EELE445-14

Lecture 3,4
Power, Energy,
Time average operator
section 2.1

Lecture 3,4 EE445 - Outcomes

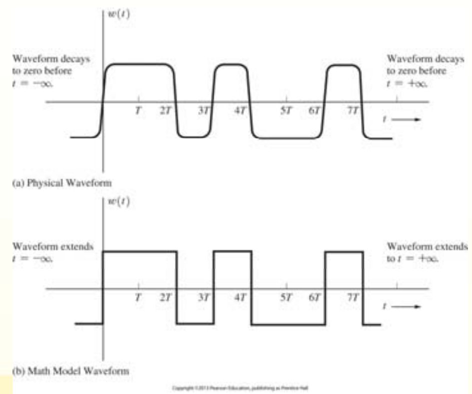
- In this lecture you:
  - be able to use the time average operator $\langle [\,] \rangle$ for finite time duration signals and periodic signals
  - Be able to find the rms value of a waveform
  - be able to find the power or energy of a waveform in the time domain
  - Parseval's Theorem, find the power or energy of a waveform in the frequency domain
  - Concept of PSD an ESD

Physically Realizable Waveforms

- measurable in the laboratory

1. waveform has significant nonzero values over a composite time interval for a finite time duration
2. continuous function of time
3. finite peak amplitude
4. real function , no complex values

Figure 2–1 Physical and mathematical waveforms.



Time average operator

Time Average Operator (**mean,** of w(t)):

$$\langle w(t)\rangle = W_{dc} = \overline{w} \equiv \lim_{T\to\infty} \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} w(t)dt$$

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Time average operator

Time Average Operator for signal of finite time duration:

$$\langle w(t)\rangle = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} w(t)dt \qquad \langle w_n\rangle = \frac{1}{N}\sum_{n=1}^{N} w_n$$

For a Periodic Signal:

$w(t) = w(t + aT_0)$ for any real a

$$\langle w(t)\rangle = \frac{1}{T_o}\int_{-\frac{T_o}{2}+a}^{\frac{T_o}{2}+a} w(t)dt \text{ for any real } a$$

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Root Mean Square- *rms*

$$W_{meansquare} = \langle w^2(t)\rangle = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} w^2(t)dt \quad \text{(Power R = 1)}$$

RMS = "root mean square" of a signal of <u>duration T</u>:

$$W_{rms} = \sqrt{\langle w^2(t)\rangle} = \sqrt{\frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} w^2(t)dt}$$

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RMS

For periodic waveforms:

$$\sqrt{\langle w^2(t)\rangle} = \sqrt{\frac{1}{T_0}\int_{-\frac{T_0}{2}+\tau}^{\frac{T_0}{2}+\tau} w^2(t)dt} \quad = \text{rms value of w(t)}$$

- where τ is an arbitrary time shift.
- <u>Choose τ to simplify the integrals!</u>

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RMS example

RMS of a sinwave:

$$\sqrt{\left\langle [A\cos(\omega_o t]^2 \right\rangle} = \frac{A}{\sqrt{2}} \qquad appendix\ A-4 \quad use:\ 2\cos^2(x) = 1+\cos(2x)$$

$$RMS\ of\ a\ SquareWave = A$$

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Example 2–2 EVALUATION OF POWER

Let the circuit of Fig. 2–2 contain a 120-V, 60-Hz fluorescent lamp wired in a high-power–factor configuration. Assume that the voltage and current are both sinusoids and in phase (unity power factor), as shown in Fig. 2–3.[†] The DC value of this (periodic) voltage waveform is

[†] Two-lamp fluorescent circuits can be realized with a high-power–factor ballast that gives an overall power factor greater than 90% [Fink and Beaty, 1978].

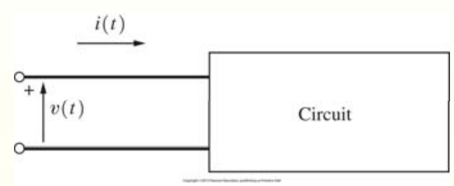

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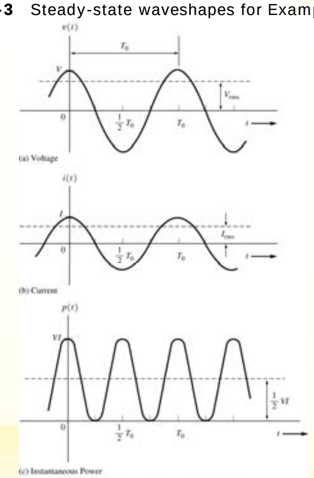
Figure 2–3 Steady-state waveshapes for Example 2–2.



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Example 2–2 EVALUATION OF POWER

$$V_{dc} = \langle v(t) \rangle = \langle V\cos\omega_0 t \rangle = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} V\cos\omega_0 t\, dt = 0 \qquad (2\text{–}8)$$

where $\omega_0 = 2\pi/T_0$ and $f_0 = 1/T_0 = 60$ HZ. Similarly, $I_{dc} = 0$. The instantaneous power is

$$p(t) = (V\cos\omega_0 t)(I\cos\omega_0 t) = \frac{1}{2}VI(1+\cos 2\omega_0 t) \qquad (2\text{–}9)$$

The average power is

$$P = \left\langle \frac{1}{2}VI(1+\cos 2\omega_0 t) \right\rangle = \frac{VI}{2T_0}\int_{-T_0/2}^{T_0/2}(1+\cos 2\omega_0 t)\, dt = \frac{VI}{2} \qquad (2\text{–}10)$$

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Power of a signal

instantanious Power $p(t) = v(t)i(t)$

average Power $\langle p(t) \rangle = \langle v(t)i(t) \rangle = \mathrm{Real}\left\{ \left\langle \dfrac{v^2(t)}{Z_{load}} \right\rangle \right\}$

$$= \frac{1}{R}\langle v^2(t) \rangle \quad when\ Z = R + j0$$

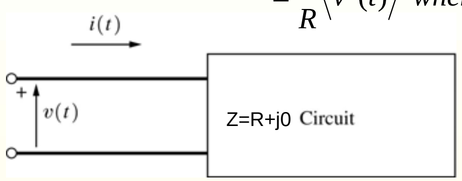

Figure 2–2 Polarity convention used for voltage and current.

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Power of a signal

Average Power in signal of duration T :

$$P = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} v(t)i\ (t)dt \ = \frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} p(t)dt$$

p(t) is the instantaneous power, P is the average power over time T

$$P = \frac{E}{T} = \frac{1}{R}\frac{1}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} v^2(t)dt \equiv \frac{v_{rms}^2}{R}$$

For Normalized Power: R=1 ohm

$$P = \frac{R}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} i^2(t)dt \ \equiv i_{rms}^2 R$$

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Energy of a Signal

Energy in signal of duration T :

$$P = \frac{E}{T} = \frac{1}{RT}\int_{-\frac{T}{2}}^{\frac{T}{2}} v^2(t)dt \qquad E = PT$$

$$E = \frac{1}{R}\int_{-\frac{T}{2}}^{\frac{T}{2}} v^2(t)dt = \ R\int_{-\frac{T}{2}}^{\frac{T}{2}} i^2(t)dt$$

We typically calulate normalized Energy or Power, R = 1

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A communication metric: Signal to Noise Ratio in dB

$$(S/N)_{dB} \equiv 10Log\left(\frac{P_{signal}}{P_{noise}}\right) = 10Log\left(\frac{\langle s(t)^2 \rangle}{\langle n(t)^2 \rangle}\right)$$

$$= 20Log\left(\frac{V_{rms}\ signal}{V_{rms}\ noise}\right)$$

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Lecture 4

The Fourier Transform and the Frequency Domain

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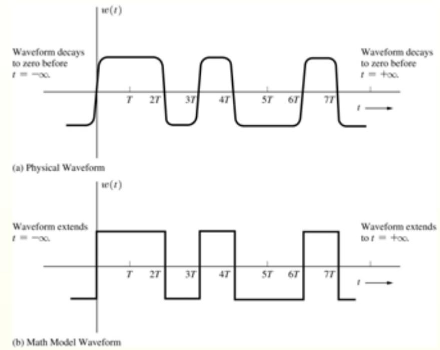
Figure 2–1 Physical and mathematical waveforms.



Digital and Analog Communication Systems, Seventh Edition

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The Fourier Transform

We use the Fourier transform to determine the frequencies of the sinusoids present in a non repetitive waveform.

The fourier series may be considered the fourier transform of a non-repetitive waveform that is repeated continuously.

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Fourier Transform

$$W(f) = \mathcal{F}[w(t)] = \int_{-\infty}^{\infty} w(t) \bullet e^{-j2\pi ft} dt$$

What is :

$\int x(t)y(t)dt$???

Correlation coeff

$$C = \frac{\int x(t)y(t)dt}{\sqrt{\int x(t)^2 dt \bullet \int y(t)^2 dt}}$$

$-1 < C < 1$

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Fourier Transform

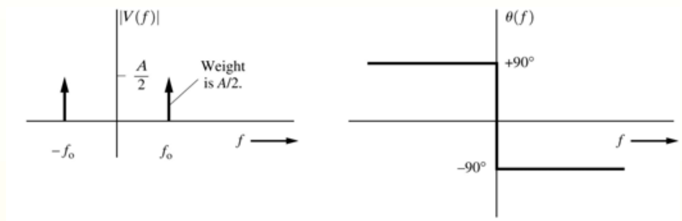
$$W(f) = \mathscr{F}[w(t)] = \int_{-\infty}^{\infty} [w(t)] \bullet e^{-j2\pi ft} dt$$

So the Fourier transform is answering the question:

how much of $e^{-j2\pi f}$ is in $w(t)$?

$$e^{-jx} = \cos(x) - j\sin(x)$$

Figure 2–4 Spectrum of a sine wave.



(a) Magnitude Spectrum

(b) Phase Spectrum ($\theta_0 = 0$)

Figure 2–5 Waveshapes and corresponding symbolic notation.

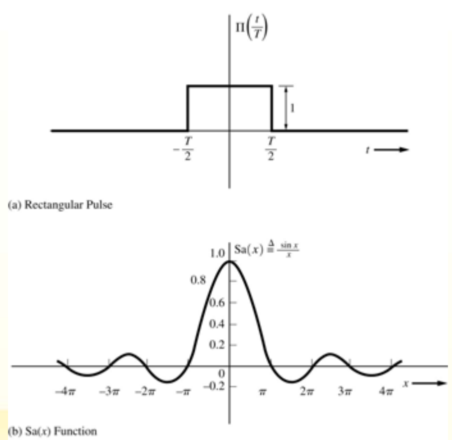
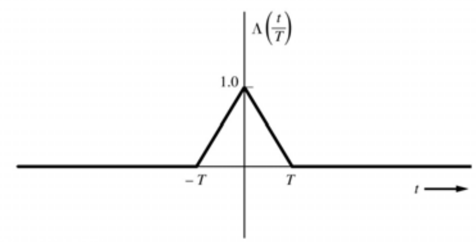
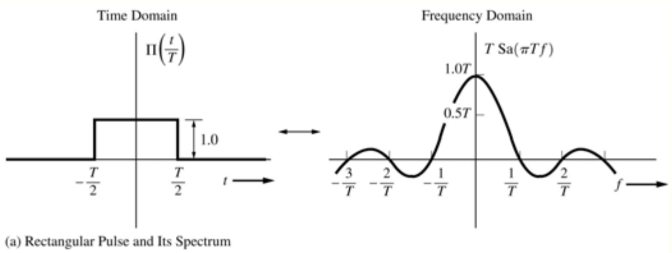


Figure 2–5 Waveshapes and corresponding symbolic notation.



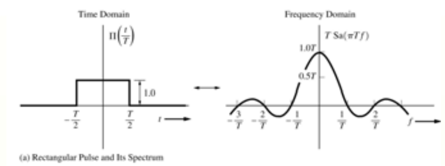
(c) Triangular Function

Figure 2–6 Spectra of rectangular, (sin *x*)/*x*, and triangular pulses.



(a) Rectangular Pulse and Its Spectrum

Figure 2–6 Spectra of rectangular, (sin *x*)/*x*, and triangular pulses.



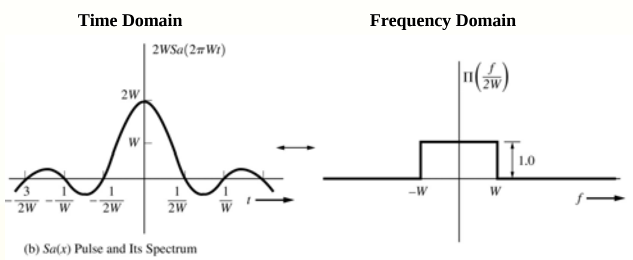
(a) Rectangular Pulse and Its Spectrum

Time - bandwidth product or bandwidth - duration product :

$$T_{rms}B_{rms} \le \frac{1}{4\pi}$$

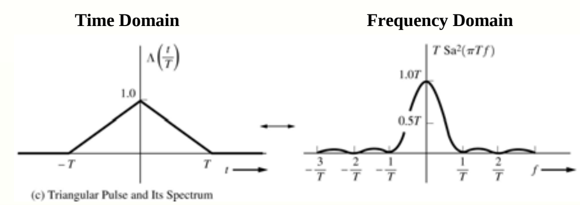
the Gaussian pulse, $w(t) = e^{-\pi t^2}$ satifies the condition with the equality sign.

Figure 2–6 Spectra of rectangular, (sin *x*)/*x*, and triangular pulses.



(b) $Sa(x)$ Pulse and Its Spectrum

Figure 2–6 Spectra of rectangular, (sin *x*)/*x*, and triangular pulses.



(c) Triangular Pulse and Its Spectrum

Fourier Transform Theorems

TABLE 2–1 SOME FOURIER TRANSFORM THEOREMS[a]

Operation	Function	Fourier Transform
Linearity	$a_1 w_1(t) + a_2 w_2(t)$	$a_1 W_1(f) + a_2 W_2(f)$
Time delay	$w(t - T_d)$	$W(f)\, e^{-j\omega T_d}$
Scale change	$w(at)$	$\frac{1}{\lvert a \rvert} W\left(\frac{f}{a}\right)$
Conjugation	$w^*(t)$	$W^*(-f)$
Duality	$W(t)$	$w(-f)$
Real signal frequency translation [$w(t)$ is real]	$w(t)\cos(\omega_c t + \theta)$	$\frac{1}{2}[e^{j\theta} W(f - f_c) + e^{-j\theta} W(f + f_c)]$
Complex signal frequency translation	$w(t)\, e^{j\omega_c t}$	$W(f - f_c)$

These theorems are useful for the homework <u>and the exams!</u>

Fourier Transform Theorems

Bandpass signal	$\mathrm{Re}\{g(t)\, e^{j\omega_c t}\}$	$\frac{1}{2}[G(f - f_c) + G^*(-f - f_c)]$
Differentiation	$\frac{d^n w(t)}{dt^n}$	$(j2\pi f)^n W(f)$
Integration	$\int_{-\infty}^{t} w(\lambda) d\lambda$	$(j2\pi f)^{-1} W(f) + \frac{1}{2} W(0)\, \delta(f)$
Convolution	$w_1(t) * w_2(t) = \int_{-\infty}^{\infty} w_1(\lambda) \cdot w_2(t - \lambda)\, d\lambda$	$W_1(f) W_2(f)$
Multiplication[b]	$w_1(t) w_2(t)$	$W_1(f) * W_2(f) = \int_{-\infty}^{\infty} W_1(\lambda)\, W_2(f - \lambda)\, d\lambda$
Multiplication by t^n	$t^n w(t)$	$(-j2\pi)^{-n} \frac{d^n W(f)}{df^n}$

[a] $\omega_c = 2\pi f_c$.

[b] $*$ denotes convolution as described in detail by Eq. (2–62).

Fourier Transform Pairs

TABLE 2–2 SOME FOURIER TRANSFORM PAIRS

Function	Time Waveform $w(t)$	Spectrum $W(f)$
Rectangular	$\Pi\left(\frac{t}{T}\right)$	$T[\mathrm{Sa}(\pi f T)]$
Triangular	$\Lambda\left(\frac{t}{T}\right)$	$T[\mathrm{Sa}(\pi f T)]^2$
Unit step	$u(t) \triangleq \begin{cases} +1, & t > 0 \\ 0, & t < 0 \end{cases}$	$\frac{1}{2}\delta(f) + \frac{1}{j2\pi f}$
Signum	$\mathrm{sgn}(t) \triangleq \begin{cases} +1, & t > 0 \\ -1, & t < 0 \end{cases}$	$\frac{1}{j\pi f}$
Constant	1	$\delta(f)$

The rectangular function is used to mathematically truncate an infinite time waveform w(t). It is the time window that w(t) is analyzed over. What is the effect on the measurement of w(t) as T approaches infinity? How about as T approaches 0?

Fourier Transform Pairs

Impulse at $t = t_0$	$\delta(t - t_0)$	$e^{-j2\pi f t_0}$
Sinc	$\mathrm{Sa}(2\pi W t)$	$\frac{1}{2W} \Pi\left(\frac{f}{2W}\right)$
Phasor	$e^{j(\omega_0 t + \varphi)}$	$e^{j\varphi}\, \delta(f - f_0)$
Sinusoid	$\cos(\omega_c t + \varphi)$	$\frac{1}{2} e^{j\varphi}\, \delta(f - f_c) + \frac{1}{2} e^{-j\varphi}\, \delta(f + f_c)$
Gaussian	$e^{-\pi (t/t_0)^2}$	$t_0 e^{-\pi (f t_0)^2}$
Exponential, one-sided	$\begin{cases} e^{-t/T}, & t > 0 \\ 0, & t < 0 \end{cases}$	$\frac{T}{1 + j2\pi f T}$
Exponential, two-sided	$e^{-\lvert t \rvert / T}$	$\frac{2T}{1 + (2\pi f T)^2}$
Impulse train	$\sum_{k=-\infty}^{k=\infty} \delta(t - kT)$	$f_0 \sum_{n=-\infty}^{n=\infty} \delta(f - n f_0)$, where $f_0 = 1/T$

compare the Phasor and the sinusoid transforms.

Energy and Power in a Waveform

Parseval's Theorem and Energy Spectral Density

Parseval's Theorem.

$$\int_{-\infty}^{\infty} w_1(t) w_2^*(t)\, dt = \int_{-\infty}^{\infty} W_1(f) W_2^*(f)\, df \qquad (2\text{–}40)$$

If $w_1(t) = w_2(t) = w(t)$, then the theorem reduces to

Rayleigh's energy theorem, which is

$$E = \int_{-\infty}^{\infty} |w(t)|^2\, dt = \int_{-\infty}^{\infty} |W(f)|^2\, df \qquad (2\text{–}41)$$

DEFINITION. The *energy spectral density (ESD)* is defined for energy waveforms by

$$\mathscr{E}(f) = |W(f)|^2 \qquad (2\text{–}42)$$

where $w(t) \leftrightarrow W(f)$. $\mathscr{E}(f)$ has units of joules per hertz.

Using Eq. (2–41), we see that the total normalized energy is given by the area under the ESD function:

$$E = \int_{-\infty}^{\infty} \mathscr{E}(f)\, df \qquad (2\text{–}43)$$

Energy and Power in a Waveform

- Energy Spectral Density, **ESD**

$$E(f) \equiv |W(f)|^2 \qquad W(f) \equiv \int_{-\infty}^{\infty} w(t) \bullet e^{-j2\pi f t} dt$$

•Power Spectral Density, **PSD,** for a truncated waveform of duration T

$$w_T(t) = \begin{cases} w(t), & -T/2 < t < T/2 \\ 0, & t \text{ elsewhere} \end{cases} = w(t)\Pi\left(\frac{t}{T}\right) \qquad (2\text{–}64)$$

Using Eq. (2–13), we obtain the average normalized power:

$$P = \lim_{T\to\infty} \frac{1}{T} \int_{-T/2}^{T/2} w^2(t)\, dt = \lim_{T\to\infty} \frac{1}{T} \int_{-\infty}^{\infty} w_T^2(t)\, dt$$

By the use of Parseval's theorem, Eq. (2–41), the average normalized power becomes

$$P = \lim_{T\to\infty} \frac{1}{T} \int_{-\infty}^{\infty} |W_T(f)|^2\, df = \int_{-\infty}^{\infty} \left(\lim_{T\to\infty} \frac{|W_T(f)|^2}{T} \right) df \qquad (2\text{–}65)$$

Energy and Power in a Waveform

DEFINITION. The *power spectral density (PSD)* for a deterministic power waveform is[†]

$$\mathscr{P}_w(f) \triangleq \lim_{T\to\infty} \left(\frac{|W_T(f)|^2}{T} \right) \qquad (2\text{–}66)$$

where $w_T(t) \leftrightarrow W_T(f)$ and $\mathscr{P}_w(f)$ has units of watts per hertz.

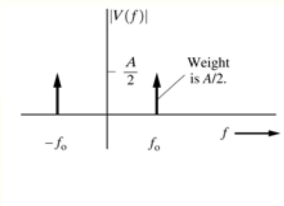
Note that the PSD is always a real nonnegative function of frequency. In addition, the PSD is not sensitive to the phase spectrum of $w(t)$, because that is lost due to the absolute value operation used in Eq. (2–66). From Eq. (2–65), the normalized average power is[†]

$$P = \langle w^2(t) \rangle = \int_{-\infty}^{\infty} \mathscr{P}_w(f)\, df \qquad (2\text{–}67)$$

That is, the area under the PSD function is the normalized average power.

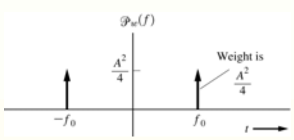
Energy and Power in a Waveform

Figure 2–4 Spectrum of a sine wave.



(a) Magnitude Spectrum

Figure 2–9 Power spectrum of a sinusoid.



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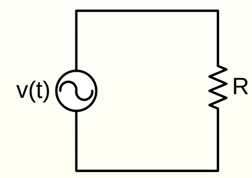
LECTURE 5

Examples,

Fourier Series from the Fourier Transform

Example- Power and Energy in Time.

A 1 KHz sinewave source is applied to a 50 ohm resistor. fine the power delivered to the load.



$$R = 50\,\Omega$$
$$v(t) = A\cos(2\pi f t)$$
$$A = 1\ volt$$
$$f = 1000\ Hz$$
$$T_o = 10^{-3}\ \sec$$

Example- Power and Energy in Time.

For a periodic Signal :

$$P = \frac{1}{R}\frac{1}{T_o}\int_{-\frac{T_o}{2}}^{\frac{T_o}{2}} v^2(t)dt$$

$$\frac{1}{T_o}\int_{-\frac{T_o}{2}}^{\frac{T_o}{2}} v^2(t)dt = \frac{1}{T_o}\int_{-\frac{T_o}{2}}^{\frac{T_o}{2}} (A\cos(2\pi f t)^2 dt$$

$$= \frac{A^2}{2T_o}\left[\int_{-\frac{T_o}{2}}^{\frac{T_o}{2}} 1dt + \underbrace{\int_{-\frac{T_o}{2}}^{\frac{T_o}{2}} \cos(4\pi f t\ dt}_{0}\right]$$

$$= \frac{A^2}{2T_o}\left[\frac{T_0}{2} - -\frac{T_0}{2}\right]$$

$$= \frac{A^2}{2}\ \ Mean\ Squared\ volts\ (volts^2)$$

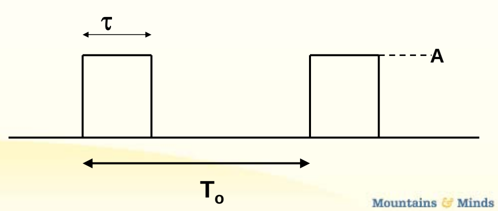
so

$$P = \frac{A^2}{2R} = \frac{1^2}{2 \bullet 50} = 0.01\,Watt = 10dBm$$

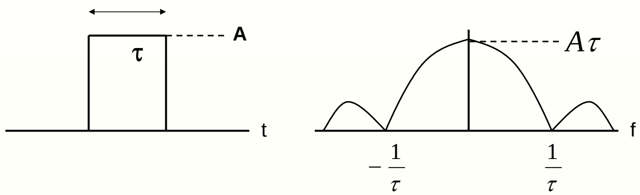
Fourier Series from Fourier Transforms

1. Find the truncated signal period $V_{To}(t)$
2. Determine the Fourier Transform of the waveform $V_{To}(t)$
3. Find the value of the Fourier Series coefficients by:
   1. Replacing f in the Transform with $f=n/T_o$
   2. Scaling the magnitude of the Transform by $1/T_o$

Duty Cycle, $D = \frac{\tau}{T_o}$



Fourier Series from Fourier Transforms

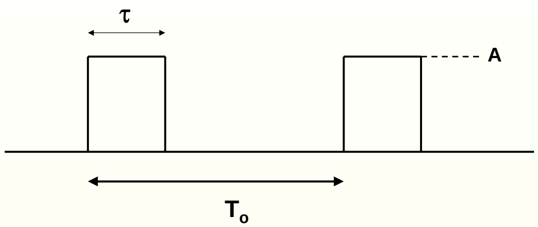


From Fourier Transform Table:

$$F\left(A \bullet \Pi\left[\frac{t}{\tau}\right]\right) = A\tau Sa(\pi f \tau)$$

Fourier Series from Fourier Transforms

now make a repetitive pulse with period T_o



Let $f = \frac{n}{T}$ and scale by $\frac{1}{T_o}$ $\quad c_n = \frac{A\tau}{T_o} Sa\left[\frac{n\pi\tau}{T_o}\right] \therefore$

Properties of a Repetitive Rectangular Pulse

- The null bandwidth, B_n of the spectrum is equal to the inverse of the pulse width, τ. $\quad B_n = \frac{1}{\tau}$
- The harmonic frequencies are n/T_o
- The number of harmonics, n, from DC to the spectral null is: $n = \frac{1}{D} = \frac{T_o}{\tau}$
- Approximately 90 percent of the power of the signal is in the spectrum from DC to the null bandwidth frequency, only 10% of the signal power is in the spectrum frequency range from the null bandwidth frequency to infinity!

Repetitive Rectangular Pulse

filename:pulsewaveform.mcd
avo Last edit date: 1/30/08

************************************ Definitions **

$\delta(f,R) \equiv \text{if}(f = R, 1, 0)$ $\qquad \text{sinc}(x) \equiv \text{if}\left(x = 0, 1, \frac{\sin(\pi \cdot x)}{\pi \cdot x}\right)$

$\Lambda(t,T) \equiv \text{if}\left(|t| \le \frac{T}{2}, 1 - \left|\frac{2t}{T}\right|, 0\right)$ $\qquad \text{rect}(t,T) \equiv \text{if}\left[\left(|t| \le \frac{T}{2}\right), 1, 0\right]$

*************************************** set up waveform *****************************

$T := 1 \cdot ms$ period $\quad D := 20\%$ duty cycle $\quad \tau := D \cdot T \quad \tau = 2 \times 10^{-4} s$ pulse width

$A := 2V \quad \frac{1}{T} = 1 \times 10^{3} \frac{1}{s}$ pps $\quad \frac{1}{\tau} = 5 \times 10^{3} \frac{1}{s}$ First null

****************************** Set up Sweep Parameters ******************

Repetitive Rectangular Pulse

Pulse shape Pt Definition ********************************

Assume a rectangular pulse shape with an amplitude of 1

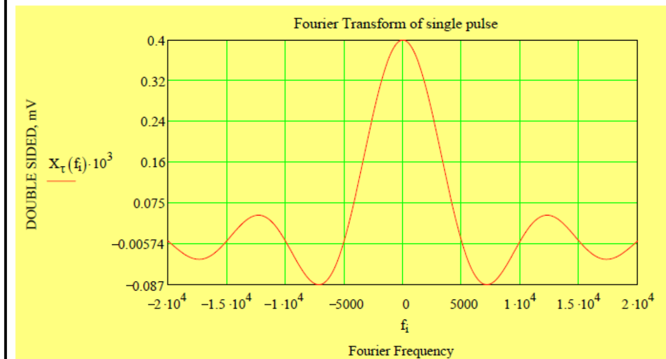
$X_\tau(f) := A\cdot\tau\cdot \mathrm{sinc}(f\cdot\tau)$ Single Pulse Fourier Transform, "double sided"

$n := -25, -24 .. 25$

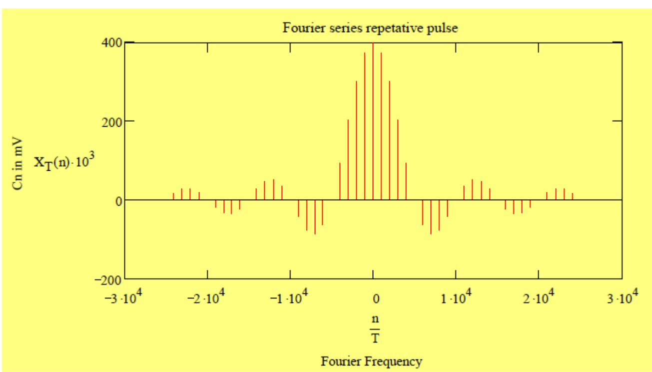
$X_T(n) := \frac{A\cdot\tau}{T}\cdot \mathrm{sinc}\left(\frac{n\cdot\tau}{T}\right)$ Fourier Series for repeatative pulse "double sided"

$X_T(0) = 0.4\ V$ DC value

Single Rectangular Pulse

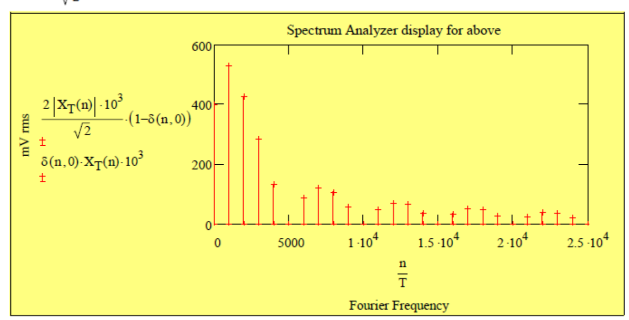


Repetitive Rectangular Pulse



Repetitive Rectangular Pulse

$\frac{2\left|X_T(1)\right|}{\sqrt{2}} = 0.529\ V$ level of fundamental as seen by SA $n := 0 .. 25$



Repetitive Rectangular Pulse

********************** Spectrum analyser Voltage levels rms ********************************

$$k := 1..7 \qquad P_{0,k} := k \qquad P_{1,k} := \frac{2\left|X_T(k)\right|}{\sqrt{2}\,V} \qquad P_{2,k} := 20\cdot\log\left(\frac{2\left|X_T(k)\right|}{\sqrt{2}\,V}\right)$$

$$P_{1,0} := \frac{X_T(0)}{V} \qquad P_{2,0} := 20\cdot\log\left(\frac{X_T(0)}{V}\right)$$

$$\begin{array}{cc} P = \begin{pmatrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ 0.4 & 0.529 & 0.428 & 0.285 & 0.132 & 2.205\times10^{-17} & 0.088 & 0.122 \\ -7.959 & -5.528 & -7.369 & -10.89 & -17.569 & -333.132 & -21.091 & -18.25 \end{pmatrix} & \begin{array}{c} \text{Harmonic} \\ \text{dBV} \\ \text{Vrms} \end{array} \end{array}$$

$$L := 5$$

$$\sum_{k=0}^{L}\left(P_{1,k}\right)^2 = 0.722$$ Power to Harmonic L

$$\frac{\displaystyle\sum_{k=0}^{L}\left(P_{1,k}\right)^2}{\left(\frac{A}{V}\right)^2\cdot D} = 90.288\%$$ Percent of power to Harmonic L

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Rectangular Pulse Power to the first null bandwidth

$$2\int_0^1 \operatorname{sinc}(x)^2\,dx\cdot100 = 90.282$$

$$P(x) := 2\left(\int_0^x \operatorname{sinc}(x)^2\,dx\right)\cdot100$$

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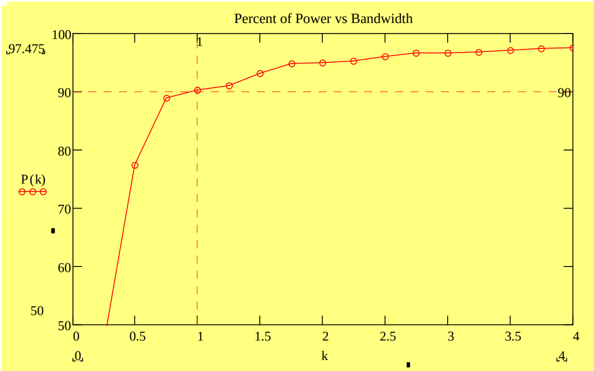
Repetitive Rectangular Pulse Power vs Bandwidth



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