RoboSoft 1st Plenary Meeting
Pisa
March 31 – April 1, 2014

Optimal energy-harvesting cycles for load-driven soft dielectric generators

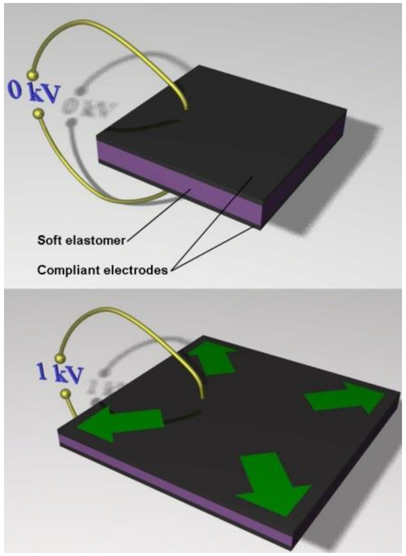
E. Bortot, R. Springhetti*, G. deBotton**, **Massimiliano Gei****

**DICAM/Solid Mechanics, University of Trento, Italy*
***Dept. of Mechanical Eng., Ben-Gurion University, Israel*

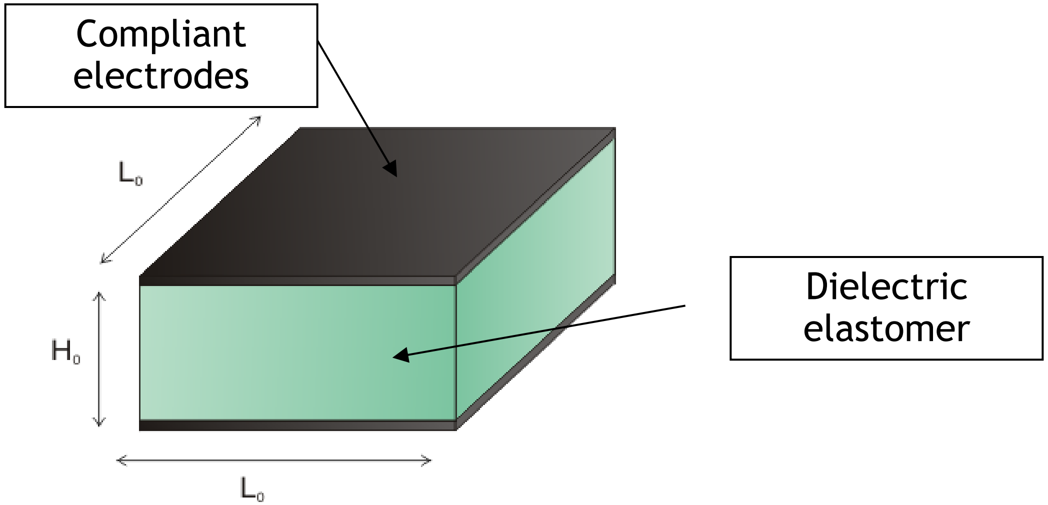
UNIVERSITY OF TRENTO - Italy

Poster 1.6

DIELECTRIC ELASTOMERS AS ELECTROMECHANICAL TRANSDUCERS



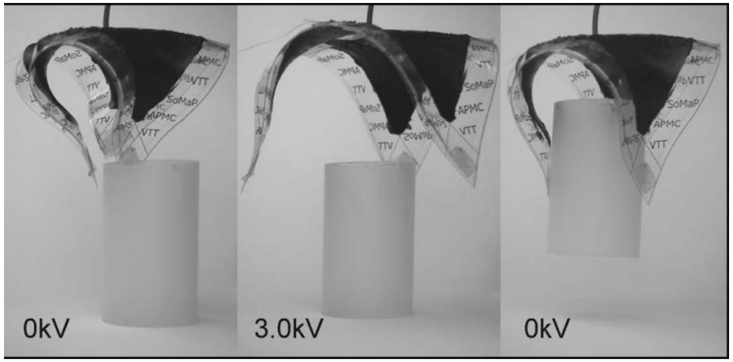
Pelrine et al., Science, 2000



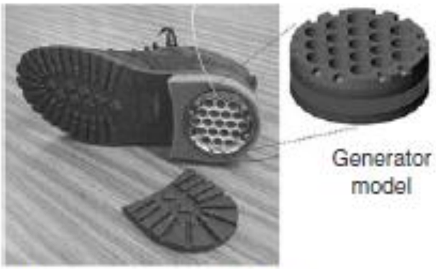
TRANSDUCER

ACTUATOR

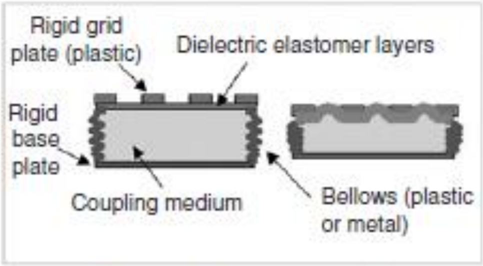
GENERATOR



Kofod et al., APL, 2007



Mockup of generator installed in boot



Schematic of generator operation

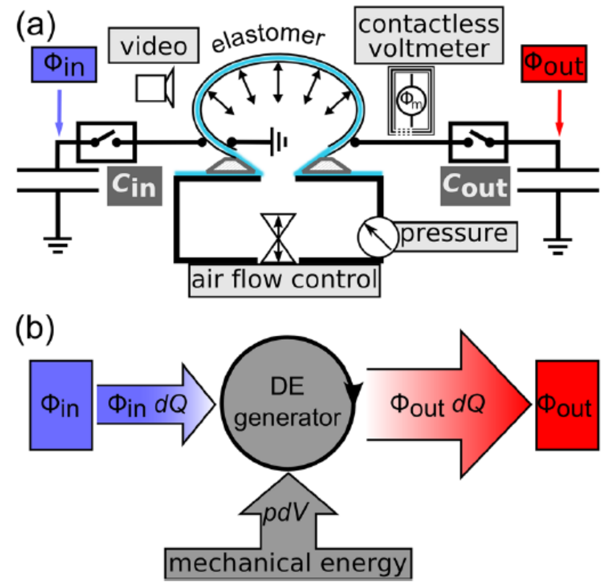
Prahlad et al., 2005

MOTIVATION – DEGs AS EMERGING TECHNOLOGY

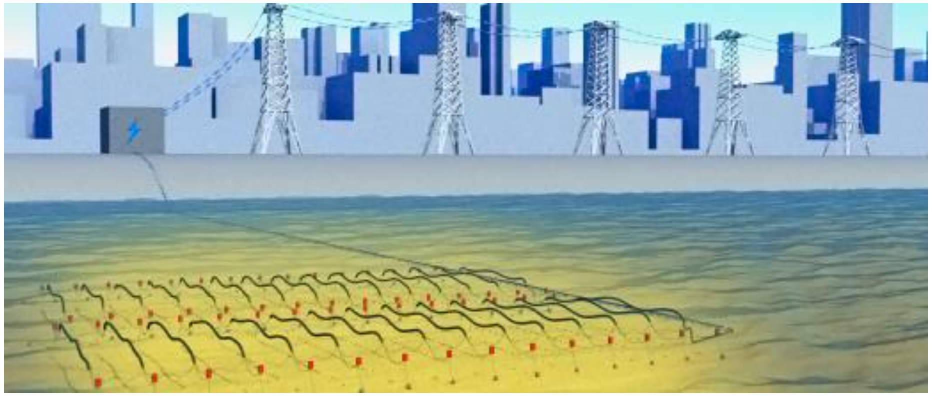
- Research activity on soft homogeneous dielectric elastomer generator (DEG) started around 2007/08 (both theoretically and experimentally).

  Relevant papers: Koh et al. (2009), Mc Kay et al. (2011), Foo et al. (2012), Appl. Phys. Lett.

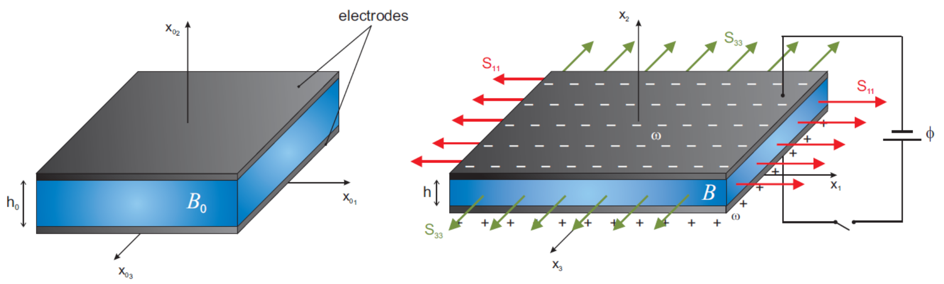
- A large scale project just started in France for exploting sea-wave motion (by SBM Offshore that designed a large soft DE ring generators of 800mm diameter with multiple layers).



Kaltseis et al. (2012) APL



LOAD-DRIVEN DE GENERATORS: THE MODEL

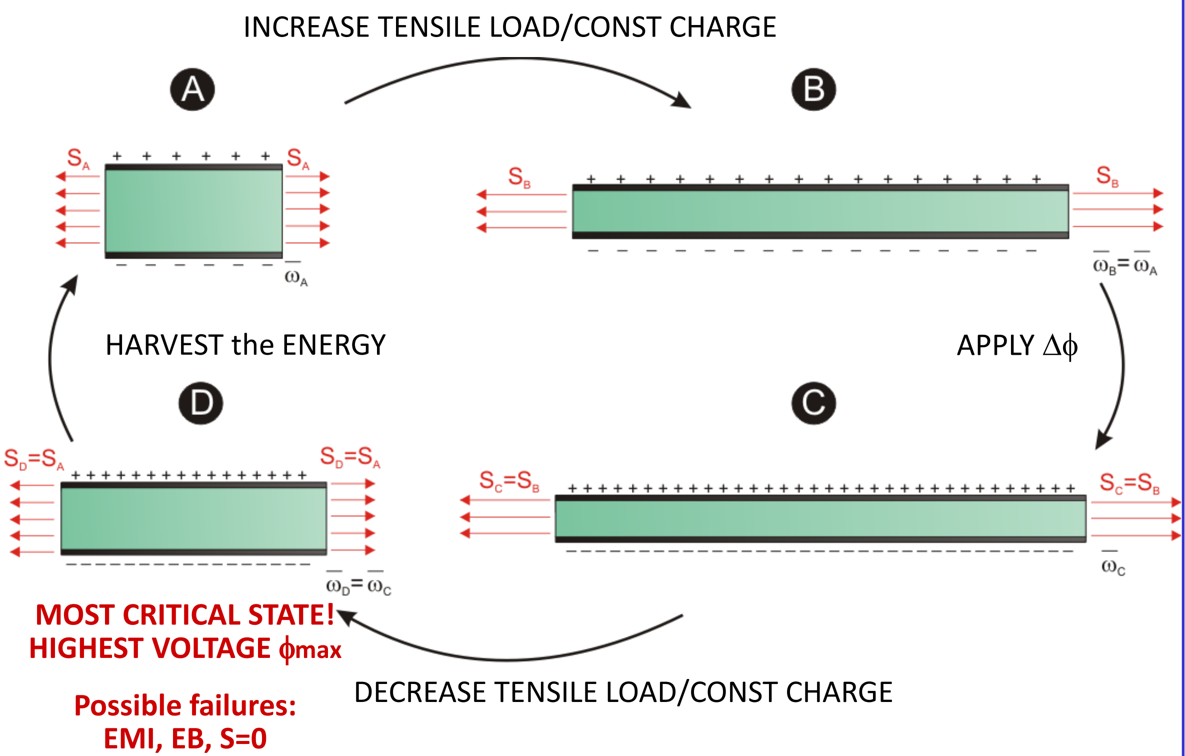


Soft dielectric generator :

- homogeneous;
- neo-hookean;
- ideal dielectric;
- subjected to a plane strain state.

Four step load-driven cycle :

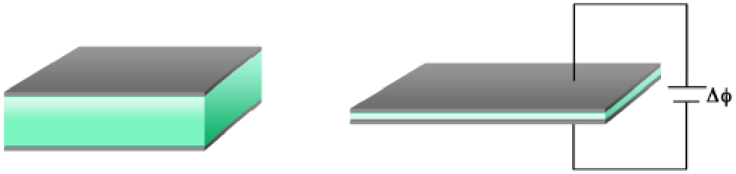
1. AB stretch of the layer by increasing the tensile load, constant charge;
2. BC increase in the charge by applying a voltage $\Delta\phi$, constant load;
3. CD release the stretch by decreasing the tensile load: the voltage between the electrodes increase;
4. DA harvest the electrical energy by removing the charge surplus at constant load.



MODES OF FAILURE

DIELECTRIC ELASTOMERS are susceptible of **SEVERAL MODES OF FAILURE**:

- ELECTROMECHANICAL INSTABILITY (EMI)



- LOSS OF THE TENSILE STRESS STATE (**S**=**0**)
- ELECTRIC BREAKDOWN (EB)
- MATERIAL RUPTURE (λ_u)

ADMISSIBLE STATE REGION for the generator

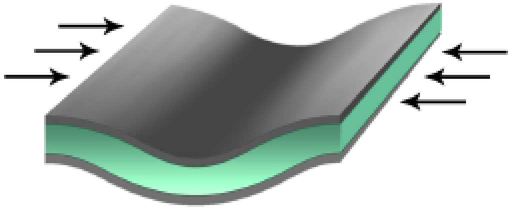
= MAXIMAL ENERGY achievable during a cycle on the ELECTRICAL PLANE

= MAXIMAL ENERGY achievable during a cycle on the MECHANICAL PLANE

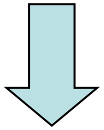
MODES OF FAILURE

DIELECTRIC ELASTOMERS are susceptible of **SEVERAL MODES OF FAILURE**:

- ELECTROMECHANICAL INSTABILITY (EMI)
- LOSS OF THE TENSILE STRESS STATE (**S**=**0**)



- ELECTRIC BREAKDOWN (EB)
- MATERIAL RUPTURE (λ_u)



ADMISSIBLE STATE REGION for the generator

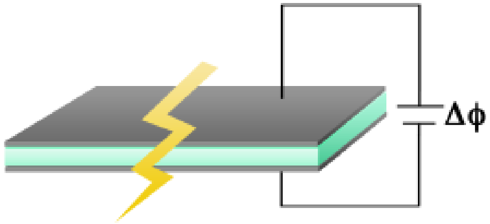
= MAXIMAL ENERGY achievable during a cycle on the ELECTRICAL PLANE

= MAXIMAL ENERGY achievable during a cycle on the MECHANICAL PLANE

MODES OF FAILURE

DIELECTRIC ELASTOMERS are susceptible of **SEVERAL MODES OF FAILURE**:

- ELECTROMECHANICAL INSTABILITY (EMI)
- LOSS OF THE TENSILE STRESS STATE (**S=0**)
- ELECTRIC BREAKDOWN (EB)



- MATERIAL RUPTURE (λ_u)

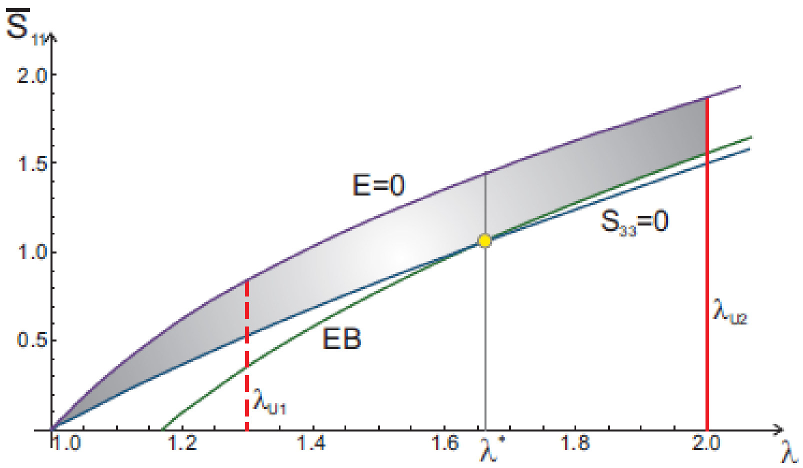
ADMISSIBLE STATE REGION for the generator

= MAXIMAL ENERGY achievable during a cycle on the ELECTRICAL PLANE

= MAXIMAL ENERGY achievable during a cycle on the MECHANICAL PLANE

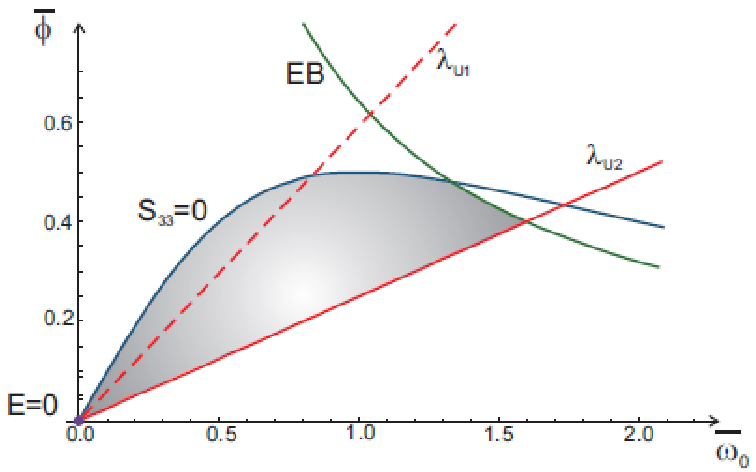
DIMENSIONLESS QUANTITIES

(a)



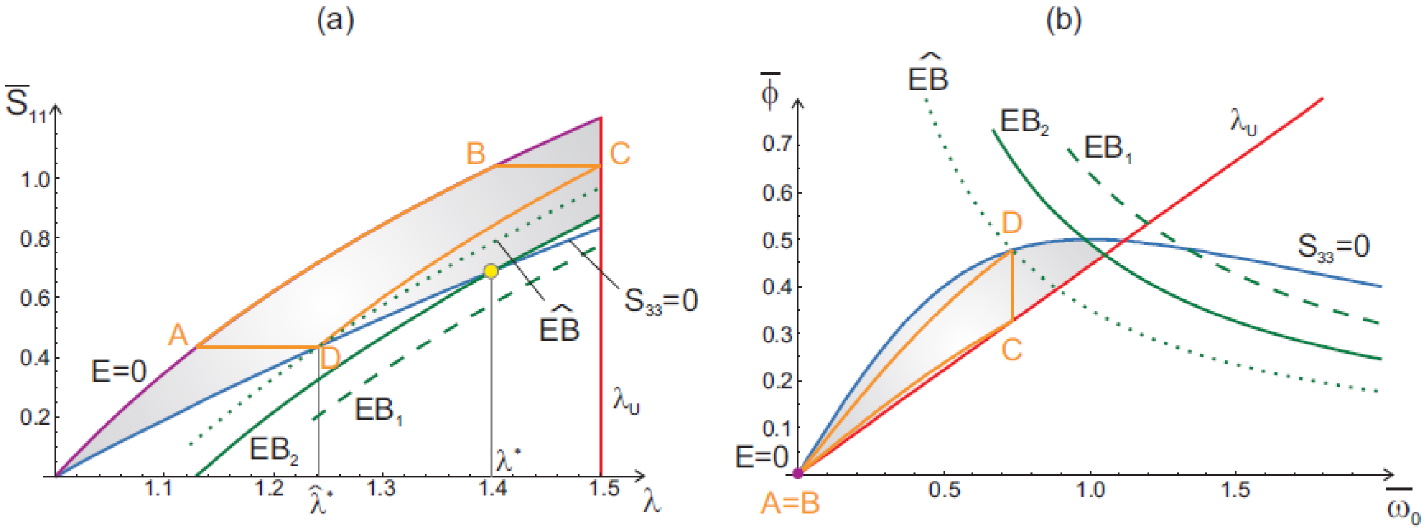
Mechanical plane

(b)

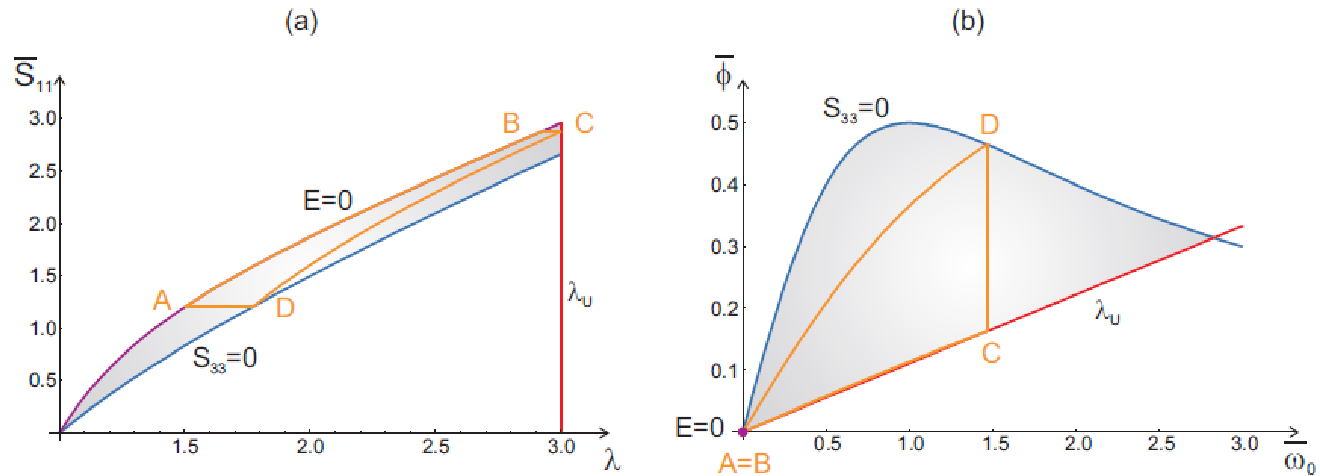


Electrical plane

OPTIMAL CYCLES FOR DIFFERENT λ_u



Optimal cycle for λ_u =1.5 with $E_{eb} \geq 0.5922$. The dotted curve EB corresponds to the transition between Cases 2a and 2b



Optimal cycle for λ_u =3 with $E_{eb} \geq 0.5922$

CONSTRAINED OPTIMIZATION PROBLEM

Expression for the dimensionless generated energy (energy density per unit shear modulus)

$$H_g = \frac{1}{2}(\lambda_A - \lambda_D)\left[\lambda_D\left(3\bar{\phi}_D^2 - 1\right) + 2\lambda_A + 3\lambda_D^{-3}\right] + \frac{1}{2}(\lambda_C - \lambda_B)\left[\lambda_B\left(3\bar{\phi}_B^2 - 1\right) + 2\lambda_C + 3\lambda_B^{-3}\right]$$

The optimization problem is formulated as follows

$$\text{find} \min_{\boldsymbol{\Lambda}} H_g[\lambda_A, \lambda_B, \lambda_C, \lambda_D] \qquad \boldsymbol{\Lambda} = [\lambda_A, \lambda_B, \lambda_C, \lambda_D]^T$$

subjected to be active constraint $f[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = -\lambda_C + \lambda_U = 0;$

and to the possible active constraints

$$h_1[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = S_{33}^D[\lambda_A, \lambda_B, \lambda_C, \lambda_D] \geq 0,$$

$$h_2[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = -\bar{E}_D^2[\lambda_A, \lambda_B, \lambda_C, \lambda_D] + \bar{E}_{eb}^2 \geq 0,$$

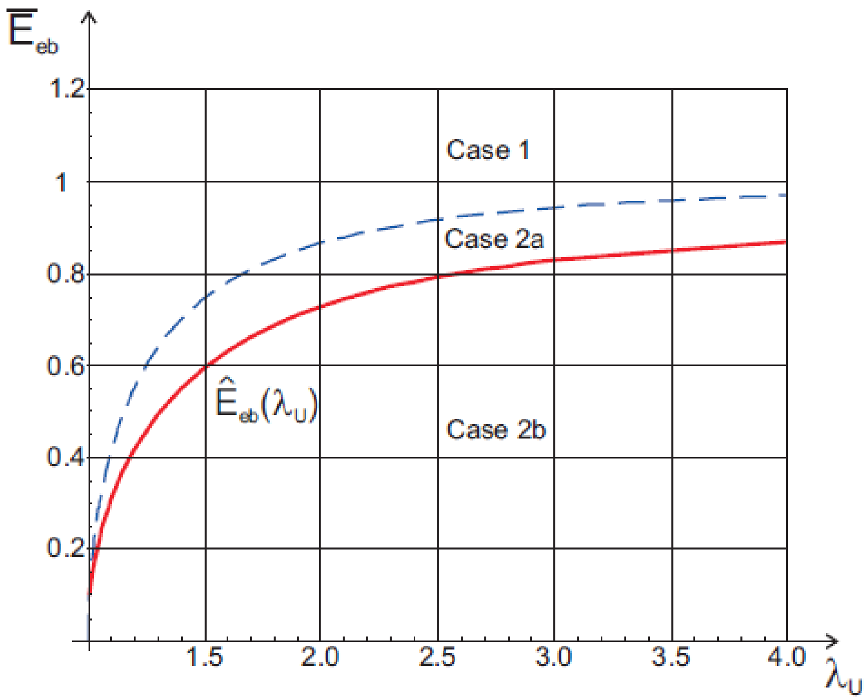
$$h_3[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = \bar{\phi}_B^2 \geq 0 \quad \text{i.e. } \bar{\phi}_B \in \mathbb{R},$$

$$h_4[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = \lambda_A - 1 \geq 0, \qquad h_5[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = -\lambda_A + \lambda_U \geq 0,$$

$$h_6[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = \lambda_B - 1 \geq 0, \qquad h_7[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = -\lambda_B + \lambda_U \geq 0,$$

$$h_8[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = \lambda_D - 1 \geq 0, \qquad h_9[\lambda_A, \lambda_B, \lambda_C, \lambda_D] = -\lambda_D + \lambda_U \geq 0.$$

UNIVERSAL CURVE TO EXPLOIT THE FULL POTENTIAL OF A DE MATERIAL



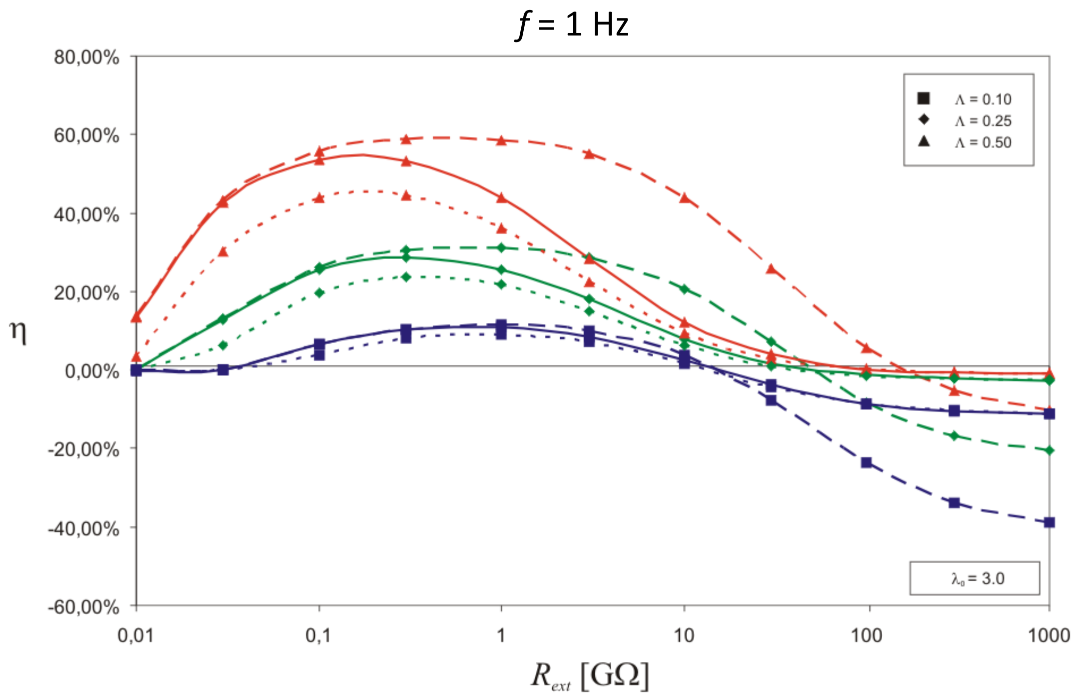
The red curve is an "universal curve" showing the ideal combination of material parameters E_{eb} – λ_u for which the maximum energy can be extracted. If the property pair (λ_u, E_{eb}) is located above this curve the optimal cycle will not depend on E_{eb} and the full potential is not exploited. Thus, in order to extract the maximum from a DEG it is recommended that the pair (λ_u, E_{eb}) be as close as possible to the curve.

GENERATED ENERGY FOR TWO MATERIALS

3M VHB-4910 and acrylonitrile butadiene rubber (NBR)

	$E_{eb_1} = 20$ MV/m					$E_{eb_2} = 100$ MV/m				
Material	$S_{\max}$ [kPa]	μH_g [kJ/m^3]	$\Delta\phi/h_0$ [kV/mm]	λ_C	M-C	$S_{\max}$ [kPa]	μH_g [kJ/m^3]	$\Delta\phi/h_0$ [kV/mm]	λ_C	M-C
VHB-4910	94.2	3.99	9.9	1.5	(2b)	87.0	5.33	14.62	1.5	(1)
NBR	94.2	0.37	15.4	1.024	(2a)	87.0	0.32	14.81	1.022	(1)
VHB-4910	246.3	7.60	2.5	3	(2b)	240.5	22.72	7.3	3	(1)
NBR	246.3	1.86	18.2	1.059	(2b)	240.5	2.48	23.3	1.064	(1)

FURTHER DEVELOPMENTS: VISCOELASTIC EFFECTS



HYPERELASTIC

VISCOELASTIC

ELECTROSTRICTIVE