Electronic Loads and Interconnected Systems

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Presentation Outline

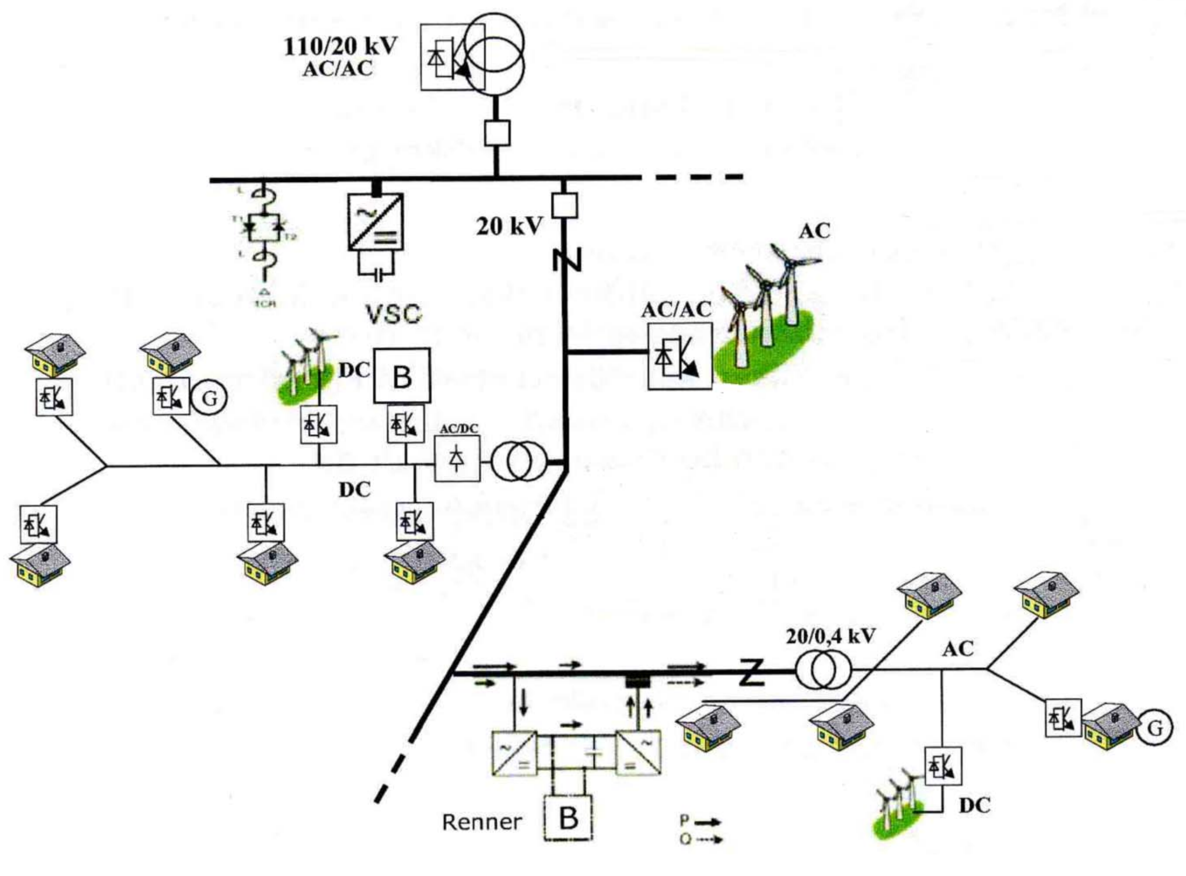
1) Motivation
2) Problems electronic loads may cause
3) Concept of negative incremental resistance
4) Theoretical basis for stability assessment
5) Examples
6) Conclusions

Important to Remember

Theory is the mother of practice !

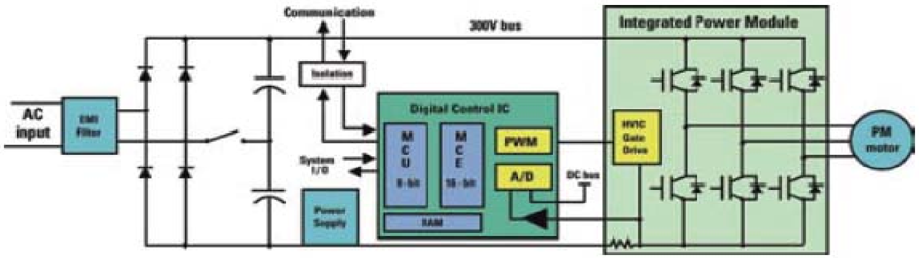
Without theoretical knowledge, the solutions may be wrong even if they seem to work.

Complicated Interconnected Distribution System

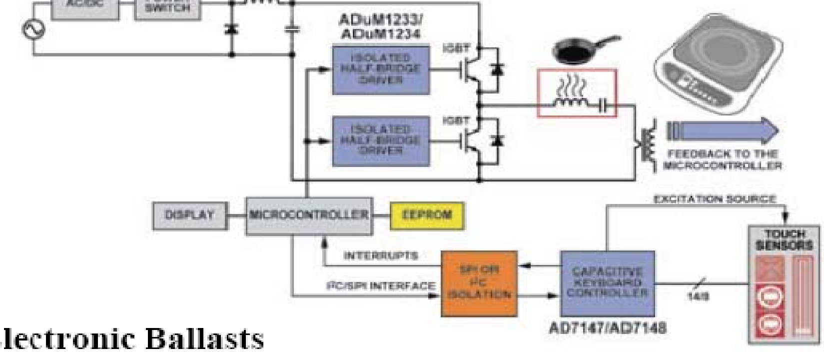


Theme of the day:

White Goods Go Green – Saving Energy in Modern Appliance Design

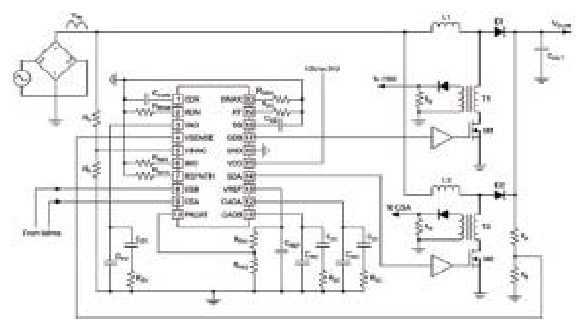


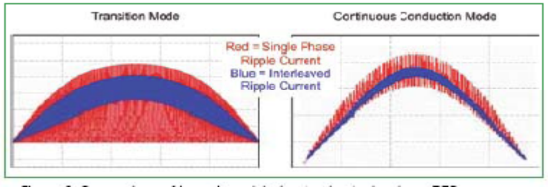
Cooking Inductively



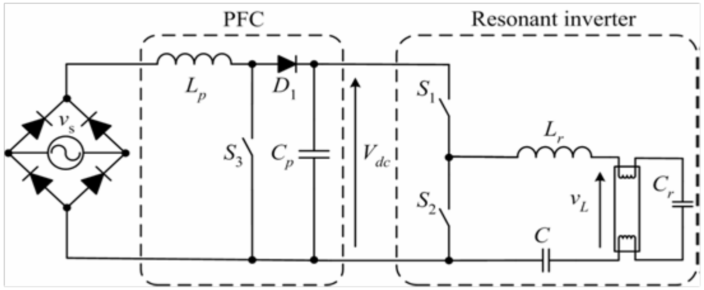
Powering White Goods

Interleaved power factor correction for motors and appliances





Electronic Ballasts



What are the problems with electronic loads ? 1

• High inrush currents due to input capacitors when the line voltage is applied due to lack of proper limiting devices. A peak of 200 A or more is measured.

• High high-frequency ripple currents (< 150 kHz) due to lack of sufficient EMI filtering and EMC standards. In the case of multiple electronic loads there appear also beat frequencies i.e., sums and differences of the individual switching frequencies of the load devices.

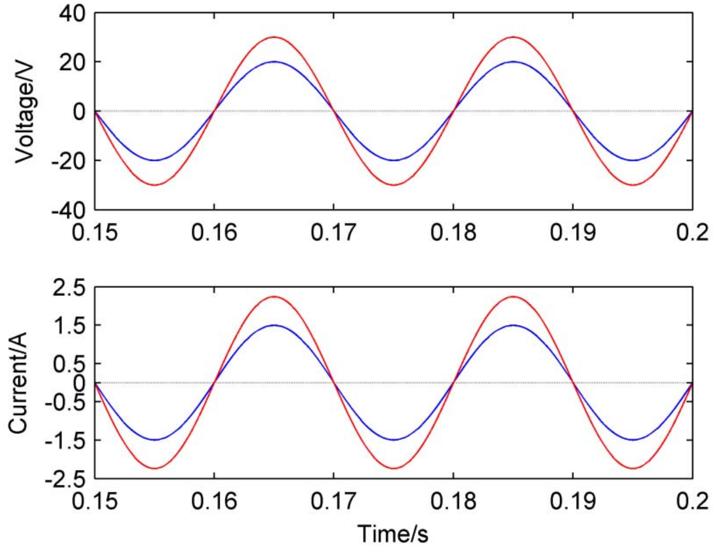
What are the problems with electronic loads ? 2

- Usually input voltage range is universal, i.e., the operation range 90 V_{rms} – 270 V_{rms} in terms of phase voltage. This will cause excess current demand during the voltage sags.

- Instabilities due to the input impedances of the electronic loads, which resemble in dynamic sense a negative incremental resistor at least at low frequencies. The negative incremental resistance eats the damping in the network and may result in instability and/or high resonant currents.

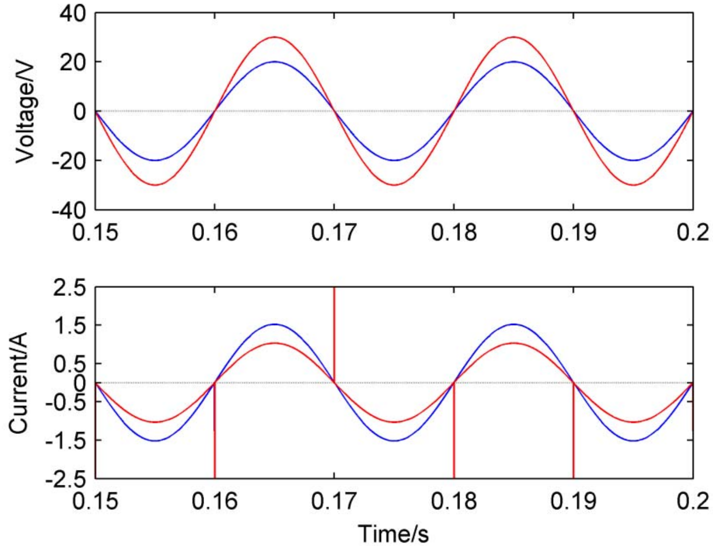
What is a negative incremental resistor ?

Resistive or passive load



voltage □ □ → current □ □

Electronic load = Constant-power load



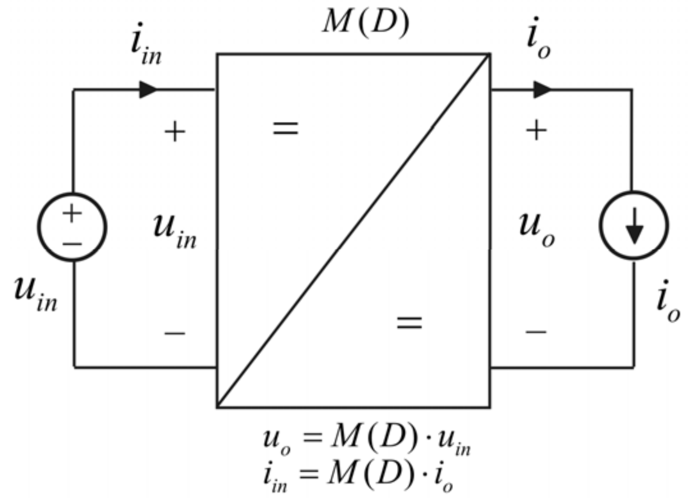
voltage □ □ → current □ □

This is a telltale sign of the existence of negative-incremental-resistance behaviour

Negative incremental resistor ??

As a consequence, the input power
$p_{in} = P_{in} = P_o / \eta$

Usually the input current of the electronic load is in phase with the input voltage. As a consequence, $P_{in} = u_{in} i_{in}$ and $i_{in} = \dfrac{P_o / \eta}{u_{in}}$.

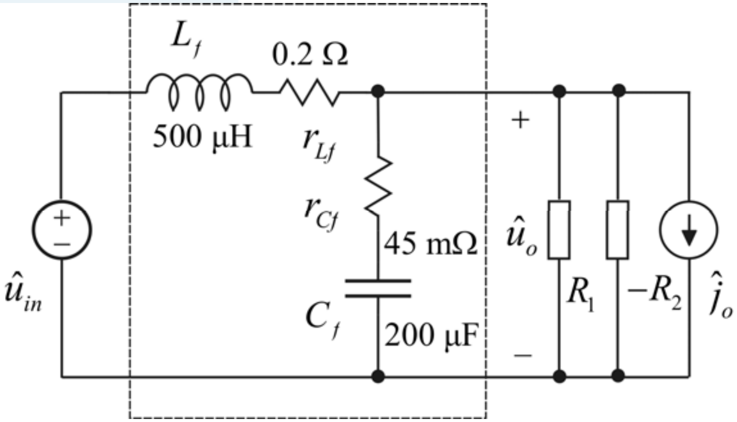


The feedback controller maintains the output voltage constant at the predefined value
$u_o = U_o \rightarrow p_o = P_o$

Dynamically, the behaviour of the input means that

$\hat{i}_{in} = -\dfrac{P_o / \eta}{U_{in}^2} \cdot \hat{u}_{in}$, where $i_{in} = \dfrac{P_o / \eta}{u_{in}}$ has been linearized by developing the proper partial derivatives at a defined operating point. $-\dfrac{U_{in}^2}{P_o / \eta}$ is known as the negative incremental resistor, because it is independent of frequency and has the phase of 180 deg.

Eats damping ??



$$\hat{u}_o = \frac{\dfrac{R(1+sr_{Cf}C_f)}{LC(R+r_{Cf})}(\hat{u}_{in}-(r_{Lf}+sL_f)\hat{j}_o)}{s^2+s\cdot\dfrac{(R(r_{Cf}+r_{Lf})+r_{Cf}r_{Lf})C_f+L_f}{L_fC_f(R+r_{Cf})}+\dfrac{R+r_{Lf}}{L_fC_f(R+r_{Cf})}}$$

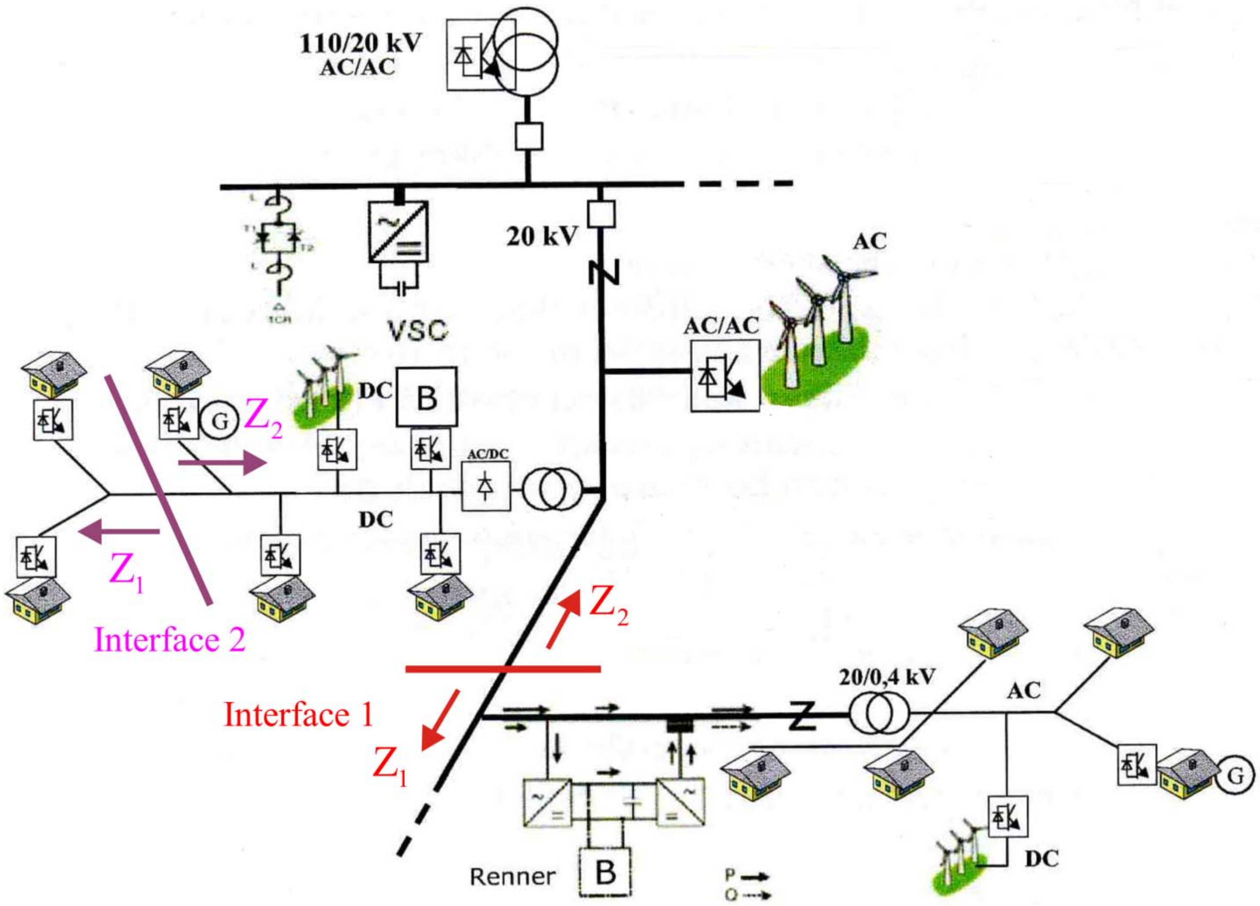
$$2\zeta\omega_n, \frac{\omega_n}{Q} \qquad\qquad \omega_n^2$$

where ζ is the damping factor, ω_n the resonant frequency, Q quality factor, $s = j\omega$ and $R = R_1 \parallel (-R_2)$. The system starts oscillating when $\zeta = 0$ or $Q = \infty$.

$$\rightarrow (R(r_{Cf}+r_{Lf})+r_{Cf}r_{Lf})C_f+L_f = 0$$

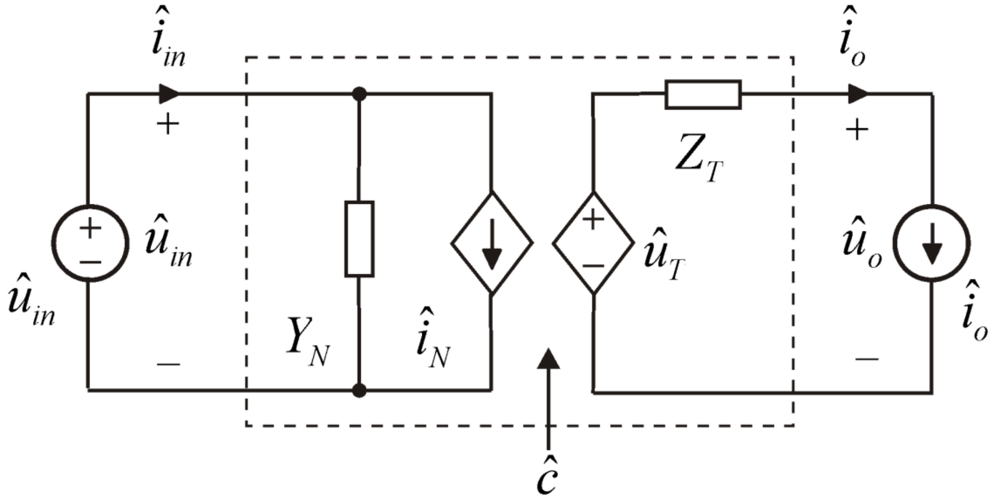
$$\rightarrow R+\frac{r_{Cf}r_{Lf}+\dfrac{L_f}{C_f}}{r_{Cf}+r_{Lf}} = 0 \rightarrow R = -\frac{r_{Cf}r_{Lf}+\dfrac{L_f}{C_f}}{r_{Cf}+r_{Lf}} \rightarrow \frac{1}{R_2} = \frac{1}{R_1}-\frac{r_{Cf}+r_{Lf}}{r_{Cf}r_{Lf}+\dfrac{L_f}{C_f}} = \frac{1}{R_1}-0.1\ \Omega^{-1}$$

How to Assess Stability ?



Voltage-Input-Voltage-Output System

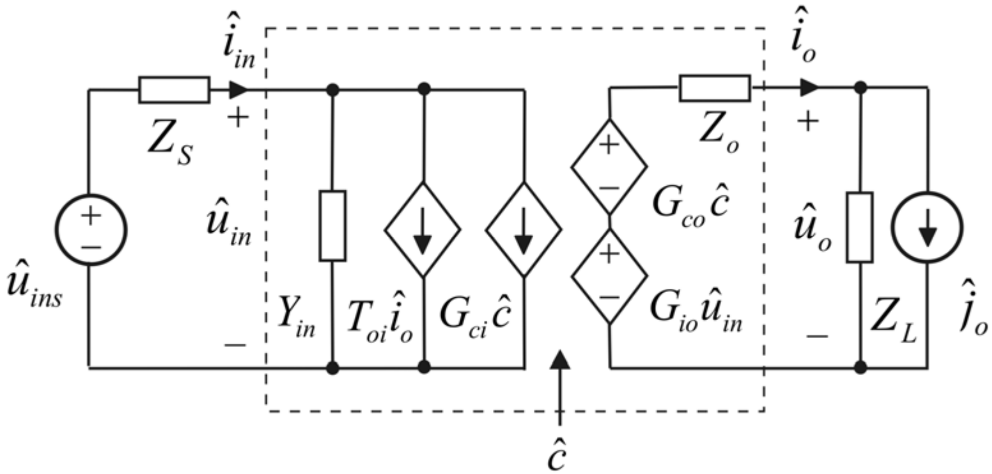
Two-Port Network with G-parameters



Matrix Form

$$\begin{bmatrix} \hat{i}_{in} \\ \hat{u}_o \end{bmatrix} = \begin{bmatrix} Y_{in} & T_{oi} & G_{ci} \\ G_{io} & -Z_o & G_{co} \end{bmatrix} \begin{bmatrix} \hat{u}_{in} \\ \hat{i}_o \\ \hat{c} \end{bmatrix}$$

Load and Source Effects 1



Load Effect

$$\begin{bmatrix}\hat{i}_{in}\\ \hat{u}_o\end{bmatrix} = \mathbf{A}\begin{bmatrix}\hat{u}_{in}\\ \hat{j}_o\\ \hat{c}\end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} Y_{in} + \dfrac{G_{io}T_{oi}}{Z_o + Z_L} & \dfrac{Z_L T_{oi}}{Z_o + Z_L} & G_{ci} + \dfrac{G_{co}T_{oi}}{Z_o + Z_L} \\ \dfrac{G_{io}}{1+\dfrac{Z_o}{Z_L}} & -\dfrac{Z_o}{1+\dfrac{Z_o}{Z_L}} & \dfrac{G_{co}}{1+\dfrac{Z_o}{Z_L}} \end{bmatrix}$$

Source Effect

$$\begin{bmatrix}\hat{i}_{in}\\ \hat{u}_o\end{bmatrix} = \mathbf{B}\begin{bmatrix}\hat{u}_{ins}\\ \hat{i}_o\\ \hat{c}\end{bmatrix}$$

$$\mathbf{B} = \begin{bmatrix} \dfrac{Y_{in}}{1+Z_sY_{in}} & \dfrac{T_{oi}}{1+Z_sY_{in}} & \dfrac{G_{ci}}{1+Z_sY_{in}} \\ \dfrac{G_{io}}{1+Z_sY_{in}} & -\dfrac{1+Z_sY_{in-sc}}{1+Z_sY_{in}}Z_o & \dfrac{1+Z_sY_{in-\infty}}{1+Z_sY_{in}}G_{co} \end{bmatrix}$$

$$Y_{in-\infty} = Y_{in-o} - \frac{G_{io-o}G_{ci-o}}{G_{co-o}} \qquad Y_{in-sc} = Y_{in-o} + \frac{G_{io-o}T_{oi-o}}{Z_{o-o}}$$

Load and Source Effects 2

Some conclusions:

If $G_{io} \approx 0$

Source effect

$$\mathbf{B} = \begin{bmatrix} \frac{Y_{in}}{1+Z_s Y_{in}} & \frac{T_{oi}}{1+Z_s Y_{in}} & \frac{G_{ci}}{1+Z_s Y_{in}} \\ 0 & -Z_o & G_{co} \end{bmatrix}$$

Load effect

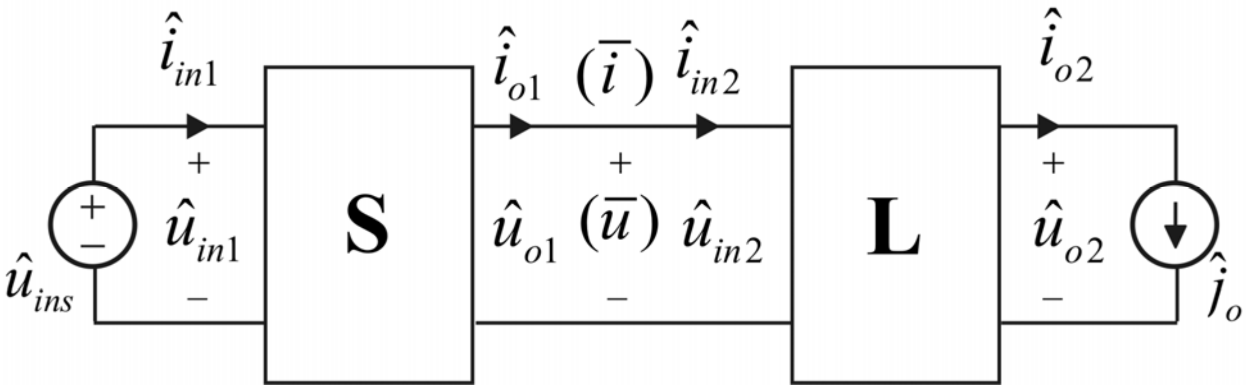
$$\mathbf{A} = \begin{bmatrix} Y_{in} & \frac{Z_L T_{oi}}{Z_o + Z_L} & G_{ci} + \frac{G_{co} T_{oi}}{Z_{o-o} + Z_L} \\ \frac{G_{io}}{1+\frac{Z_o}{Z_L}} & -\frac{Z_o}{1+\frac{Z_o}{Z_L}} & \frac{G_{co}}{1+\frac{Z_o}{Z_L}} \end{bmatrix}$$

If $Z_o \approx 0$

$$\mathbf{B} = \begin{bmatrix} \frac{Y_{in}}{1+Z_s Y_{in}} & \frac{T_{oi}}{1+Z_s Y_{in}} & \frac{G_{ci}}{1+Z_s Y_{in}} \\ \frac{G_{io}}{1+Z_s Y_{in}} & 0 & \frac{1+Z_s Y_{in-\infty}}{1+Z_s Y_{in}} G_{co} \end{bmatrix}$$

$$\mathbf{A} = \begin{bmatrix} Y_{in} + \frac{G_{io} T_{oi}}{Z_L} & T_{oi} & G_{ci} + \frac{G_{co} T_{oi}}{Z_L} \\ G_{io} & 0 & G_{co} \end{bmatrix}$$

Internal & Input-Output Stability 1



$$\begin{bmatrix} \hat{i}_{in1} \\ \bar{u} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} \hat{u}_{in1} \\ \bar{i} \end{bmatrix} \qquad \begin{bmatrix} \bar{i} \\ \hat{u}_{o2} \end{bmatrix} = \begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} \begin{bmatrix} \bar{u} \\ \hat{i}_{o2} \end{bmatrix}$$

Internal & Input-Output Stability 2

Internal Stability

$$\begin{bmatrix} \bar{i} \\ \bar{u} \end{bmatrix} = \begin{bmatrix} \dfrac{S_{21}L_{11}}{1-S_{22}L_{11}} & \dfrac{L_{12}}{1-S_{22}L_{11}} \\ \dfrac{S_{21}}{1-S_{22}L_{11}} & \dfrac{S_{22}L_{12}}{1-S_{22}L_{11}} \end{bmatrix} \begin{bmatrix} \hat{u}_{in1} \\ \hat{i}_{o2} \end{bmatrix}$$

Input-Output Stability

$$\begin{bmatrix} \hat{i}_{in1} \\ \hat{u}_{o2} \end{bmatrix} = \begin{bmatrix} S_{11} + \dfrac{S_{12}S_{21}L_{11}}{1-S_{22}L_{11}} & \dfrac{S_{12}L_{12}}{1-S_{22}L_{11}} \\ \dfrac{S_{21}L_{21}}{1-S_{22}L_{11}} & L_{22} + \dfrac{S_{22}L_{12}L_{21}}{1-S_{22}L_{11}} \end{bmatrix} \begin{bmatrix} \hat{u}_{in1} \\ \hat{i}_{o2} \end{bmatrix}$$

Internal & Input-Output Stability 3

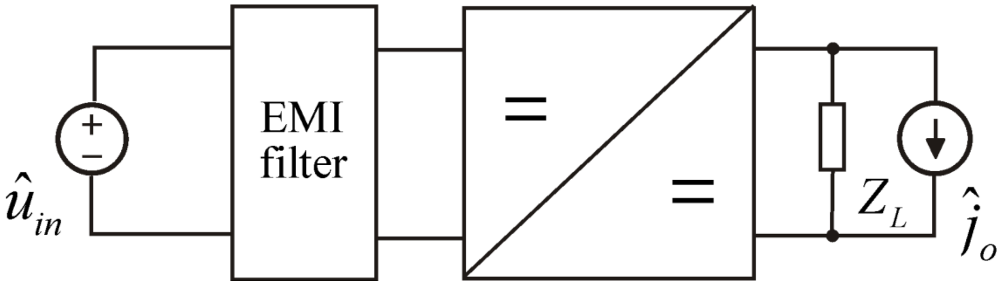
System theory requires that all the transfer functions in the mappings have to be stable for system stability to exist!

Usually the original transfer functions are stable and therefore, the product

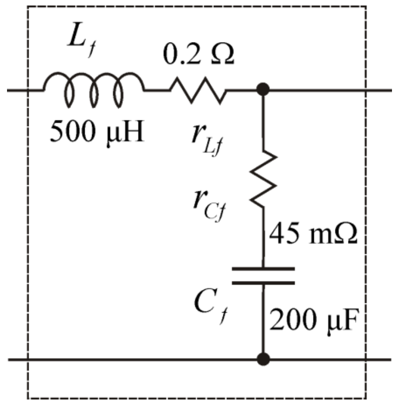
$$-S_{22}L_{11} = Z_o / Z_{in}$$

determines the *internal* and *input-output* stability, which can be assessed by using *Nyquist* stability criterion.

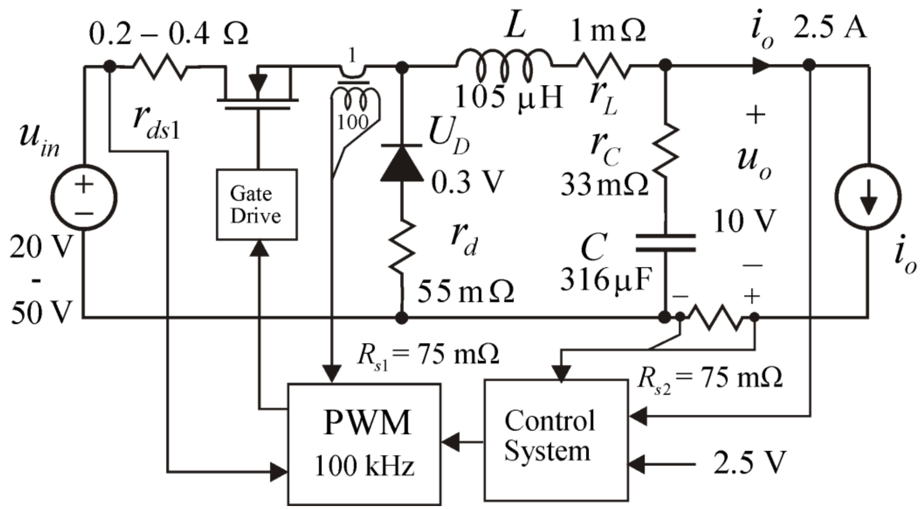
Interconnected System: EMI Filter & Switched-Mode Converter 1



EMI filter

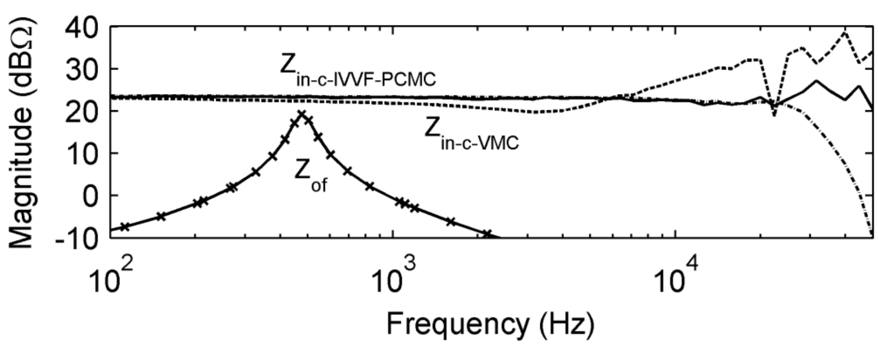


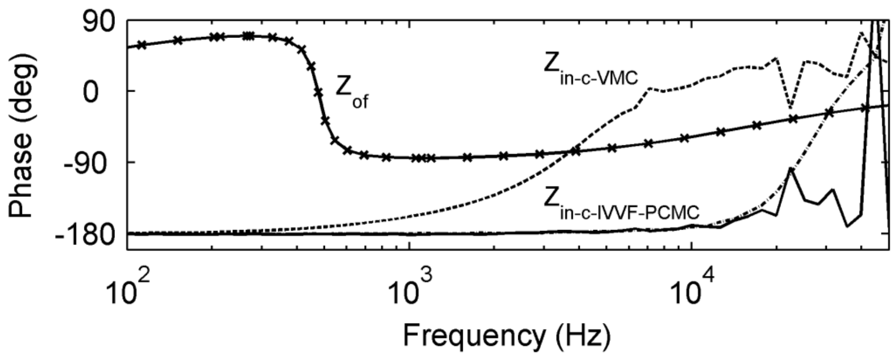
Buck converter



Interconnected System: EMI Filter & Switched-Mode Converter 2

LC-filter output impedance & input impedance of the converter





At low freqeuncies $Z_{in} \approx -R_{con}$

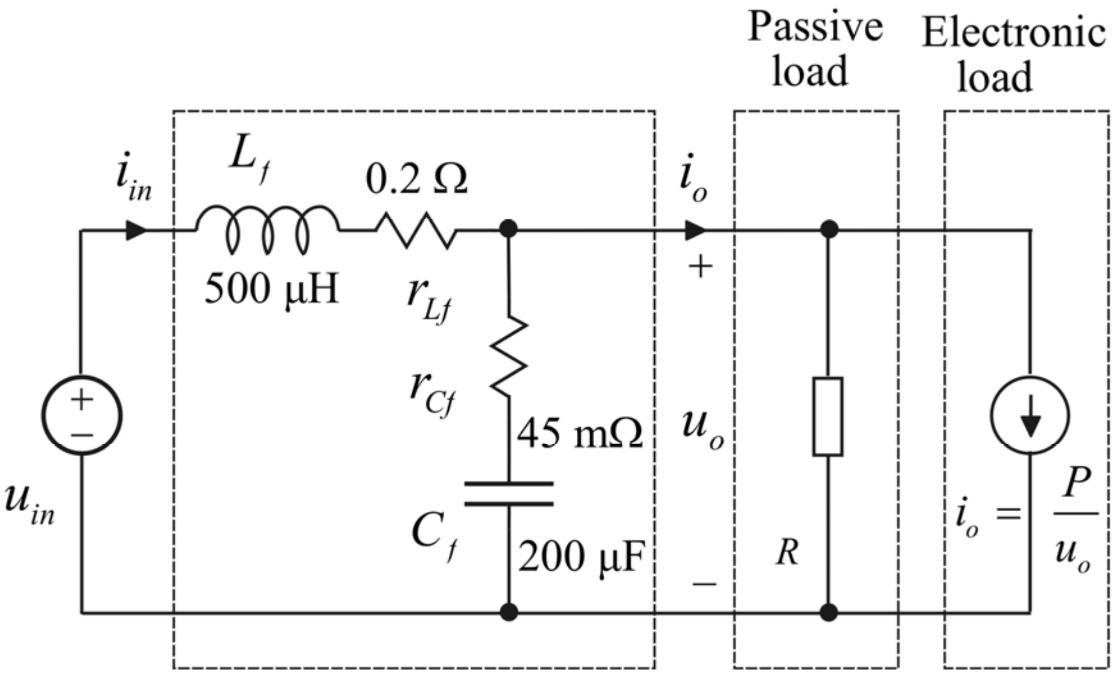
At the EMI-filter resonant frequency

$$f_o = \frac{1}{2\pi\sqrt{L_f C_f}} \quad Z_{of} \approx R_{EMI}$$

If $Z_{of} = Z_{in}$ at $f_o = \frac{1}{2\pi\sqrt{L_f C_f}}$

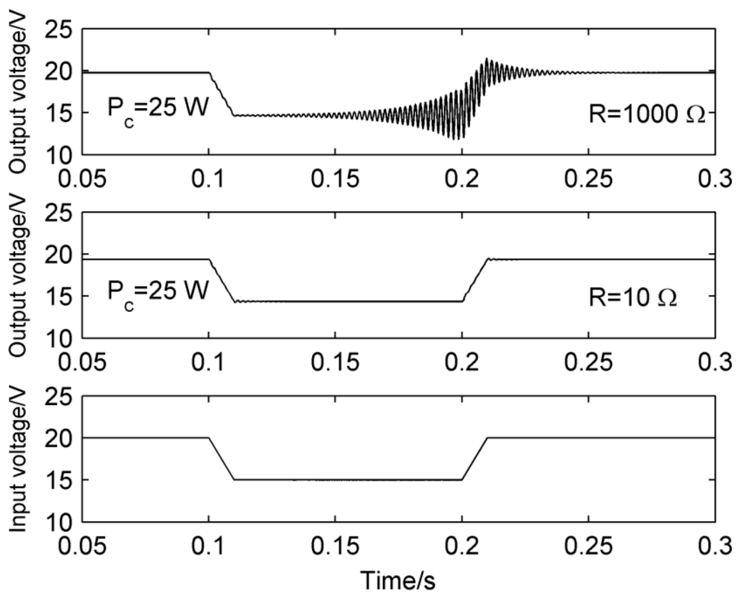
then $Z_{of} / Z_{in} = -1$ and consequently, the system will be unstable.

Interconnected System: LC Circuit & Constant-Power Load

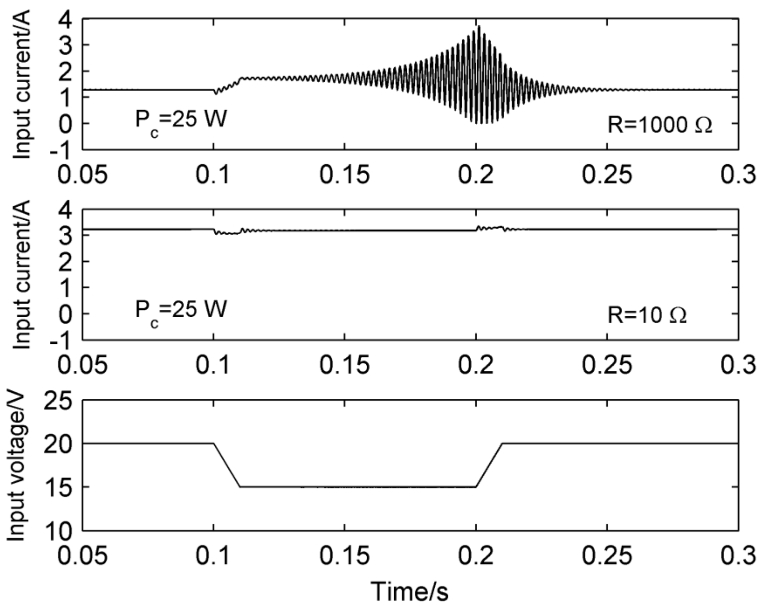


Interconnected System: LC Circuit & DC-Constant-Power Load

Output voltage

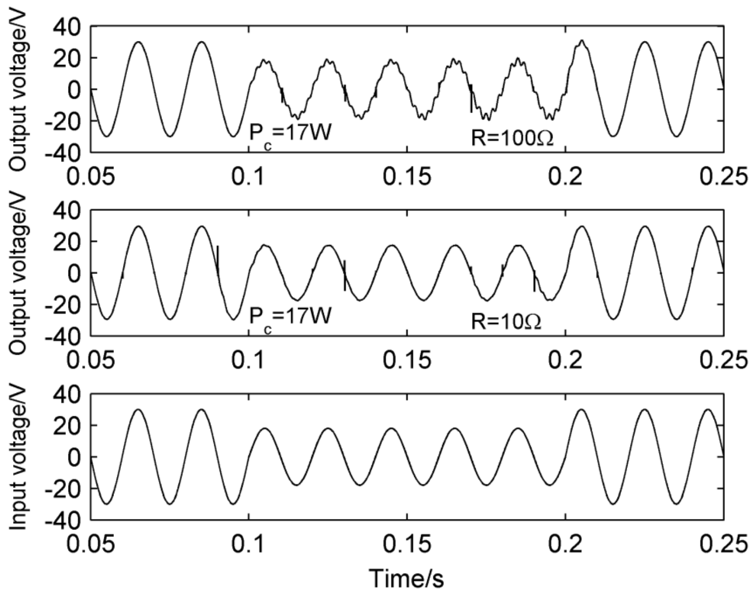


Input current

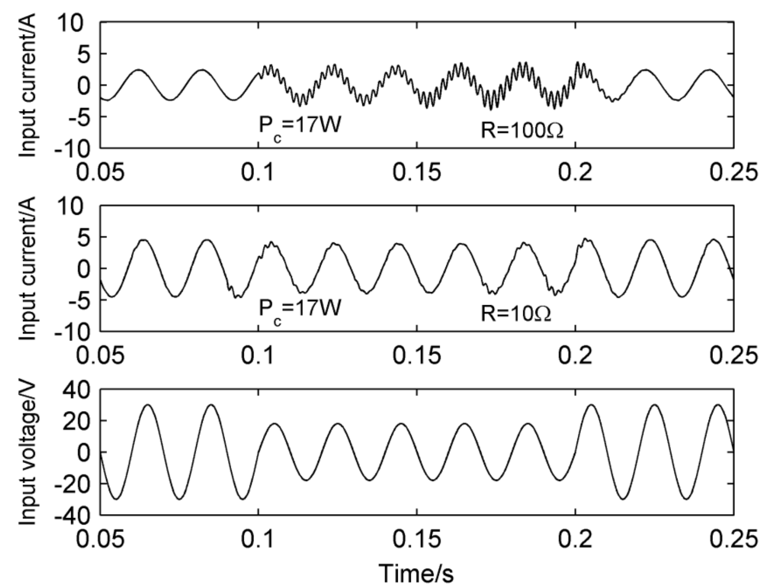


Interconnected System: LC Circuit & AC-Constant-Power Load

Output voltage



Input current



Conclusions

- The origin of the stability problems is the system impedances. The input impedance of the electronic loads may resemble dynamically a negative incremental resistor, which reduces the damping of the resonances within the system and may lead to instability or high resonant currents to appear.
- The universal input voltage range would cause easily ampacity problems during the brown outs.
- The noise currents of the electronic loads may disturb the line communication systems and also excide the possible high-frequency resonances with high resonant currents.
- The high inrush currents may rupture the circuit breakers or damage the internal circuits of the loads such as diodes, fuses, etc.

Future Themes !

- The network compatibility of the electronic load ? Does it exist?
- Can we do something to improve the compatibility?
- Who is responsible ? The distribution company or the customer ?