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Magnetic Energy Harvesting from AC Current-Carrying Conductors: Operation Principles and Applications

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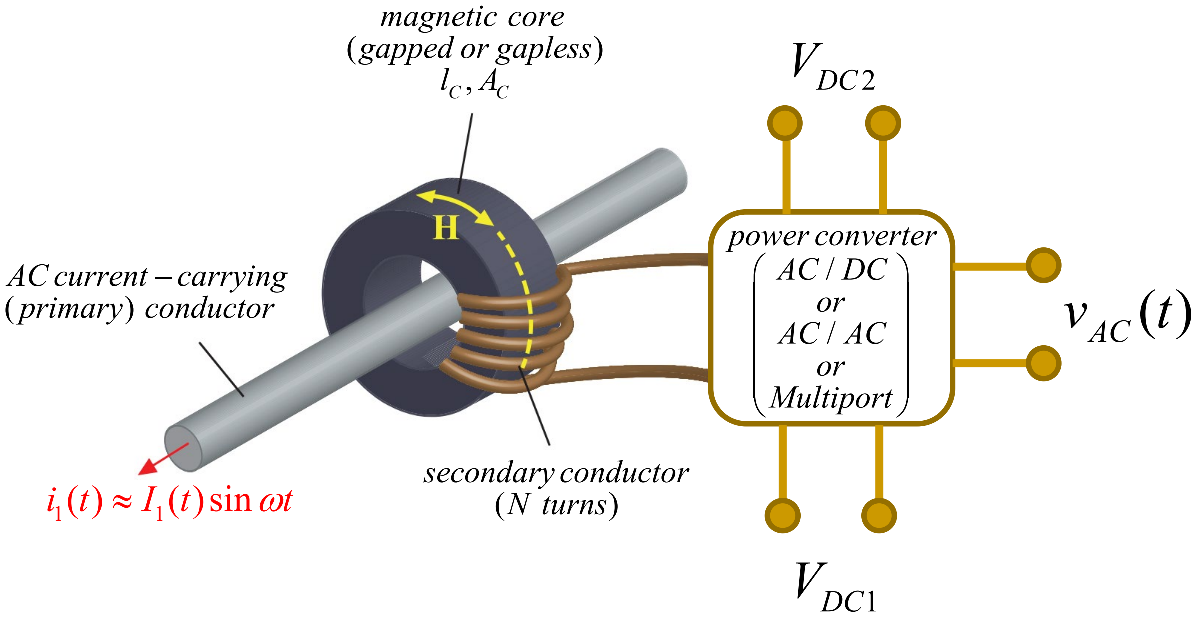
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Magnetic Energy Harvester
(MEH)



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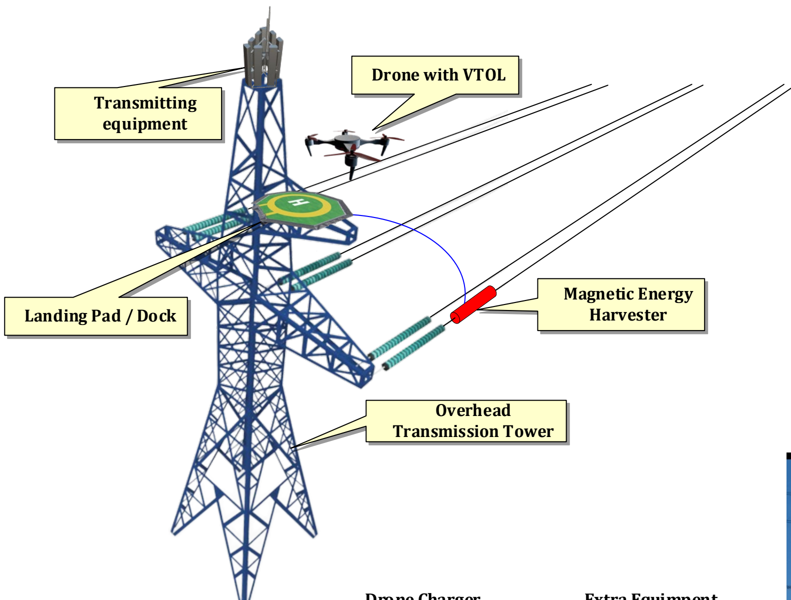
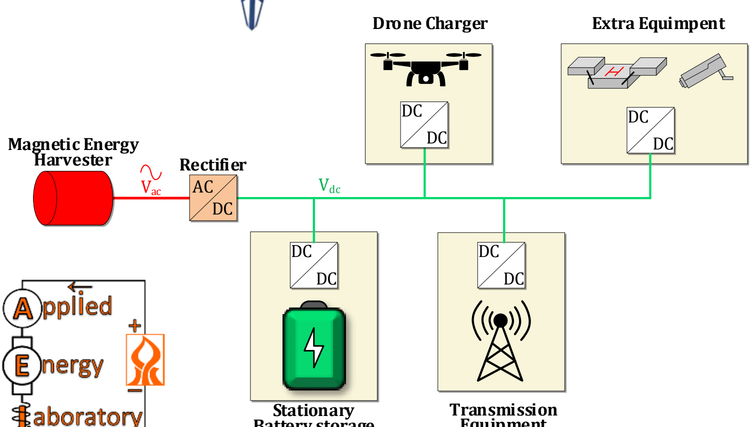
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Target Applications





Relevant power levels:
20W – 2000W

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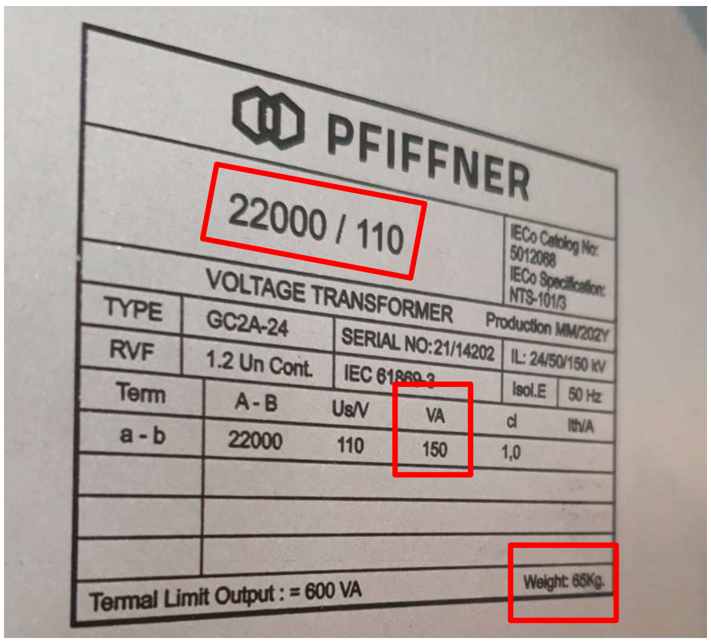
Existing Alternative: Two-phase transformer

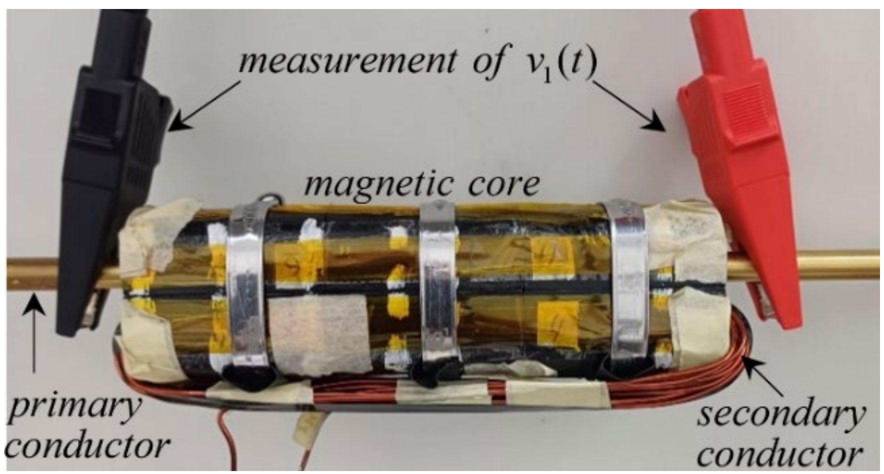


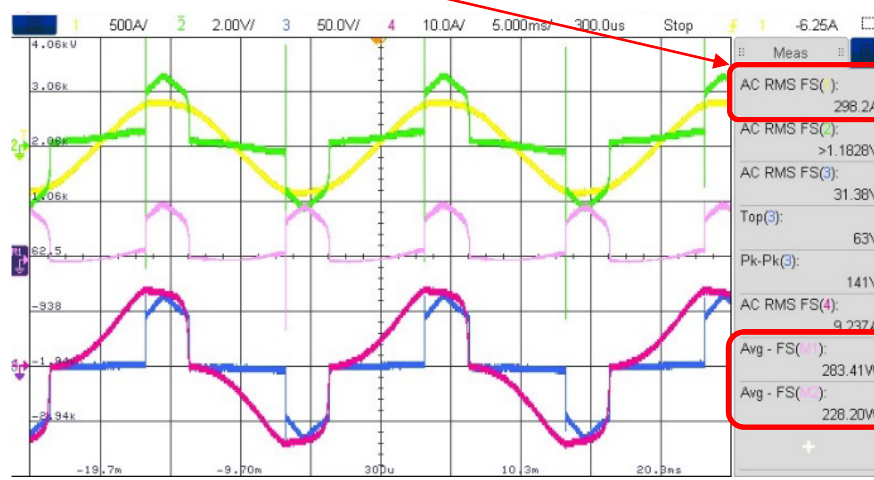
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Magnetic Energy Harvester

$$300\,A_{RMS},\ 50Hz \Rightarrow\ 230W$$

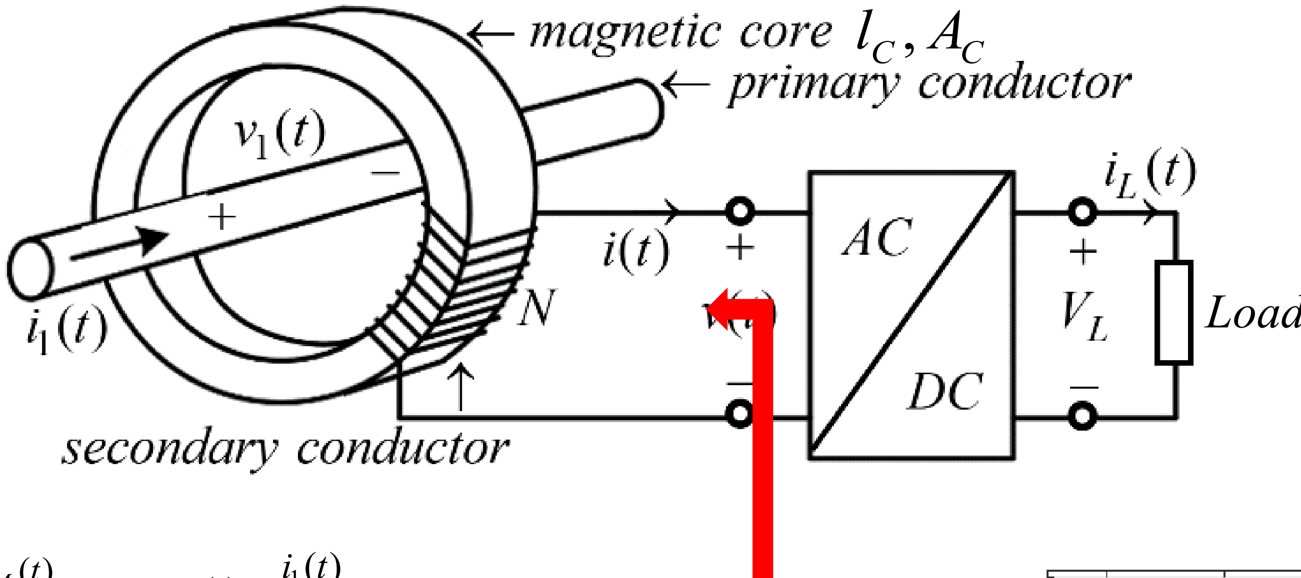
Silicon steel core



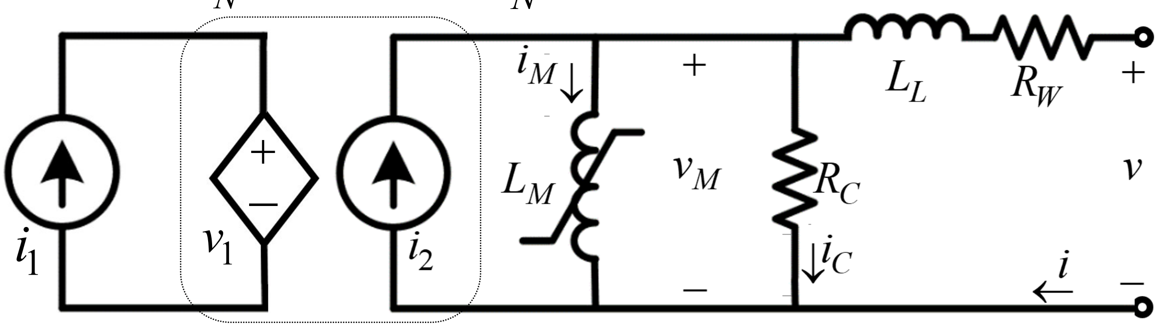


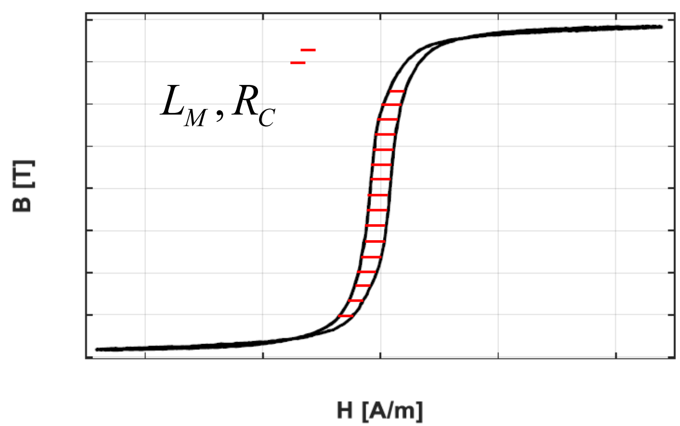
~1kg

Magnetic Energy Harvesting from AC Current-Carrying Conductor



$v_1(t) = \frac{v_M(t)}{N}$ $\quad i_2(t) = \frac{i_1(t)}{N}$





ideal 1:N current transformer

$$i_1(t) = I_1 \sin(\omega t) \Rightarrow i_2(t) = N^{-1} I_1 \sin(\omega t) = I_2 \sin(\omega t)$$

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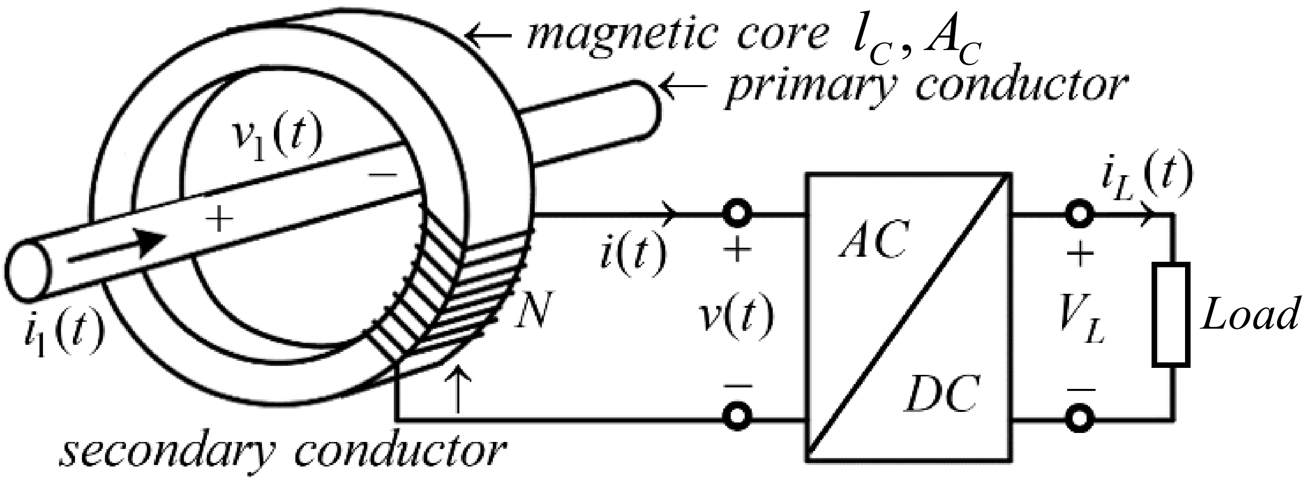
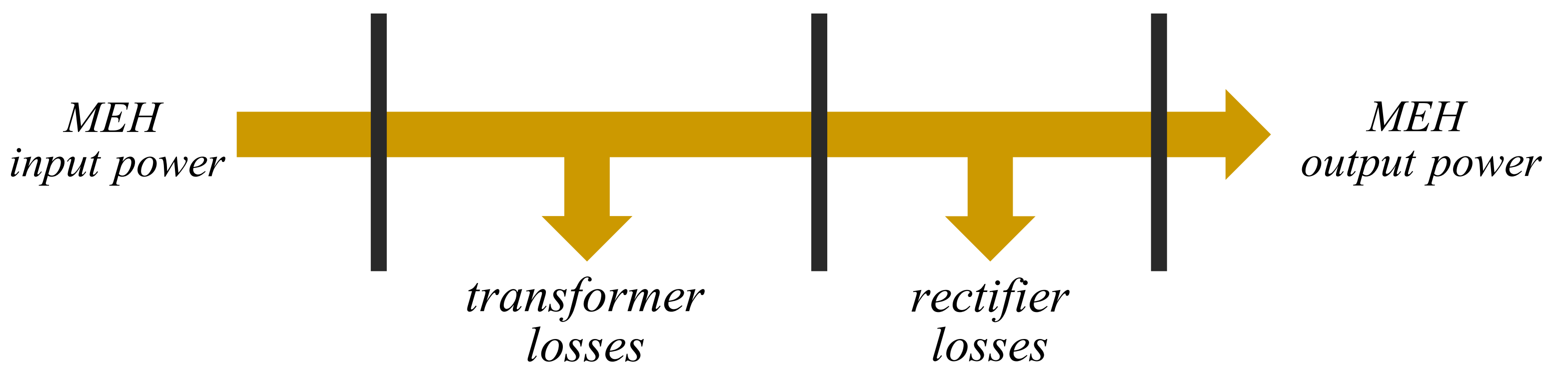
Power flow





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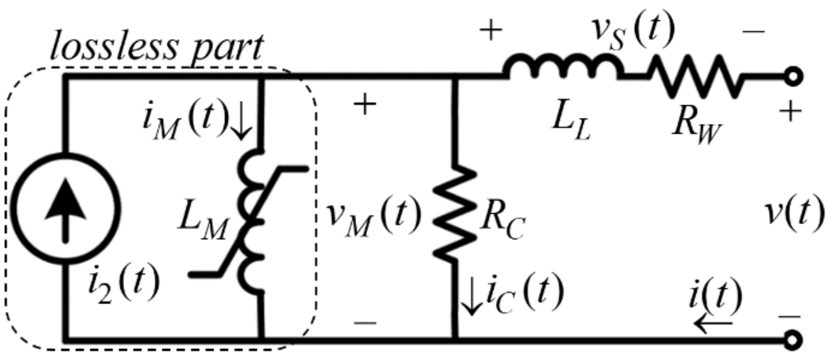
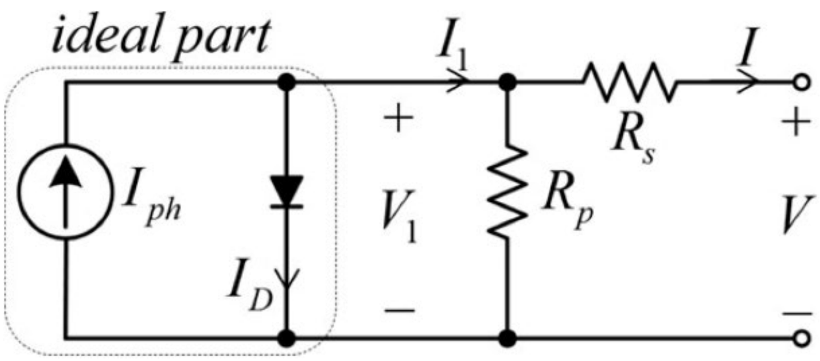


MEH transformer



Photovoltaic module

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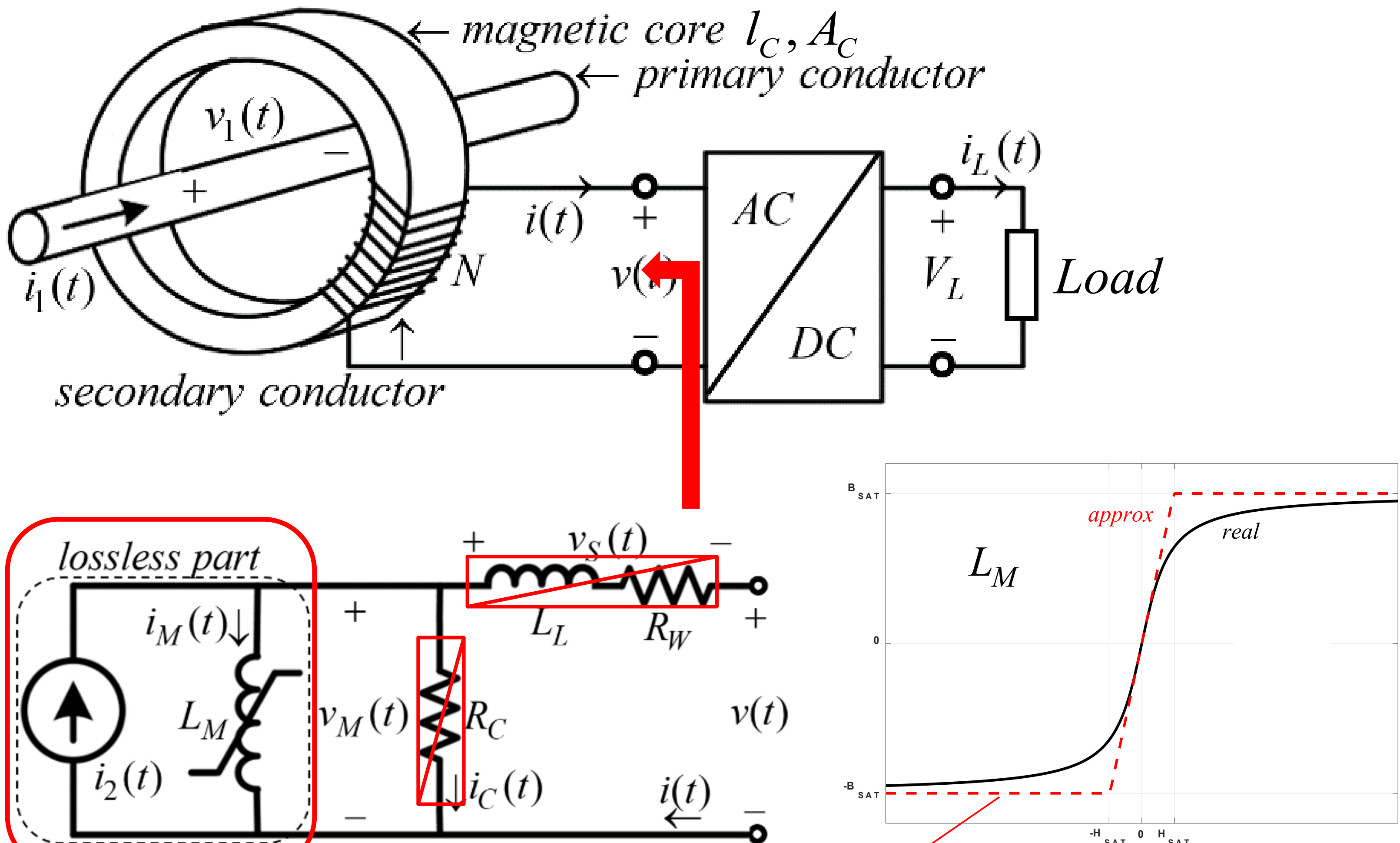
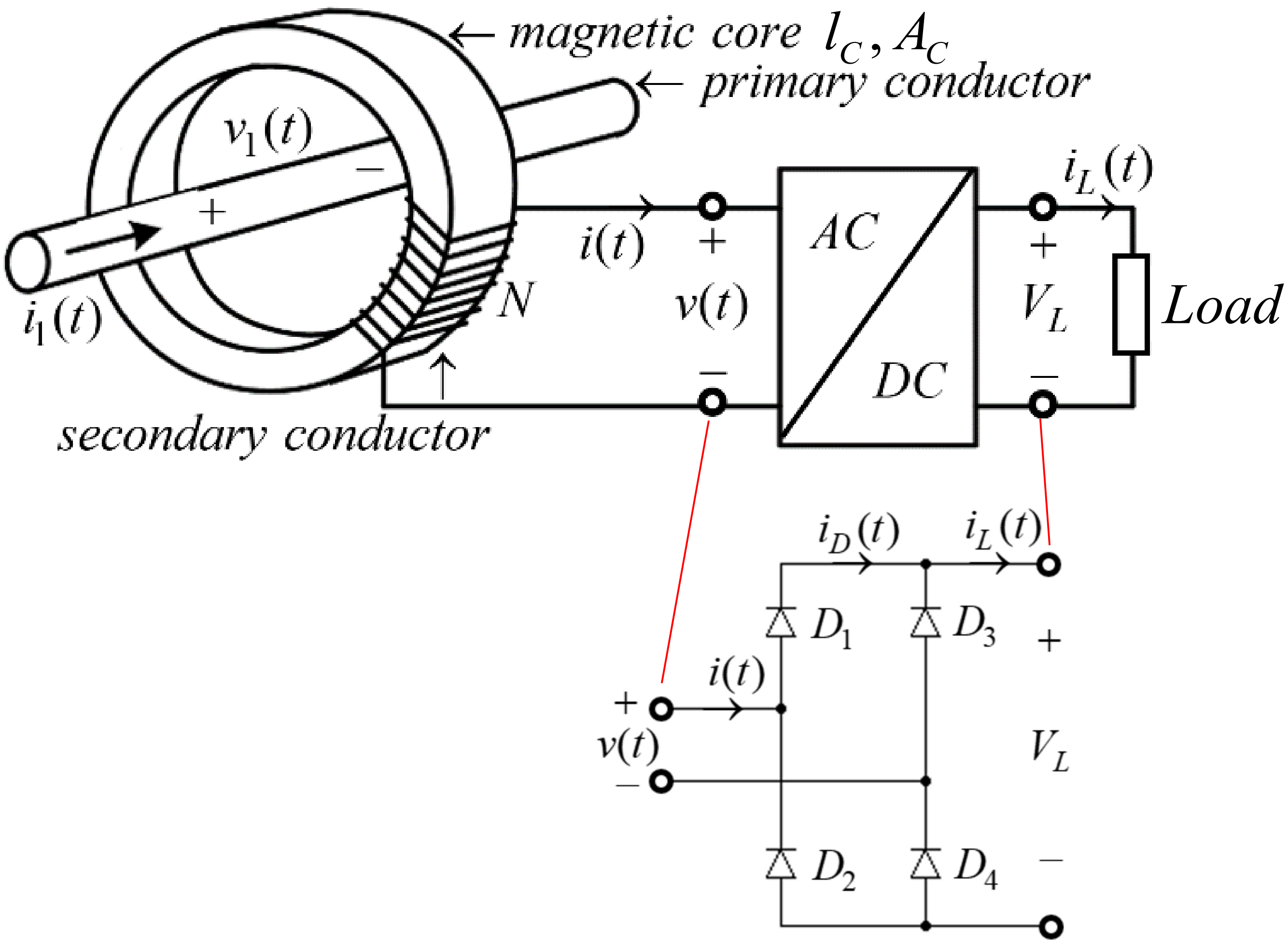


$$i_2(t) = N^{-1} i_1(t)$$

$$B = \begin{cases} \mu H, & |H| \le H_{SAT} \\ sgn(H) B_{SAT}, & |H| \ge H_{SAT} \end{cases},$$

Magnetic Energy Harvesting from AC Current-Carrying Conductor

Passive MEH (PMEH)



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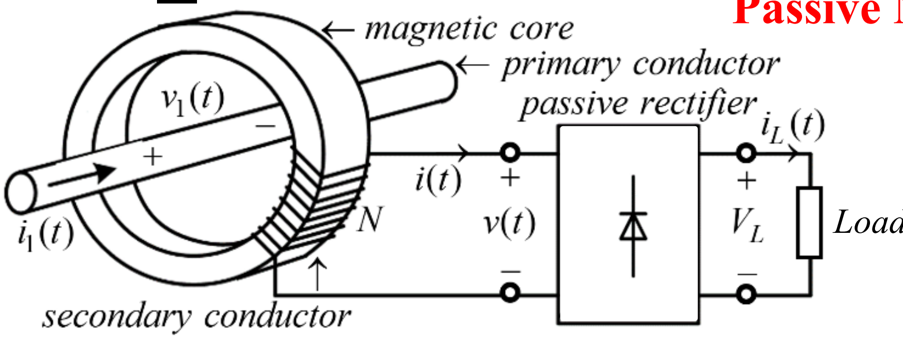
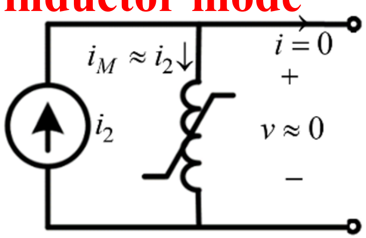
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Passive MEH (PMEH)

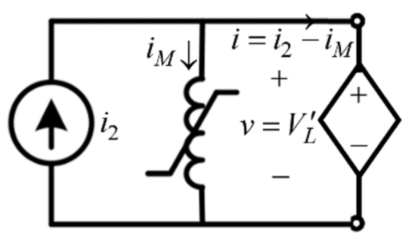
$\theta = \omega t$



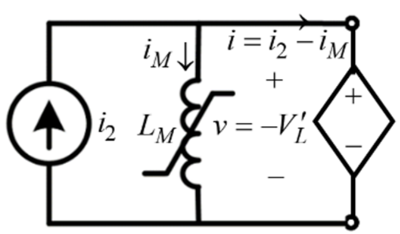
inductor mode



(a) state 1, $-\pi+\theta_2 \le \theta \le \theta_1$.

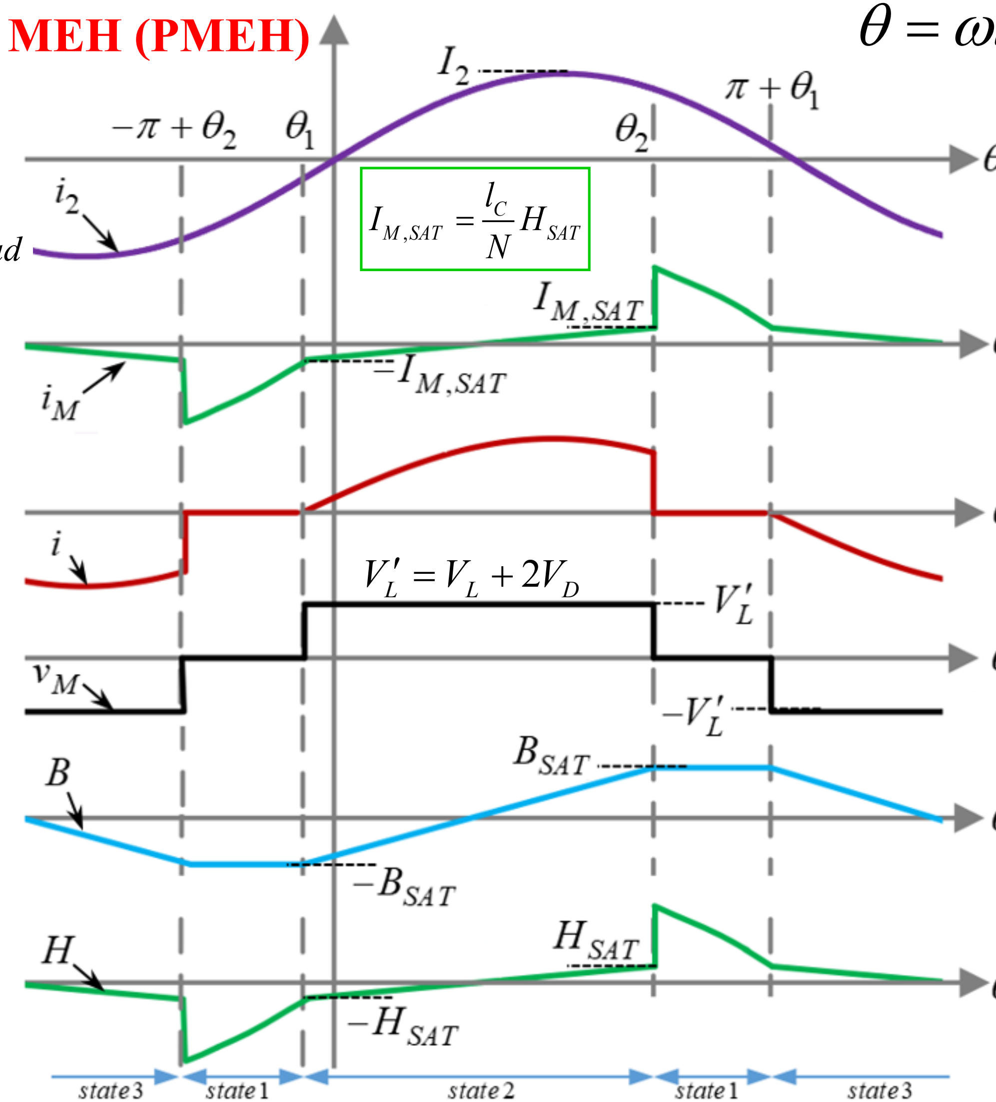


(b) state 2, $\theta_1 \le \theta \le \theta_2$



(c) state 3, $\pi+\theta_1 \le \theta \le \pi+\theta_2$

transformer modes



Magnetic Energy Harvesting from AC Current-Carrying Conductor

Passive MEH (PMEH)

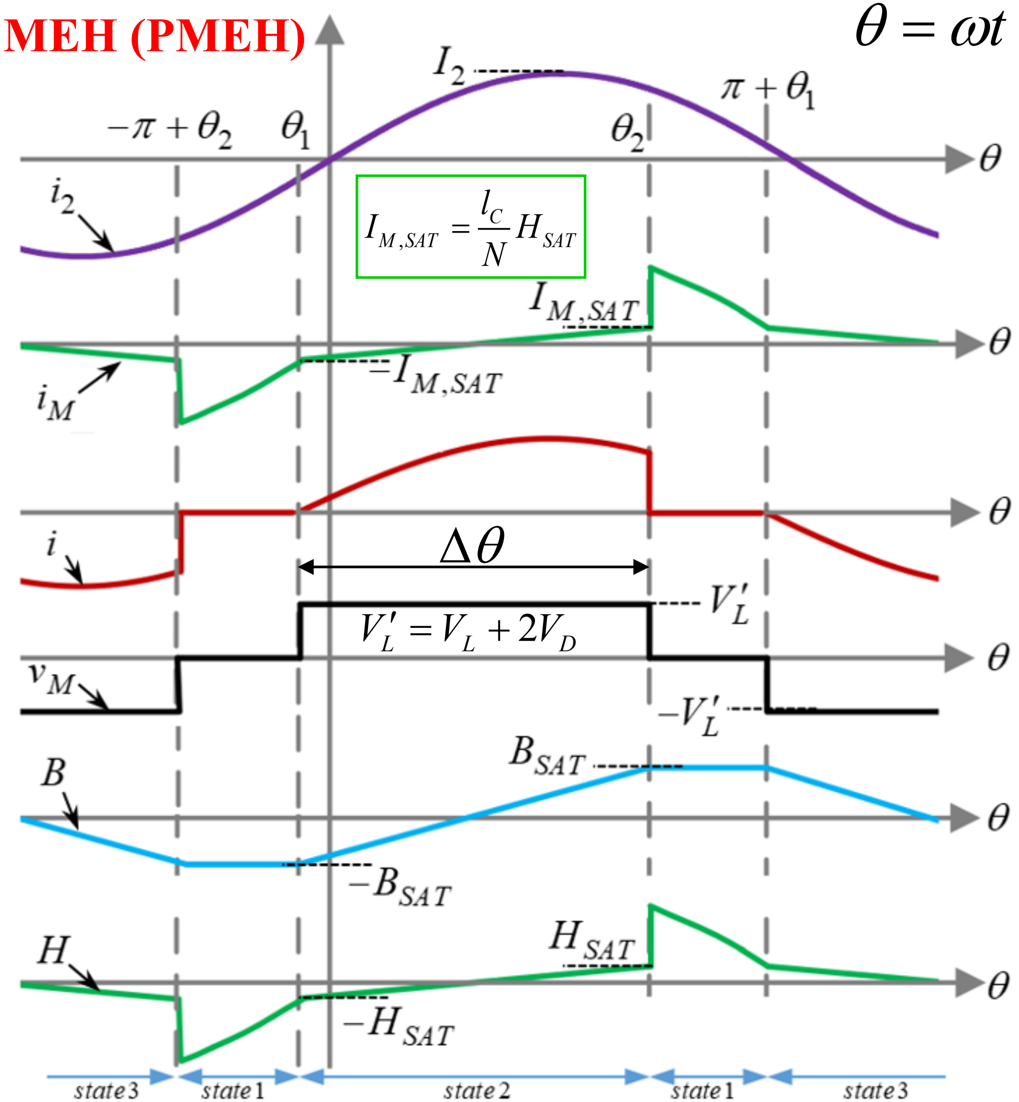
$$\theta_1 = -\sin^{-1}\left(\frac{NI_{M,SAT}}{I_1}\right) \approx 0$$

"High-Currents-Carrying Conductor"

$$\theta_2 = \theta_1 + \underbrace{\frac{2\omega B_{SAT} N A_C}{V_L'}}_{\Delta\theta} \approx \Delta\theta$$

"Transfer window length"

$$\theta = \omega t$$



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Magnetic Energy Harvesting from AC Current-Carrying Conductor

Passive MEH (PMEH)

$$P = \frac{1}{\pi}\int_{\theta_1}^{\theta_2} v_M(\theta) i_2(\theta) d\theta \approx \frac{V_L' I_1}{\pi N}\left(\sin(\theta_1)\sin(\Delta\theta) + \cos(\theta_1)(1-\cos(\Delta\theta))\right)$$

$$\boxed{\max P(\Delta\theta) = P\left(\Delta\theta^* \approx 0.75\pi\ rad \Rightarrow DCM\right) \approx 0.46\omega B_{SAT} A_C I_1}$$

Optimized PMEH should operate in discontinuous conduction mode

Design guidelines: harvest *P given I_1, ω, V_L**

$$A_C = \frac{P^*}{0.46\omega B_{SAT} I_1},$$

$$N = \frac{0.17\pi V_L' I_1}{P^*}.$$

A. Abramovitz, M. Shvartsas and A. Kuperman, "On the maximum power of passive magnetic energy harvesters feeding constant voltage loads under high primary currents," *IEEE Trans. Power Electron.*, vol. 39, no. 10, pp. 12076 – 12080, Oct. 2024.

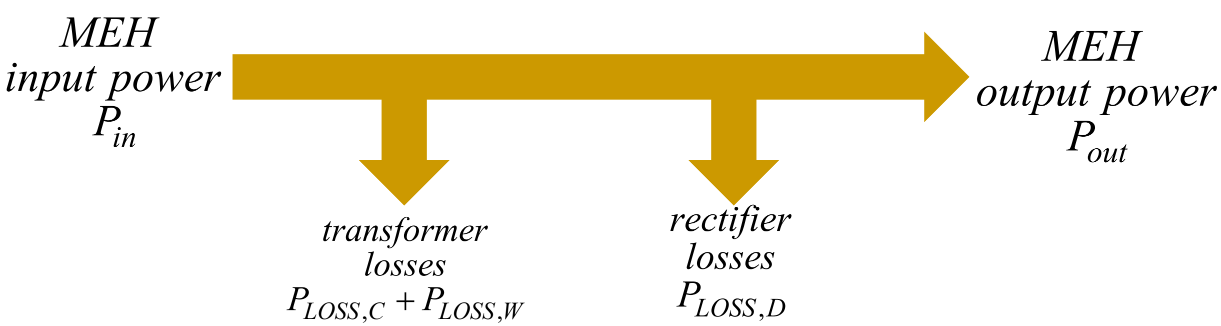
Magnetic Energy Harvesting from AC Current-Carrying Conductor

PMEH conversion losses

$$\left.\begin{aligned} P_{LOSS,C} &= \frac{V_{M,RMS}^2}{R_C} \approx \frac{\Delta\theta}{\pi}\frac{\left(V_L'\right)^2}{R_C} \\ P_{LOSS,W} &= I_{RMS}^2 R_W \approx \frac{I_1^2}{2\pi N^2}\sqrt{\Delta\theta - \frac{\sin\left(2\Delta\theta\right)}{2}}R_W \end{aligned}\right\} \textit{transformer losses}$$

$$P_{LOSS,D} = 2\left(I_{D,RMS}^2 R_D + I_{D,AV}V_D\right)$$

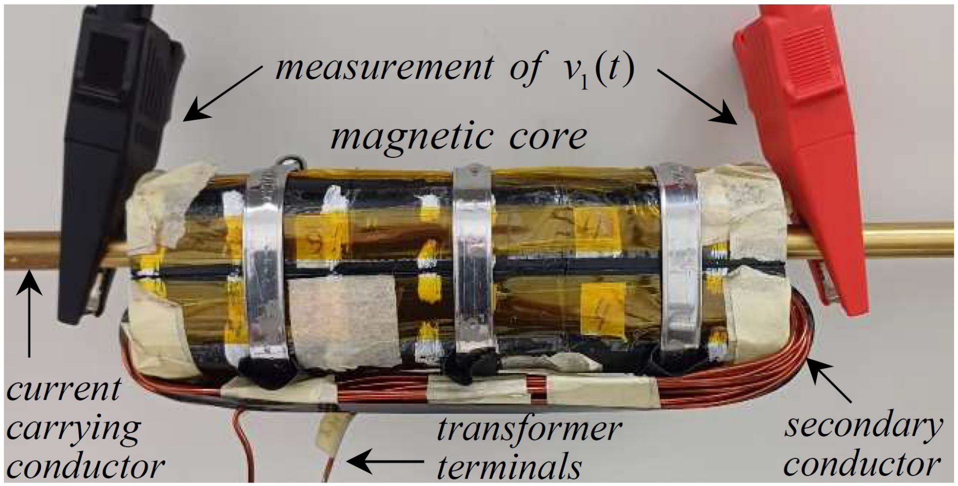
$$\left.\approx \frac{I_1^2}{4\pi N^2}\left(\Delta\theta - \frac{\sin\left(2\Delta\theta\right)}{2}\right)R_D + \frac{I_1}{2\pi N}\left(1-\cos\left(\Delta\theta\right)\right)V_D\right\} \textit{rectifier losses}$$



$$P_{out} = P_{in} - \left(P_{LOSS,C} + P_{LOSS,W} + P_{LOSS,D}\right),\ \eta = \frac{P_{out}}{P_{in}} \approx 1 - \frac{P_{LOSS,C} + P_{LOSS,W} + P_{LOSS,D}}{P_{in}}$$

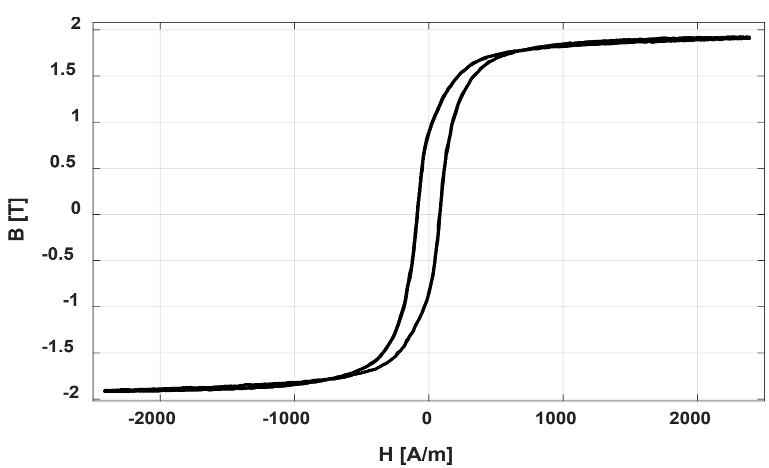
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Example



$$V_L = 48V$$

$$P_O^* = 175W @ 300 A_{RMS}$$



Test bench parameter values

Parameter	Value	Units
ω	2π·50	rad/s
μ	0.015	H/m
B_{SAT}	2	T
l_C	0.12	m
A_C	0.0018	m^2
N	55	---
R_W	0.65	Ω
V_D	0.3	V
R_D	0.0045	Ω
R_C	250	Ω

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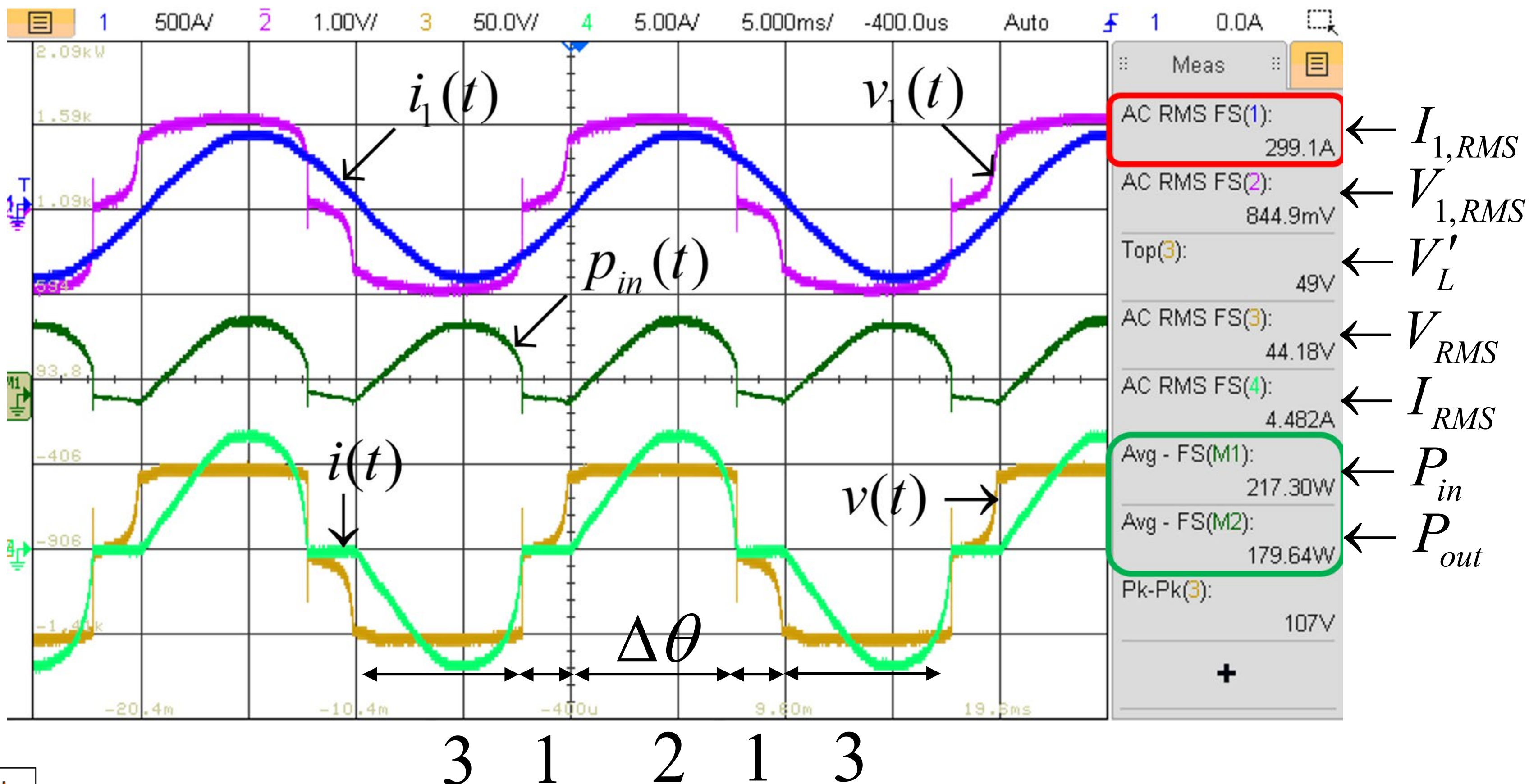
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Example



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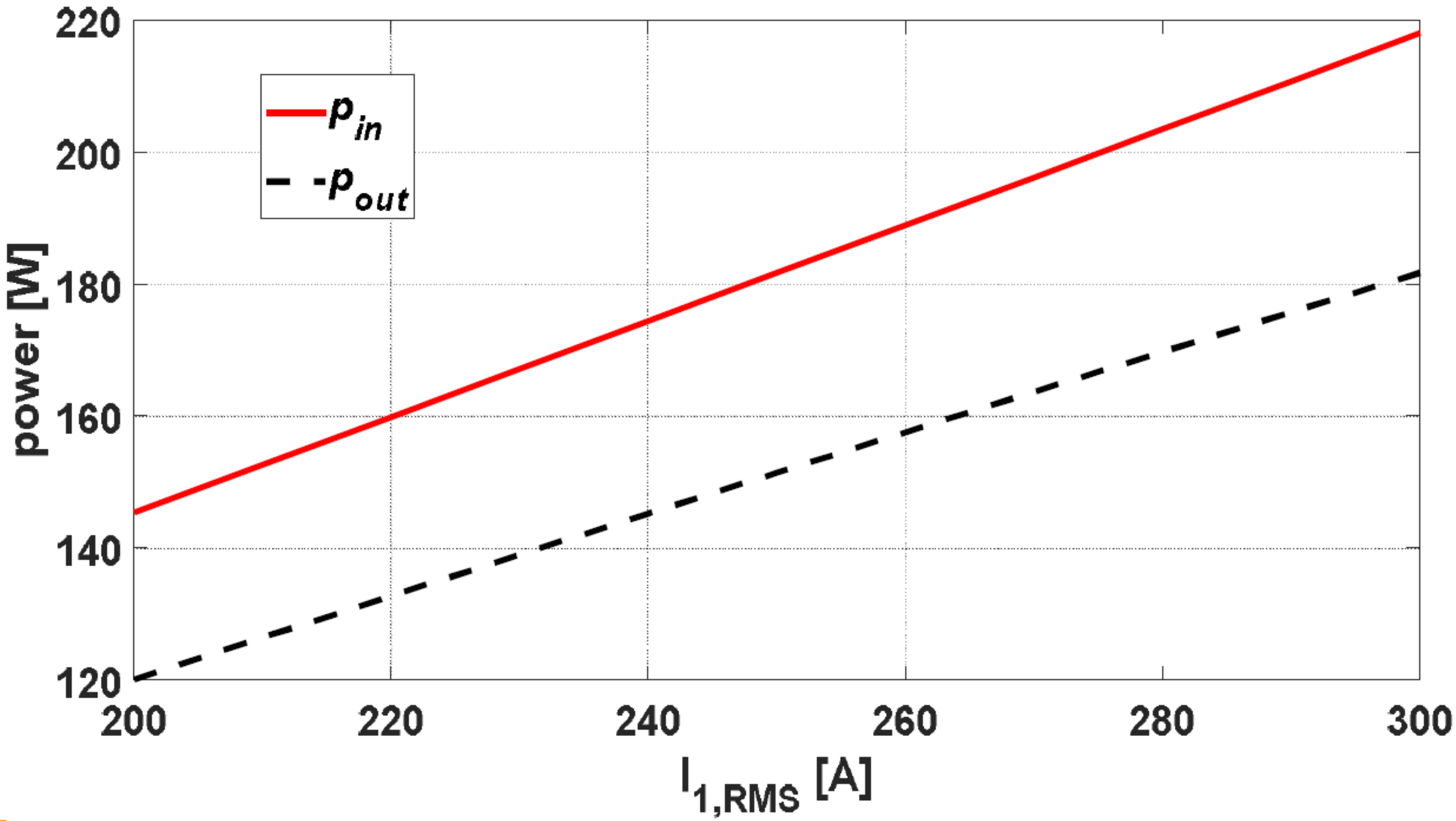
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Example



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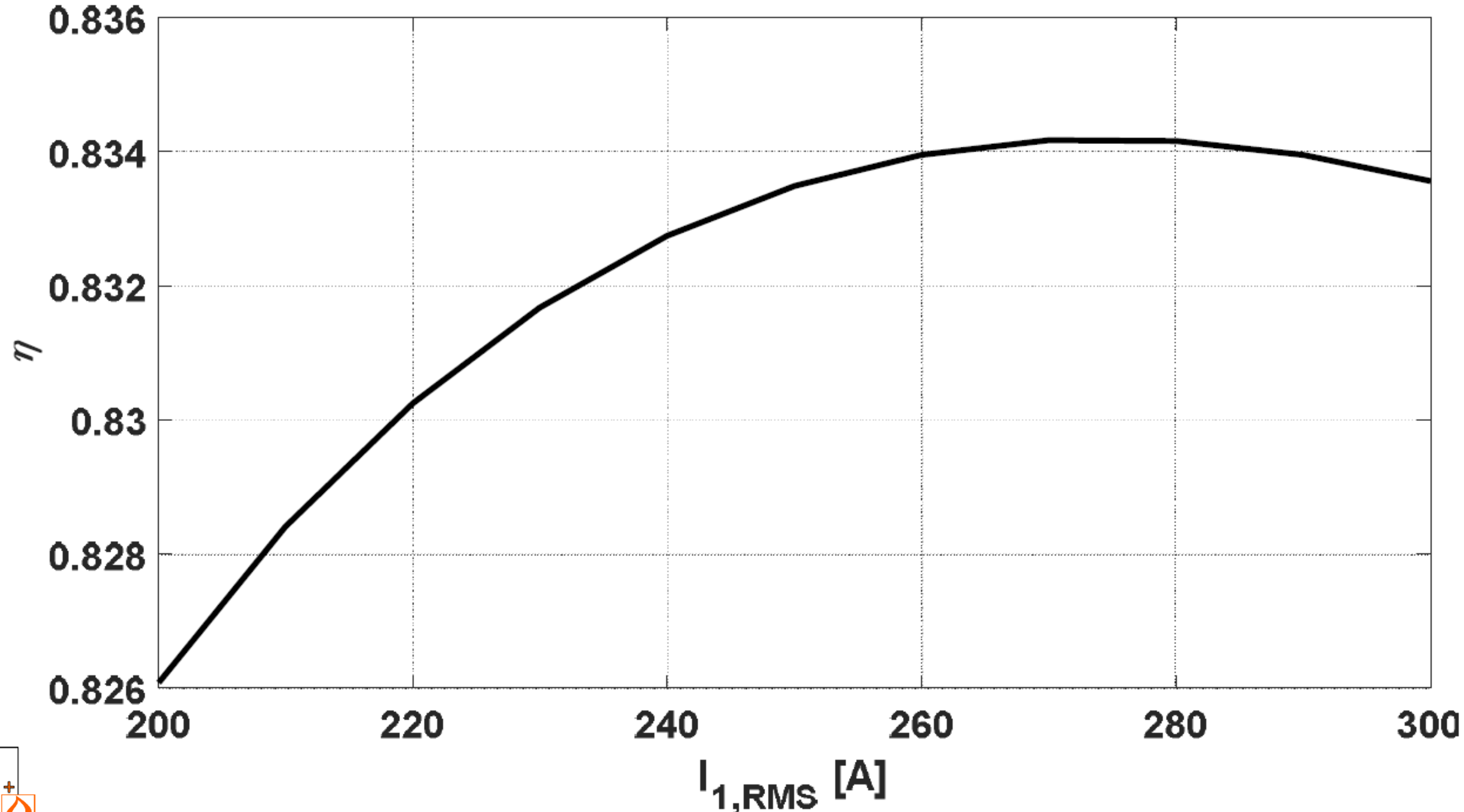
Magnetic Energy Harvesting from AC Current-Carrying Conductor

Example



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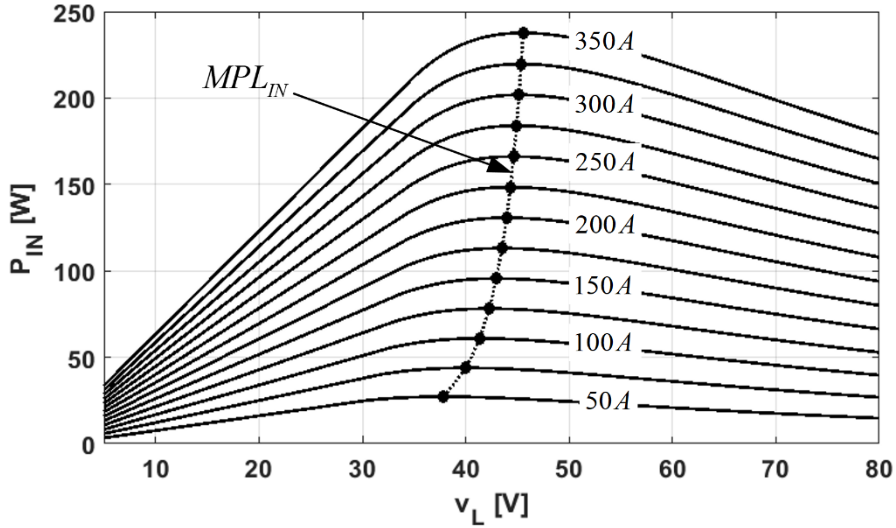
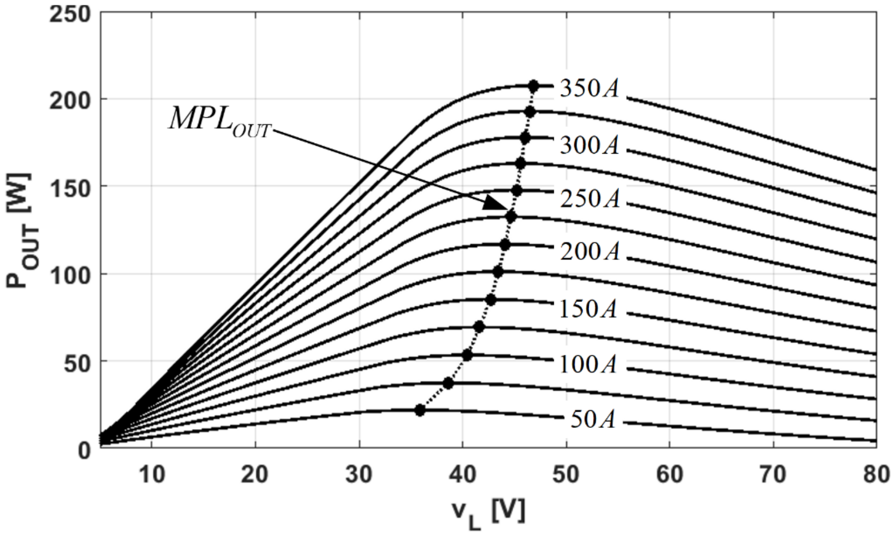
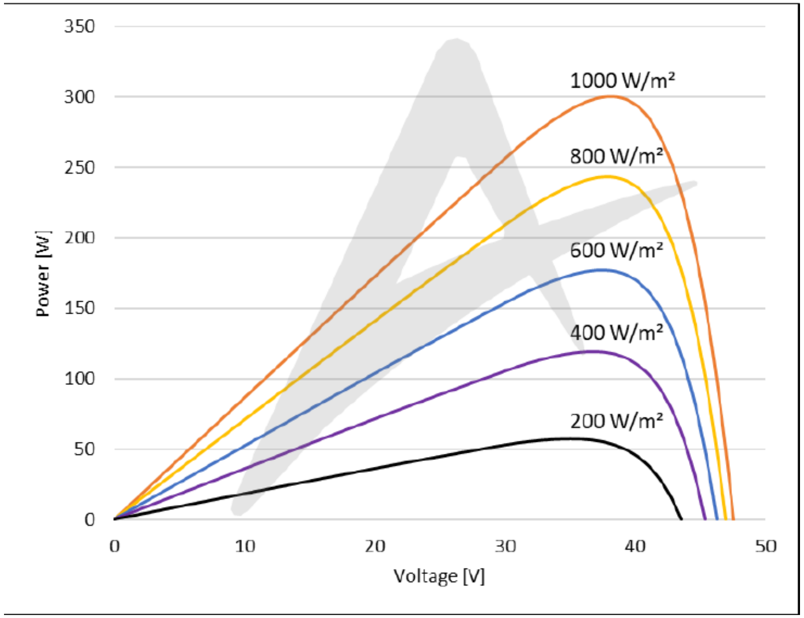
Characteristic curves Family



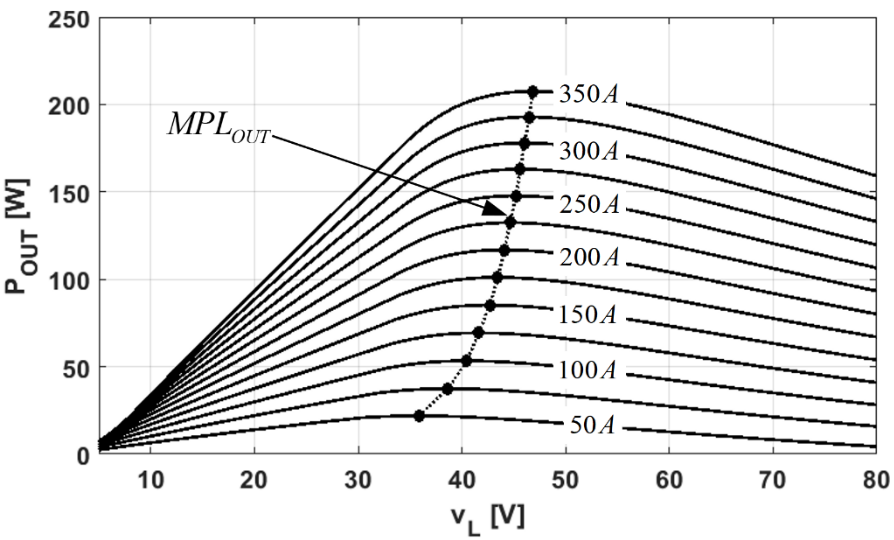


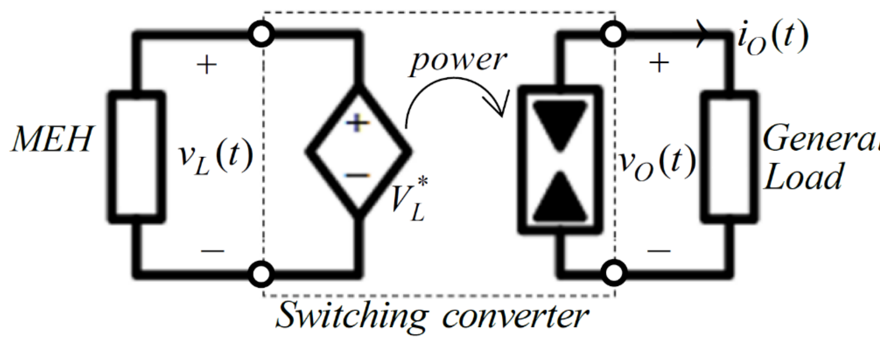


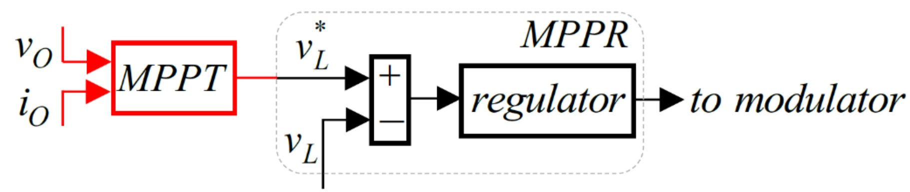
Photovoltaic module

Magnetic Energy Harvesting from AC Current-Carrying Conductor

Maximum power point tracking



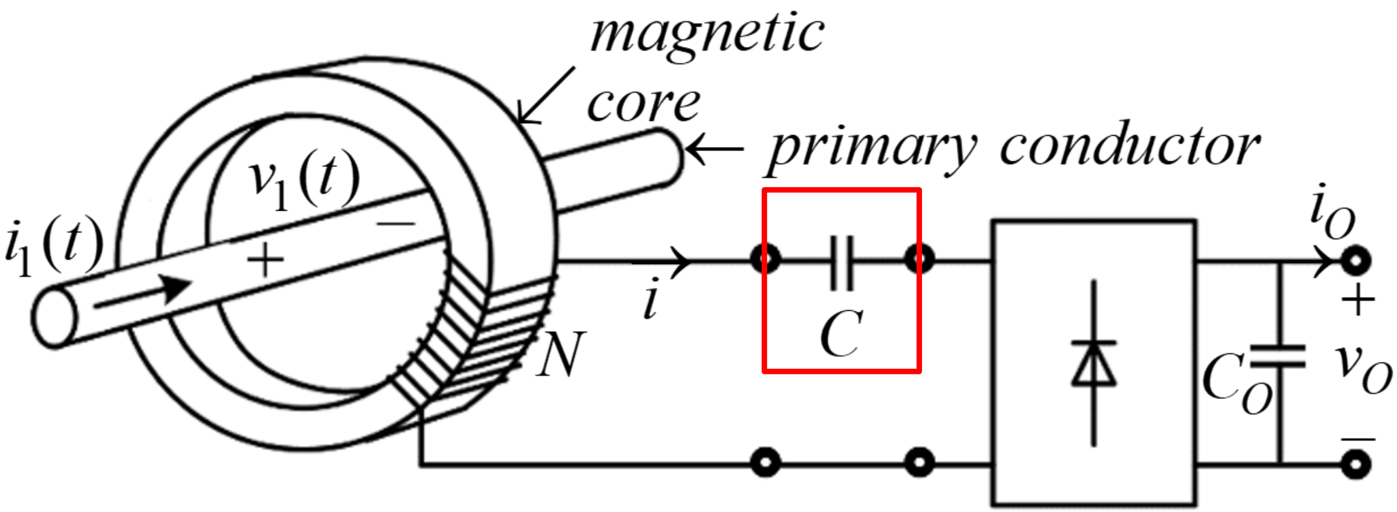




A. Abramovitz, M. Shvartsas and A. Kuperman, "Enhanced maximum power point reaching method for passive magnetic energy harvesters operating under low primary currents," *IEEE Trans. Power Electron*., vol. 39, no. 6, pp. 6619 – 6623, Jun. 2024.

Magnetic Energy Harvesting from AC Current-Carrying Conductor

PMEH Equipped with AC-side series-connected capacitor



$\max P \approx 0.46\omega B_{SAT} A_C I_1$ *without capacitor*

$\max P \approx 0.585\omega B_{SAT} A_C I_1$ *with capacitor*

+27%

$$but \ldots C = \frac{0.52}{B_{SAT}(\omega N)^2 A_C} I_1$$

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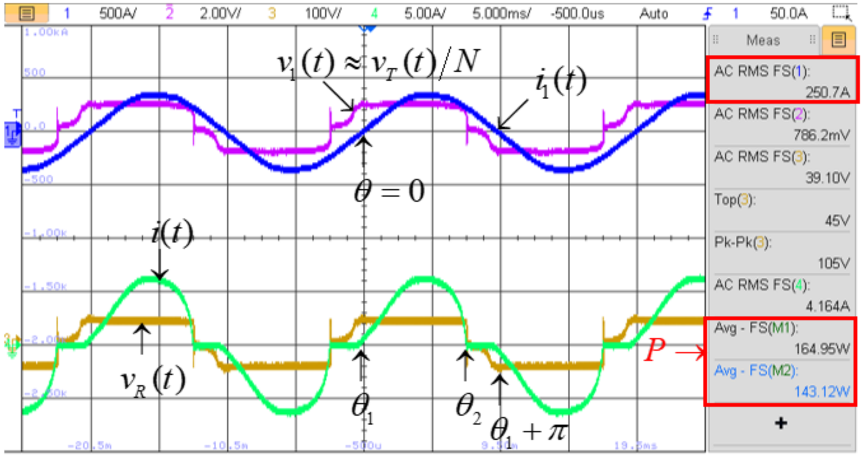
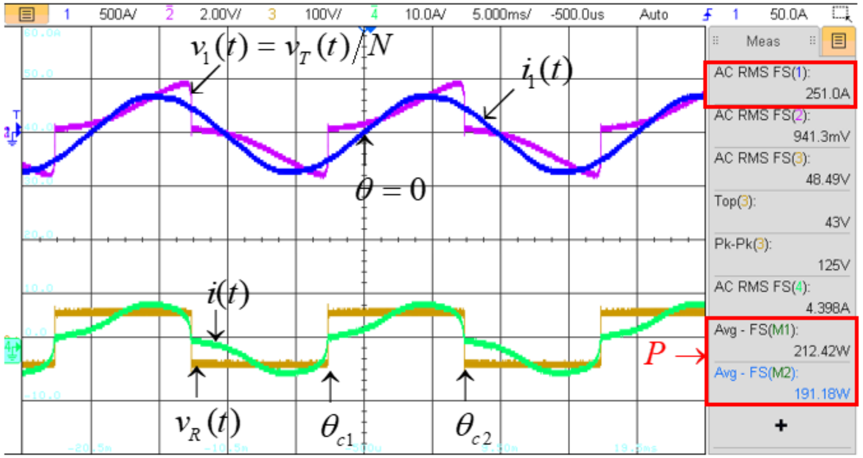
A. Kuperman, "Comments on 'An effective power improving method of magnetic field energy harvesters using a series-connected capacitor for wireless sensors in smart grid'," *IEEE Trans. Power Electron.*, DOI: 10.1109/TPEL.2024.3478394.

Magnetic Energy Harvesting from AC Current-Carrying Conductor

PMEH Equipped with AC-side series-connected capacitor



(a) MEH without series-connected capacitor



(b) MEH with optimal series-connected capacitor

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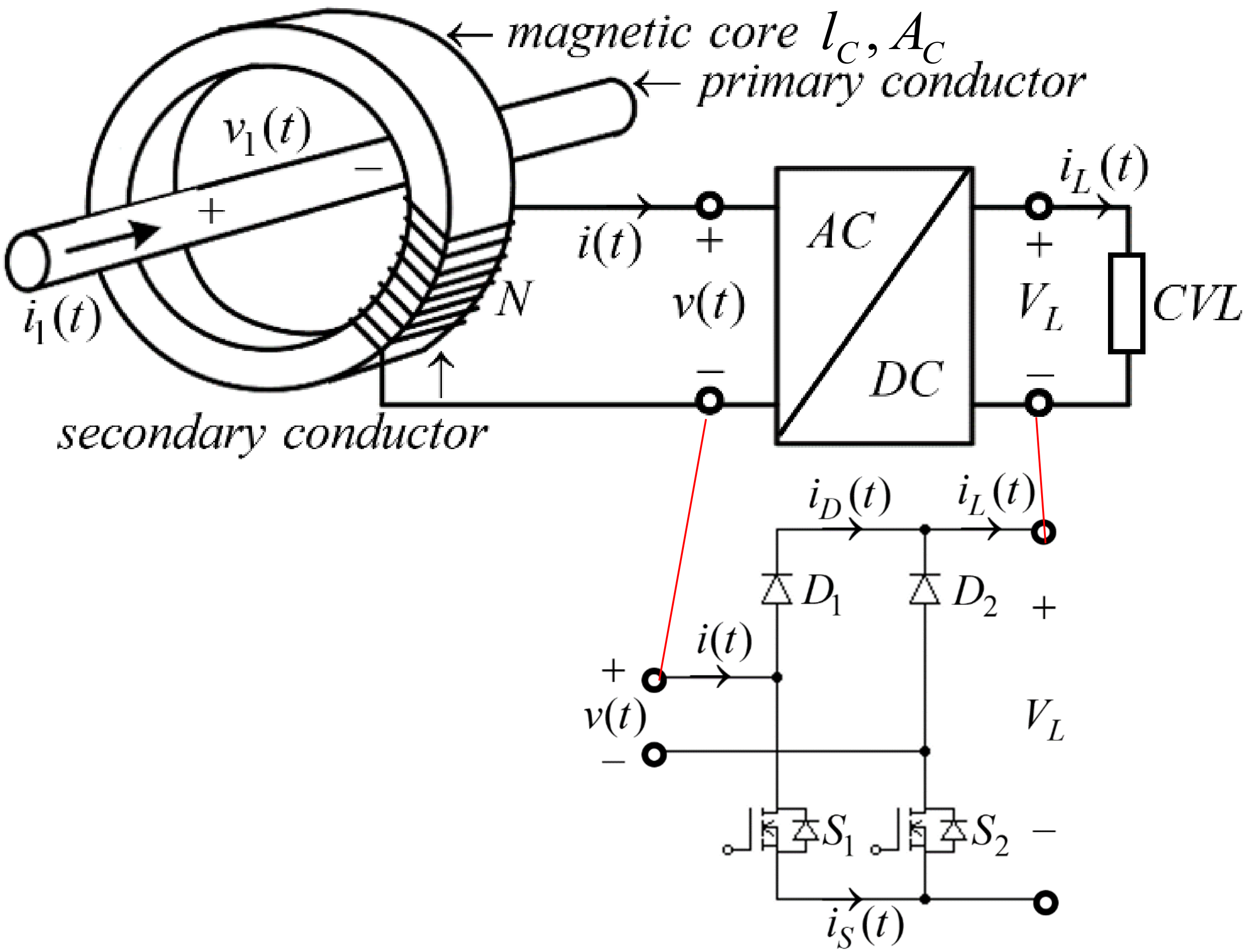
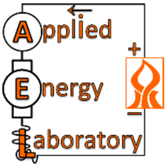
Magnetic Energy Harvesting from AC Current-Carrying Conductor

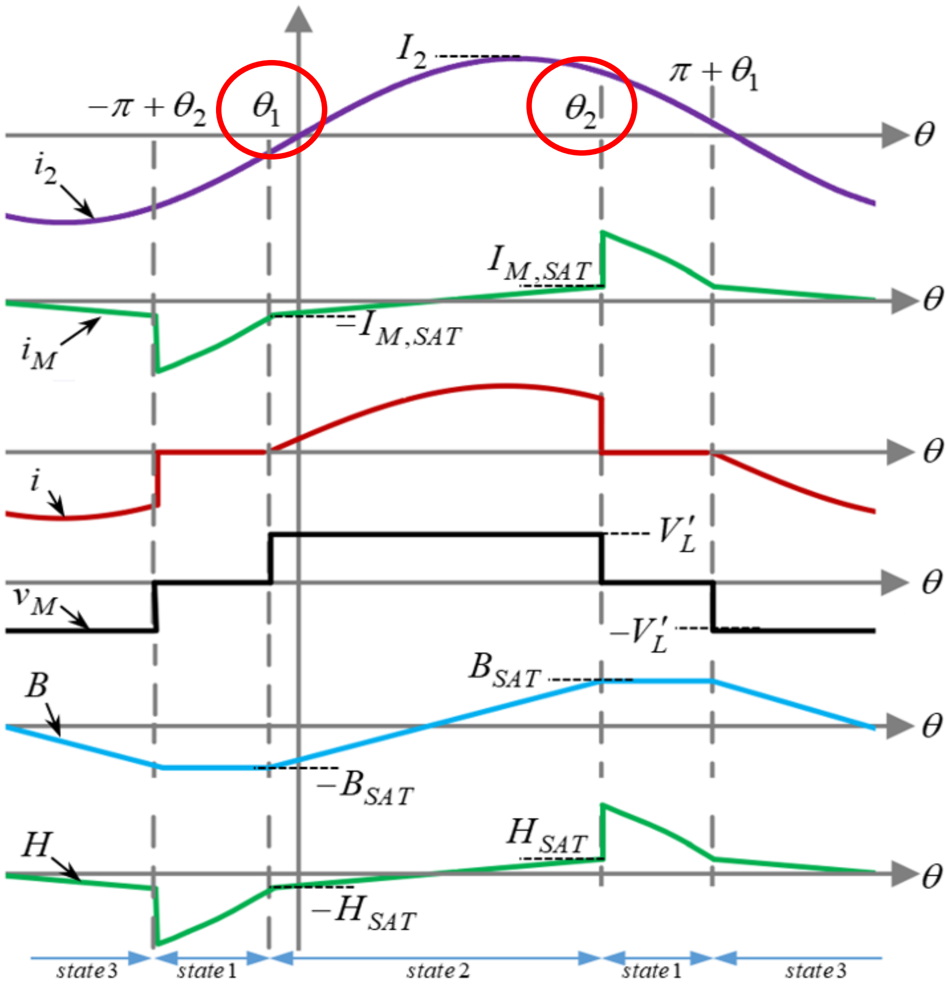
Active MEH (AMEH)



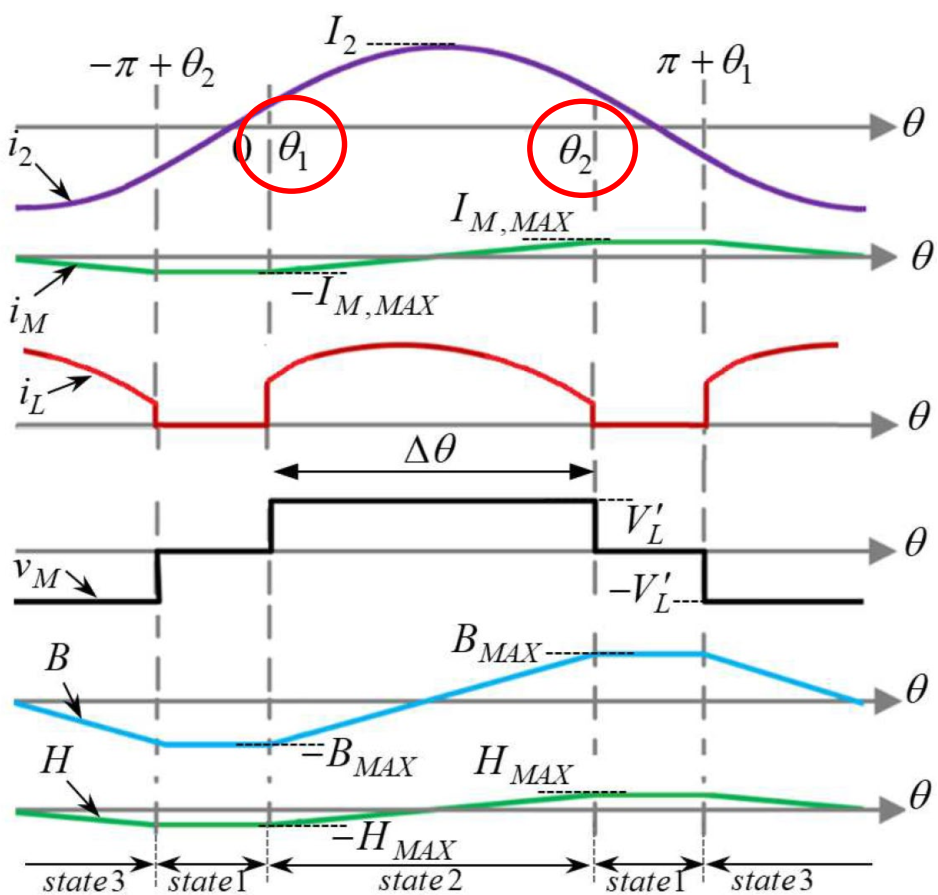


Magnetic Energy Harvesting from AC Current-Carrying Conductor

Passive MEH (PMEH)

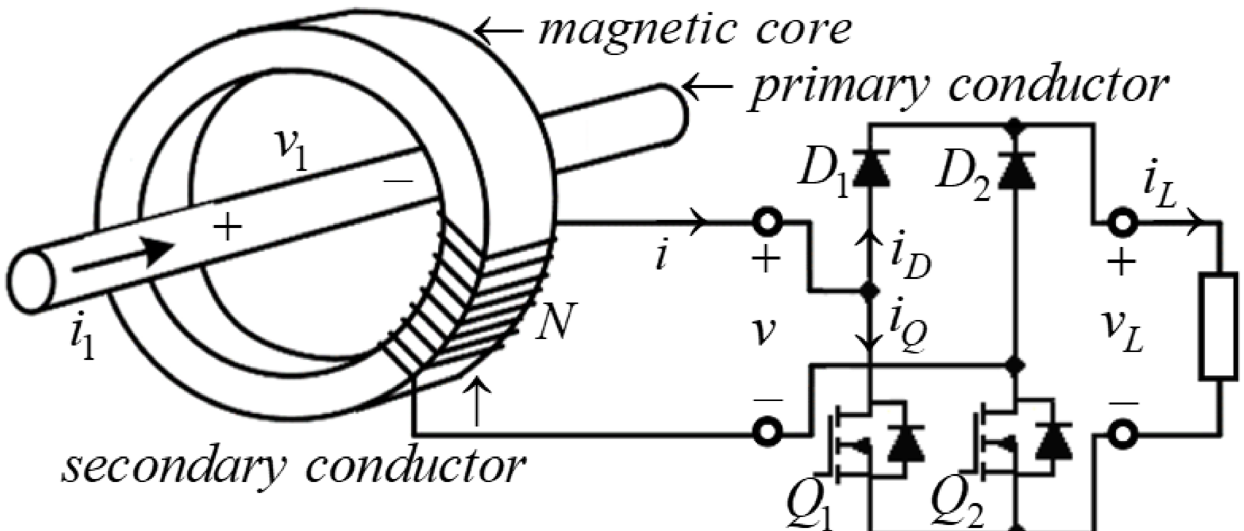


Active MEH (AMEH)



Magnetic Energy Harvesting from AC Current-Carrying Conductor

Active MEH (AMEH)



$$\max P \approx 0.46\omega B_{SAT} A_C I_1$$ *PMEH without capacitor*

+38.4%

$$\max P \approx 0.637\omega B_{SAT} A_C I_1$$ *AMEH*

A. Abramovitz, M. Shvartsas and A. Kuperman, "Performance of active magnetic energy harvesters feeding constant-voltage-type loads under high primary currents," *IEEE J. Emerg. Sel. Top. Ind. Electron.*, To appear.

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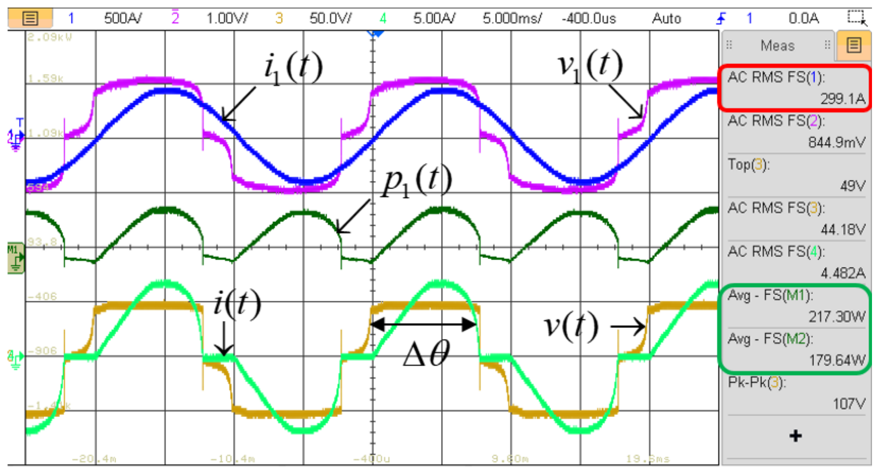
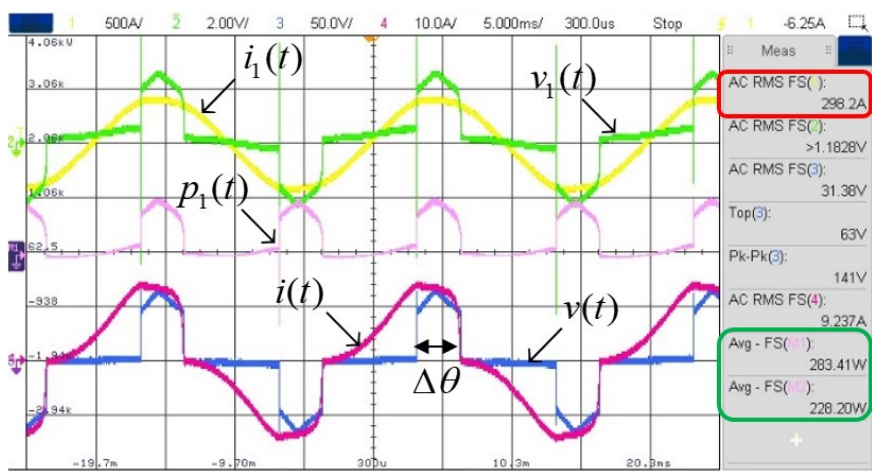
Active MEH (AMEH)



(a) Passive MEH



(b) Active MEH

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