Sustainable Systems: Power Electronics Issues

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Background

Power electronics is not only an enabling technology for sustainable energy systems, but it also motivates a re-examination of the fundamental analytical framework - **circuitry and theory**.

A dynamic interplay among theory, laboratory experiment and industrial practice.

Emphasis on faster phenomena - harmonics, EMI, **transients**.

Merging of established fields - instrumentation, protection, control.

Functions in a power electronic converter

Main converter functions: **1.** Switching - abrupt changes in the energy flow,
2. Conduction - enables the energy flow,,
3. Storage - compensates for variations in the energy flow,
4. Control - oversees the first three functions and interfaces with the environment.

A technological invariant - product of power and the switching frequency is (approximately) constant for a switch technology (Ge, Si, SiC)

Power Switches Today

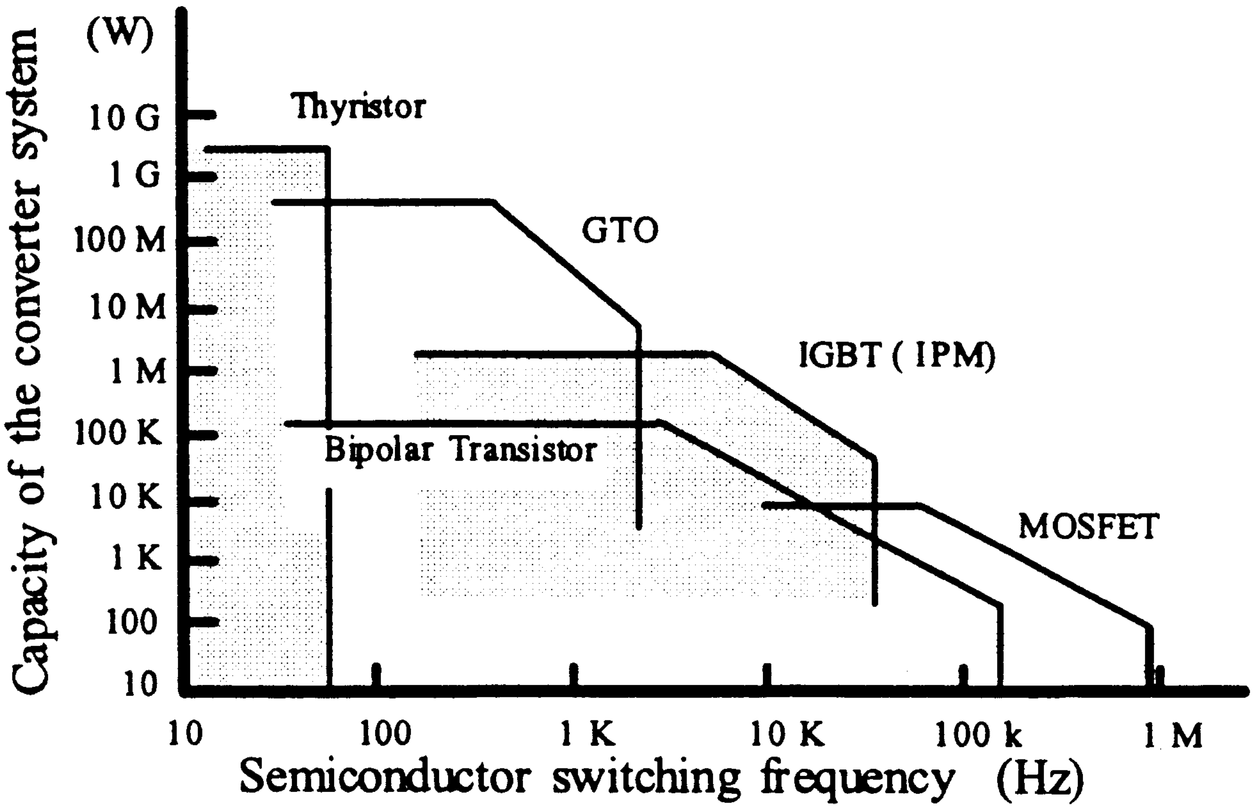


Figure 1: Semiconductor switches today [Uchida, Yamada 2000].

Basic Inverter Topology

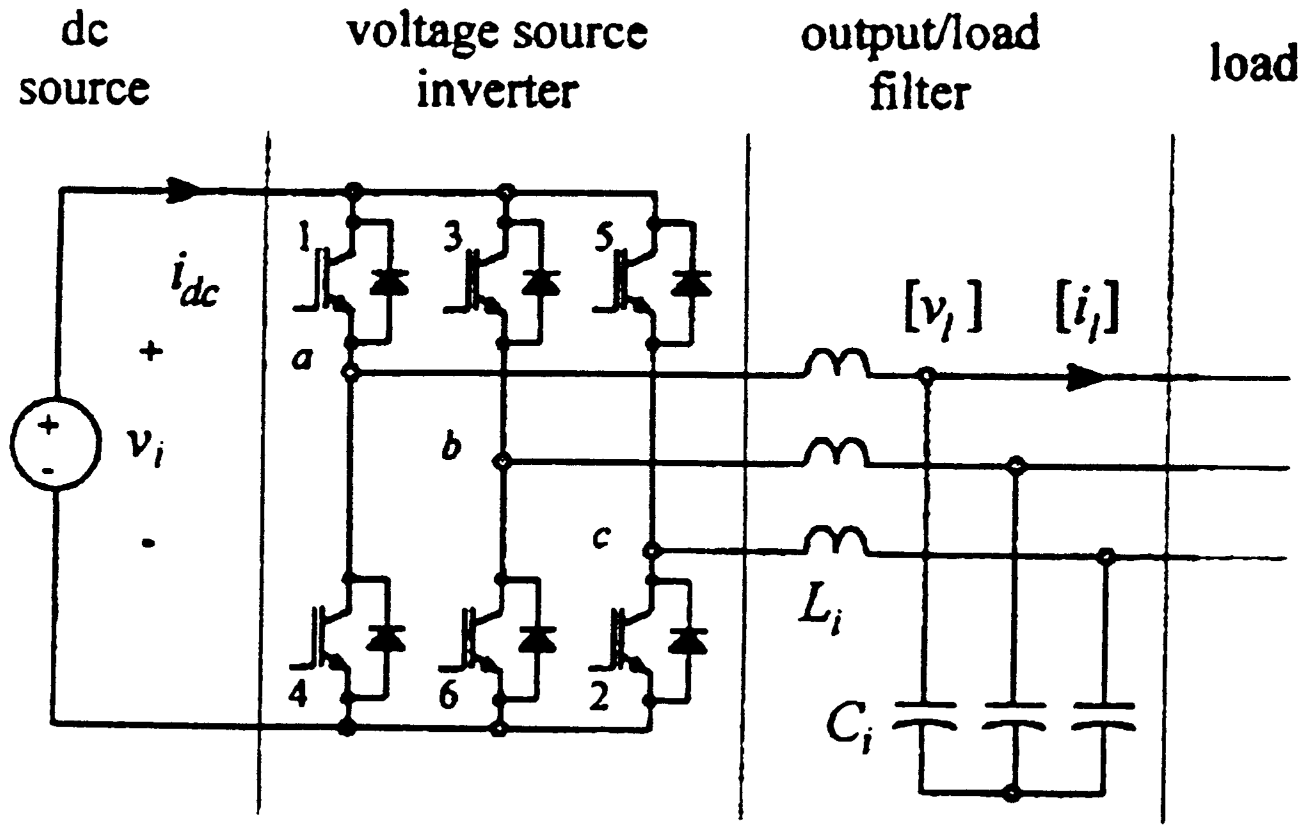


Figure 2: Basic inverter topology - voltage sourced inverter [Espinoza et al. 1999].

Industrial Concerns

Packaging is essential for cost reduction.

Simplified topologies and increased product integration at the low end.

Emerging concerns:

1. Emissions: electromagnetic, acoustic, thermal;
2. Material take-back.

System Integration

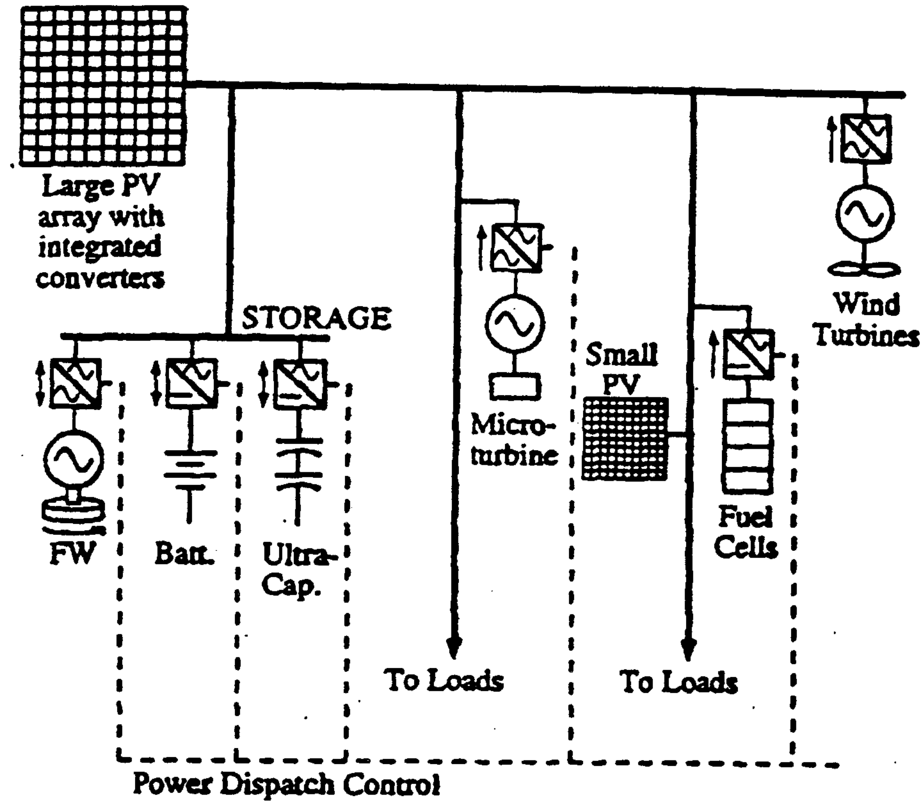


Figure 3: Distributed generation - a new energy supply framework [Divan,Brumsickle 1999]

Power Electronics and Wind Energy

Various degrees of utilization of power electronics are possible in sustainable energy sources - e.g., wind:

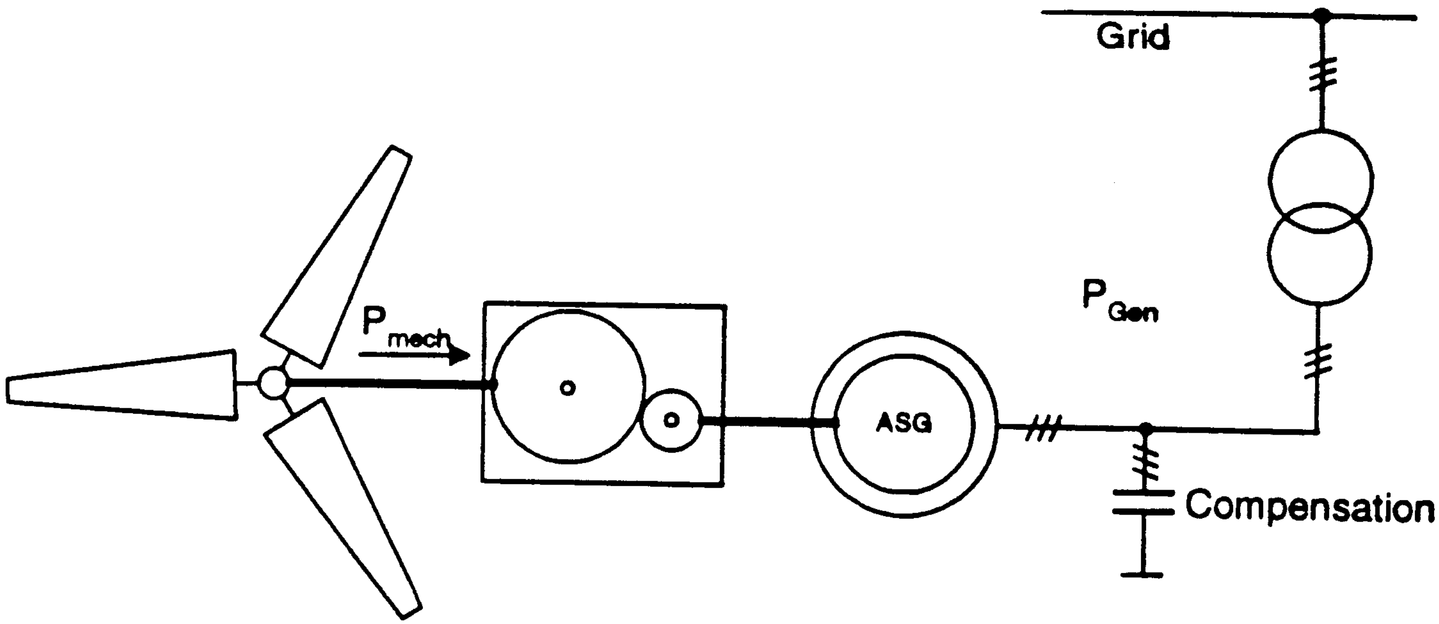


Figure 4: Danish concept [Muller et al., 2000].

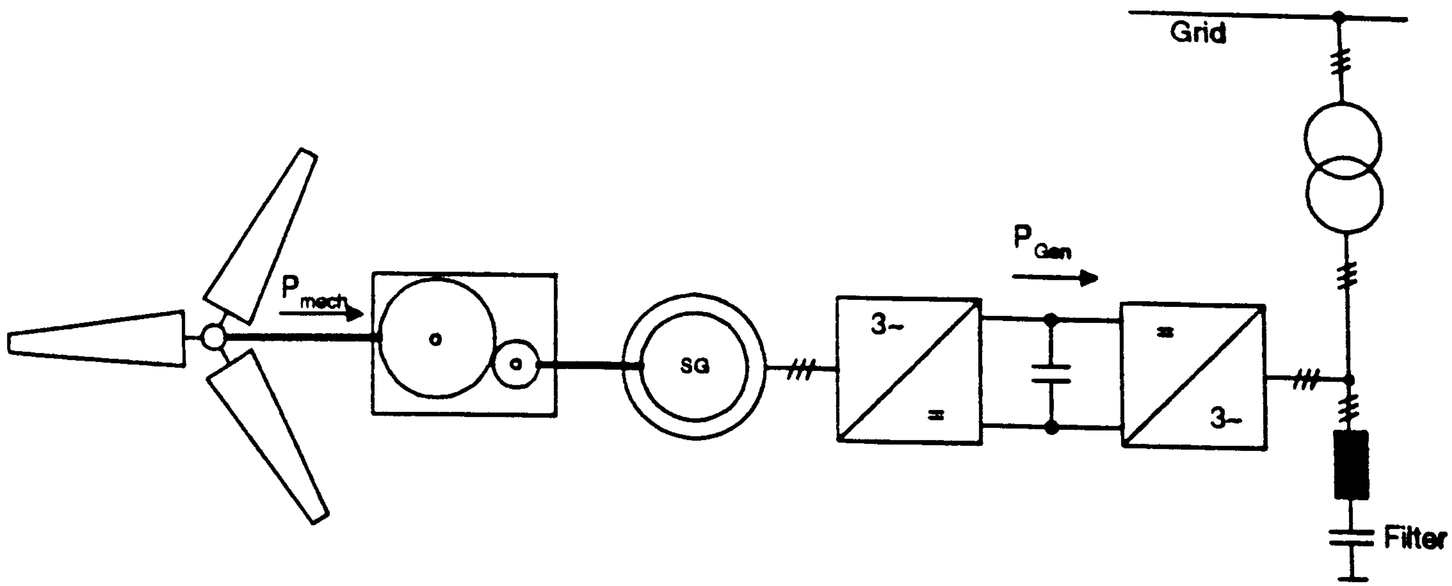


Figure 5: In-line solution.

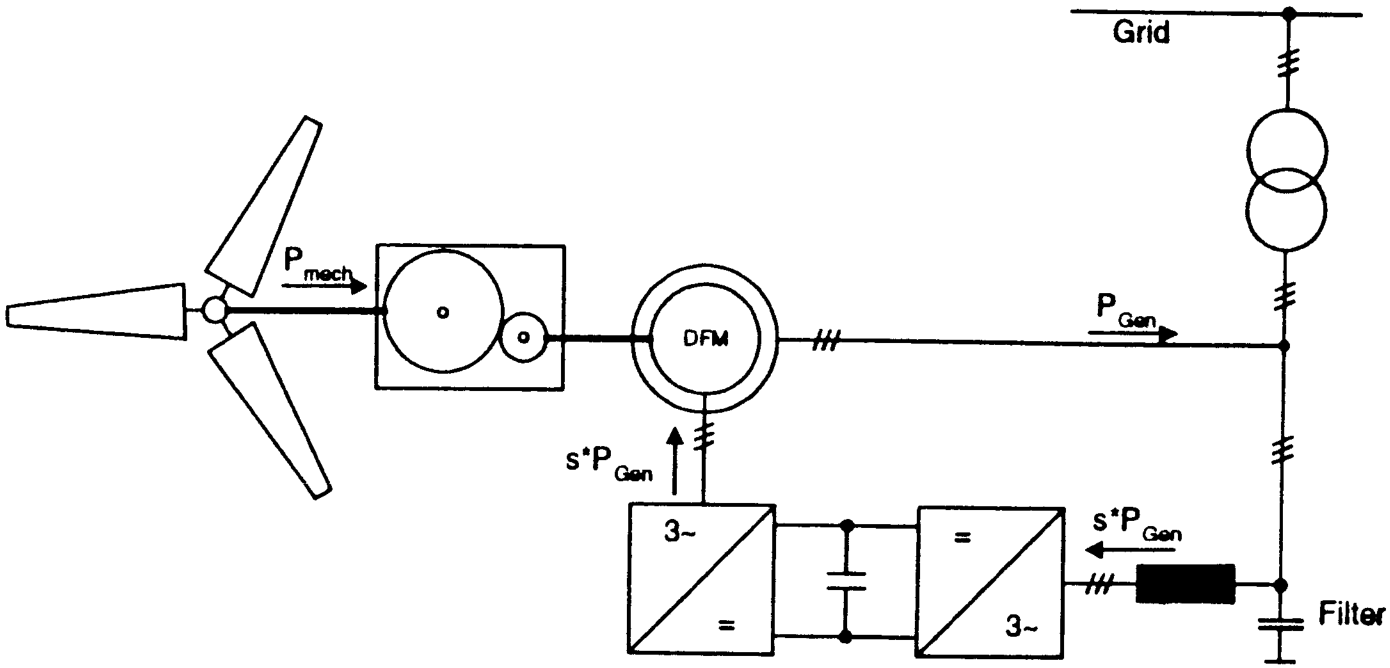
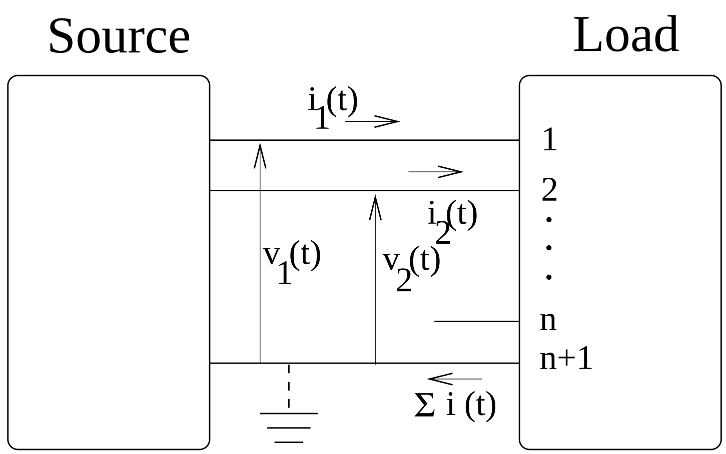


Figure 6: Doubly-fed induction machine.

Theory - compensation of inactive power

Vector waveforms (e.g. voltages, currents) $x(t)$ are T-periodic; fundamental frequency is $\omega = {}^{2\pi}/_{T}$; **no** limit on the number of harmonics.



The ℓ-th harmonic (vector) is

$$< x >_\ell = \frac{1}{T} \int_T x(t) e^{-j\ell\omega t} dt \tag{1}$$

Collective rms quantities $\|x\|^2 = < x^\top x >_0$.

Time-domain definitions, ctd. 1

The *instantaneous power* is

$$p(t) = v(t)^\top i(t) \tag{2}$$

The *instantaneous* projection of $i(t)$ onto the subspace spanned by $v(t)$ is defined to be the *active current* $i_a(t)$ [Depenbrock(1964), Akagi(1983), Willems(1992)]:

$$i_a(t) = \frac{i(t)^\top v(t)}{v(t)^\top v(t)} v(t) = \frac{p(t)}{v(t)^\top v(t)} v(t) \tag{3}$$

The *inactive current* $i_x(t)$

$$i_x(t) = i(t) - i_a(t) \tag{4}$$

i_x is orthogonal to i_a (and v) at any time instant; consequently $p(t) = v(t)^\top i(t) = v(t)^\top i_a(t)$.

Time-domain definitions, ctd. 2

A different notion of active current is due to Fryze (1931):

$$i_{act}(t) = \frac{< p(t) >_0}{\|v\|^2} v(t) = \frac{< p(t) >_0}{< v(t)^\top v(t) >_0} v(t) \tag{5}$$

In circuit terms:

- $i_a(t)$ is the smallest current (by rms) that supplies the same $p(t)$ as the load current $i(t)$,

- $i_{act}(t)$ is the smallest current (by rms) that supplies the same **dc component** $< p(t) >_0$ of $p(t)$ as the load current $i(t)$.

Example

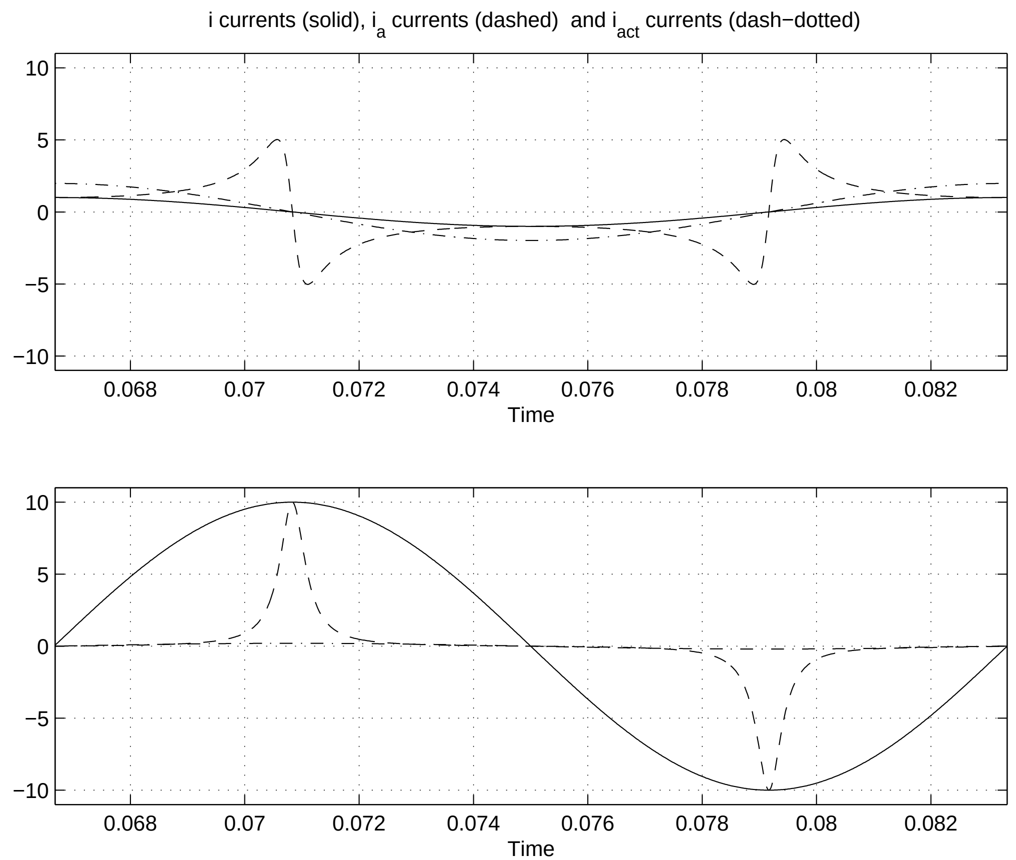
Consider a *resistive* two phase circuit with

$$v(t) = \begin{bmatrix} V_1 \cos(\omega t) \\ V_2 \sin(\omega t) \end{bmatrix}, \quad i(t) = \begin{bmatrix} {}^{VI}\!/_{V_1} \cos(\omega t) \\ {}^{VI}\!/_{V_2} \sin(\omega t) \end{bmatrix}$$

We pick $V_1 = 1,\ V_2 = 0.1,\ VI = 1$

Note that both voltages and currents contain **only** the fundamental frequency component.

Example, ctd. 1



Example, ctd. 2

In this example $\|v\|^2 = {(V_1^2+V_2^2)}/{2} = 0.505$, $\|i\|^2 = (VI)^2({1}/{2V_1^2} + {1}/{2V_2^2}) = 50.5$; also

$$i_a(t) = \frac{2VI}{V_1+V_2}\sum_{\ell=0}^{\infty}(-\frac{V_1-V_2}{V_1+V_2})^{\ell}\begin{bmatrix}\cos(2\ell+1)\omega t\\ \sin(2\ell+1)\omega t\end{bmatrix}$$

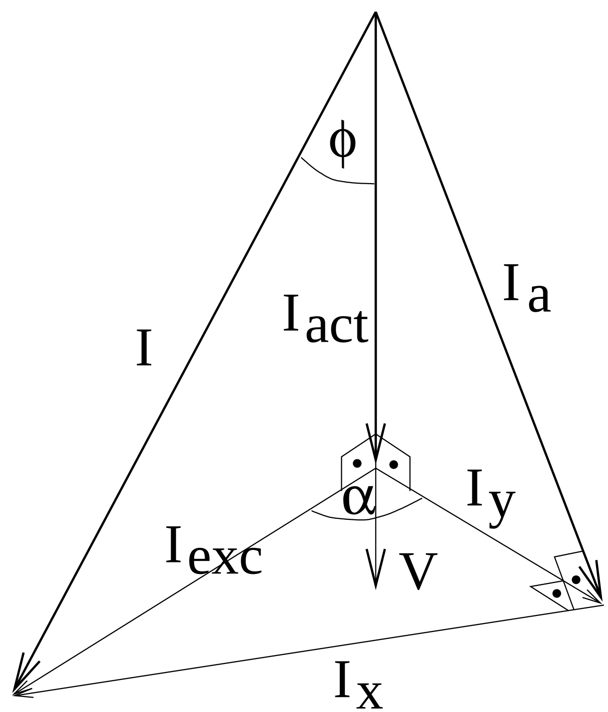
for our numerical values $\|i_a\|^2 = {(VI)^2}/{V_1V_2} = 10$;

$$i_{act}(t) = \frac{2VI}{V_1^2+V_2^2}\begin{bmatrix}V_1\cos(\omega t)\\ V_2\sin(\omega t)\end{bmatrix}$$

and $\|i_{act}\|^2 = {2(VI)^2}/{(V_1^2+V_2^2)} = 1.98$.

Frequency domain results

In the (potentially infinite dimensional Hilbert) space of Fourier coefficients:



We define the inner product of vector signals x and y, with corresponding matrices X and Y, as

$$< x^\top y >_0 = \frac{1}{T}\int_T x(t)^\top y(t) dt = \mathtt{tr}(X^H Y) \quad (6)$$

Dynamic Extensions

A (possibly complex) waveform $x(\cdot)$ can be represented on the interval $(t-T,t]$ using (short-time) Fourier series:

$$x(\tau)=\sum_{k=-\infty}^{\infty} X_k(t)e^{jk\omega_s\tau}$$

where $X_k(t)$ are the complex, slowly time-varying Fourier coefficients, or *dynamic phasors*.

$$X_k(t)=\frac{1}{T}\int_{t-T}^{t} x(\tau)e^{-jk\omega_s\tau}d\tau =< x >_k (t)$$

Our dynamical models describe evolution of $X_k(t)$; for real $x(\cdot)$ we have $X_{-k}=X_k^*$
A useful facts:

$$\frac{dX_k}{dt}=\left\langle \frac{d}{dt}x\right\rangle_k - j\ k\ \omega_s X_k$$

Polyphase Systems in Transients

Dynamic symmetric components - recall $\alpha = e^{j\frac{2\pi}{3}}$,

$$\begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}(\tau) = \sum_{\ell=-\infty}^{\infty} e^{j\ell\omega_s\tau} \underbrace{\frac{1}{\sqrt{3}} \begin{bmatrix} 1 & 1 & 1 \\ \alpha^* & \alpha & 1 \\ \alpha & \alpha^* & 1 \end{bmatrix}}_{\mathcal{M}} \begin{bmatrix} X_{p,\ell} \\ X_{n,\ell} \\ X_{z,\ell} \end{bmatrix}(t)$$

$$\begin{bmatrix} X_{p,\ell} \\ X_{n,\ell} \\ X_{z,\ell} \end{bmatrix}(t) = \frac{1}{T}\int_{t-T}^{t} e^{-j\ell\omega_s\tau}\, \mathcal{M}^H \begin{bmatrix} x_a \\ x_b \\ x_c \end{bmatrix}(\tau)d\tau = \begin{bmatrix} < x >_{p,\ell} \\ < x >_{n,\ell} \\ < x >_{z,\ell} \end{bmatrix}(t).$$

$$\frac{d}{dt}\begin{bmatrix} X_{p,\ell} \\ X_{n,\ell} \\ X_{z,\ell} \end{bmatrix}(t) = \mathcal{M}^H \begin{bmatrix} < {}^{d}\!/\!_{d\tau} x_a(\tau) >_\ell \\ < {}^{d}\!/\!_{d\tau} x_b(\tau) >_\ell \\ < {}^{d}\!/\!_{d\tau} x_c(\tau) >_\ell \end{bmatrix}(t) - j\ell\omega_s \begin{bmatrix} X_{p,\ell} \\ X_{n,\ell} \\ X_{z,\ell} \end{bmatrix}(t)$$

Long Term Vision

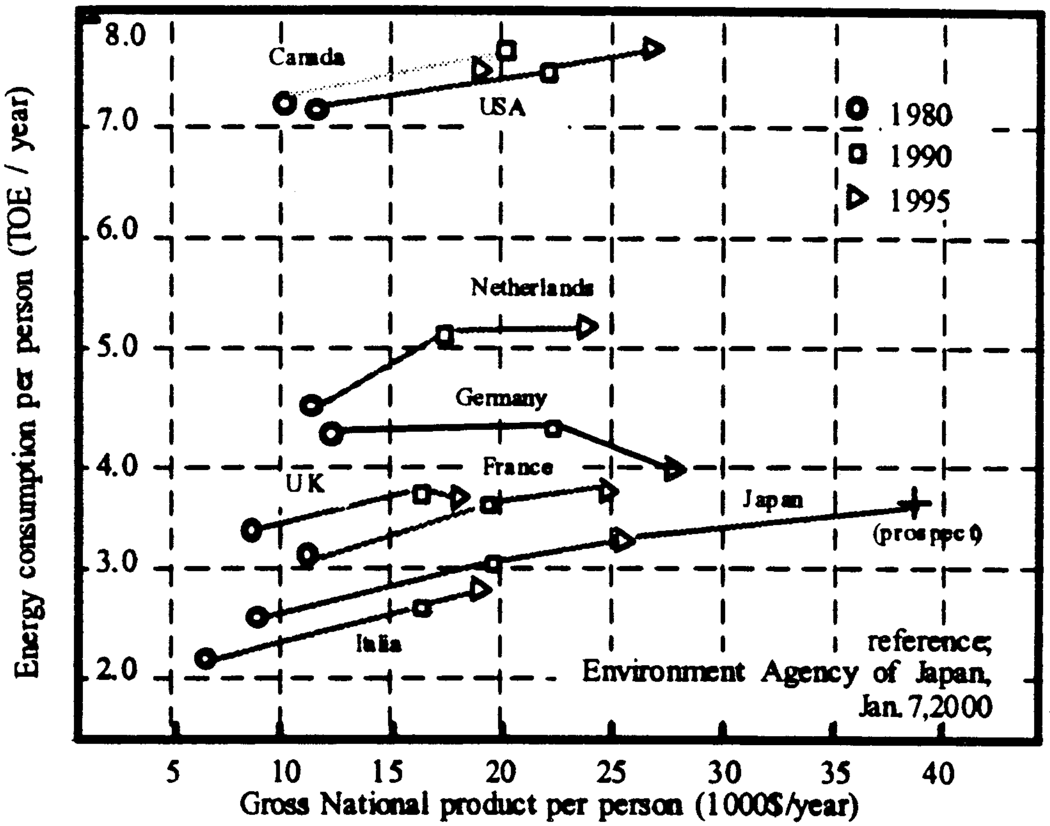


Figure 7: GNP and Energy Consumption [Uchida.Yamada 2000].