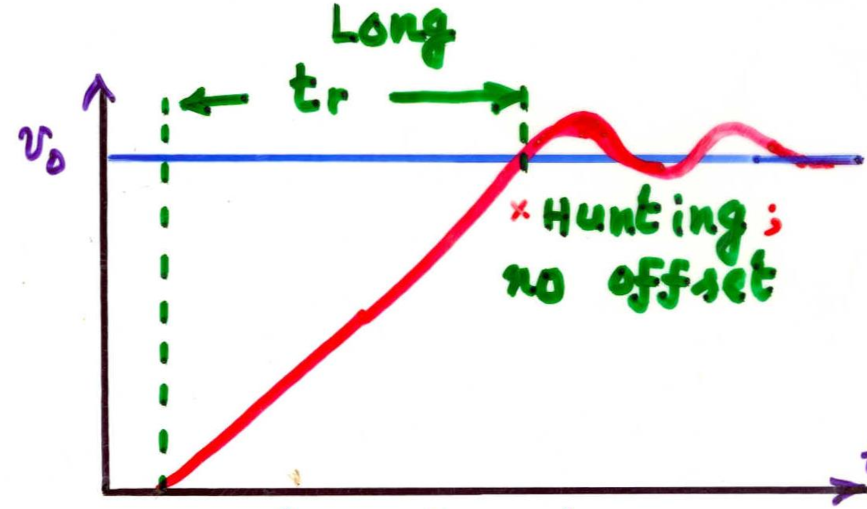


$$V_{out} = -(-V_{SP} + V_{PV})$$
$$= V_{SP} - V_{PV}$$

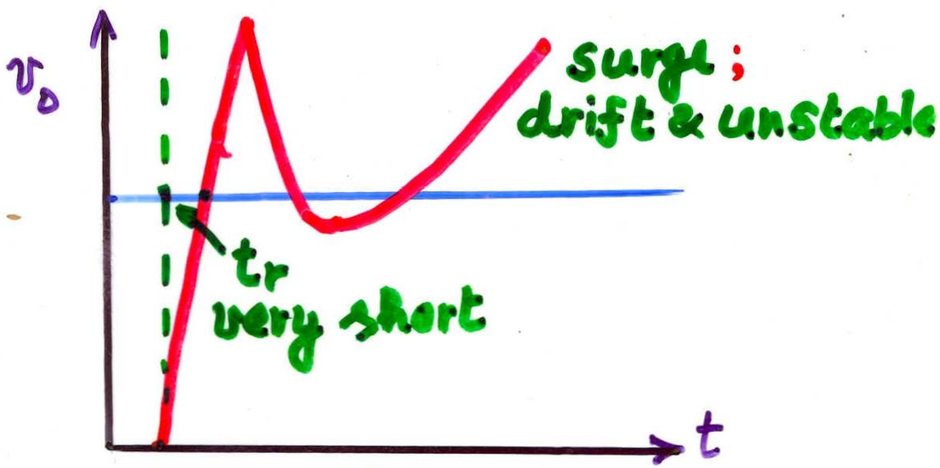
Response of controllers



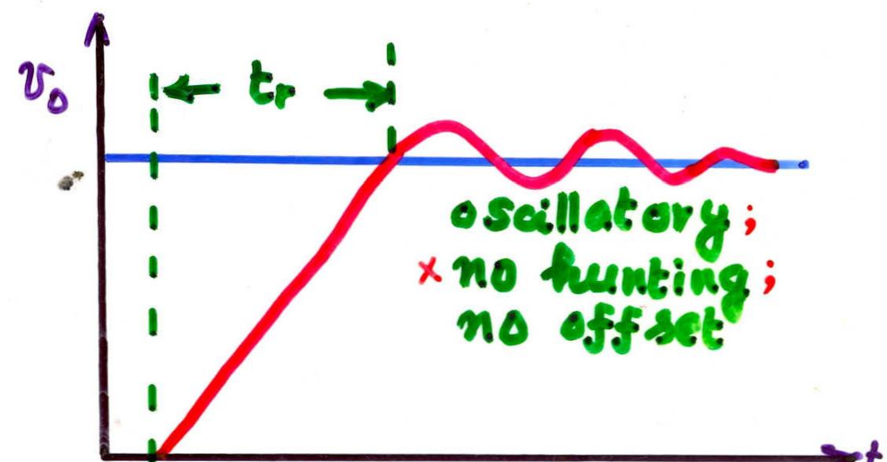
Proportional action



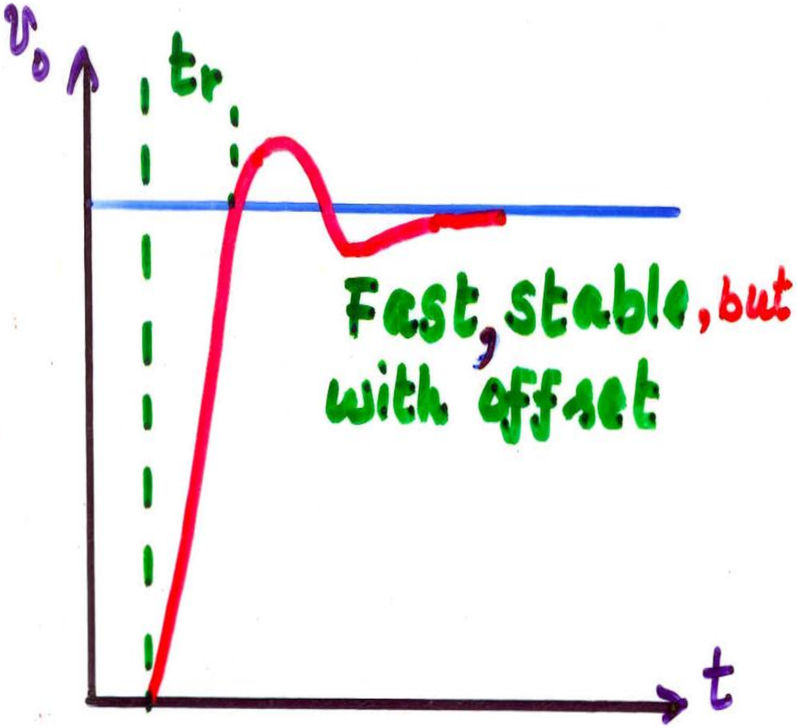
Integral action



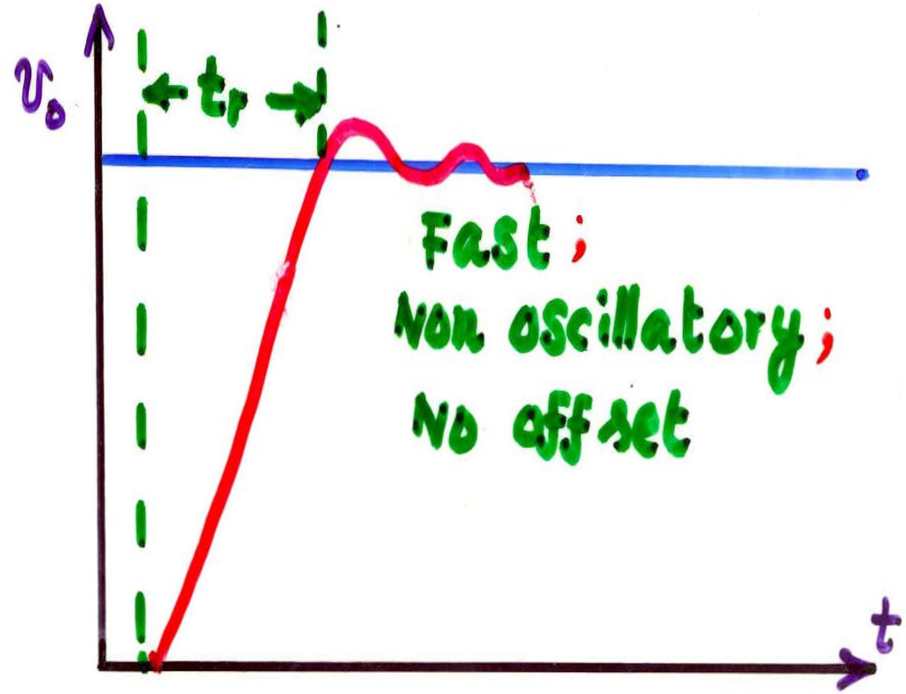
Derivative action



Proportional + Integral



Proportional plus Derivative



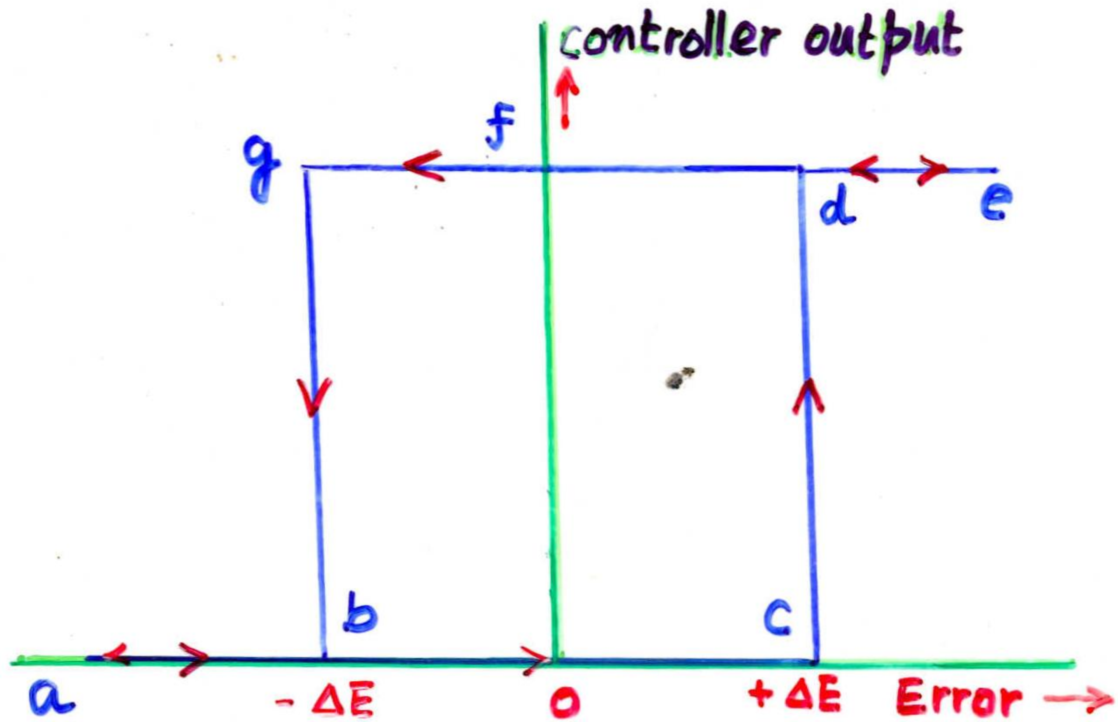
Proportional + Integral + Derivative

t_r : Rise time

ON/OFF CONTROLLERS :

The output of ON/OFF controller is either Fully on or Fully OFF. ⇒ actuator applies full power to the process or turns off the power completely.

(eg): Home Heating thermostat.



(i) If the temp falls below SP, the controller turns on the furnace

(ii) when the temp. has risen above the SP, the controller turns the furnace OFF.

- will lead to chattering -

※ Practical on/off controller will have a deadband to avoid chattering.

(i) when the error is a large -ve value, PV >> SP and the controller is OFF. (point a)

(ii) when the error has moved +ve (from a to c thro' b), the controller o/p switches to 100% ; continues as long as the error is +ve.

(iii) When the error becomes zero (point f), the controller does not immediately turn off.

The controller's output will go OFF only after the error falls below a certain set -ve error at points g and b.

(iv) With such a dead band, the error can never be maintained at zero.

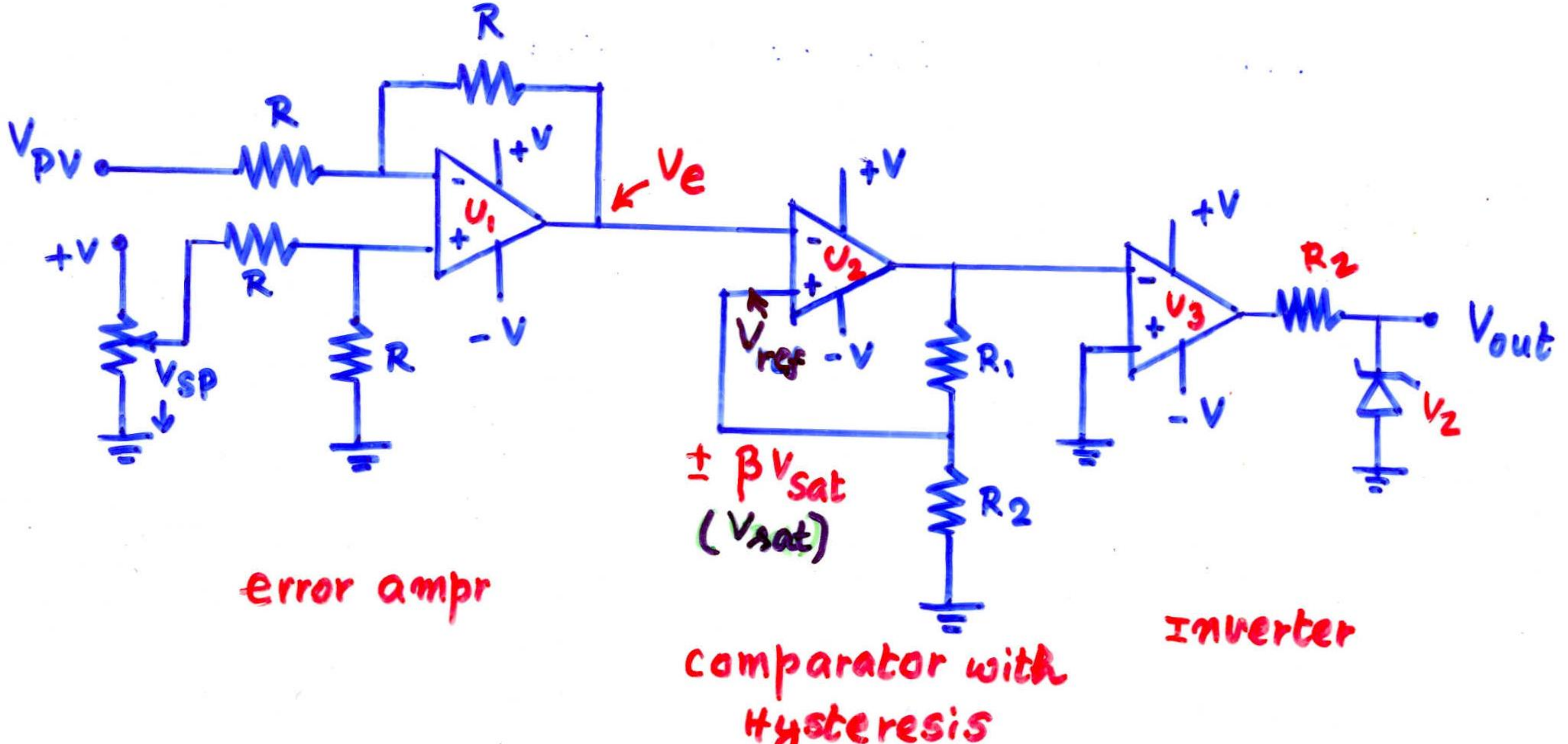
It will fluctuate between $\pm \Delta E$ as the controller cycles from full off to full on, ... etc.

Without the residual error (dead band) : The controller has to make rapid full range swings for small variations in PV.

Such rapid swings will seriously damage the electromechanical actuators and other components.

Hence, a deadband is necessary to prevent this cycling.

An Electronic ON/OFF controller



When V_e is quite -ve, output of U_2 goes to $+V_{sat}$ as V_{ref} is ≈ zero initially.

$$\text{Now } V_{ref} = \frac{R_2}{R_1+R_2}(+V_{sat}) = \beta V_{sat}.$$

only when V_e is more +ve than βV_{sat},

U_2 will switch to -ve saturation.

Now $V_{ref} = -\beta V_{sat}$ & the error must now become more -ve than $-\beta V_{sat}$ before U_2 will switch to a +ve saturation again.

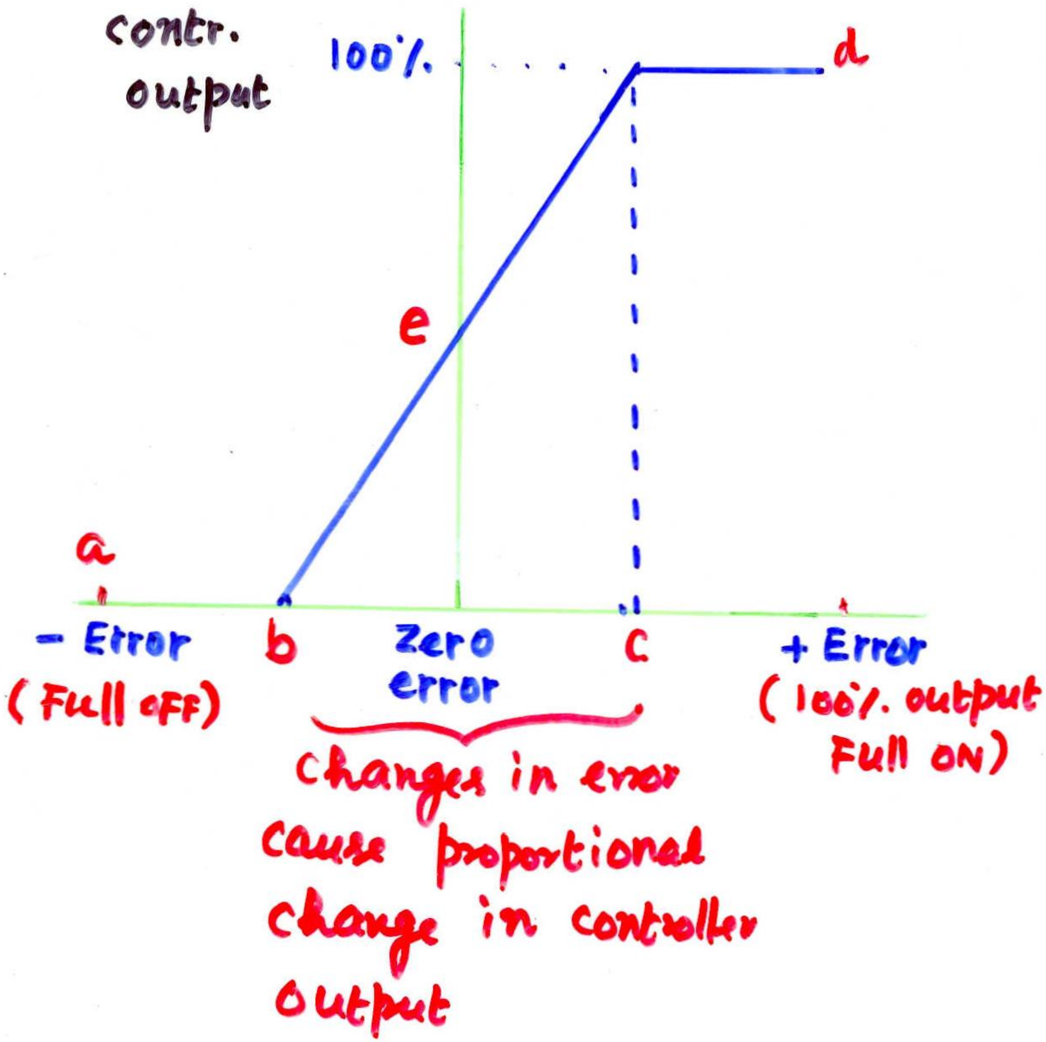
So U_2 produces the deadband or hysteresis

$$\Delta E = \pm \beta V_{sat}.$$

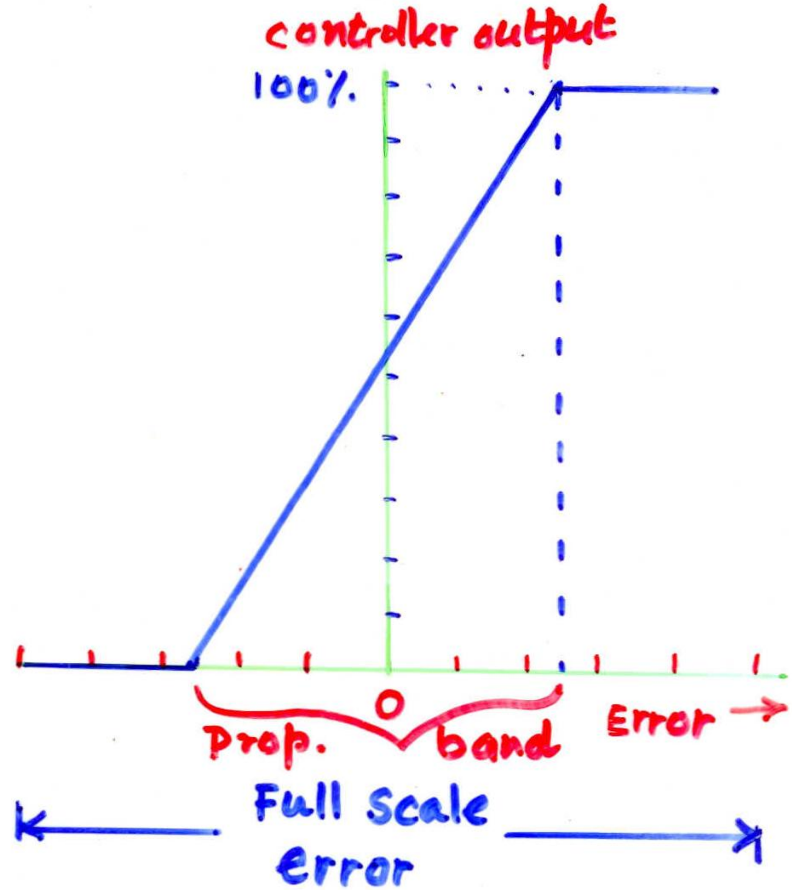
opamp U_3 inverts the levels from U_2 & the Zener at the output restricts V_{out} to the max. specified controller output.

Note: The on/off controller can be used in systems where we can tolerate some noticeable error (residual)

PROPORTIONAL CONTROLLERS: For Linear region of control.

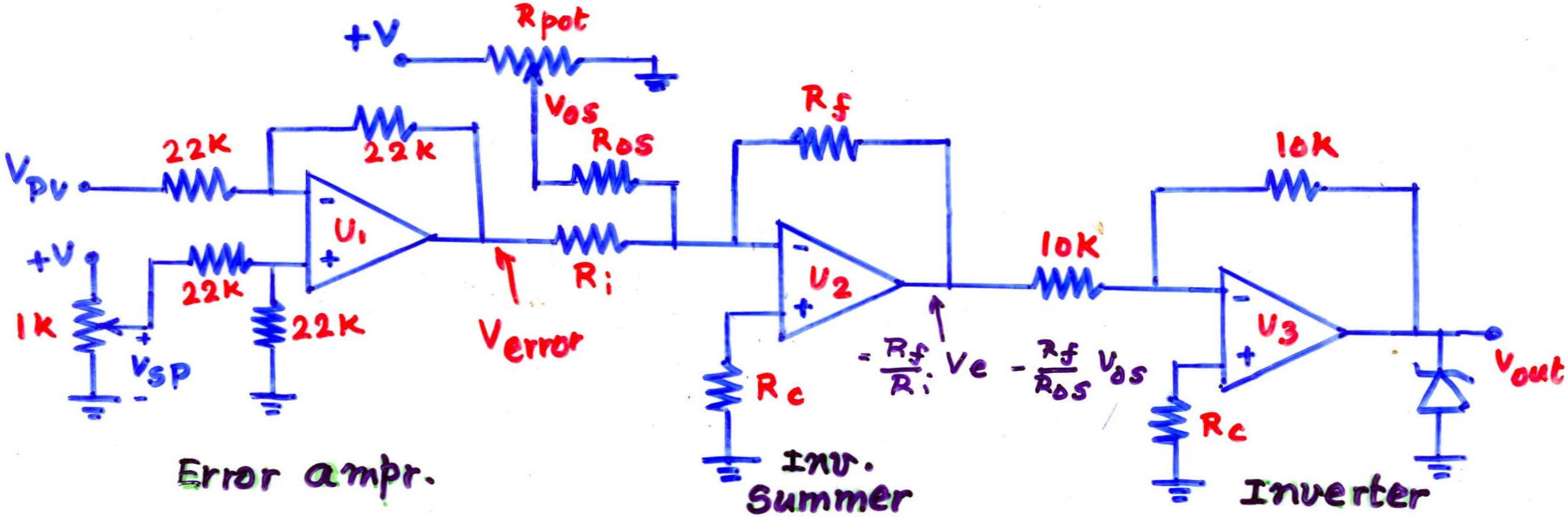


General Transfer curve



Transfer curve with 50% P-band

Schematic of Proportional Controller :



U_1 : produces error signal from SP and PV

U_2 : provides the proportional band (inverting summer)

U_3 : inverter to compensate for the inversion produced by U_2.

The circuit eqn. is :

$$V_{out} = -\left[-\left(\frac{R_f}{R_i}\right)V_{error} - \left(\frac{R_f}{R_{os}}\right)V_{os}\right]$$

$$= \frac{R_f}{R_i} V_{error} + \frac{R_f}{R_{os}} V_{os}$$

Usually $R_f = R_{os}$, giving

$\therefore \quad V_{out} = \frac{R_f}{R_i} V_{error} + V_{os} \Rightarrow$ when $V_{error} = 0$, $V_{out} = V_{os}$

(point e in Fig. a)

We can vary V_{os} to set desired controller output for zero error.

Often it is set to half of the controller's Full scale output.

The slope of the transfer curve is determined by the gain given to V_{error} by the inverting amplifier.

$$\text{i.e.,} \quad m = \frac{R_f}{R_i} = \frac{V_{out}(FS)}{\%\,band \times V_{error}(FS)}$$

Note : The proportional controller shown in Fig. is INVERSE ACTING.

A rise in PV is inverted by U_1 (out of phase), back in phase at the output of U_2 and inverted again (out of phase) by U_3.

This gives the error V_s output plot a +ve slope.

To convert this into direct-acting, simply omit U_3 in the Fig.

The output will now move in phase with PV.

The error V_s output plot will be negative slope

Drawback of Proportional Controller :

The error can't be eliminated completely.

To reduce the error, the controller must raise its output.

But to raise its output, the controller must have some error.

This residual error can be reduced by increasing the gain of U_2 but, too much gain will cause the system to oscillate !

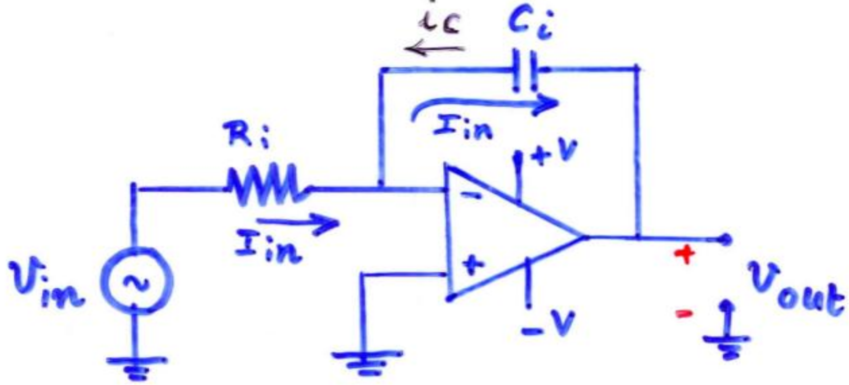
Integral Controller

To eliminate the residual system error, the controller's response must be changed.

In Proportional controller, the output was proportional to the system error.

The integral controller has an output whose rate of change is proportional to the error.

As long as there is any error, the output will continue to change & when the error becomes zero, the controller holds the output which was necessary to produce no error.



$$I_{in} = -i_c = -C_i \frac{dv_c}{dt}$$

$$\frac{dv_c}{dt} = \frac{i_c}{C_i}$$

$$v_c = \frac{1}{C_i}\int i_c \, dt + v_{ini}$$

$v_c = -\frac{1}{C_i}\int I_{in}\, dt + V_{ini}$; V_{ini} = initial charge on C_i

$$= -\frac{1}{C_i}\int \frac{v_{in}}{R_i}\, dt + V_{ini} = -\frac{1}{R_i C_i}\int v_{in}\, dt + V_{ini}$$

i.e., $v_c = K_I \int v_{in}\, dt + V_{ini}$ where

$K_I = -\frac{1}{R_i C_i}$ is the integration constant

If $v_c = v_{out}$ and $v_{in} = v_{error}$ of the controller,

then $v_{out} = K_I \int v_{error}\, dt + V_{ini}$ where

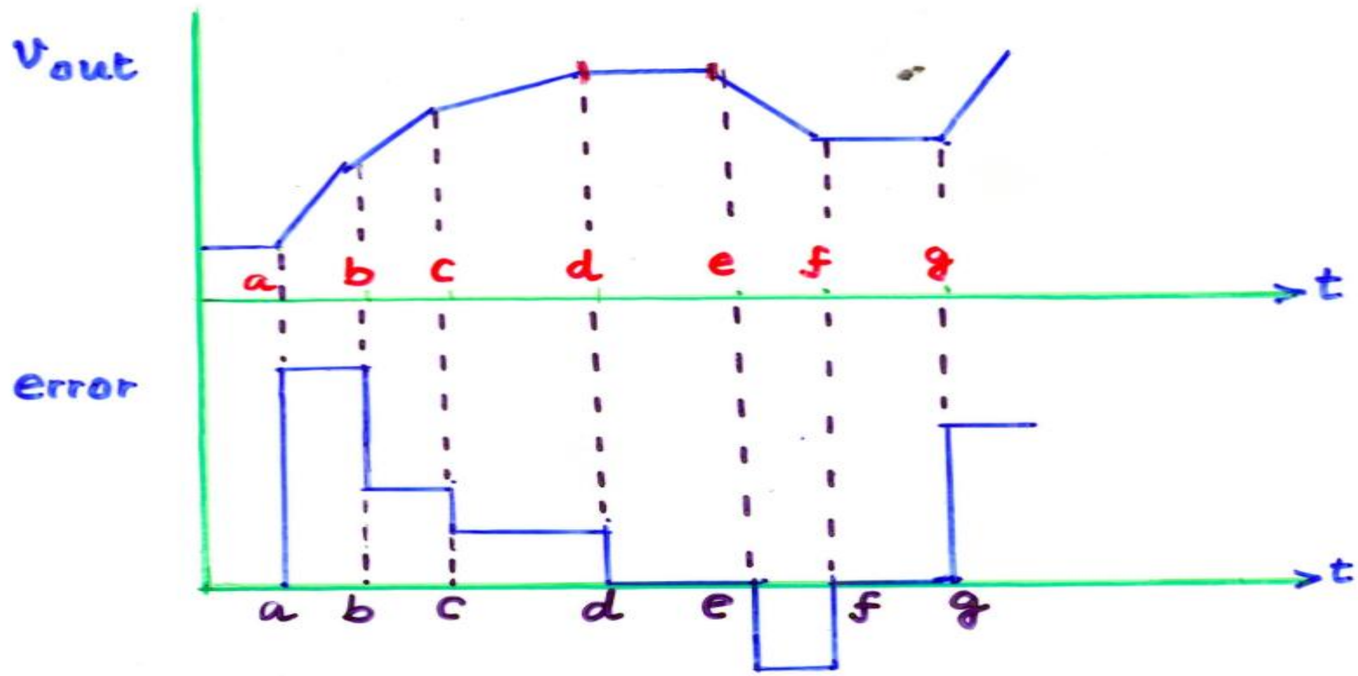
V_{ini} = initial controller offset

Differentiating the above eqn., we get

$d\,v_{out} = K_I\, v_{error}\, dt$; $\boxed{\dfrac{d v_{out}}{dt} = K_I\, v_{error}}$ which implies that the rate of change of output of an integral controller is proportional to the error.

i.e., Large error : rapid change in v_o

Small error : slow change in v_o



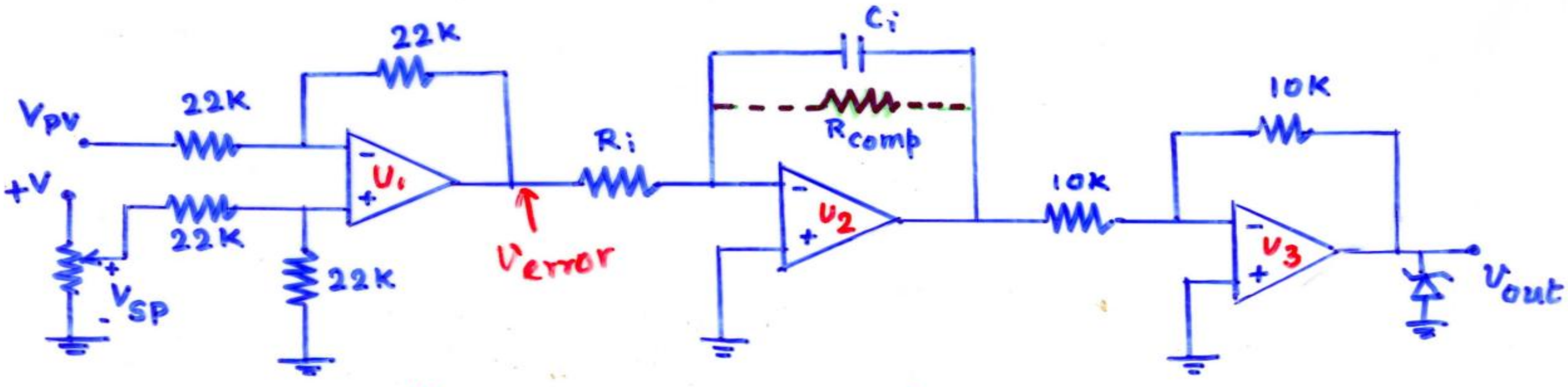
∴ Large error between a & b causes v_o to change rapidly

Decreases in error between b & d cause v_o to change more slowly (but v_o continues to rise)

When the error goes to zero at d, the controller's output does not change but holds the output which dropped the error to zero.

Negative error between e & f causes a -ve rate of change of v_o. i.e., the output falls

Schematic of Integral controller :



Error amplifier　　　Integrator　　　Inverter

Need for R_{comp} : without this, bias currents in some opamps are large enough to charge C_i even with zero error voltage which will cause v_{out} of U_2 to saturate.

Select $R_{comp} > 10\,R_i$ if U_2 saturates with $V_{error} = 0$

$V_e = 0 \Rightarrow$ zero volt. on each side of $R_i \Rightarrow$ no current thro' R_i

$\therefore$ C_i can neither charge nor discharge $\Rightarrow$ it should hold its voltage.

However when we add R_{comp} to keep bias currents from charging C_i, the capacitor can slowly discharge thro' R_{comp}.

i.e., with zero error, V_{out} will slowly fall as C_i discharges thro' R_{comp}.

$\therefore$ A trade off is to be made.

Choosing U_2 as an opamp with very low bias currents is the only solution.

A FET or CMOS opamp will not cause any noticeable change in V_{out} even without R_{comp}.

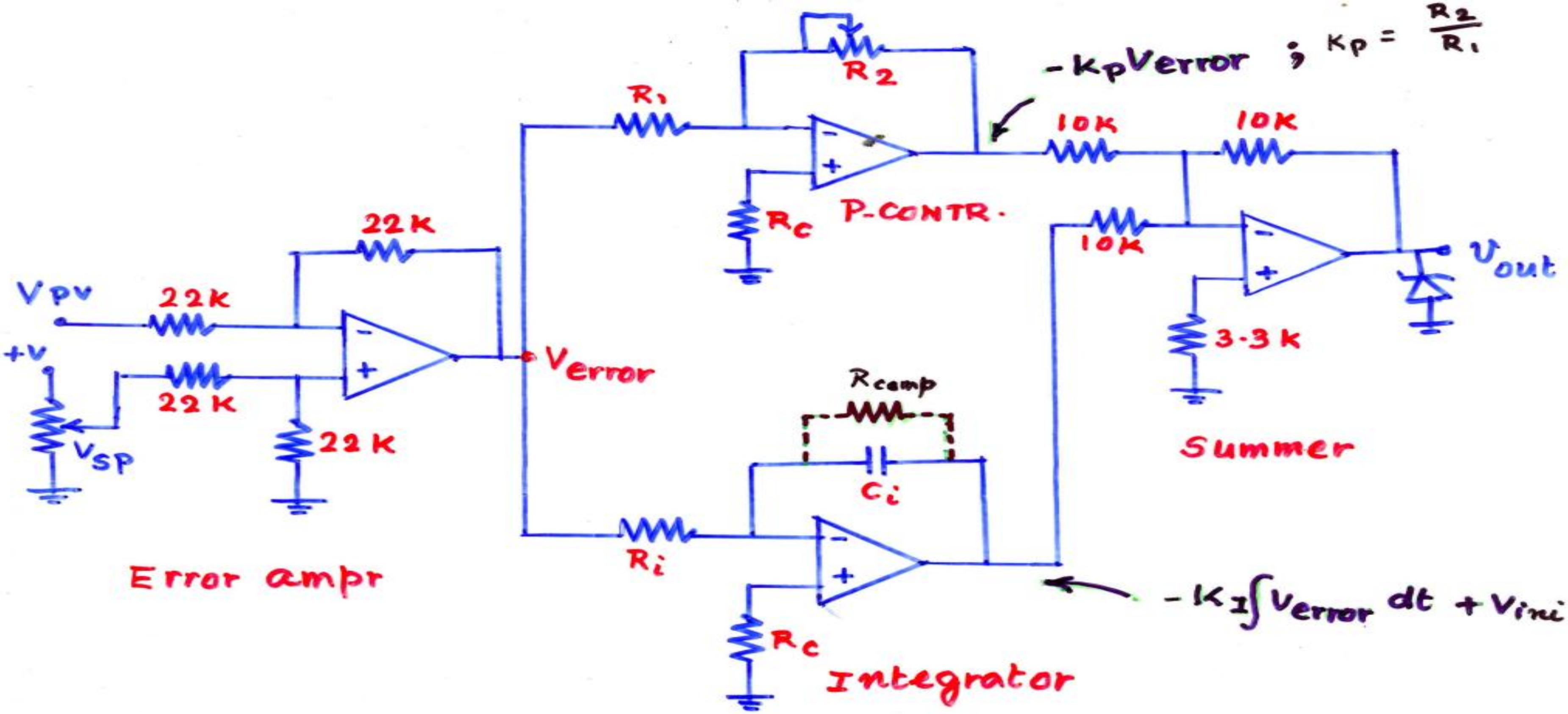
PI Controller

It combines the good transient response from P- controller and steady state error elimination from I- controller.

Configurations :

(i) Parallel PI Controller

(ii) Series PI Controller



$$V_{out} = K_P V_{error} + K_I \int V_{error}\, dt + V_{ini}$$

Taking Laplace Transform,

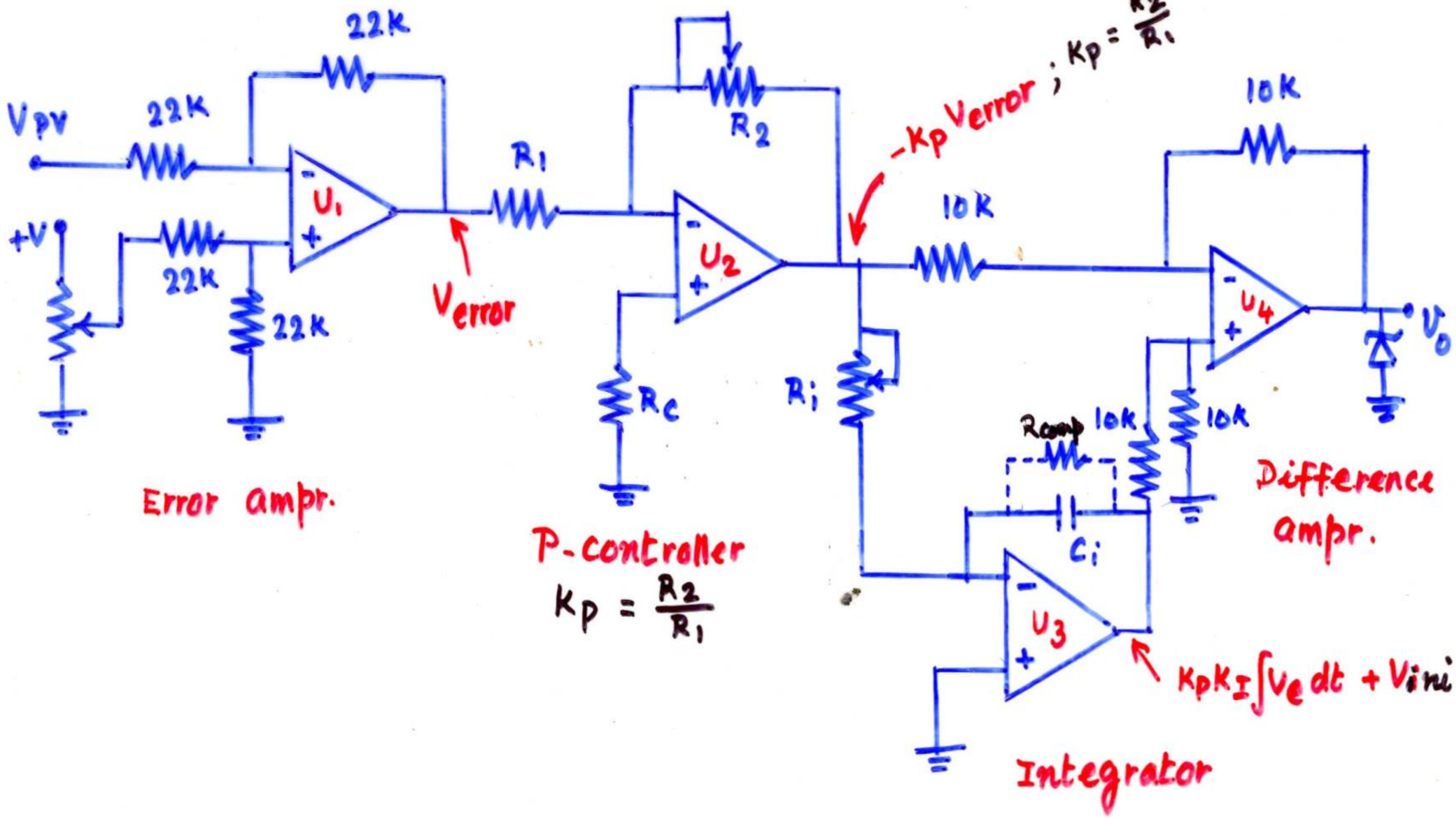
$$V_{out} = K_P V_{error} + \frac{K_I V_{error}}{s} = V_{error}\left[K_P + \frac{K_I}{s}\right]$$

The T.F. of the ckt. $= V_{out}/V_{error} = K_P + \frac{K_I}{s}$

$$= \frac{K_P s + K_I}{s} = \frac{s + (K_I/K_P)}{(1/K_P)\, s}$$

$$\boxed{\text{i.e., } \frac{V_{out}}{V_{error}} = \frac{s + (K_I/K_P)}{(1/K_P)\, s}}$$

SERIES PI CONTROLLER



$$V_{out} = \frac{10K}{10K}\left[\left(K_P K_I \int V_e\, dt + V_{ini}\right) - \left(-K_P V_e\right)\right]$$

$$= K_P V_e + K_P K_I \int V_e\, dt + V_{ini}$$

Taking Laplace Transform, we get

$$V_{out} = K_P V_e + \frac{K_P K_I}{s} V_e$$

$$\therefore \text{ The T.F.} = \frac{V_{out}}{V_e} = K_P + \frac{K_P K_I}{s} = \frac{K_P s + K_P K_I}{s}$$

$$= \frac{K_P[s + K_I]}{s} = K_P \frac{(s/K_I) + 1}{s/K_I}$$

i.e., $\boxed{\text{T.F.} = K_P \frac{[T_i s + 1]}{T_i s}}$ where $T_i = \frac{1}{K_I} = R_i C_i$ &

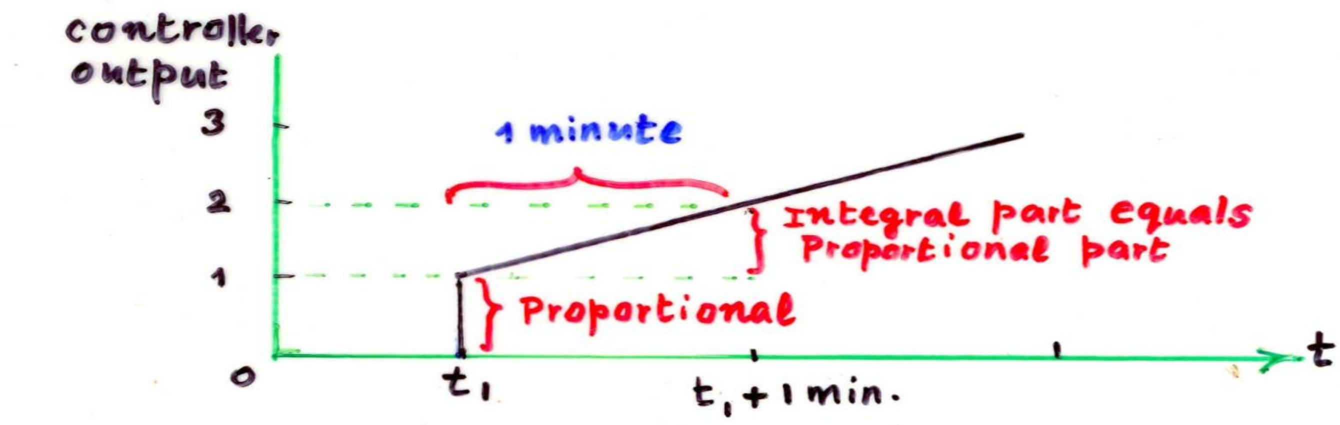
$$K_P = \frac{R_2}{R_1}$$

Note : (i) The Controller is normally specified in terms of T.F.

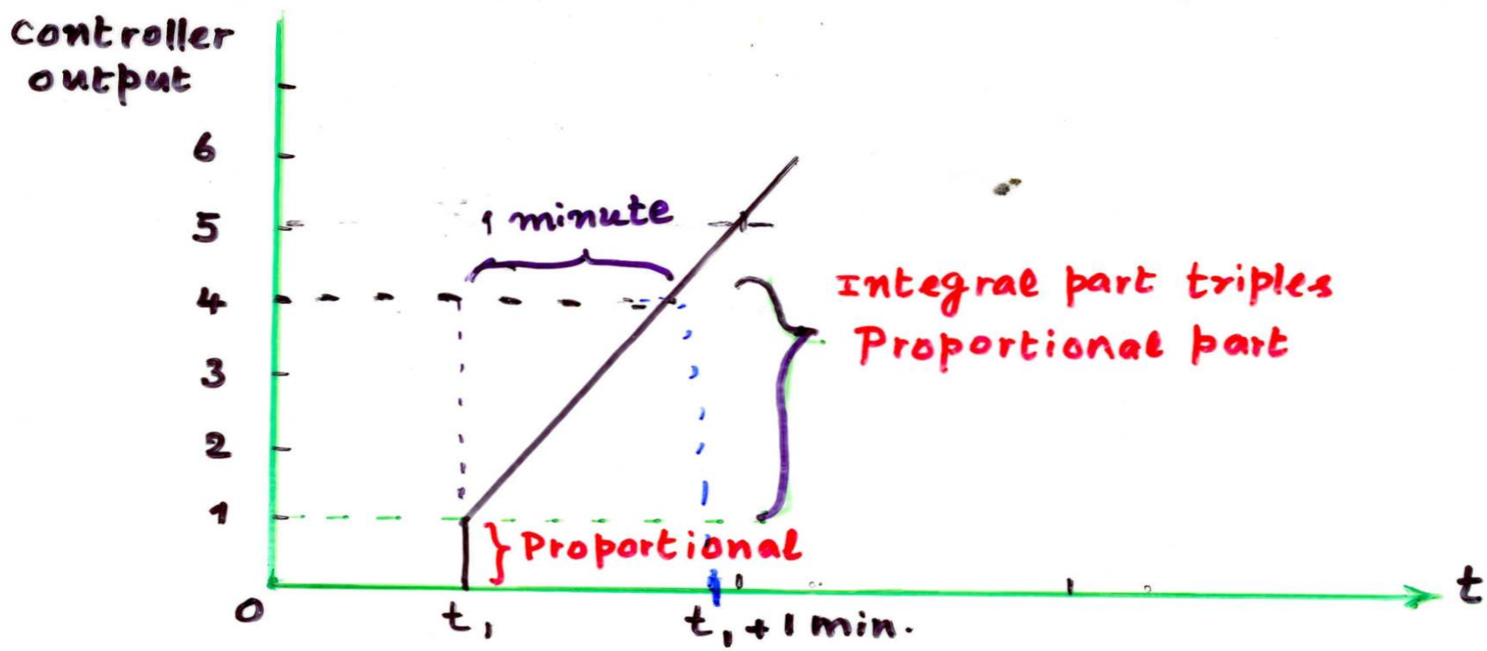
(ii) The const. K_I will be given in terms of resets/min.

Electrical significance of K_I :

With respect t
PI controller



(a) K_I = 1 reset per minute



(b) K_I = 3 resets per minute

In Fig. a, at time t_1, there is a step in error which causes the Proportional part of the controller to step up.

Assuming that the error remains constant, the integral part of the controller will now cause the output to ramp up.

The ramp rate is set by K_I

With a K_I of 1 reset/min., the ramp will send the output up the same amount that the proportional part did.

In Fig. b, the Integral part of the controller causes a ramp which triples the output produced by the Proportional controller.

This is caused by a K_I of 3 resets/min.

Design a parallel PI controller to satisfy the Transfer Function given below:

$$\frac{V_o}{V_i} = \frac{1.5s + 0.2}{0.5s}$$

Solution:

Dividing both Nr. & Dr. by 0.5,

$$T.F. = \frac{3s + 0.4}{s} \Rightarrow K_p = 3 ; K_I = 0.4$$

$$\left(T.F. = \frac{K_p s + K_I}{s} \right)$$

Recalling $K_p = \frac{R_f}{R_i} = 3$; $R_f = 3R_i$;

220K + 100K pot

Selecting R_i as 100K, R_f = 300K (330K)

$\because K_I = \frac{1}{R_i C_i}$; $\frac{1}{R_i C_i} = 0.4$; Choose C_i as 100μF,

then $R_i = \frac{1}{0.4 C_i}$ = 25K (22K + 5K pot)

$$R_{comp1} = R_f \| R_i \simeq 75K \;(66K + 10K\ pot)\; ; \; R_{comp2} = R_i \| X_c \text{ where}$$

$$X_c = \frac{1}{2\pi f C_i} = 31.85\,\Omega \; ; \; R_{comp2} = 25K \| 32\,\Omega \simeq 33\,\Omega$$

To design series PI controller for the above T.F. :

$$\text{Recall T.F.} = \frac{K_p s + K_p K_I}{s} = K_p \left[\frac{1 + \frac{1}{K_I} s}{\frac{1}{K_p} s} \right] = \frac{1.5s + 0.2}{0.5s}$$

Dividing both Nr. & Dr. by 0.5,

$$\text{T.F.} = \frac{3s + 0.4}{s} \; ; \text{ i.e., } K_p = 3, \quad K_I = \frac{0.4}{K_p} = 0.133$$

$$K_p = 3 \Rightarrow \frac{R_f}{R_i} = 3 \; ; \; R_f = 3R_i \; ; \; R_i = 33K \; ; \; R_f = 100K$$

$$K_I = 0.133 \Rightarrow \frac{1}{R_i C_i} = 0.133 \; ; \text{ If } C_i = 100\,\mu F, \; R_i = 77K$$

(66K + 27K pot)

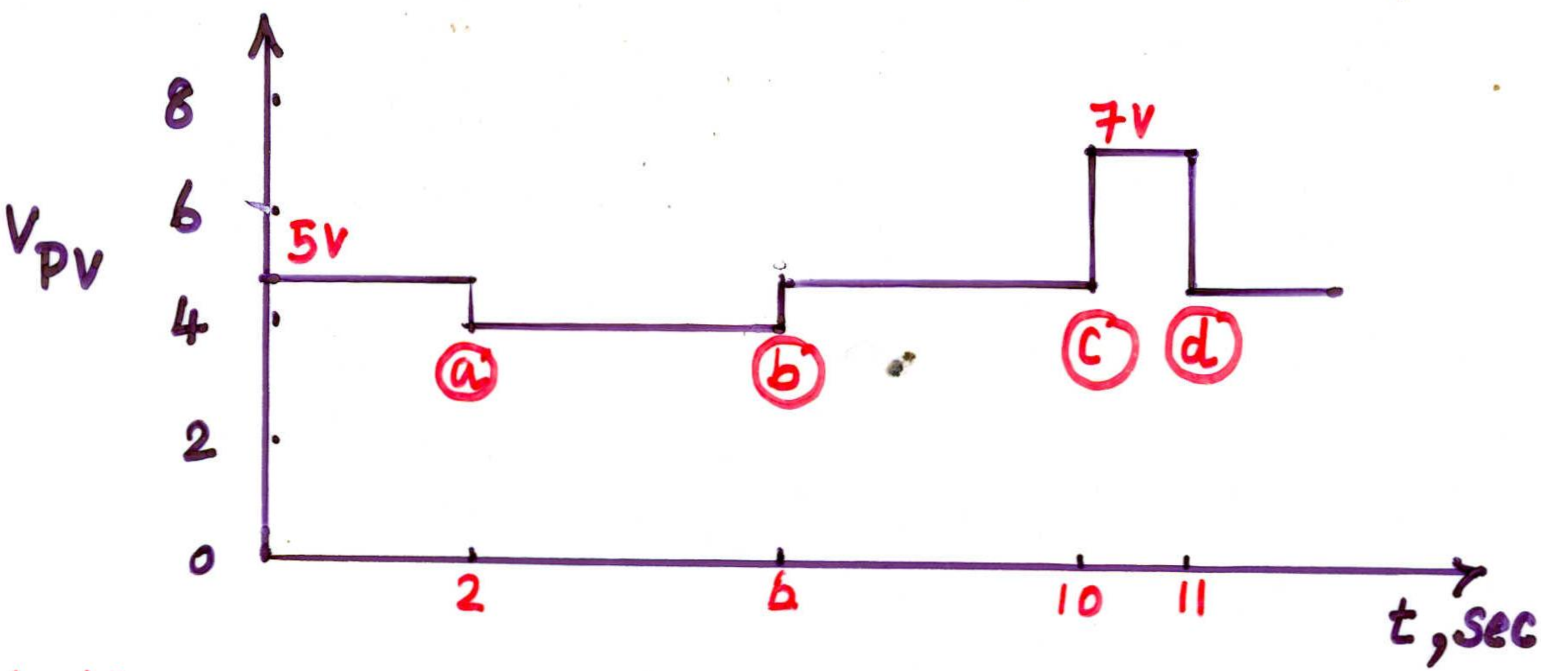
Determine the response of series PI controller to the input given in Fig. shown below.

Assume $V_{sp} = 5V$; $V_{ini} = 0V$; $V_{sat} = \pm 15V$

$R_1 = 3.3K$, $R_2 = 10K$ (Proportional stage)

$R_i = 10K$, $C_i = 100\,\mu F$ (Integral stage)

The gain of error amplifier is unity.



Solution :

$$V_{error} = V_{sp} - V_{pv} = 5V - V_{pv}$$

The gain K_p of $U_2 = \frac{R_2}{R_1} = \frac{10K}{3.3K} = 3.$

U_3 is actually a Ramp generator for a fixed input, with Rate $= V/R_iC_i$ where

$V = V_{error} K_p$ & $R_i = 10K$, $C_i = 100\mu F$

$$\therefore \text{Rate} = \frac{3Ve}{10K \times 100\mu F} = \frac{3Ve}{1\,sec}.$$

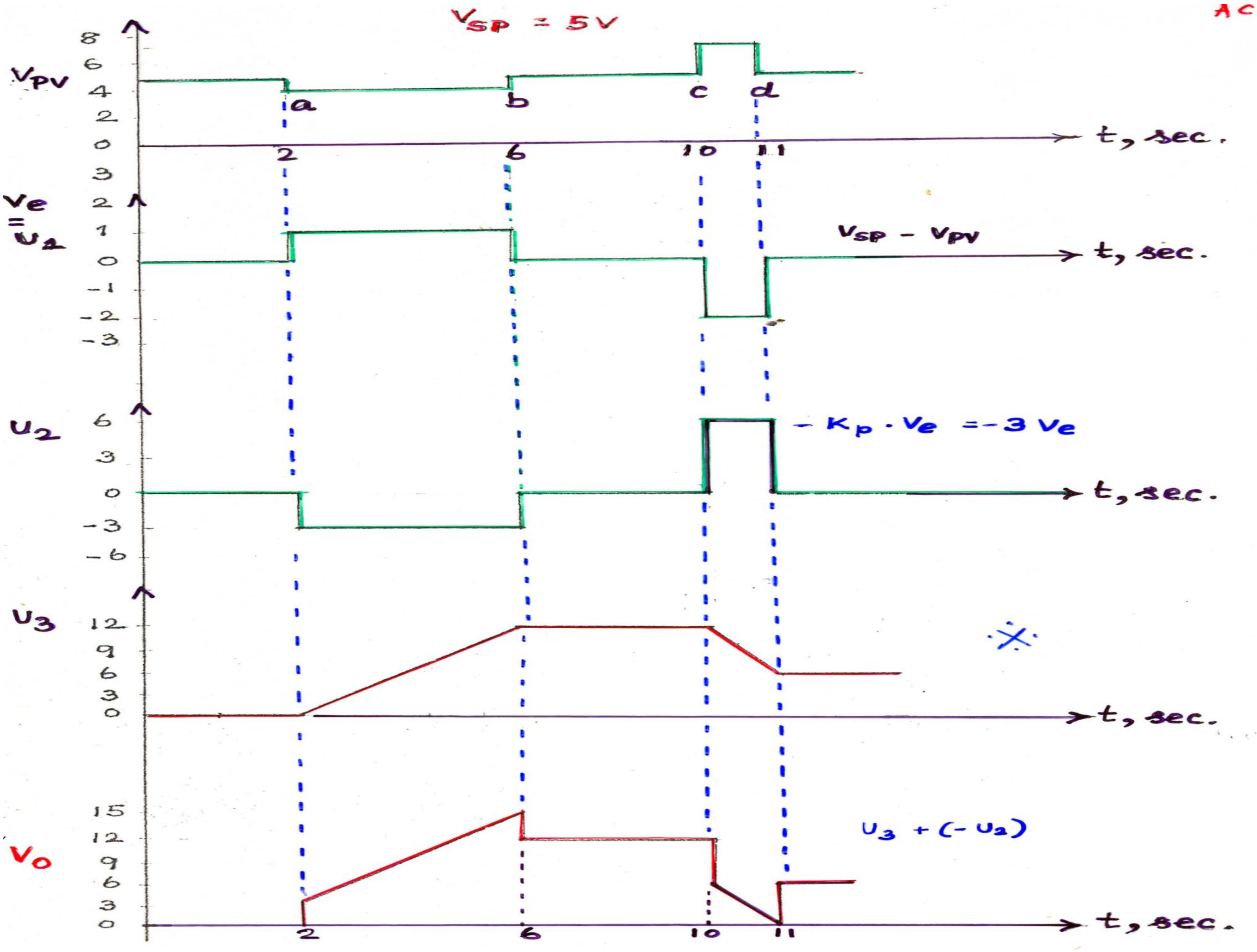
Hence for the time

a – b : $V_e = 1V \Rightarrow U_3$ will ramp at 3V/s

b – c : $V_e = 0V \Rightarrow U_3$ will hold its o/p constant

c – d : $V_e = -2V \Rightarrow U_3$ will ramp downward at 6V/s rate.

The overall o/p is the point by point summation of U_3's output and the inversion of U_2's output.



AC
VSP = 5V
VPV
8
6
4
2
0
a
b
c
d
t, sec.
2
6
10
11
Ve = U1
3
2
1
0
-1
-2
-3
VSP - VPV
t, sec.
U2
6
3
0
-3
-6
- Kp · Ve = -3 Ve
t, sec.
U3
12
9
6
3
0
t, sec.
15
12
9
6
3
0
Vo
U3 + (- U2)
t, sec.
2
6
10
11

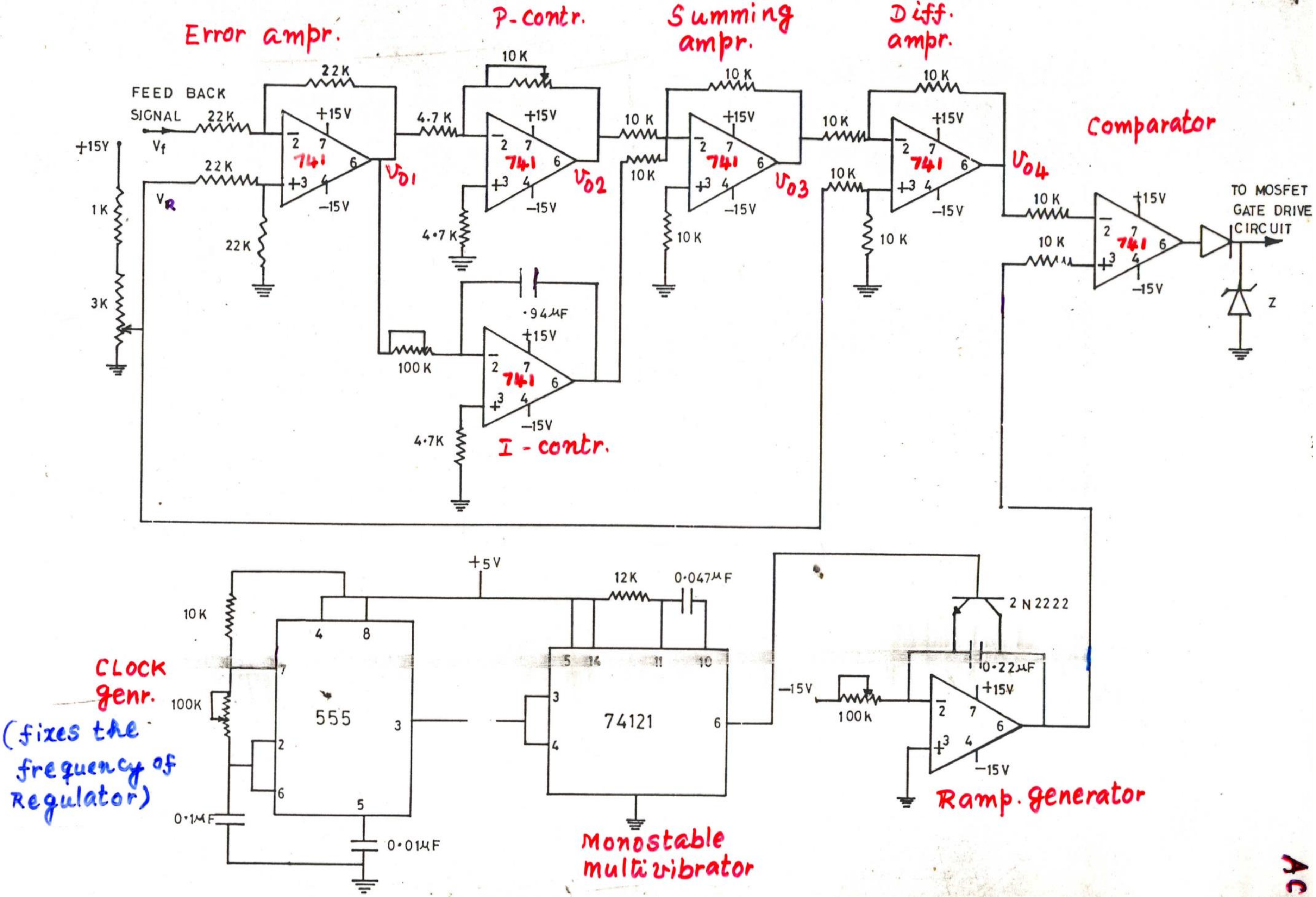


FIG.4.6 OVERALL CIRCUIT FOR IMPLEMENTATION OF CLOSED LOOP CONTROLLER
Using PI stage for a Switching Regulator

AC-16

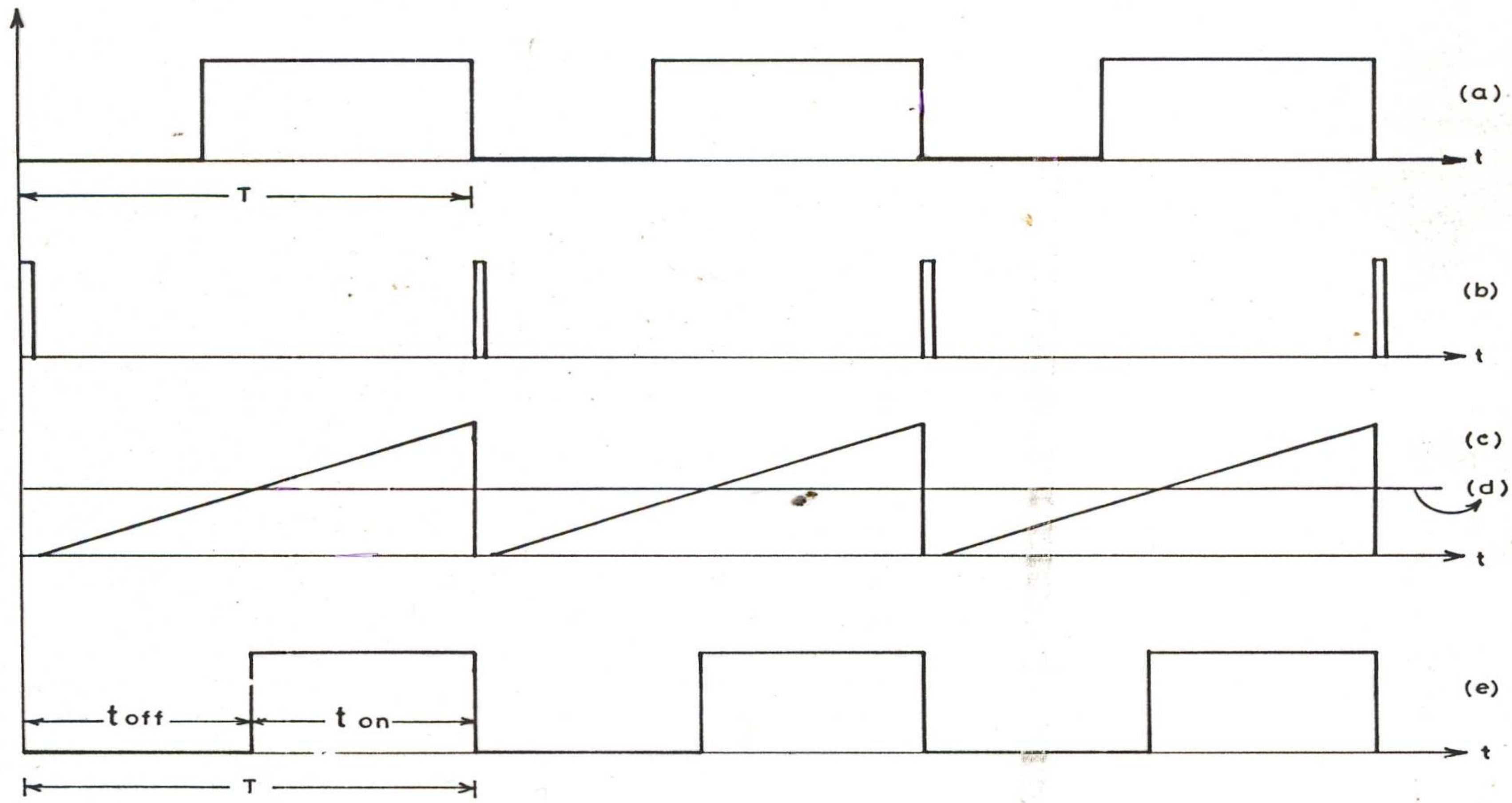


FIG.2.6 WAVEFORMS OF CLOSED LOOP CONTROLLER

(a) OUTPUT OF CLOCK GENERATOR

(b) OUTPUT OF MONOSTABLE MULTIVIBRATOR

(c) OUTPUT OF RAMP GENERATOR

(d) OUTPUT OF PI CONTROLLER (v_{o4} or V_c)

(e) CHOPPER GATE DRIVE PULSES

Operation of the closed Loop controller

Case i : Let $V_{in} = 200V$, $\delta = 0.5 \Rightarrow v_0 = 100V$ &

$v_f = 10V$ (say)

Prop. gain = 1.5

Let V_{dc} required = 50V $\Rightarrow V_{Ref} = 5V$ (say)

Now $v_{01} = (V_{Ref} - V_f) = -5V$

$v_{02} = -(-5V) \times 1.5 = +7.5V$

$v_{03} = -7.5V$

$v_{04} = (V_{Ref} - v_{03}) = 5V - (-7.5V) = 12.5V$

e., the control voltage = 12.5V $\Rightarrow \delta$ will decrease and hence the output will reduce from 100V

Case ii : Let $V_{in} = 200V$, $\delta = 0.5 \Rightarrow v_o = 100V$ &

Prop. gain $= 1.5$ $\qquad$ $v_f = 10V$ (say)

Let V_{dc} required $= 150V \Rightarrow V_{Ref} = 15V$

Now $v_{o1} = (V_{Ref} - V_f) = 5V$

$v_{o2} = -(+5V)\times 1.5 = -7.5V$

$v_{o3} = +7.5V$

$v_{o4} = (V_{Ref} - v_{o3}) = (15V - 7.5V) = 7.5V$

i.e., the control voltage $= 7.5V \Rightarrow \delta$ will increase and hence the output will increase from 100V.