

Fourier Transforms for Circuit and LTI Systems Analysis

Colophon

An annotatable worksheet for this presentation is available as [Worksheet 14](https://cpjobling.github.io/eg-247-textbook/fourier_series/3/worksheet14.html) (https://cpjobling.github.io/eg-247-textbook/fourier_series/3/worksheet14.html).

- The source code for this page is [content/fourier_transform/3/ft3.ipynb](https://github.com/cpjobling/eg-247-textbook/blob/master/content/fourier_transform/3/ft3.ipynb) (https://github.com/cpjobling/eg-247-textbook/blob/master/content/fourier_transform/3/ft3.ipynb).
- You can view the notes for this presentation as a webpage ([HTML](https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3.html) (https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3.html)).
- This page is downloadable as a [PDF](https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3.pdf) (https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3.pdf) file.

In this section we will apply what we have learned about Fourier transforms to some typical circuit problems. After a short introduction, the body of this chapter will form the basis of an examples class.

Agenda

- The system function
- Examples

The System Function

System response from system impulse response

Recall that the convolution integral of a system with impulse response $h(t)$ and input $u(t)$ is

$$h(t) * u(t) = \int_{-\infty}^{\infty} h(t - \tau)u(\tau) d\tau.$$

We let

$$g(t) = h(t) * u(t)$$

Then by the time convolution property

$$h(t) * u(t) = g(t) \Leftrightarrow G(\omega) = H(\omega) \cdot U(\omega)$$

The System Function

We call $H(\omega)$ the *system function*.

We note that the system function $H(\omega)$ and the impulse response $h(t)$ form the Fourier transform pair

$$h(t) \Leftrightarrow H(\omega)$$

Obtaining system response

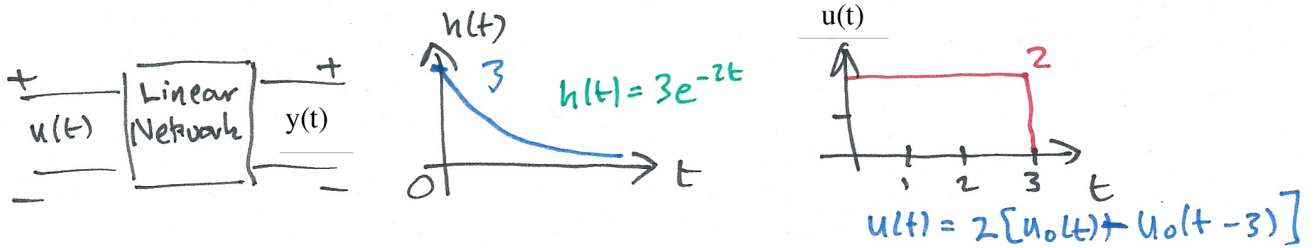
If we know the impulse response $h(t)$, we can compute the system response $g(t)$ of any input $u(t)$ by multiplying the Fourier transforms of $H(\omega)$ and $U(\omega)$ to obtain $G(\omega)$. Then we take the inverse Fourier transform of $G(\omega)$ to obtain the response $g(t)$.

1. Transform $h(t) \rightarrow H(\omega)$
2. Transform $u(t) \rightarrow U(\omega)$
3. Compute $G(\omega) = H(\omega) \cdot U(\omega)$
4. Find $\mathcal{F}^{-1} \{G(\omega)\} \rightarrow g(t)$

Examples

Example 1

Karris example 8.8: for the linear network shown below, the impulse response is $h(t) = 3e^{-2t}$. Use the Fourier transform to compute the response $y(t)$ when the input $u(t) = 2[u_0(t) - u_0(t - 3)]$. Verify the result with MATLAB.



Solution



Matlab verification

In [1]:

```
syms t w
U1 = fourier(2*heaviside(t),t,w)
```

U1 =

$2\pi\text{dirac}(w) - 2i/w$

In [2]:

```
H = fourier(3*exp(-2*t)*heaviside(t),t,w)
```

H =

$3/(2 + w*1i)$

In [3]:

```
Y1=simplify(H*U1)
```

Y1 =

$3\pi\text{dirac}(w) - 6i/(w*(2 + w*1i))$

In [4]:

```
y1 = simplify(ifourier(Y1,w,t))
```

y1 =

$(3\exp(-2*t)*(\text{sign}(t) + 1)*(\exp(2*t) - 1))/2$

Get y2

Substitute $t - 3$ into t .

In [5]:

```
y2 = subs(y1,t,t-3)
```

y2 =

```
(3*exp(6 - 2*t)*(sign(t - 3) + 1)*(exp(2*t - 6) -  
1))/2
```

In [6]:

```
y = y1 - y2
```

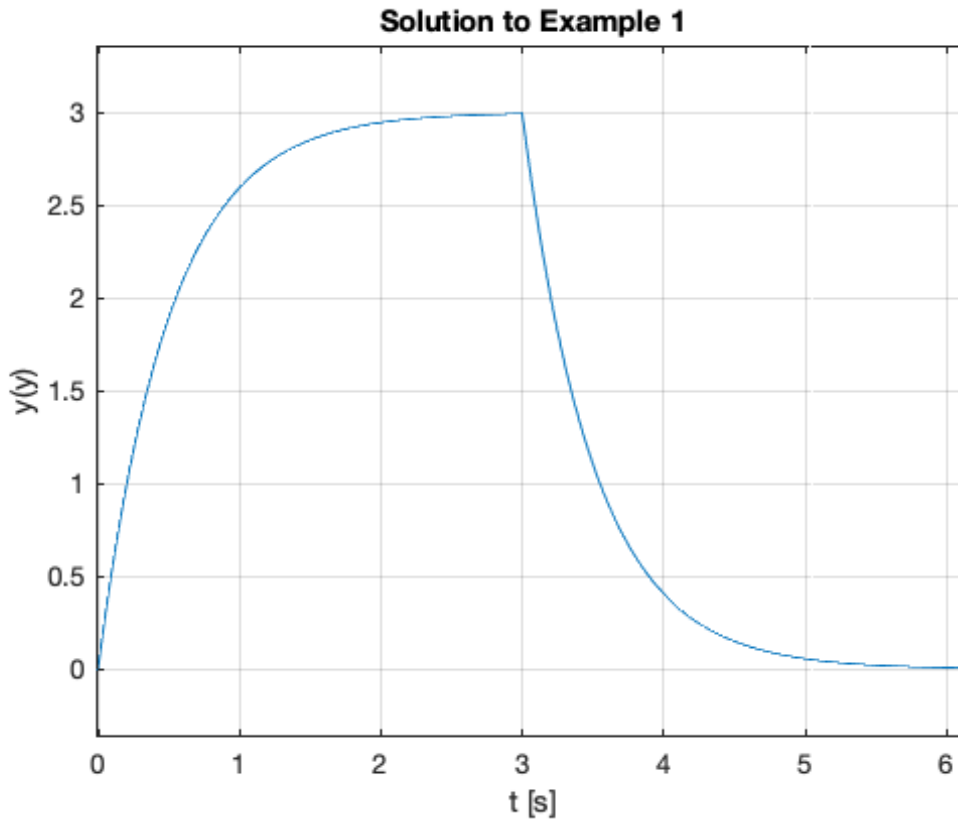
y =

```
(3*exp(-2*t)*(sign(t) + 1)*(exp(2*t) - 1))/2 - (3*  
exp(6 - 2*t)*(sign(t - 3) + 1)*(exp(2*t - 6) - 1))  
/2
```

Plot result

In [7]:

```
ezplot(y)
title('Solution to Example 1')
ylabel('y(t)')
xlabel('t [s]')
grid
```



See [ft3_ex1.m](https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3_ex1.m) (https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3_ex1.m)

Result is equivalent to:

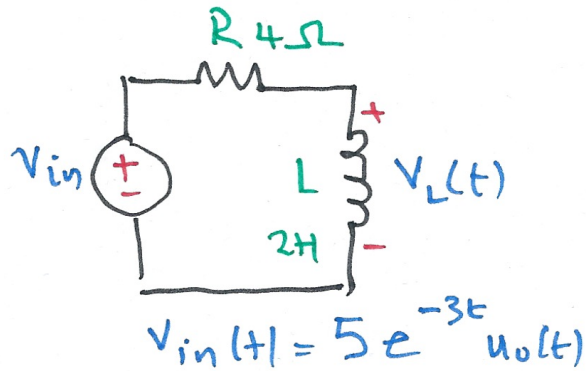
$$y = 3*\text{heaviside}(t) - 3*\text{heaviside}(t - 3) + 3*\text{heaviside}(t - 3)*\exp(6 - 2*t) - 3*\exp(-2*t)*\text{heaviside}(t)$$

Which after gathering terms gives

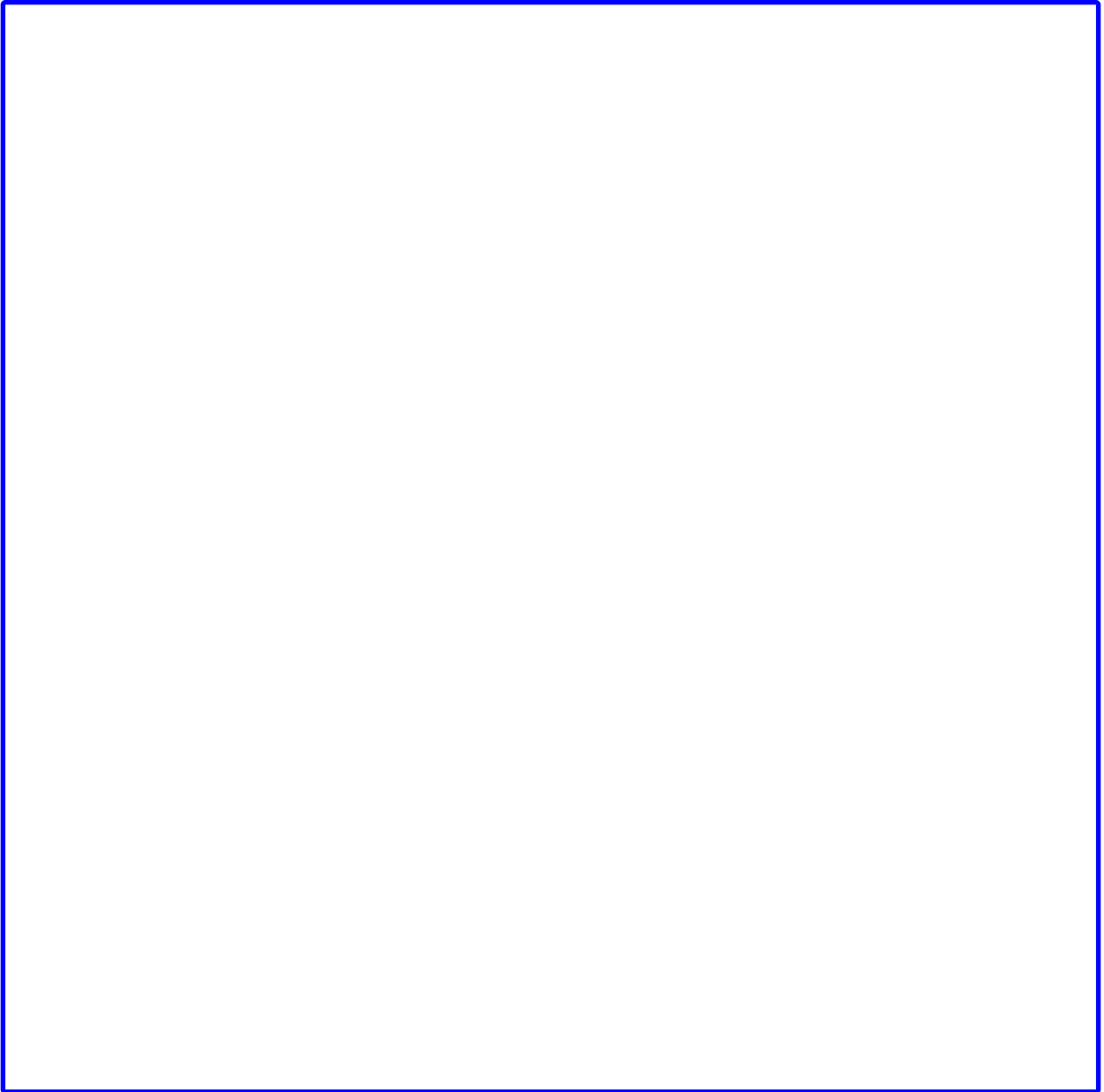
$$y(t) = 3(1 - 3e^{-2t})u_0(t) - 3(1 - 3e^{-2(t-3)})u_0(t - 3)$$

Example 2

Karris example 8.9: for the circuit shown below, use the Fourier transform method, and the system function $H(\omega)$ to compute $V_L(t)$. Assume $i_L(0^-) = 0$. Verify the result with Matlab.



Solution



Matlab verification

In [8]:

```
syms t w
H = j*w/(j*w + 2)
```

H =

$$(w*1i)/(2 + w*1i)$$

In [9]:

```
Vin = fourier(5*exp(-3*t)*heaviside(t),t,w)
```

Vin =

$$5/(3 + w*1i)$$

In [10]:

```
Vout=simplify(H*Vin)
```

Vout =

$$(w*5i)/((2 + w*1i)*(3 + w*1i))$$

In [11]:

```
vout = simplify(ifourier(Vout,w,t))
```

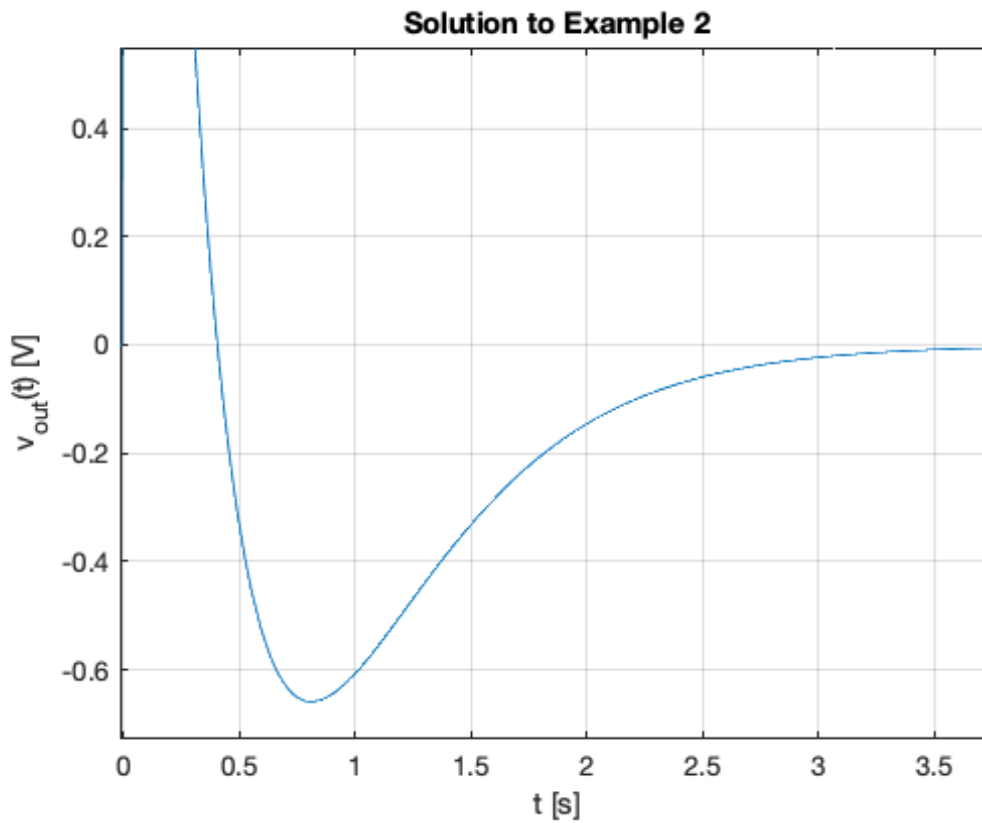
vout =

$$-(5*\exp(-3*t)*(sign(t) + 1)*(2*\exp(t) - 3))/2$$

Plot result

In [12]:

```
ezplot(vout)
title('Solution to Example 2')
ylabel('v_{out}(t) [V]')
xlabel('t [s]')
grid
```



See [ft3_ex2.m](https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3_ex2.m) (https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3_ex2.m).

Result is equivalent to:

$$v_{out} = -5 \cdot \exp(-3 \cdot t) \cdot \text{heaviside}(t) \cdot (2 \cdot \exp(t) - 3)$$

Which after gathering terms gives

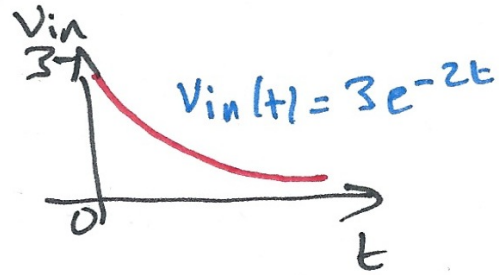
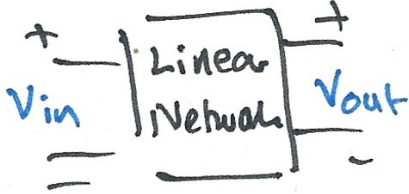
$$v_{out} = 5 \left(3e^{-3t} - 2e^{-2t} \right) u_0(t)$$

Example 3

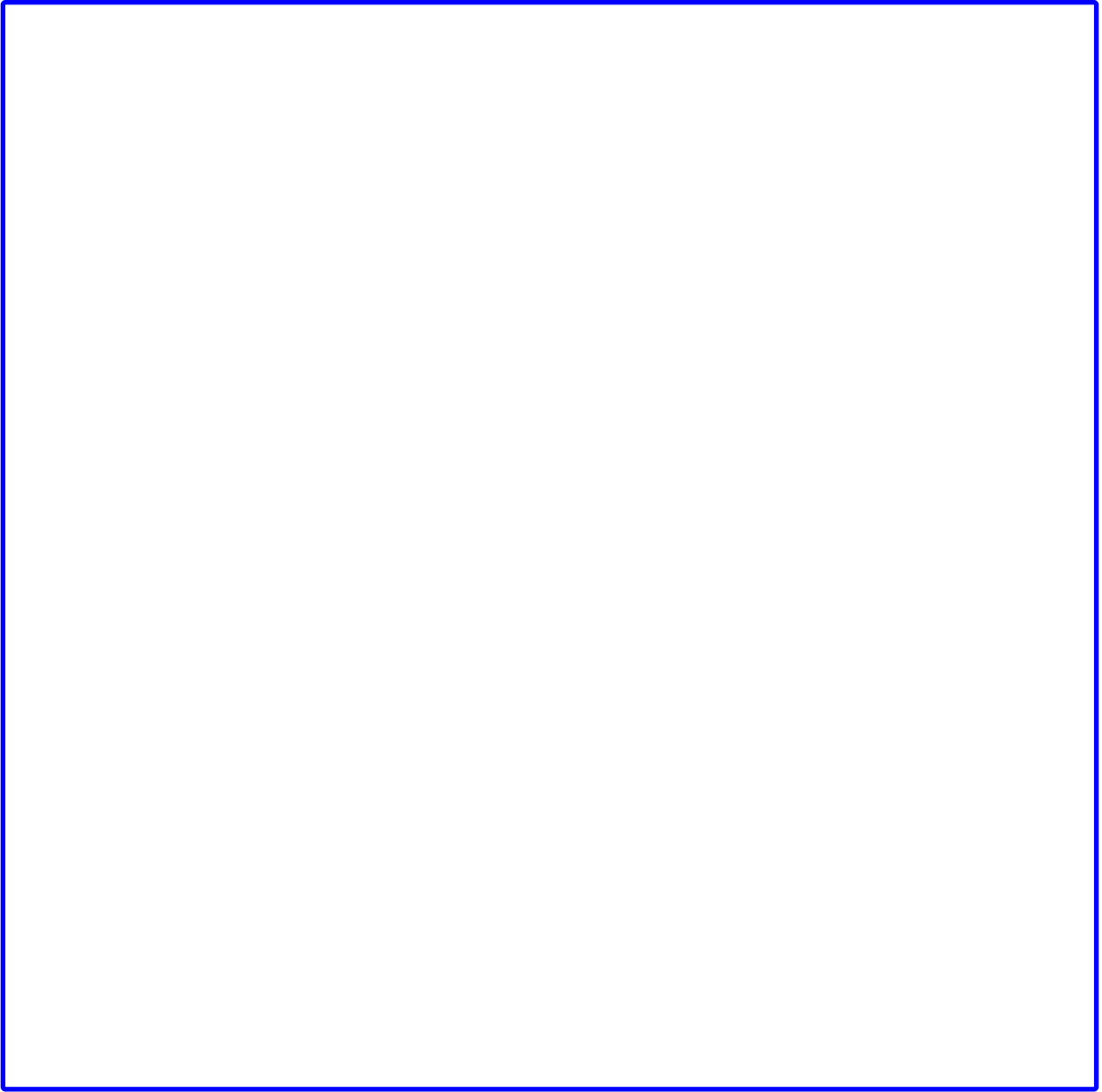
Karris example 8.10: for the linear network shown below, the input-output relationship is:

$$\frac{d}{dt}v_{\text{out}} + 4v_{\text{out}} = 10v_{\text{in}}$$

where $v_{\text{in}} = 3e^{-2t}$. Use the Fourier transform method, and the system function $H(\omega)$ to compute the output v_{out} . Verify the result with Matlab.



Solution



Matlab verification

In [13]:

```
syms t w
H = 10/(j*w + 4)
```

H =

$$10/(4 + w*1i)$$

In [14]:

```
Vin = fourier(3*exp(-2*t)*heaviside(t),t,w)
```

Vin =

$$3/(2 + w*1i)$$

In [15]:

```
Vout=simplify(H*Vin)
```

Vout =

$$30/((2 + w*1i)*(4 + w*1i))$$

In [16]:

```
vout = simplify(ifourier(Vout,w,t))
```

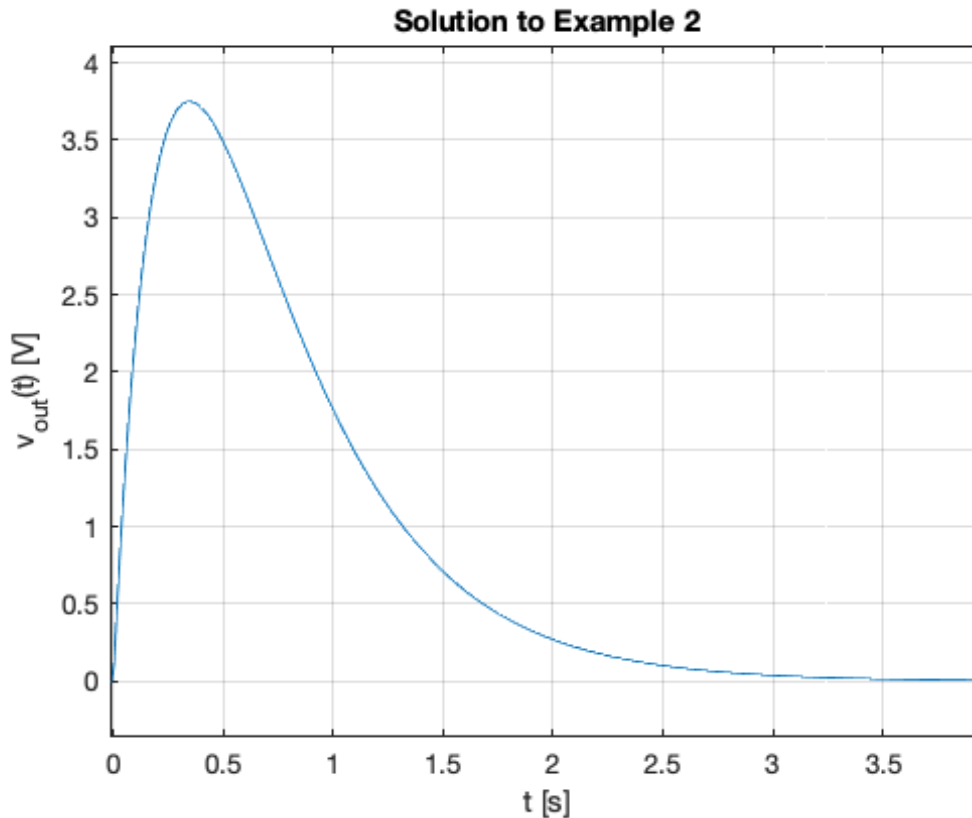
vout =

$$(15*\exp(-4*t)*(sign(t) + 1)*(exp(2*t) - 1))/2$$

Plot result

In [17]:

```
ezplot(vout)
title('Solution to Example 2')
ylabel('v_{out}(t) [V]')
xlabel('t [s]')
grid
```



See [ft3_ex3.m](https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3/ft3_ex3.m) (https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3/ft3_ex3.m).

Result is equivalent to:

$$15 \cdot \exp(-4 \cdot t) \cdot \text{heaviside}(t) \cdot (\exp(2 \cdot t) - 1)$$

Which after gathering terms gives

$$v_{out}(t) = 15 \left(e^{-2t} - e^{-4t} \right) u_0(t)$$

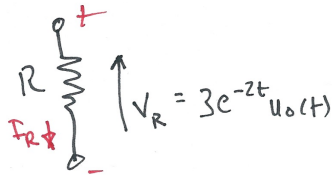
Example 4

Karris example 8.11: the voltage across a $1\ \Omega$ resistor is known to be

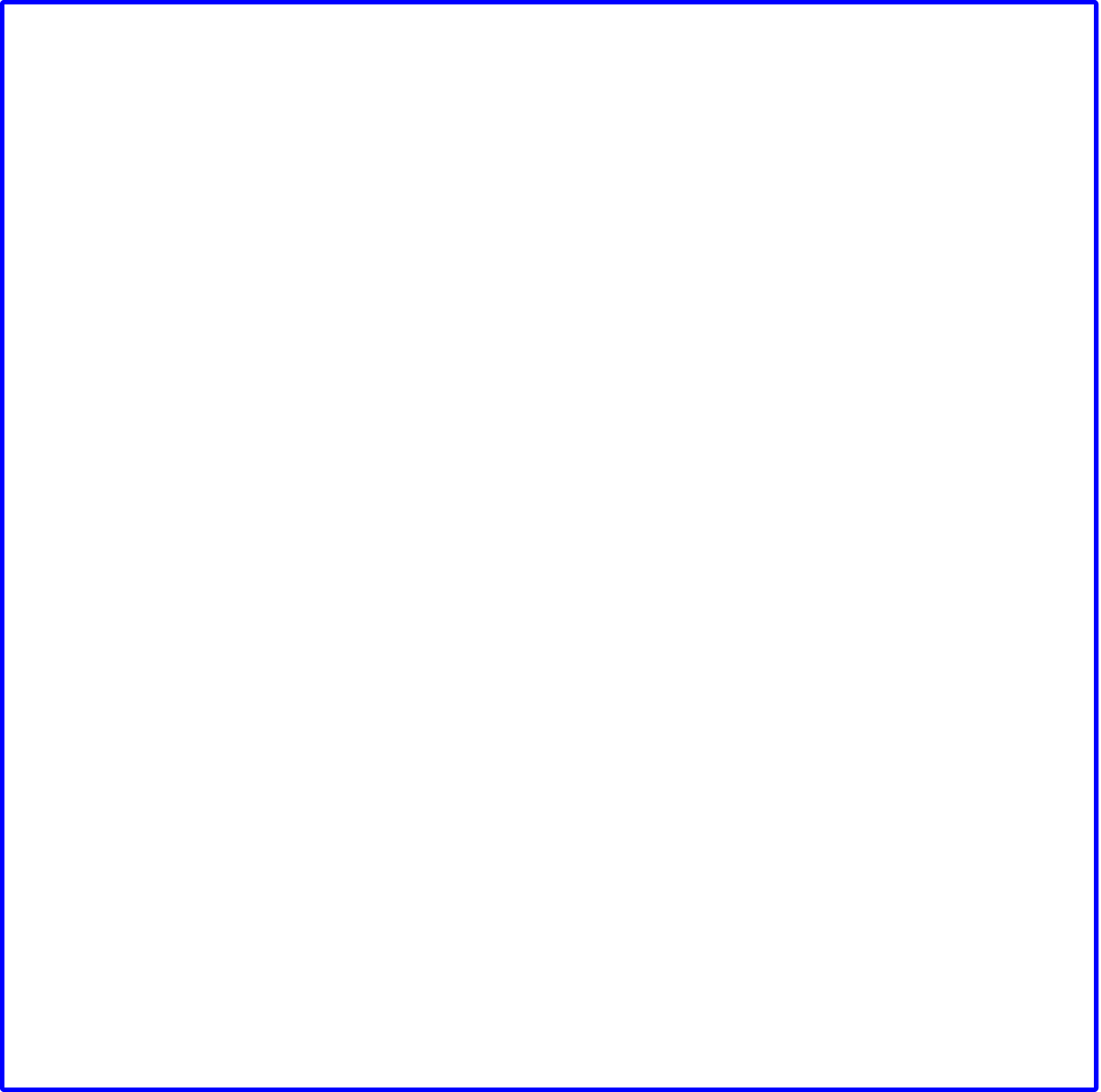
$V_R(t) = 3e^{-2t}u_0(t)$. Compute the energy dissipated in the resistor for $0 < t < \infty$, and verify the result using Parseval's theorem. Verify the result with Matlab.

Note from [tables of integrals \(http://en.wikipedia.org/wiki/Lists_of_integrals\)](http://en.wikipedia.org/wiki/Lists_of_integrals)

$$\int \frac{1}{a^2 + x^2} dx = \frac{1}{a} \arctan \frac{x}{a} + C.$$



Solution



Matlab verification

In [18]:

```
syms t w
```

Calcuete energy from time function

In [19]:

```
Vr = 3*exp(-2*t)*heaviside(t);  
R = 1;  
Pr = Vr^2/R  
Wr = int(Pr,t,0,inf)
```

Pr =

$9\exp(-4t)\text{heaviside}(t)^2$

Wr =

$9/4$

Calculate using Parseval's theorem

In [20]:

```
Fw = fourier(Vr,t,w)
```

Fw =

$3/(2 + w*1i)$

In [21]:

```
Fw2 = simplify(abs(Fw)^2)
```

Fw2 =

$9/\text{abs}(2 + w*1i)^2$

In [22]:

```
Wr=2/(2*pi)*int(Fw2,w,0,inf)
```

Wr =

(51607450253003931*pi)/72057594037927936

See [ft3_ex4.m \(https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3/ft3_ex4.m\)](https://cpjobling.github.io/eg-247-textbook/fourier_transform/3/ft3/ft3_ex4.m)

Solutions

- Example 1: [ft3-ex1.pdf \(https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex1.pdf\)](https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex1.pdf)
- Example 2: [ft3-ex2.pdf \(https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex2.pdf\)](https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex2.pdf)
- Example 3: [ft3-ex3.pdf \(https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex4.pdf\)](https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex4.pdf)
- Example 3: [ft3-ex4.pdf \(https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex4.pdf\)](https://cpjobling.github.io/eg-247-textbook/fourier_transform/solutions/ft3-ex4.pdf)