Data Conversion and Lab (17.368)

Fall 2013

Lecture Outline

Class # 09

October 31, 2013

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Today's Lecture Outline

- Administrative
- Detailed Technical Discussions
  - Voltage-to-Frequency Converters (VFC)
- Lab
  - **Due date for Lab #3 moved to next week (11/7/13)**
  - Lab #4

Course Admin

Administrative

- Admin for tonight ...
  - Syllabus Highlights
    - Numerous changes
  - Either Lab #5 or Lab #6 ... your choice?????
    - Propose only performing Lab #6 (VFC)
  - Projects

Syllabus Review

Week	Date	Topics	Lab	Lab Report Due
1	09/05/13	Introduction/Basic Data Conversion, Course Overview, Op Amps in Data Conversion		
2	09/12/13	Op Amp Lab	1	
3	09/19/13	Sample and Hold Lecture and Lab	2	
4	09/26/13	A/D Conversion Fundamentals and Lab	3	1
5	10/03/13	A/D Conversion Lab Continuation	3 con't	
6	10/10/13	**Examination 1**		
7	10/17/13	D/A Conversion Fundamentals and Lab	3	
8	10/24/13	D/A Conversion Lab Continuation	4	2
9	10/31/13	**V/F and F/V Conversion Lecture**	4 con't	
10	11/07/13	**Microcontroller and Sensors**	5	**3**
11	11/14/13	**Lab Only – No Lecture**	5 con't	4
12	11/21/13	**Examination 2**	Project	5
X	**11/28/13**	**No Class – Thanksgiving**		
13	12/05/13	Work on Course Project	Project	
14	12/12/13	Final Exam/Course Project Brief and Demonstration	Demo	

Detailed Technical Discussion

References …

Lecture material is covered in …

- *AN-276* (Analog-to-Digital Conversion Using Voltage-to-Frequency Converters)

- *AN-361* (V/F Converters)

The above Application Notes can be found on the course webpage

- The Data Conversion Handbook, pages 214 – 218
  - On-Line 3.91 – 3.96

- The Art of Electronics, pages 624-625

Introduction to <u>AND</u> Application

of

V/F and F/V Converters

Voltage to Frequency and Frequency to Voltage Converters

- ***Voltage to Frequency*** (V/F) converters or VFC

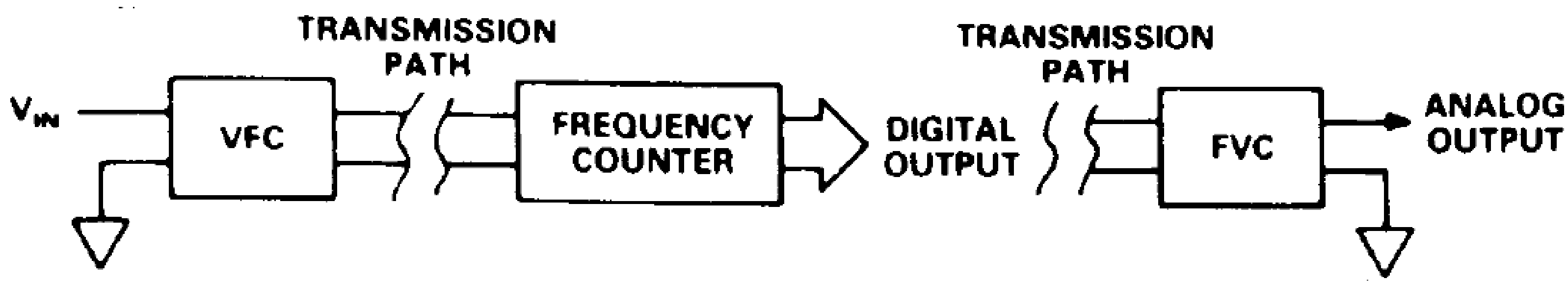
... and ...

- ***Frequency to Voltage*** (F/V) converters or FVC

Voltage to Frequency and Frequency to Voltage Converters

- Basic overall Diagram ...

Analog in ... VFC ... Transmit ... FVC ... Analog out



Voltage to Frequency Converters

- *Voltage to Frequency* converters ...
    - Takes an analog input voltage which can be either a ...
        - D.C. voltage ...
        - Or ... a slowly varying analog signals

    ... and ...

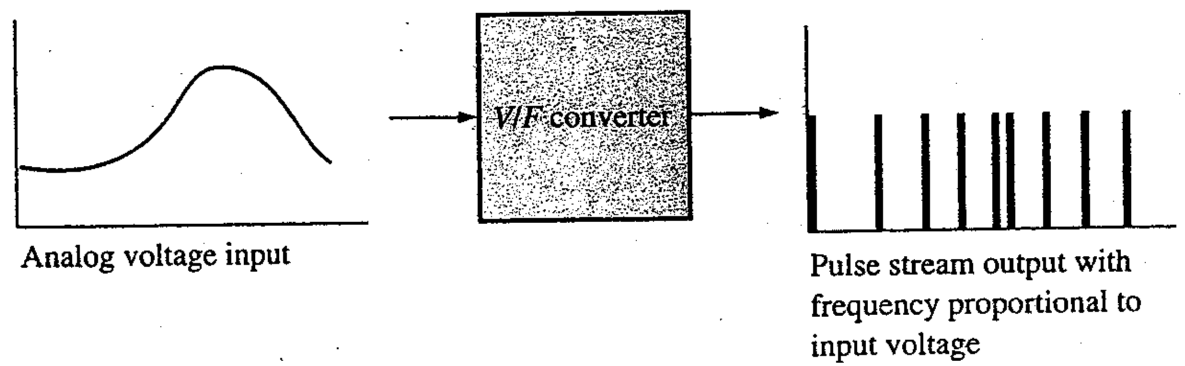
    - Converts/generates the voltage to digital output pulses at ...
        - A repetition rate that is linearly proportional to the analog input voltage

Voltage to Frequency and Frequency to Voltage Converters

- The pulse stream output of the voltage to frequency converter is then transmitted to a receiving station
- The receiving station ...
  - Converts the pulse stream back to its original input voltage by means of a ...
    - ***Frequency to Voltage*** converter

Voltage-to-Frequency Conversion

- The digital output pulses are at a rate that is linearly proportional to the analog input voltage



Voltage-to-Frequency converters

- *Voltage to Frequency* converters are:

  - Integrating-type A/D converters ...

Voltage to Frequency and Frequency to Voltage Converters

- The converted analog signal ... which is the pulse train that is at a frequency proportional to the input ...
  - Is much less susceptible to interference than a high resolution analog signal

Frequency-to-Voltage converters

- ***Frequency-to-Voltage*** converters ...
  - Perform the exact opposite operation to the ***Voltage-to-Frequency*** converters ... which is ...
    - They **generate** a D.C ... Or slowly varying analog signal ...
      - With an amplitude that is ....
        - » Linearly proportional to the digital input frequency of the pulse stream

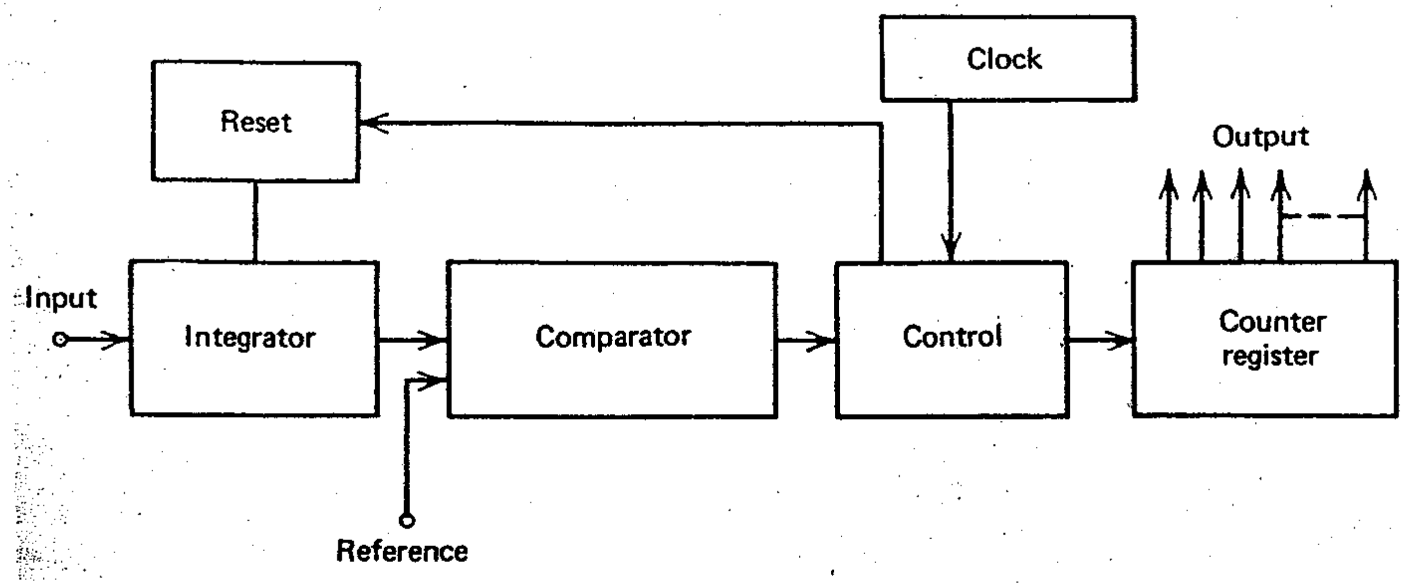
Uses
of
V/F and F/V Converters

Voltage to Frequency and Frequency to Voltage Converters

- *Voltage-to-Frequency* and *Frequency-to-Voltage* converters are extremely useful in certain situations ... when ...
  - Data is required to be transmitted from one location to another ...
  - And ... environmental or other factors may distort the signal
    - *For example* ... To transmit a high-accuracy analog signal through a noisy environment without interference
  - OR ... we may want to transmit signals long distances without losing accuracy
  - OR ... when output frequency, rather than digital code is desired

Voltage-to-Frequency Converters …

Basic V/F Converter Block Diagram

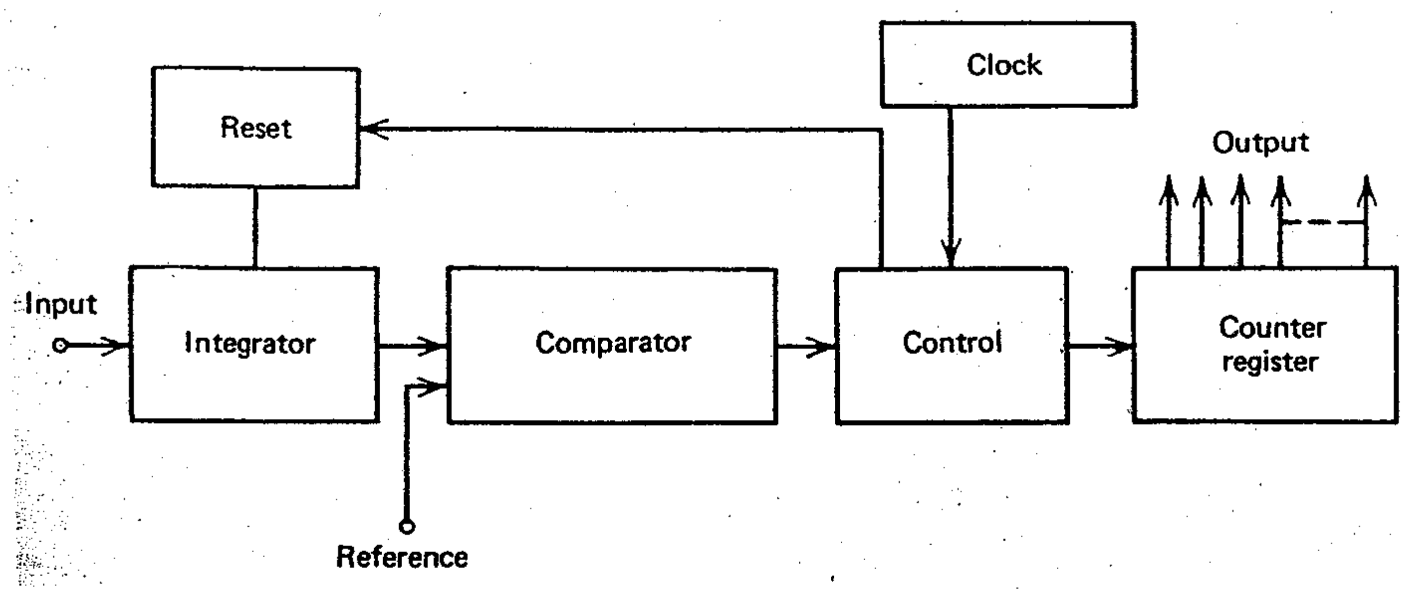


1. The input analog signal is ...

   – Integrated and fed to a comparator

continued ...

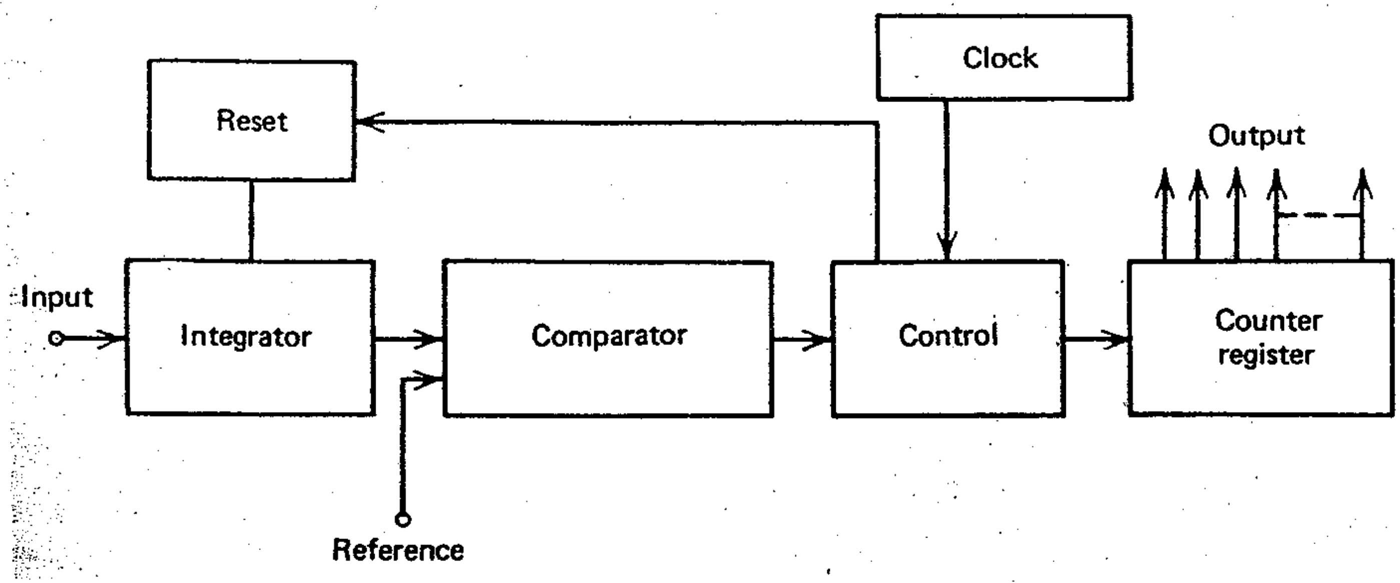
Basic V/F Converter Block Diagram



2. When the comparator changes its state ...
   - The integrator is reset and ...
3. The process repeats itself for the new analog input

continued ...

Basic V/F Converter Block Diagram



4. The counter counts the number of integration cycles ...

   – Providing a digital output

Types
of
Voltage-to-Frequency
Converters

Common Types of Voltage to Frequency

- Current-Steering ***Multivibrator***
- ***Charge-Balance***

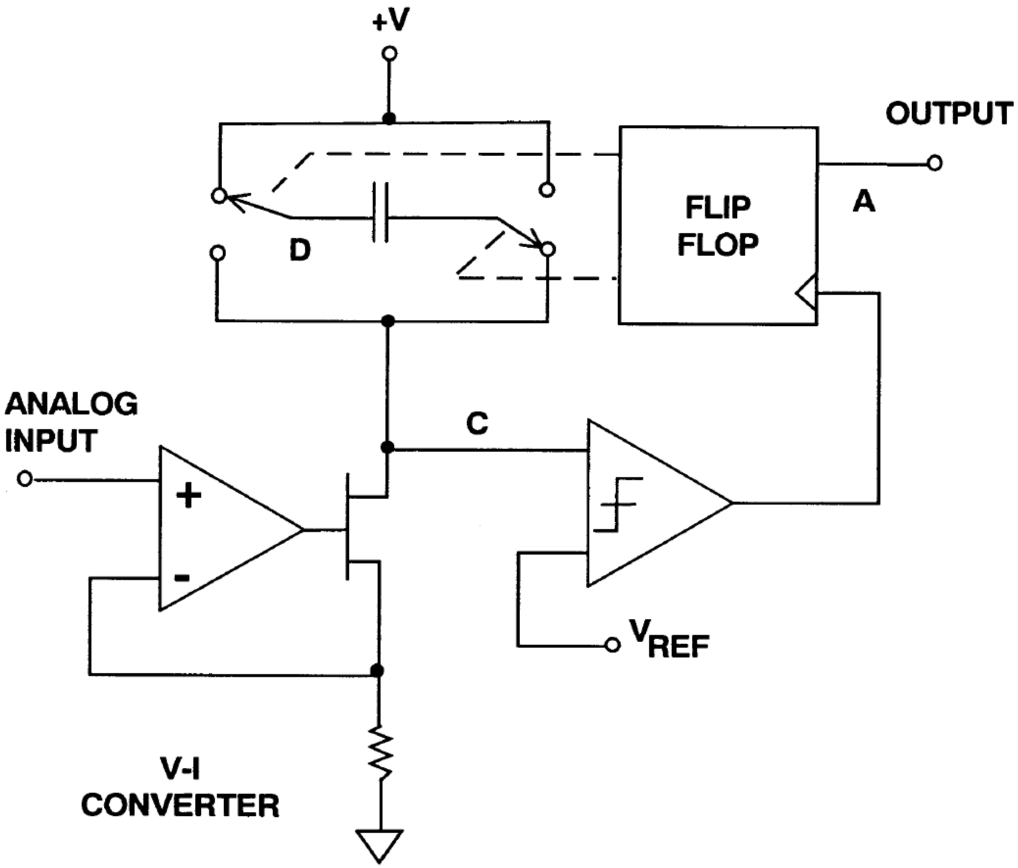
Current-Steering Multivibrator

Voltage-to-Frequency Converters

Current-steering *Multivibrator* Voltage to Frequency Converters

- Input voltage is converted to a current ...
  - Which charges and discharges a capacitor ... based on ...
    - The switching thresholds which are set by a stable reference
- And the output ...
  - Is a frequency proportional to the input

Current-steering *Multivibrator* Voltage to Frequency Converters



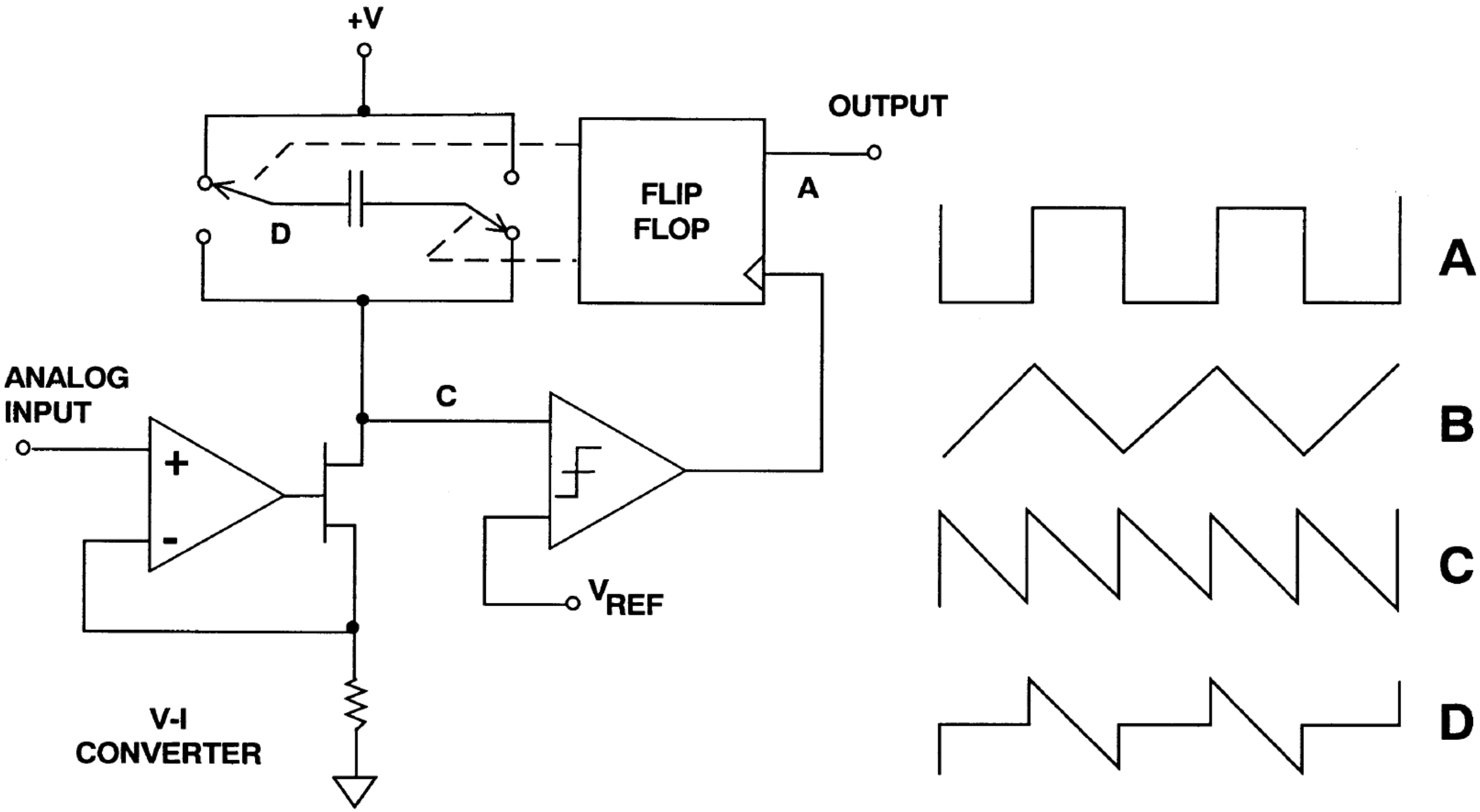
Current-steering *Multivibrator* Voltage to Frequency Converters

- The current-steering multivibrator VFC is actually a current-to-frequency converter
  - However, practical circuits invariably contain a voltage-to-current converter at the input
- The principle of operation is evident ...
  - The current discharges the capacitor until a threshold is reached ... and ...
  - When the capacitor terminals are reversed, the half-cycle repeats itself

Current-steering *Multivibrator* Voltage to Frequency Converters

- The waveform across the capacitor is ...
  - A linear triangular wave
- The waveform on either terminal with respect to ground is ...
  - More complex ...
    - » See next slide ...

Current-steering *Multivibrator* Voltage to Frequency Converters

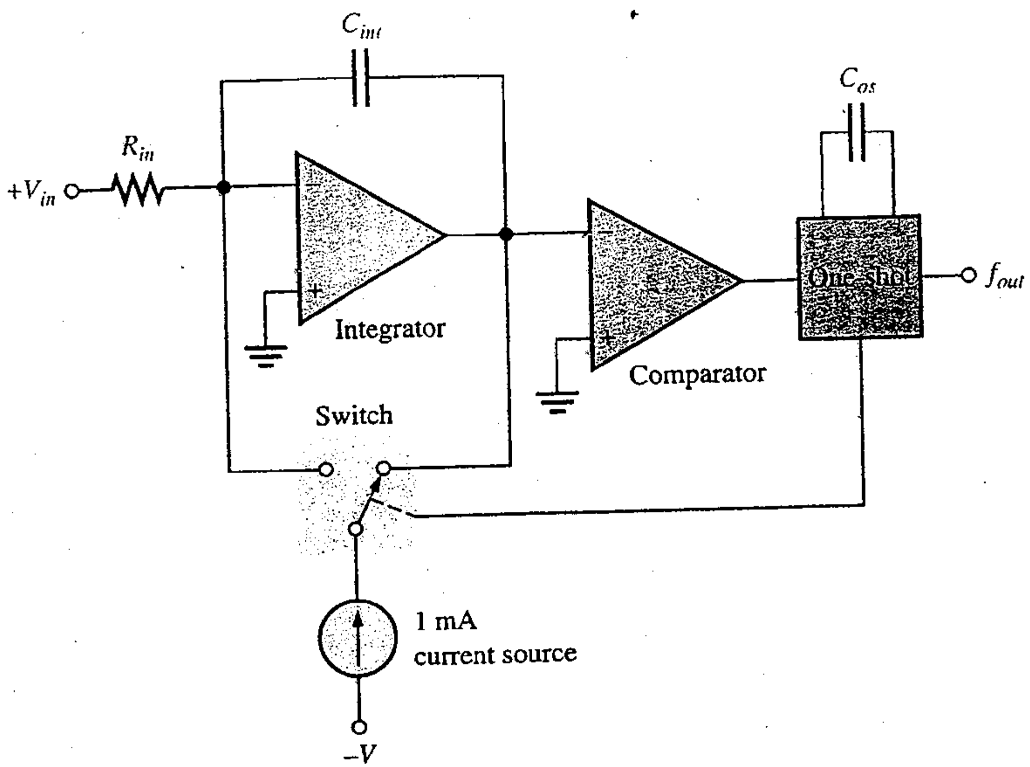


WAVEFORM "B" IS TAKEN DIFFERENTIALLY ACROSS THE CAPACITOR

Charge-Balance Voltage-to-Frequency Converters …

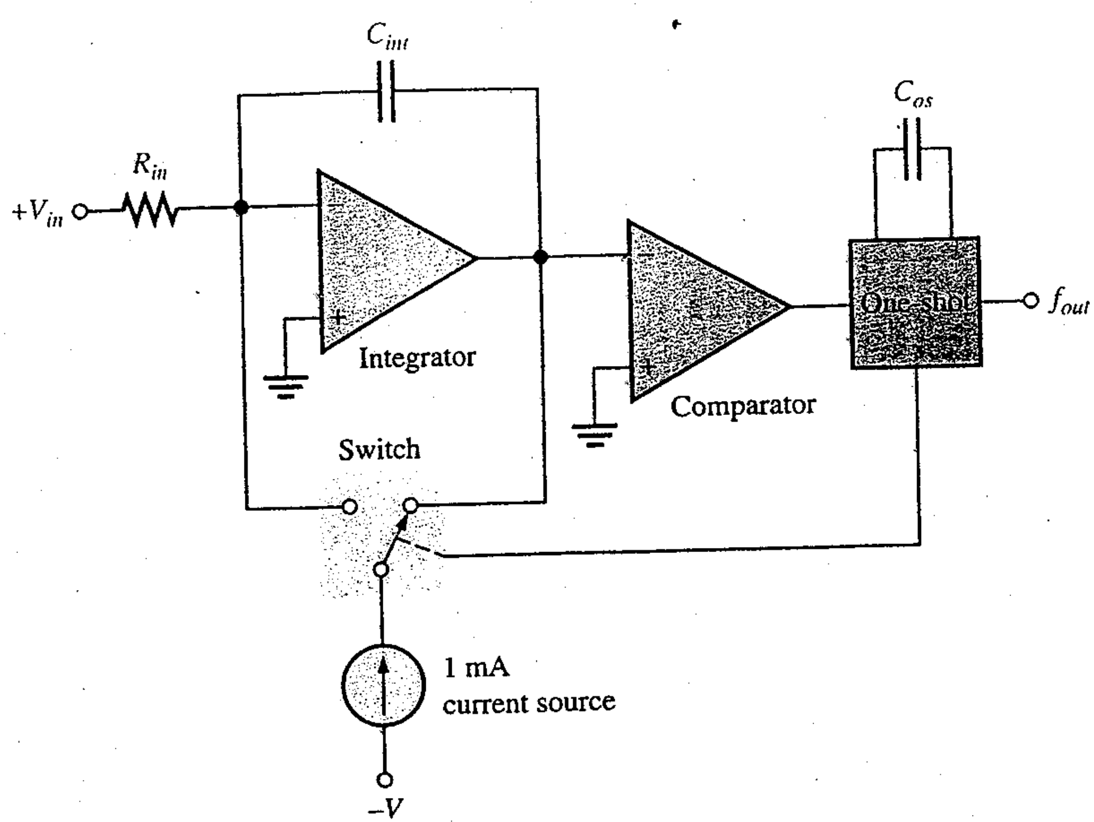
Charge-Balance Voltage-to-Frequency Converter Circuit

- Below is a relatively common implementation of a V/F Converter



The *Charge-Balance* V/F converter consists of ...

- An Integrator … A comparator … A one-shot multivibrator … A current source … … AND … an electronic switch



Charge-Balance V/F converter

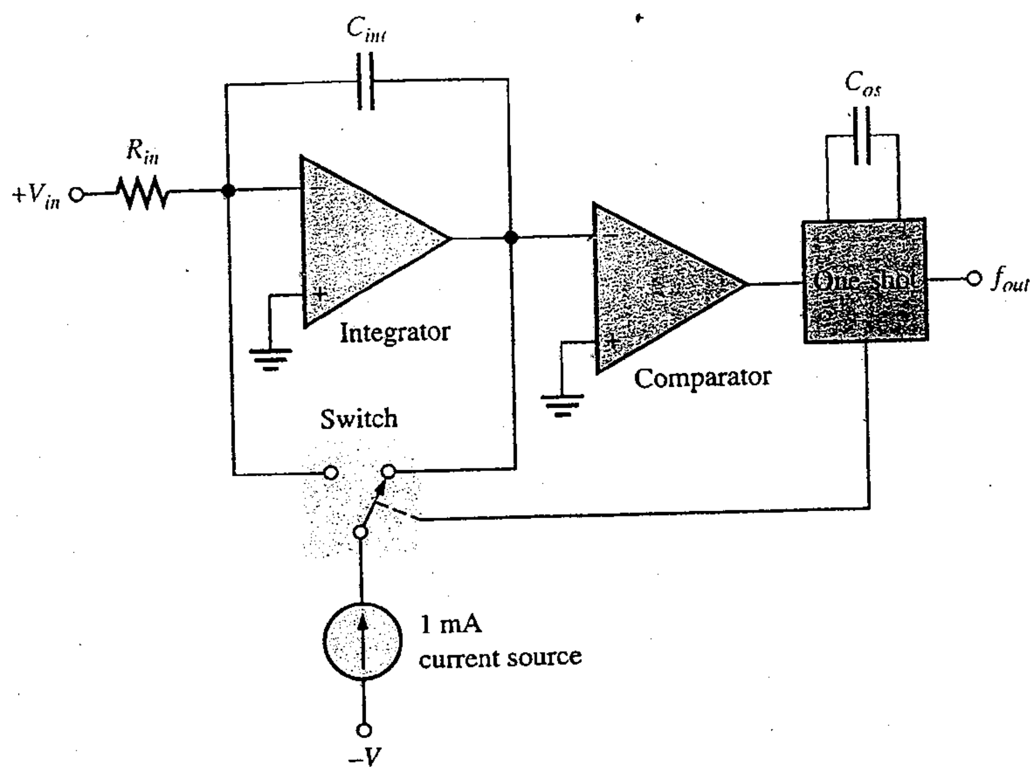
- The ...
  - Input resistor $\mathbf{R_{IN}}$ ...
  - The integration capacitor $\mathbf{C_{int}}$ ...
  - AND the one-shot timing capacitor $\mathbf{C_{OS}}$ ...
- Are components whose values are ...
  - Selected based on desired performance

Charge-Balance Voltage to Frequency Converters

- So ... how does the ***Charge-Balance VFC*** function?

  » Lets walk through the process ...

Charge-Balance Voltage-to-Frequency Converter Circuit



A positive input voltage produces … an input current

$$I_{IN} = \frac{V_{IN}}{R_{IN}}$$

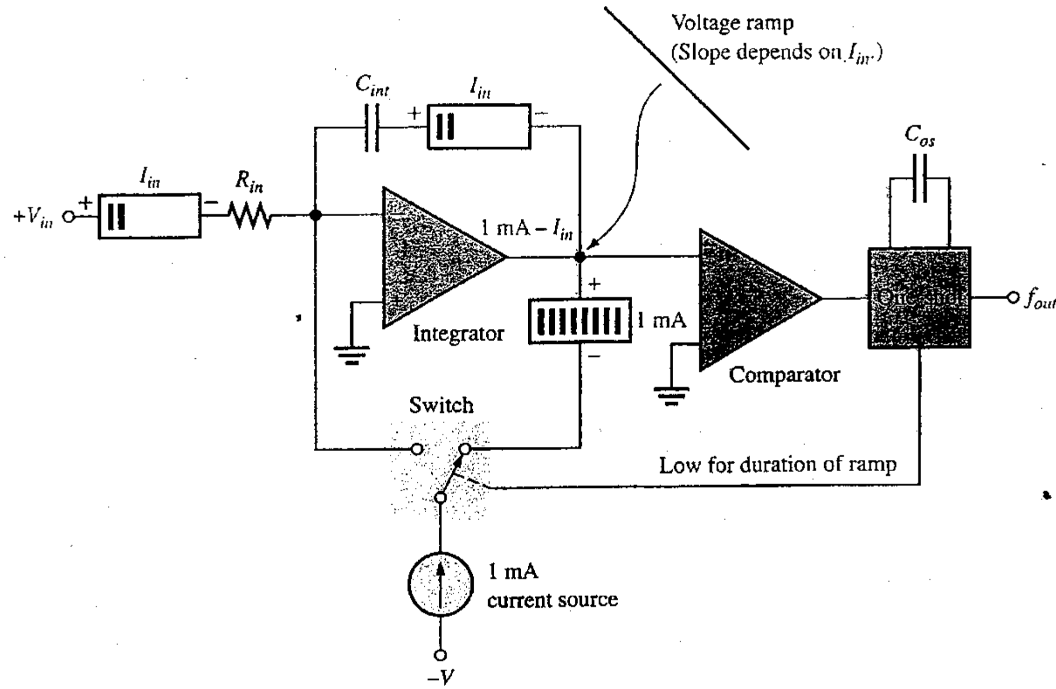
That will charge the capacitor C_{int}

Charge-Balance Voltage-to-Frequency Converter Circuit

- There are two modes that take place during the conversion ...
  - The *Integrate Mode* ... and ...
  - The *Reset Mode*

Integrate Mode …

Voltage-to-Frequency Converter - Integrate Mode

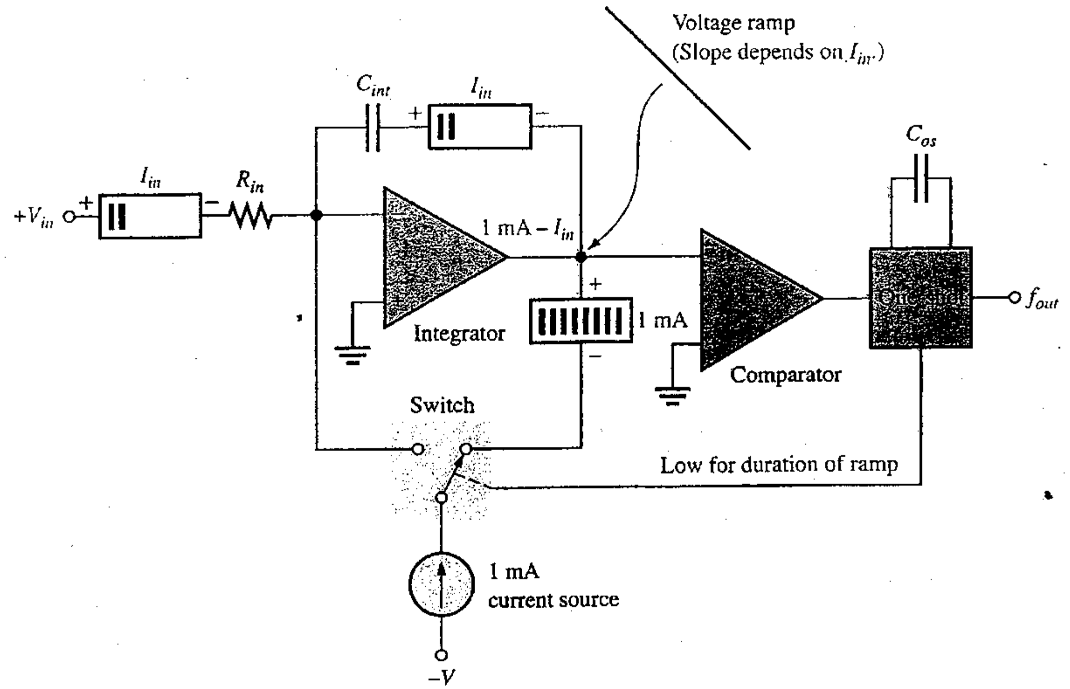


(a) *V/F* converter in the integrate mode

The integrator output voltage is a downward ramp

The Slope depends on I_{IN}

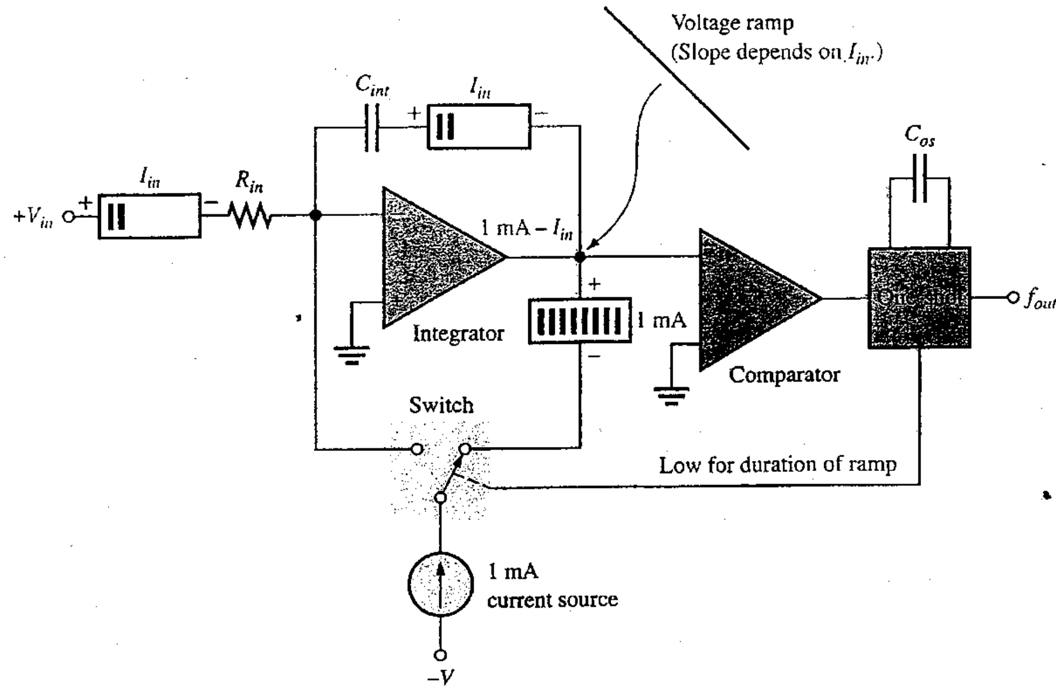
Voltage-to-Frequency Converter - Integrate Mode



(a) V/F converter in the integrate mode

When the integrator output voltage reaches zero

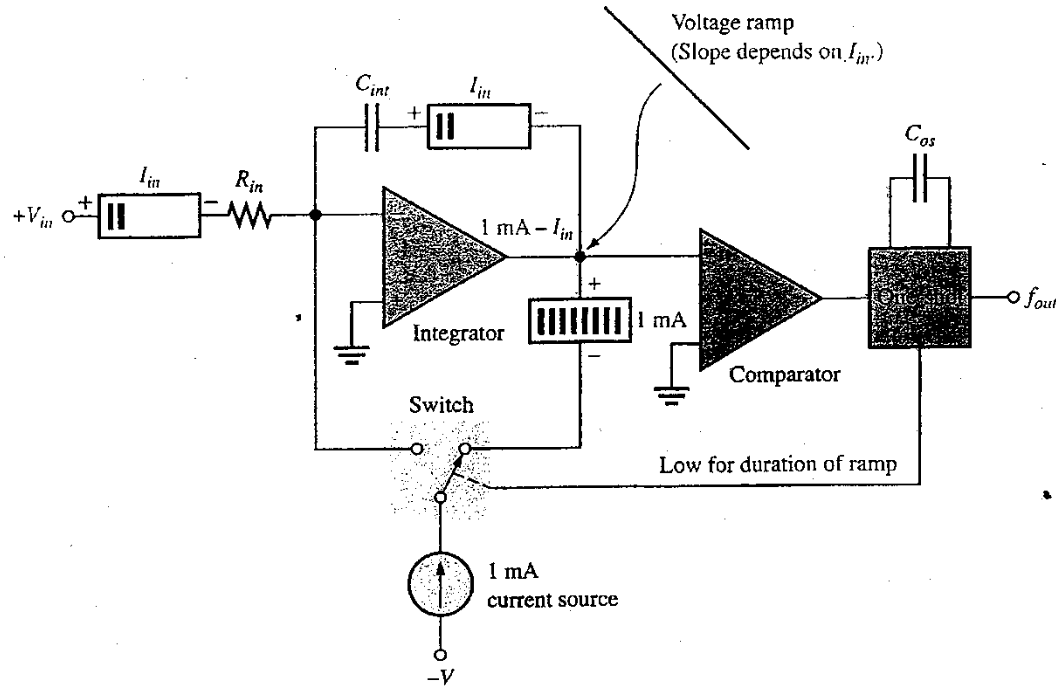
Voltage-to-Frequency Converter - Integrate Mode



(a) V/F converter in the integrate mode

The comparator triggers the one-shot multivibrator

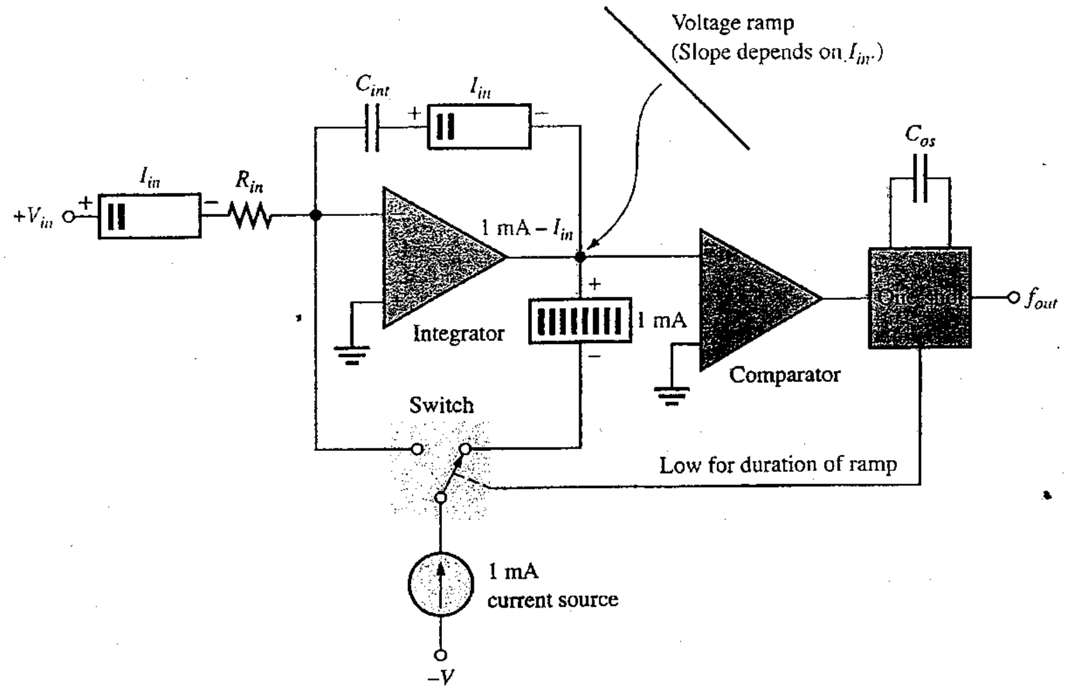
Voltage-to-Frequency Converter - Integrate Mode



(a) *V/F* converter in the integrate mode

The one-shot produces a pulse with a fixed width … t_{OS} …

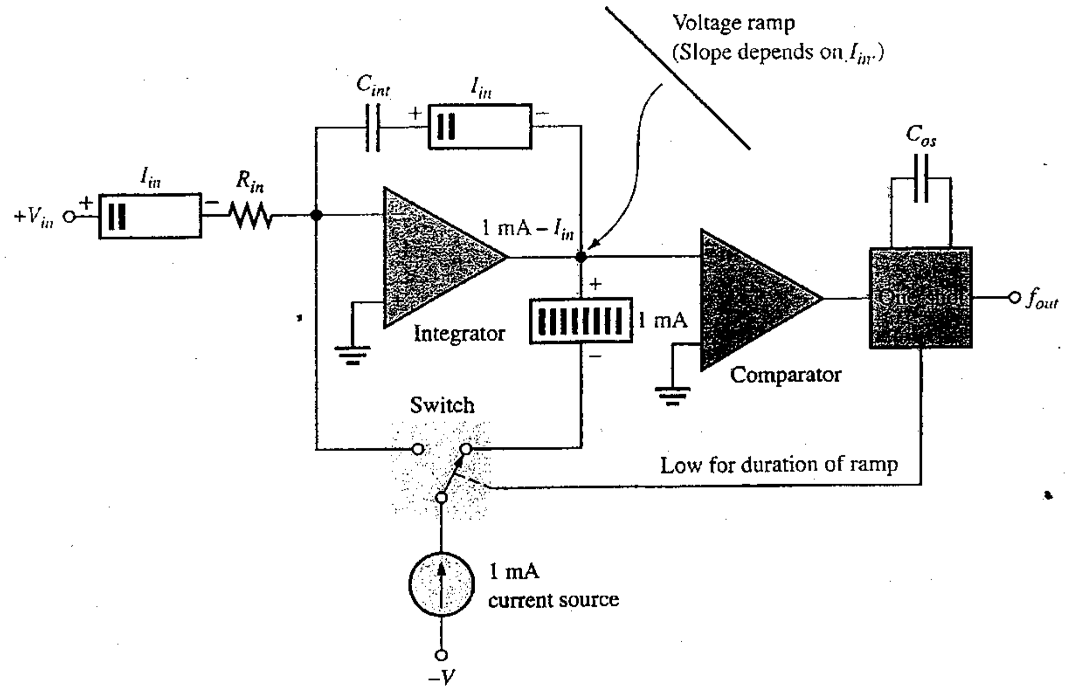
Voltage-to-Frequency Converter - Integrate Mode



(a) V/F converter in the integrate mode

… that switches the 1 mA current source to the input of the integrator

Voltage-to-Frequency Converter - Integrate Mode

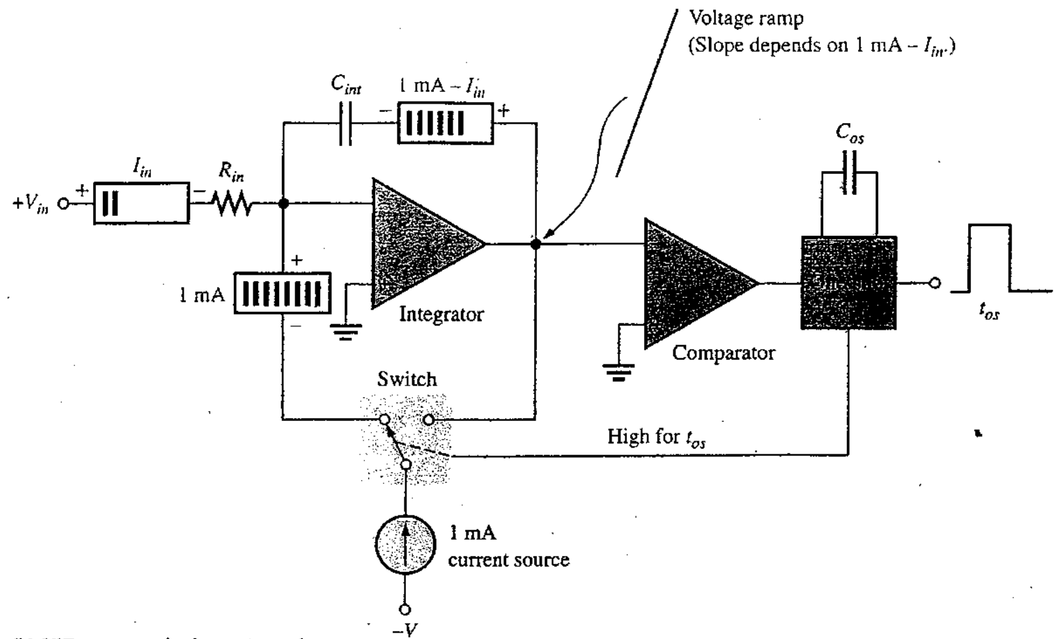


(a) *V/F* converter in the integrate mode

AND … initiates the reset mode

Reset Mode …

Voltage-to-Frequency Converter - *Reset Mode*

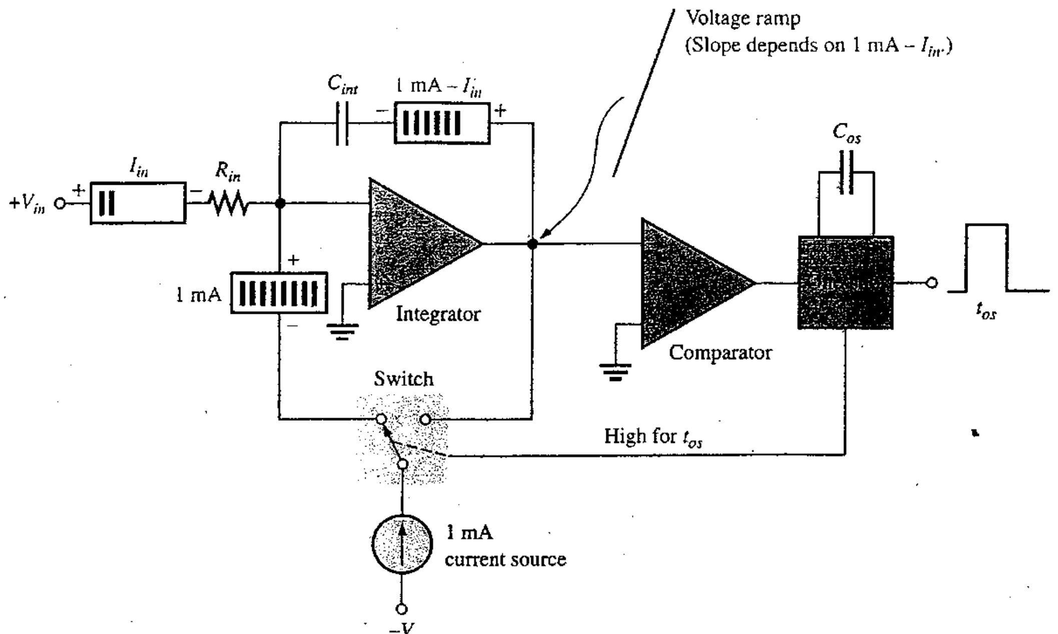


(b) *V/F* converter in the reset mode

The current through the integrating capacitor (C_{INT}) is …

In the opposite direction from the integrate mode

Voltage-to-Frequency Converter - *Reset Mode*



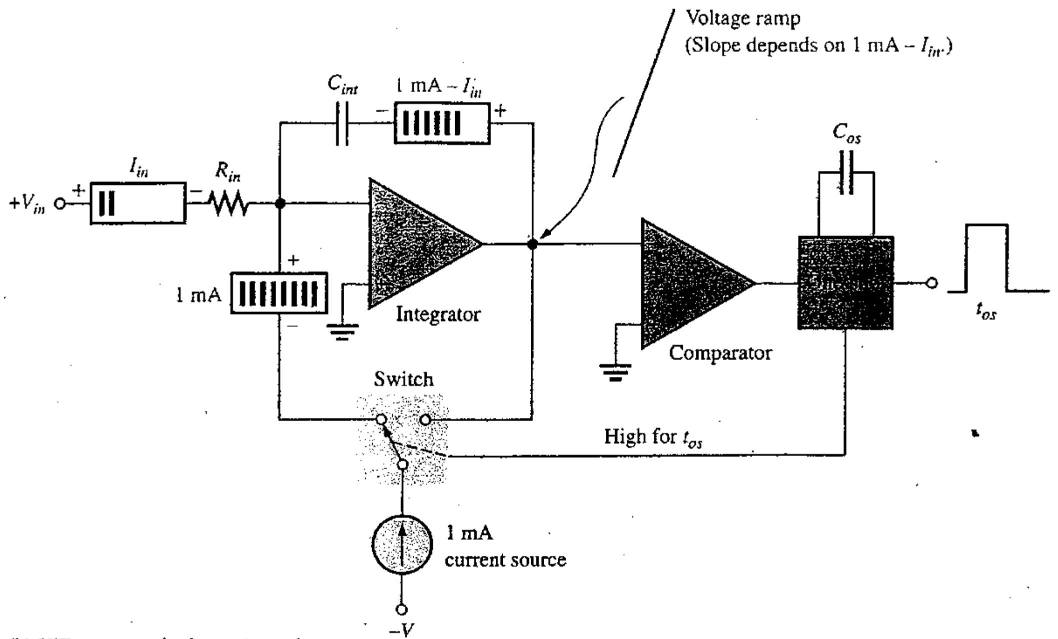
(b) *V/F* converter in the reset mode

This produces an upward ramp on the integrator output as indicated

Slope depends on 1 ma – I_{IN}

(Which is the opposite current through the capacitor)

Voltage-to-Frequency Converter - *Reset Mode*

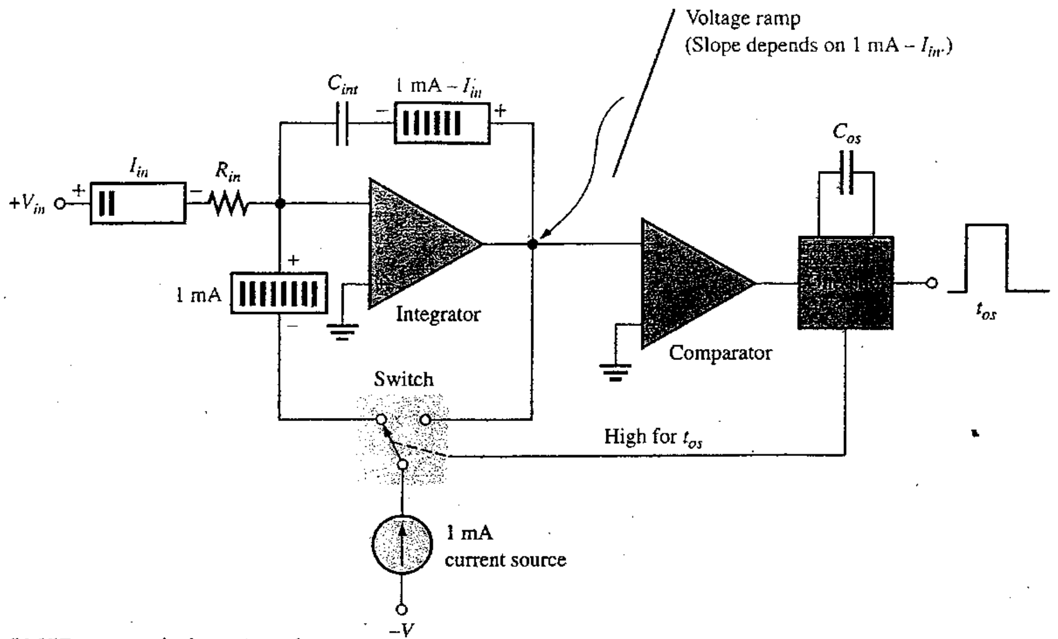


(b) *V/F* converter in the reset mode

The current (1 ma – I_{IN}) … is smaller … thus …

Decreasing the slope of the upward ramp … and …

Voltage-to-Frequency Converter - *Reset Mode*

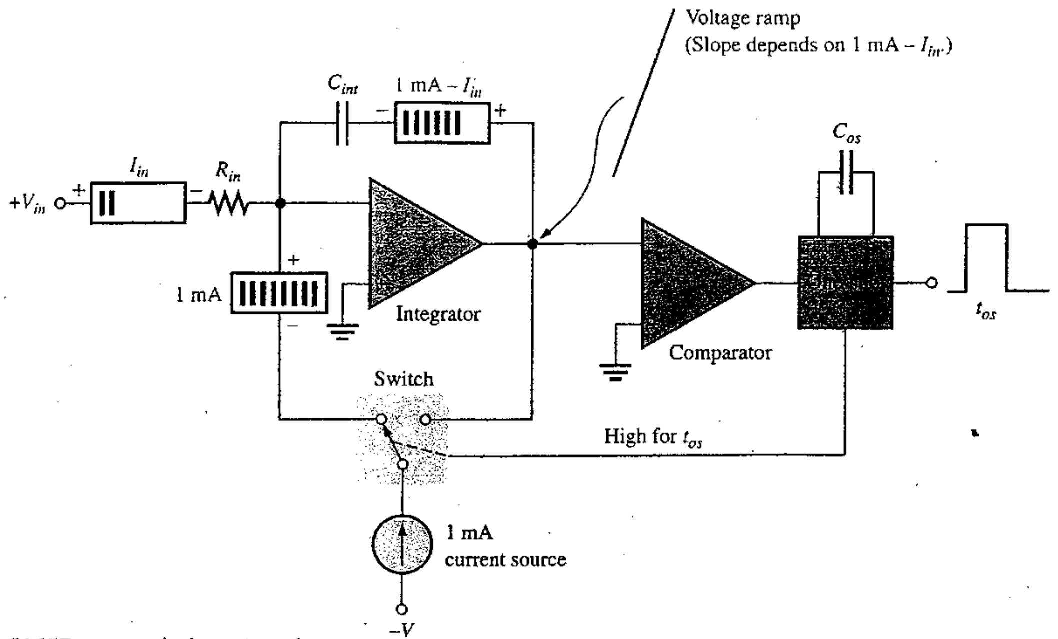


(b) *V/F* converter in the reset mode

… Reducing the amplitude of the integrator output voltage …

(since there is fixed reset time t_{OS})

Voltage-to-Frequency Converter - *Reset Mode*

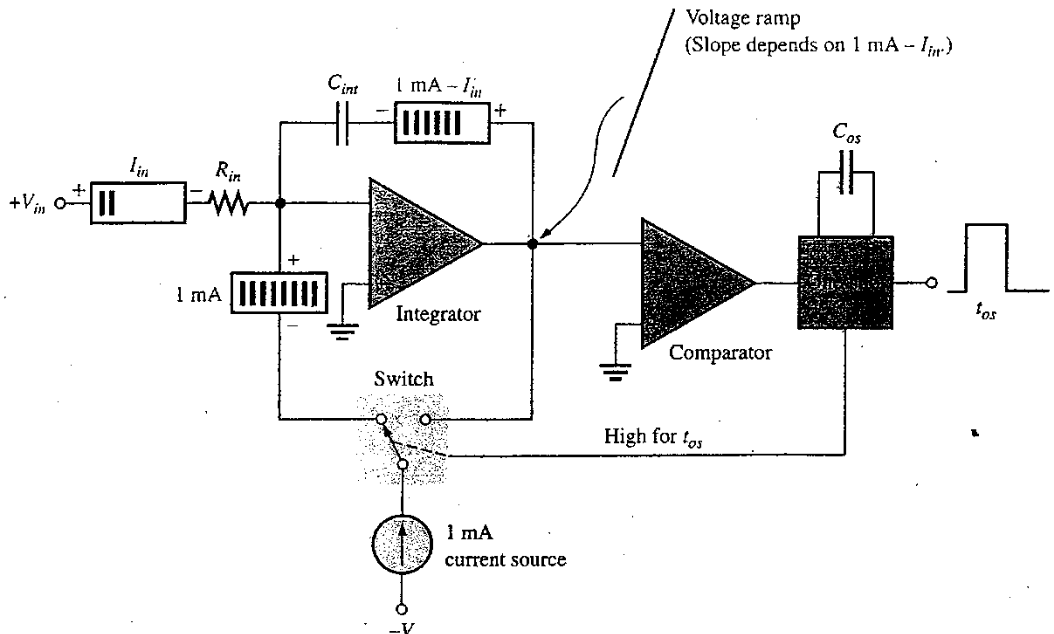


(b) *V/F* converter in the reset mode

After the one-shot times out (after time t_{OS}) …

The …

Voltage-to-Frequency Converter - *Reset Mode*

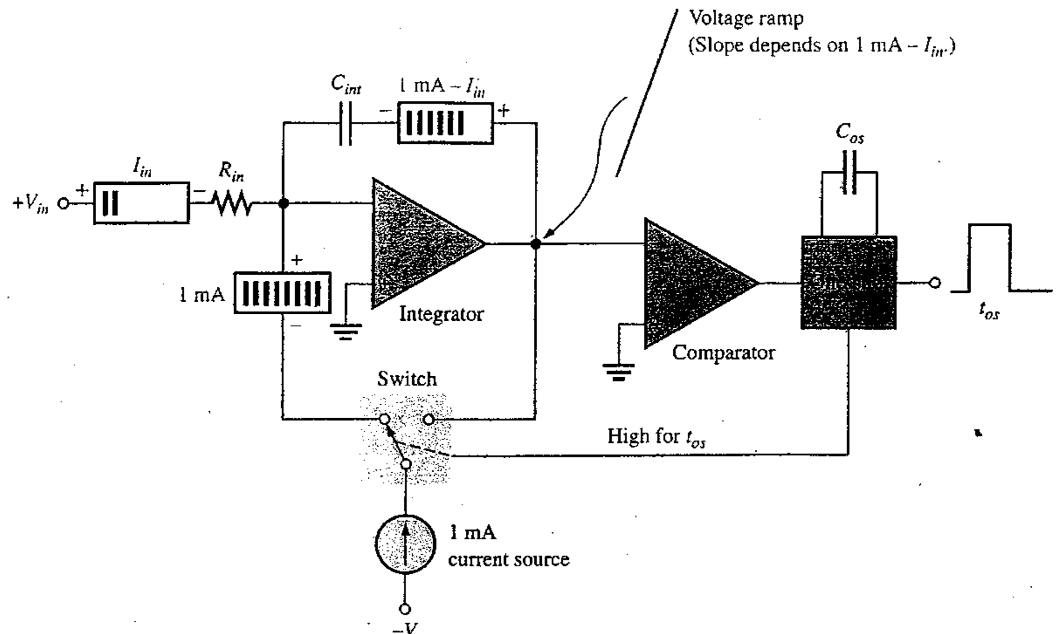


(b) *V/F* converter in the reset mode

… Current source is switched back to the integrator output …

… AND …

Voltage-to-Frequency Converter - *Reset Mode*

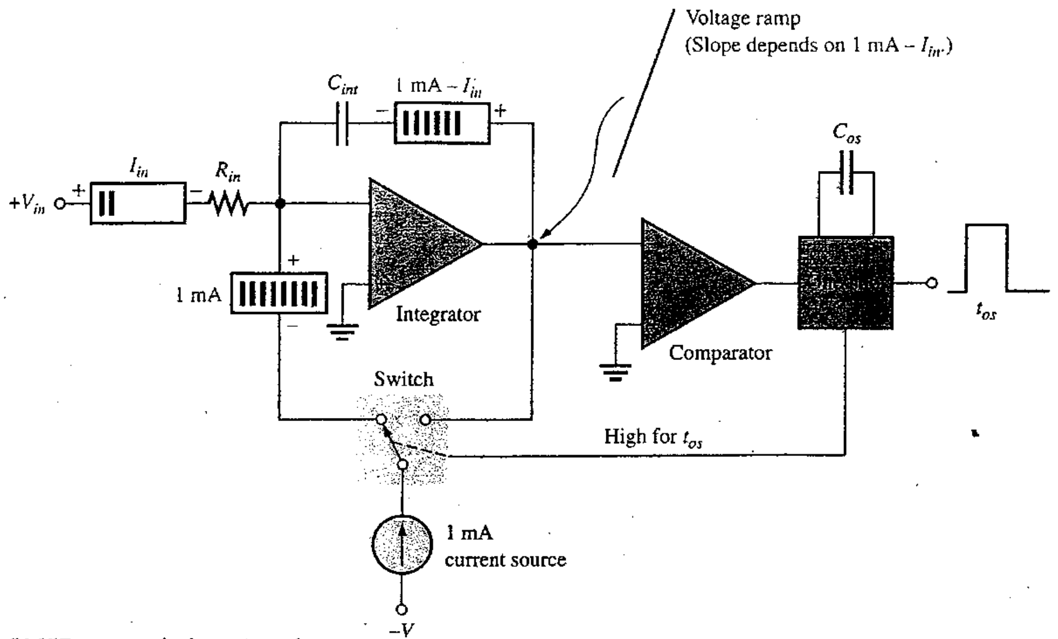


(b) V/F converter in the reset mode

… initiating another integrate mode …

… THEN …

Voltage-to-Frequency Converter - *Reset Mode*



(b) *V/F* converter in the reset mode

The cycle repeats with the integrate mode

Charge-Balance Voltage to Frequency Converters

- The rate at which charge is removed must balance the rate at which it is being supplied
  - So the frequency at which the charge source is triggered
  - Will be proportional to the input to the integrator

Voltage-to-Frequency Converters

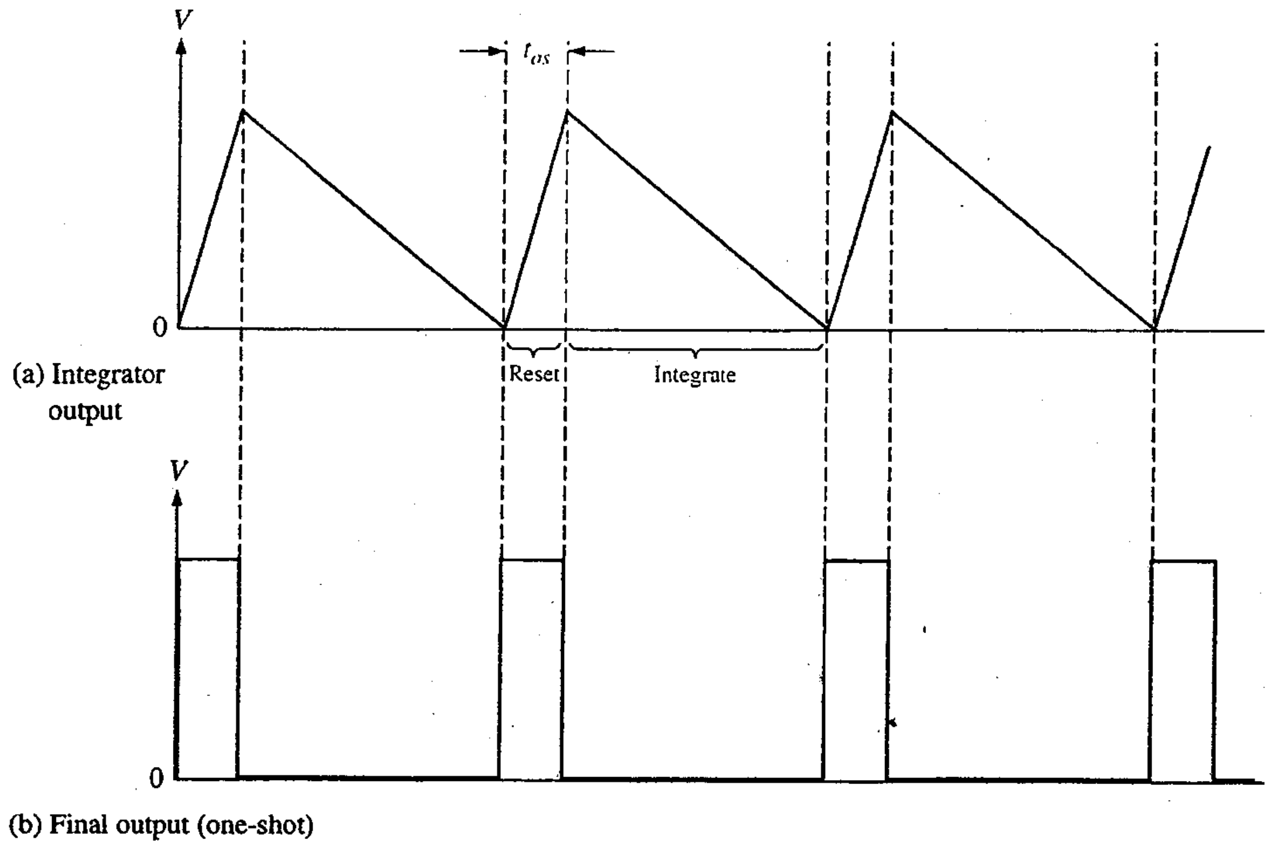
If we have a Constant Input Voltage

Constant Input Voltage

- Now ... lets say that ...

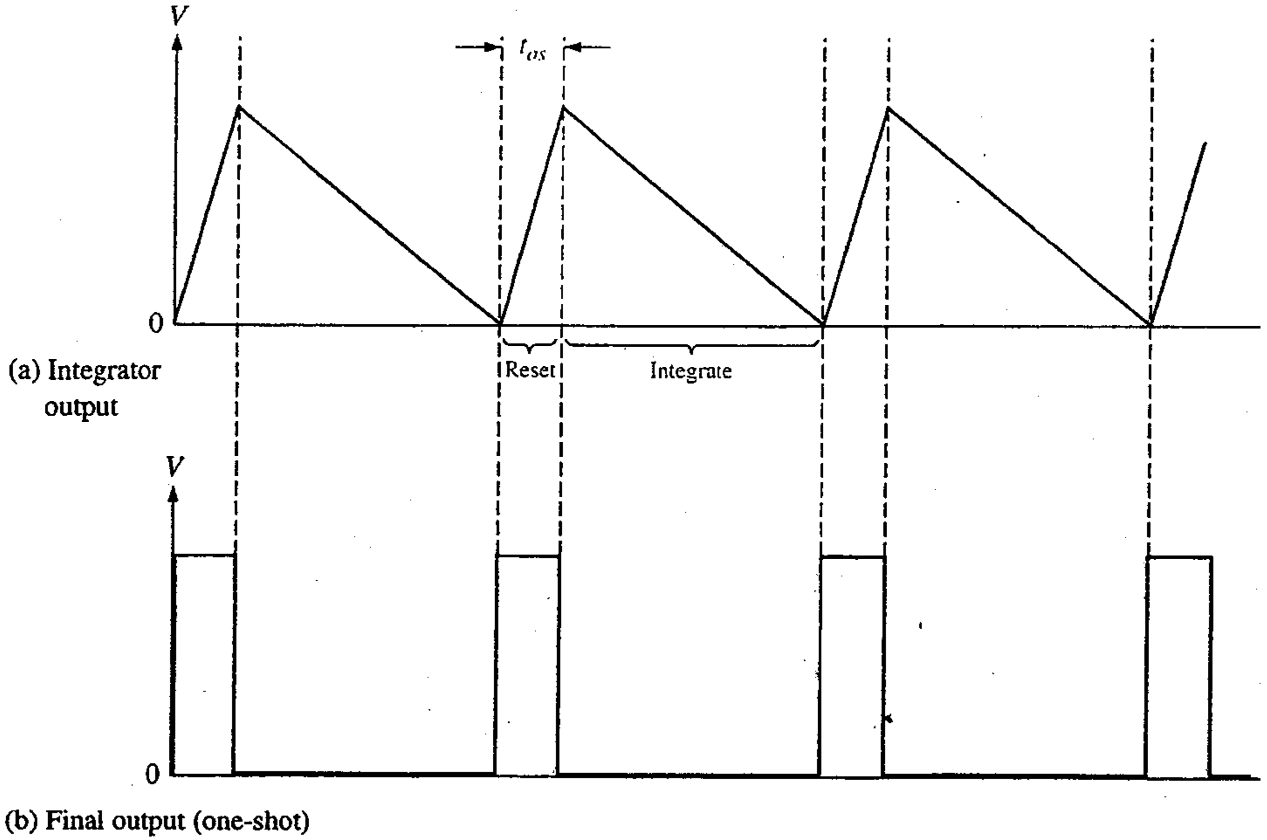
  » The input voltage is held constant ...

Constant Input Voltage



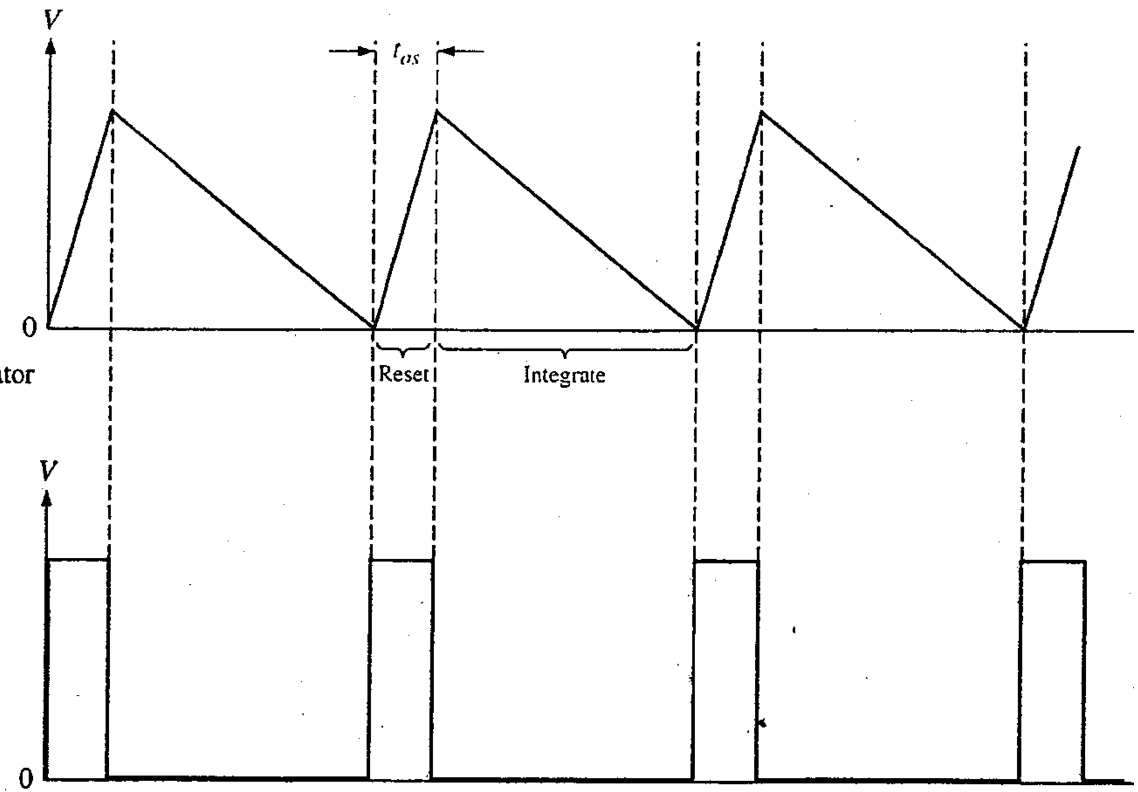
The output waveform of the integrator is shown

Constant Input Voltage



The amplitude and the integrate time remains constant

Constant Input Voltage



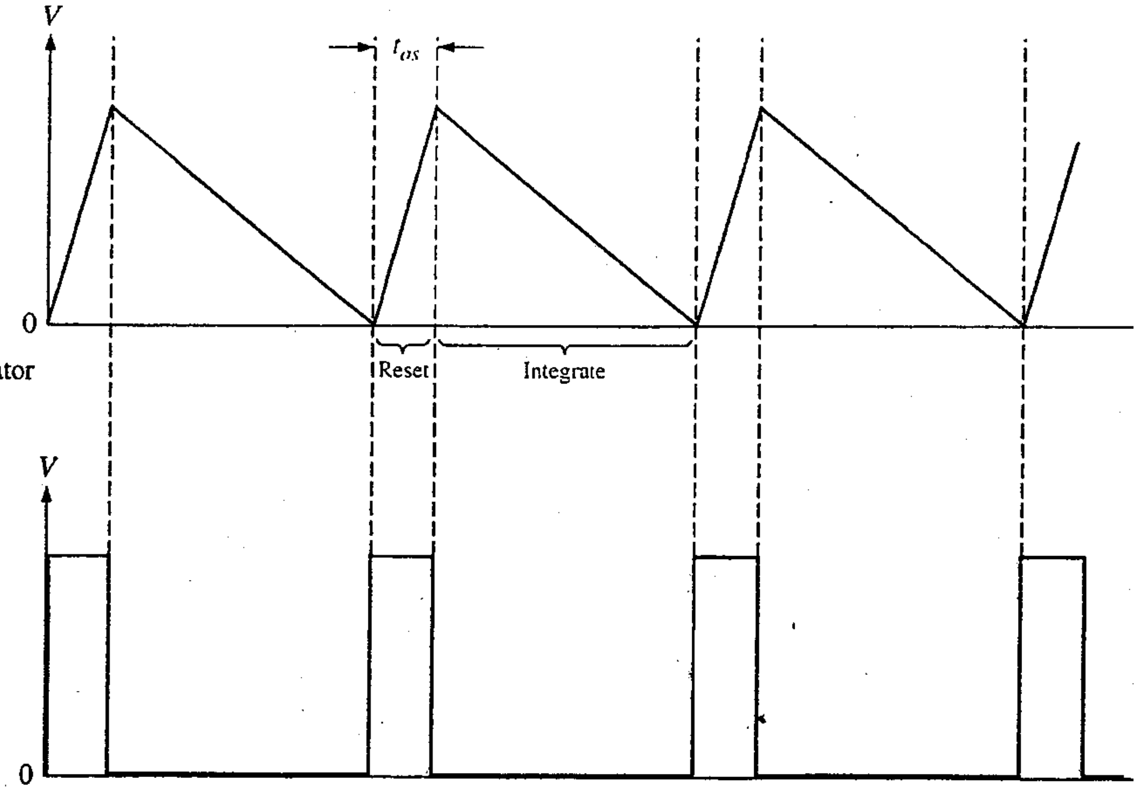
(a) Integrator output

(b) Final output (one-shot)

The final output of the V/F converter is …

Taken off the one-shot multivibrator

Constant Input Voltage



(a) Integrator output

(b) Final output (one-shot)

As long as the input voltage is constant …

The output pulse stream has a constant frequency

Voltage-to-Frequency Converters

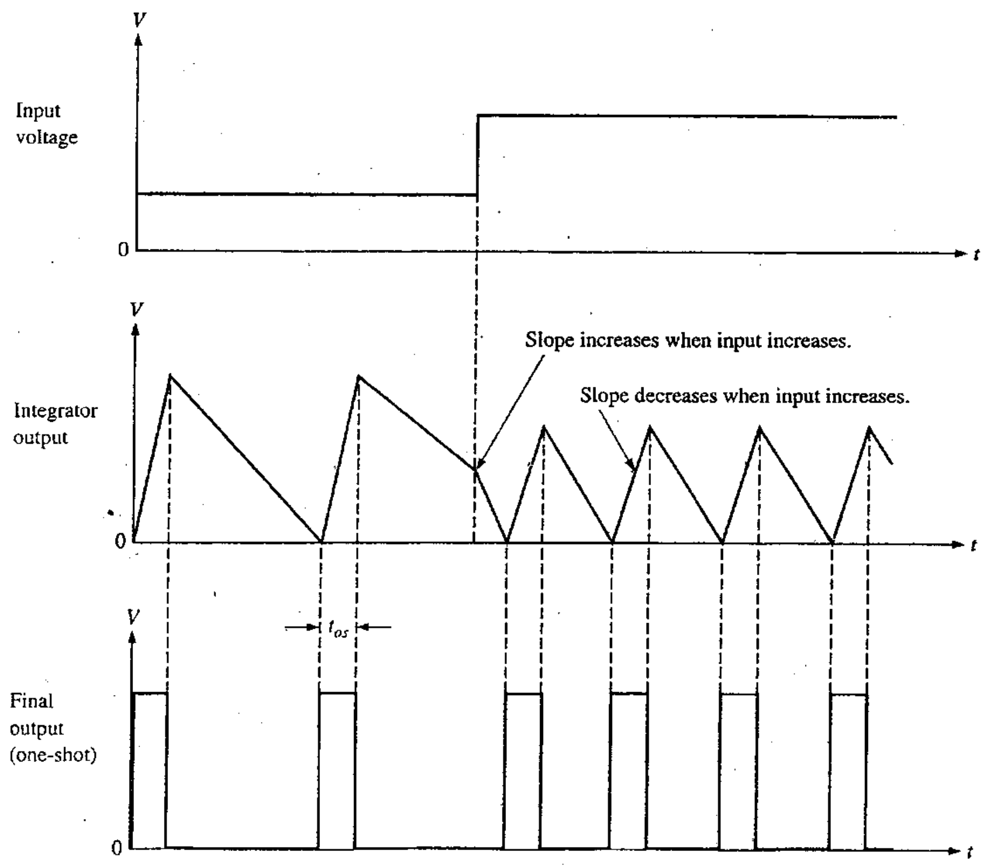
If we have an Increased Input Voltage

Increased Input Voltage

- Now ... lets say that ...

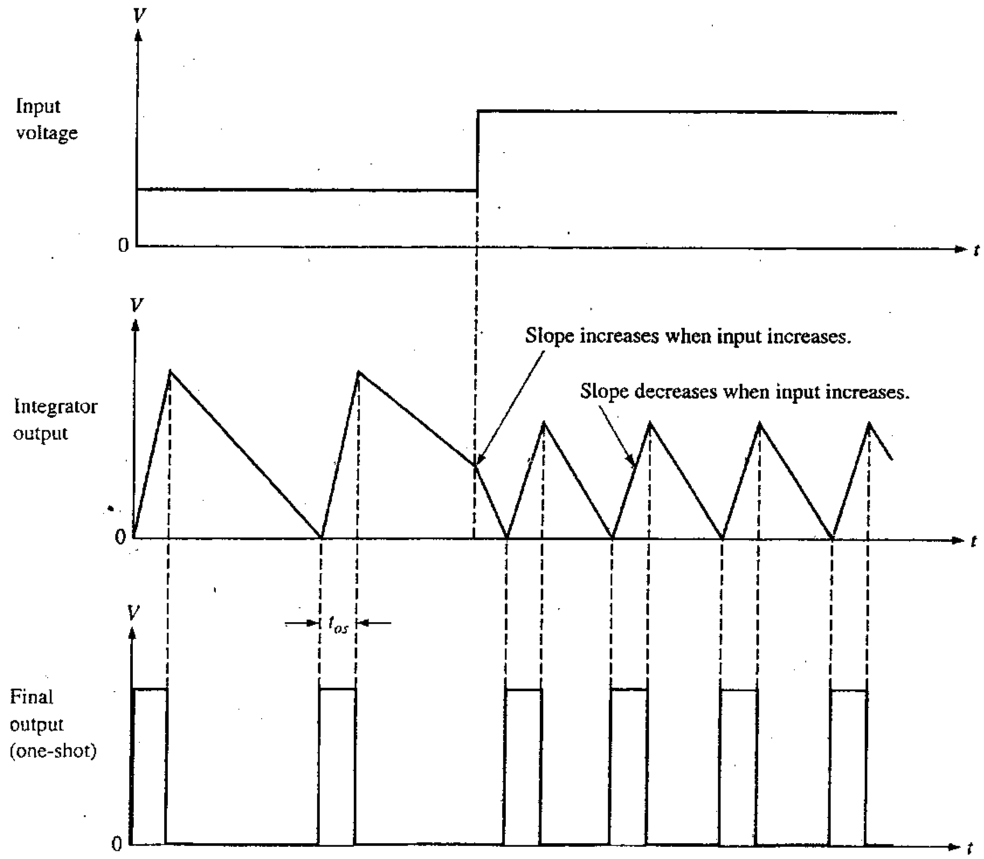
  » The input voltage is increased ...

Increased Input Voltage



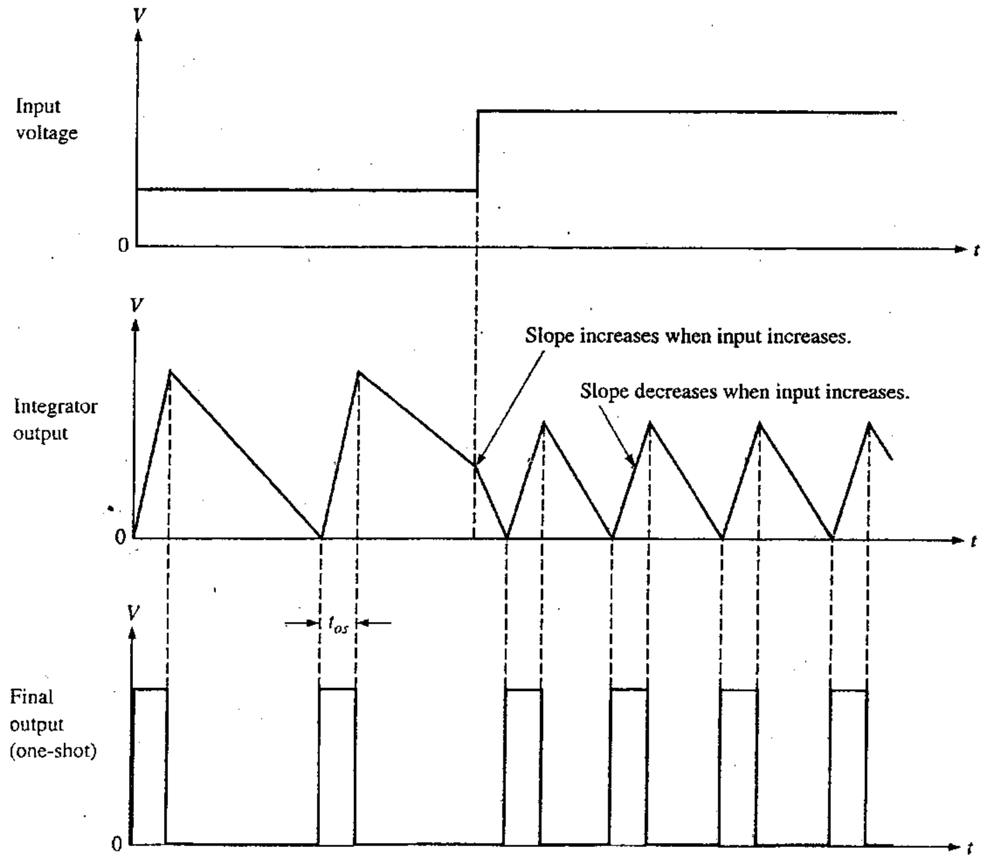
The input current also increases …

Increased Input Voltage



Hence the current through the integrating capacitor (I_C) during the integrate mode increases …

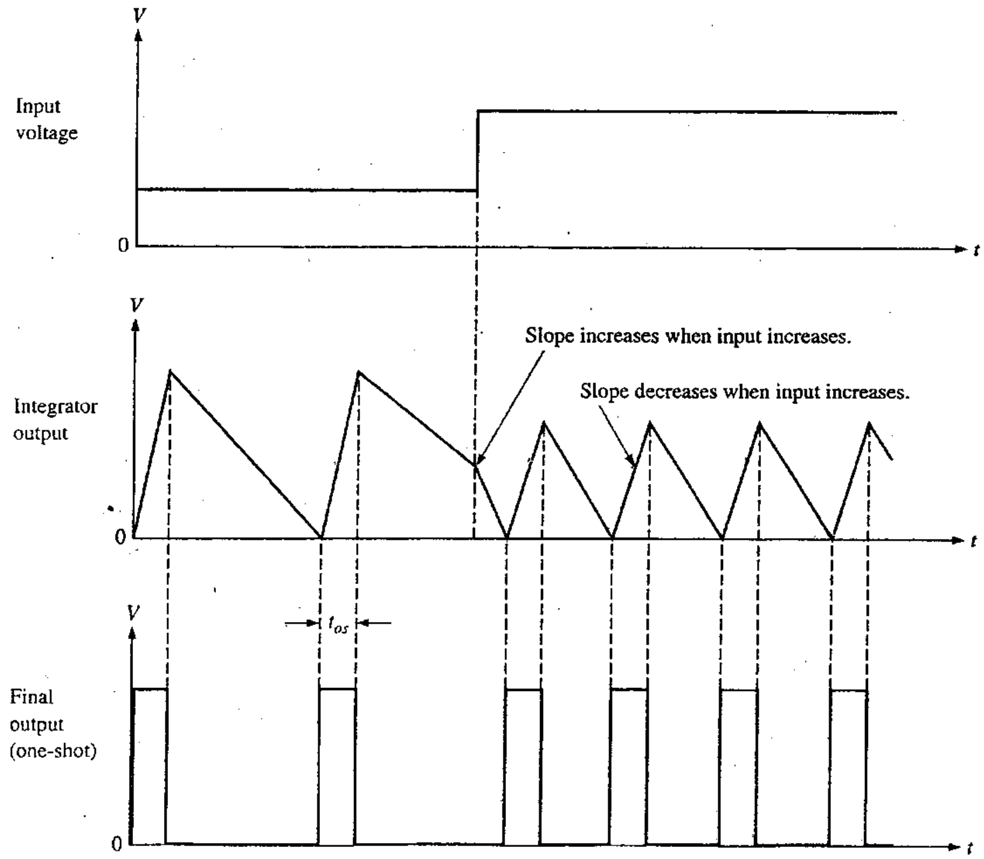
Increased Input Voltage



But …

$$I_C = \left(\frac{V_C}{t}\right) * C$$

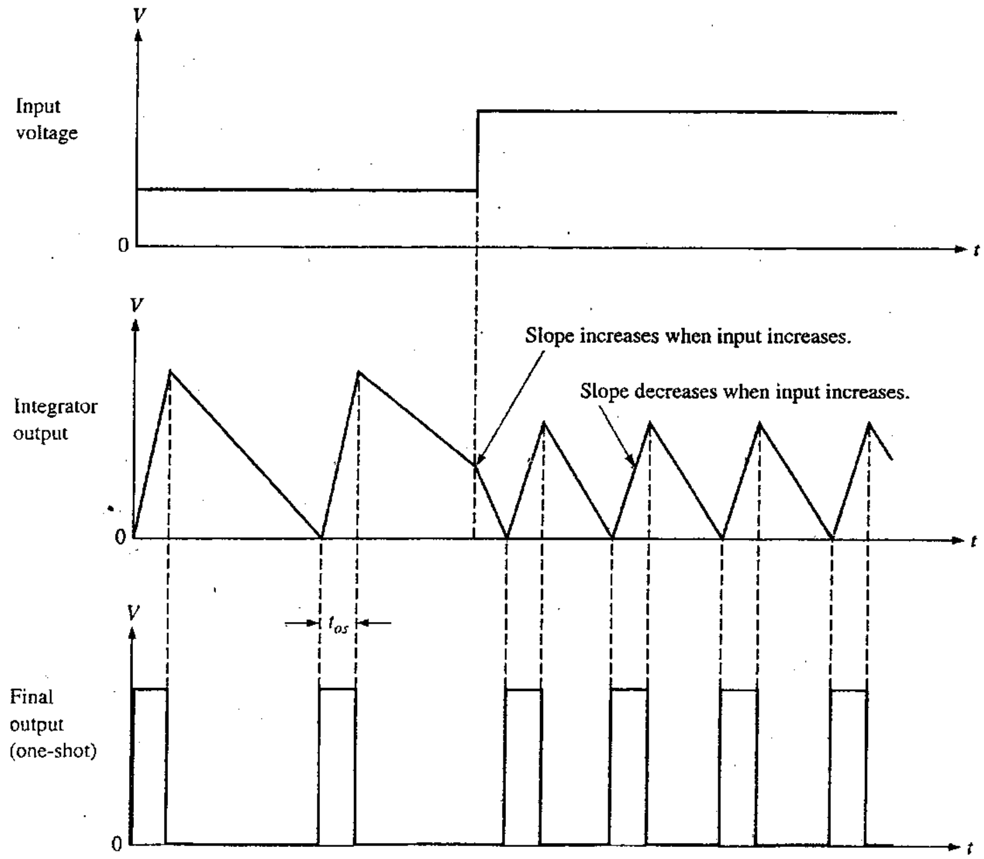
Increased Input Voltage



Therefore, since I_C increases … it means that the slope …

$\left(\frac{V_C}{t}\right)$ increases … since C … is a constant

Increased Input Voltage

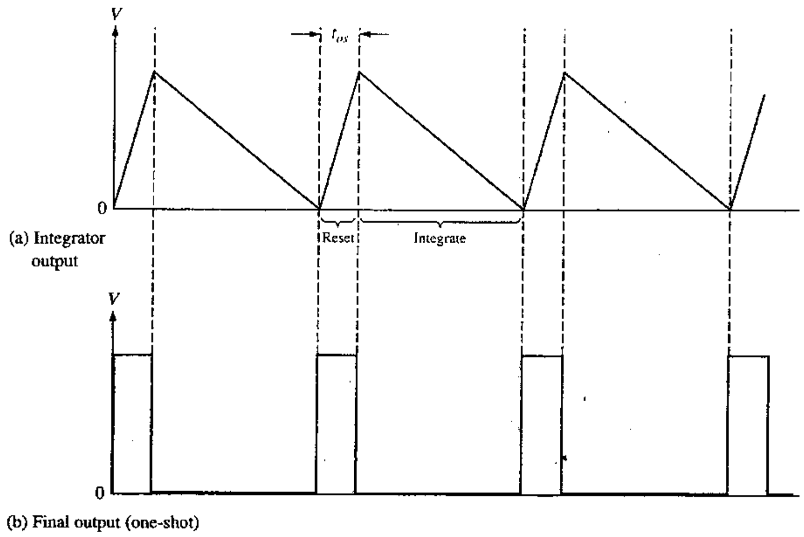


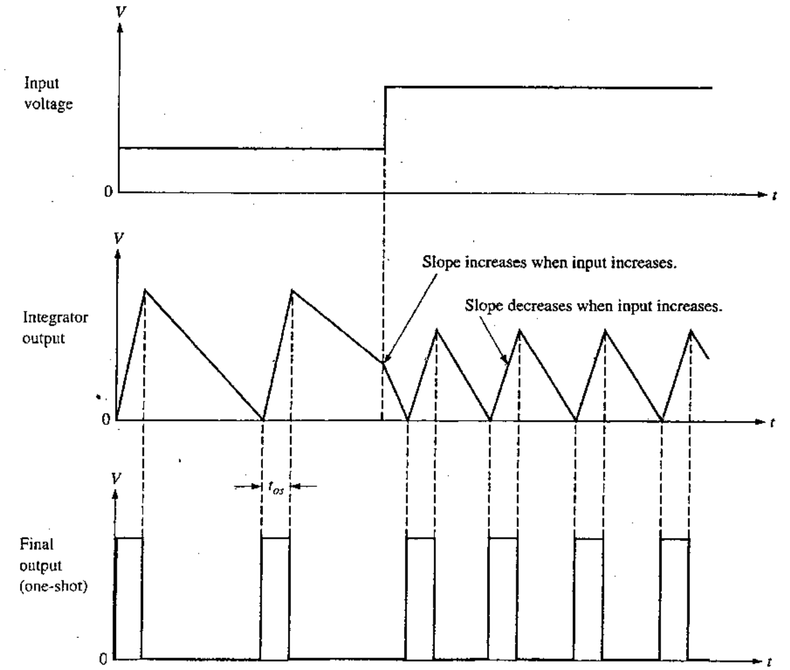
This reduces the period of the final output voltage

Output Freq Proportional to Input Voltage

- We saw that decreasing the slope of the upward ramp ... and ...
- ... reducing the amplitude of the integrator output voltage ...
  - Further decreases the output period ... or ...
  - Increases the output frequency

Output Freq Proportional to Input Voltage





Output Freq Proportional to Input Voltage

- As the input voltage varies ...
- ... the output frequency is directly proportional to the input
- Thus, we could say in the ideal case that ...

$$\frac{f_{OUT}}{f_{FS}} = \frac{V_{IN}}{V_{FS}}$$

OR

$$f_{OUT} = \frac{f_{FS}}{V_{FS}} \cdot V_{IN} = G \cdot V_{IN}$$

Output Freq Proportional to Input Voltage

- Where f_{OUT} is the frequency of the output signal ...
- V_{IN} is the input voltage ...
- f_{FS}, V_{FS} are the respective Full-Scale Quantities.
- G is the gain of the VFC in events-per-second (hz) per volt

Voltage-to-Frequency Converters
AS
Analog to Digital Converters

VFC as Analog to Digital Converters

- As we discussed ... A ***voltage-to-frequency*** converter is a device which ...
  - Accepts at it's input an analog voltage or current signal ...
  - And ... provides at its output a train of pulses or square waves at a frequency which is proportional to the input value

VFC as Analog to Digital Converters

- Therefore ... a ***Voltage-to-Frequency*** converter can be used as a building block in an ***analog-to-digital*** conversion system, by ...
  - Using the VFC to clock a counter for a certain period of time (count time) ... and ...
  - Reading the output digital word

VFC as Analog to Digital Converters

- This digital word will be proportional to the analog input
- The time required to convert an analog signal into a digital word is:
  - Related to the maximum full-scale frequency of the VFC ...

    ... AND ...

  - The required resolution of the measurement

VFC as Analog to Digital Converters

- In general, the required count time for an analog to digital conversion using a VFC is ...

$$T_{COUNT} = \frac{N}{FS_{out}}$$

- where N is the number of codes for a given resolution and FS_{out} is the VFS full-scale output frequency

- The time of conversion is constant for all conversions for given N and FS_{out}

Example

VFC as Analog to Digital Converters

An Example

- A VFC device has ...
  - A full scale frequency of 1MHz (1000000 Hz)
  - Resolution of 16 bits
- What is the time required to convert the signal?

  - If this device is used in an application where a resolution of 16 bits, or 1 part in 65,536 is desired ... 2^{16} = 65,536

  - Then ... the time required to convert the analog signal into a 16-bit digital word will be 65.536 msec

65,536/1000000 = 0.065536 seconds = 65.536 msec

Example

VFC as Analog to Digital Converters

Another Example

- A VFC device has ...
  - A full scale frequency of 1MHz (1000000 Hz)
  - Resolution of 18 bits
- What is the time required to convert the signal?

  - If this device is used in an application where a resolution of 18 bits, or 1 part in 262,144 is desired ... 2^{18} = 262,144

  - Then ... the time required to convert the analog signal into a 18-bit digital word will require a count time slightly greater than 0.262 seconds

    262,144/1000000 = 0.262144 seconds

Example

VFC as Analog to Digital Converters
Another Example

- Assuming full-scale input voltage for a 10-bit A/D converter ...
- 1024 cycles of F_{OUT} would be counted to achieve the binary equivalent of the input signal
- If ... $f_{FS} = 100kHz$
- ... the time of conversion would be ...

$$t = \frac{N}{f_{FS}} = \frac{1024}{100kHz} = 10.24m\sec$$

- This is CONSTANT!

PULSE COUNTING …

PULSE COUNTING

- One way to perform an analog-to-digital conversion using a voltage-to-frequency converter is ...
  - To have a single-chip microcomputer count the number of pulses that occur in a fixed time period
  - The total number of pulses counted during this period is then proportional to the input voltage of the VFC

Example

PULSE COUNTING
An Example

- What is the total full-scale count if ...
  – a 1V full-scale input produces a l00 kHz signal from the VFC
  – and the count period is 100 ms?

f_{FS} = 100KHz = 100,000 Hz

V_{FS} = 1 Volt

T = 100 msec = .1 sec

Then ... the Total Count = (.1)*(100,000) = 10,000

PULSE COUNTING – *Example (con't)*

- Scaling from this maximum is then used to determine the input voltage
- i.e., a count of 5,000 corresponds to an input voltage of 0.5V....

- ... is related to the maximum full-scale frequency of the VFC and the required resolution of the measurement

- Now ... using ...

$$\frac{f_{OUT}}{f_{FS}} = \frac{V_{IN}}{V_{FS}}$$

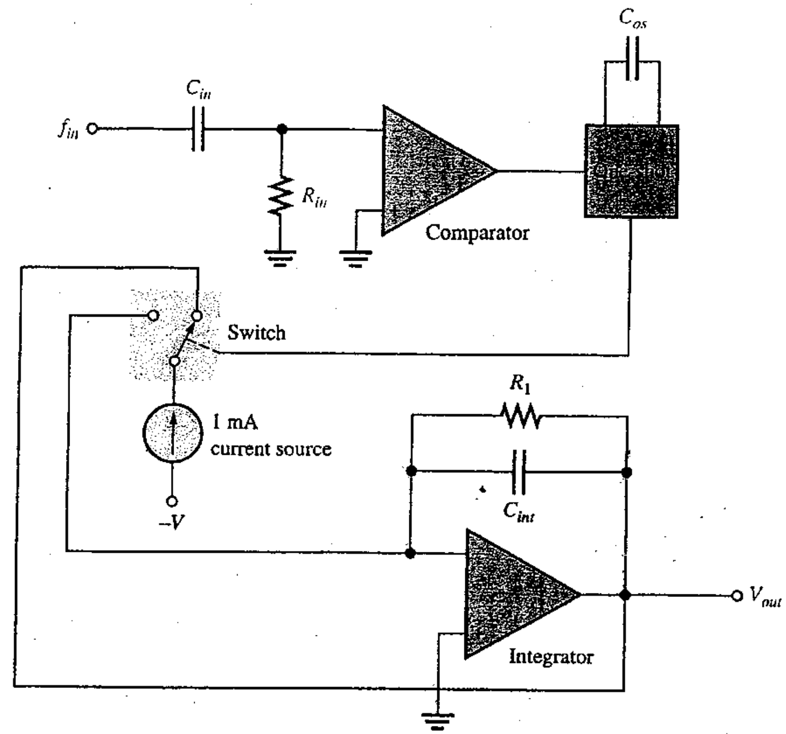
- $f_{OUT} = f_{FS} * V_{IN}/V_{FS}$ = 100,000 * (.5)/(1) = 50,000 Hz
- Total Count = (.1)*(50,000) = 5,000

Frequency-to-Voltage Converters …

Frequency-to-Voltage Converter Circuit

- The elements for the Frequency-to-Voltage converters are ...
  - Exactly the same as the ones we've seen in the V/F converter
- We, therefore, will briefly describe what is happening

Frequency-to-Voltage Converter Circuit



Frequency-to-Voltage Converter Circuit

- When an input frequency is applied to the comparator input ...
  - It triggers the one-shot multivibrator which ...
    - Produces a fixed pulse width (t_{OS}) ...
      - Determined by the one shot capacitor (C_{OS})

Frequency-to-Voltage Converter Circuit

- This switches the 1 mA current source to the integrator input ...
  - AND the integrating capacitor (C_{INT}) discharges
- Between the one-shot pulses ...
- ... The integrating capacitor (C_{INT}) discharges through R_1
- The higher the input frequency ...
- ... the closer the one-shot pulses are together ...
- ... and the less the integrating capacitor (C_{INT}) discharges

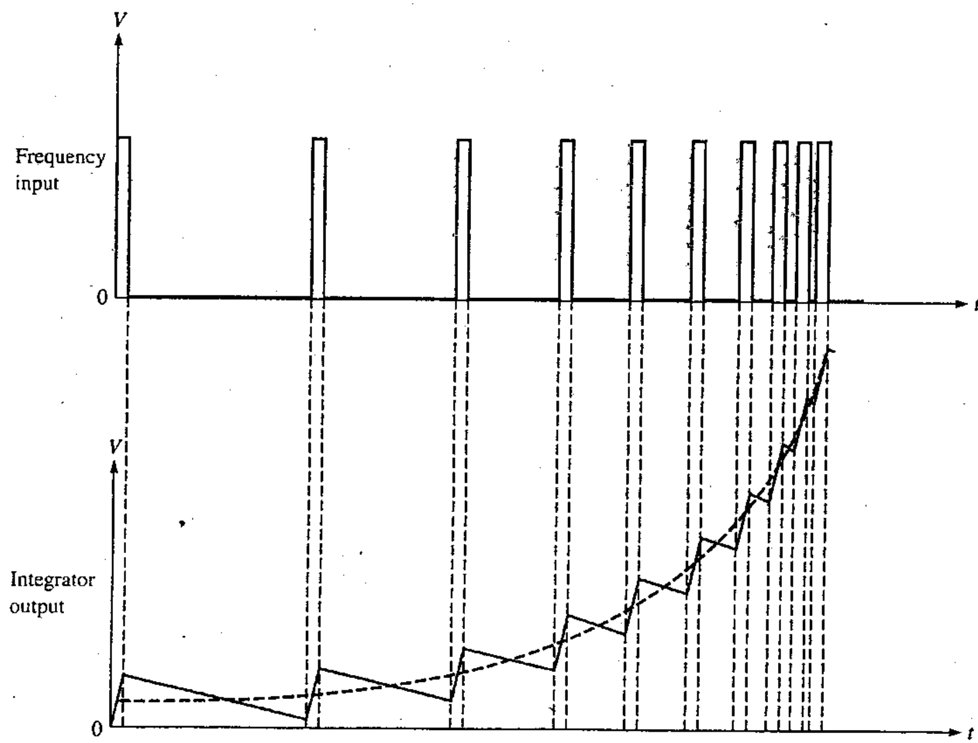
Frequency-to-Voltage Converter Circuit

- This causes ...
  - ... the integrator output to increase as the frequency increases ...
  - ... and ... to decrease as the input frequency decreases.
- The integrator output is the final voltage of the F/V converter (V_{OUT})
- The integrating capacitor (C_{INT}) and R_1 act as a filter ...

Frequency-to-Voltage Converter Output

- AND ... tends to smooth out the ripples on the integrator output
  - ... as indicated by the dashed curve on the next slide

Frequency-to-Voltage Converter Output



Errors in VF Converters

Errors in V/F Converters

- Offset errors
- Gain errors
- Linearity errors

Errors in V/F Converters

- Offset and gain errors
  - Can be “trimmed” by the user
    - Application Note AN-361 provides a procedure

Errors in V/F Converters

- Linearity errors
  - Cannot be “trimmed” by the user
  - These type errors are usually minimal, if capacitors are chosen properly
    - Must be stable with temperature variation
    - Cannot suffer from dielectric absorption
      - Dielectric absorption --- if a capacitor is charged, discharged and then open circuited it may recover some charge
    - Use Teflon or polypropylene or zero-temperature coefficient ceramic capacitors

Frequency-to-Voltage Converters

Applications

Application of V/F and F/V Converters

- One application of V/F and F/V Converters is the remote sensing of a quantity ... such as ...
  - Temperature ...
  - Pressure ...
  - Etc

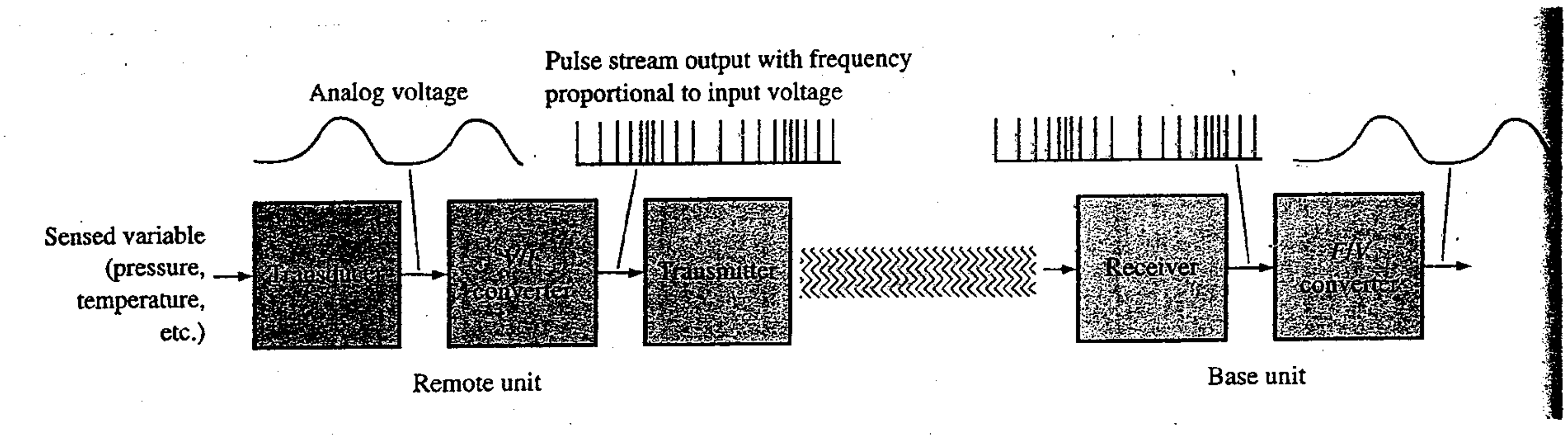
Application of V/F and F/V Converters

- That is converted to an analog voltage by a transducer ...
- The analog voltage ... is then converted to a pulse frequency by a V/F converter ...
  - ... which is then transmitted by some method ...
    - Radio Link ... OR ...
    - Fiber-optical link ... Etc.
- ... to a base unit receiver that includes a F/V converter

Application of V/F and F/V Converters

- The F/V converter converts it back to an analog voltage signal ...
  - ... from which we can obtain the original sensed quantity ...
- This is all illustrated on the next slide

Frequency-to-Voltage System



Lab

Lab #6 …

Lab # 6 – Overview

- Voltage-to-Frequency conversion
- Frequency-to-Voltage conversion
- Input a signal into a VFC and convert it back via a FVC
- *READ THE DATA SHEET* ... this is one of the most informative data sheets I have used

Next Class

Next Class Topics

- Microcontroller and Sensors Lecture
- Continue with Labs
- Start Projects

Homework

Homework

1. Lab Reports are due as follows:

    a) Lab Report #3 Due 11/07/13

    b) Lab Report #4 Due 11/14/13

    c) Lab Report (#5 or #6) Due 11/21/13

2. Read the following ...

    – VFC Data Sheet

Time to start the lab …

Questions?

References …

References

1. None