Design of Underground Power Electronics and its Thermal Management

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Contents

Introduction

FLEXINet

- **FLEXINet**: Integrates Thermal and Electric energy storage to **improve** the **flexibility** and **sustainability** of the electrical network.

- For easy integration, the **placement** of the underground thermal energy storage system and the high-energy battery becomes critical.

- **Dimensions** of high-energy **battery system and Power Electronics Interface** (PEI) are **immense** and can occupy ample space for residential use and therefore are **placed underground.**

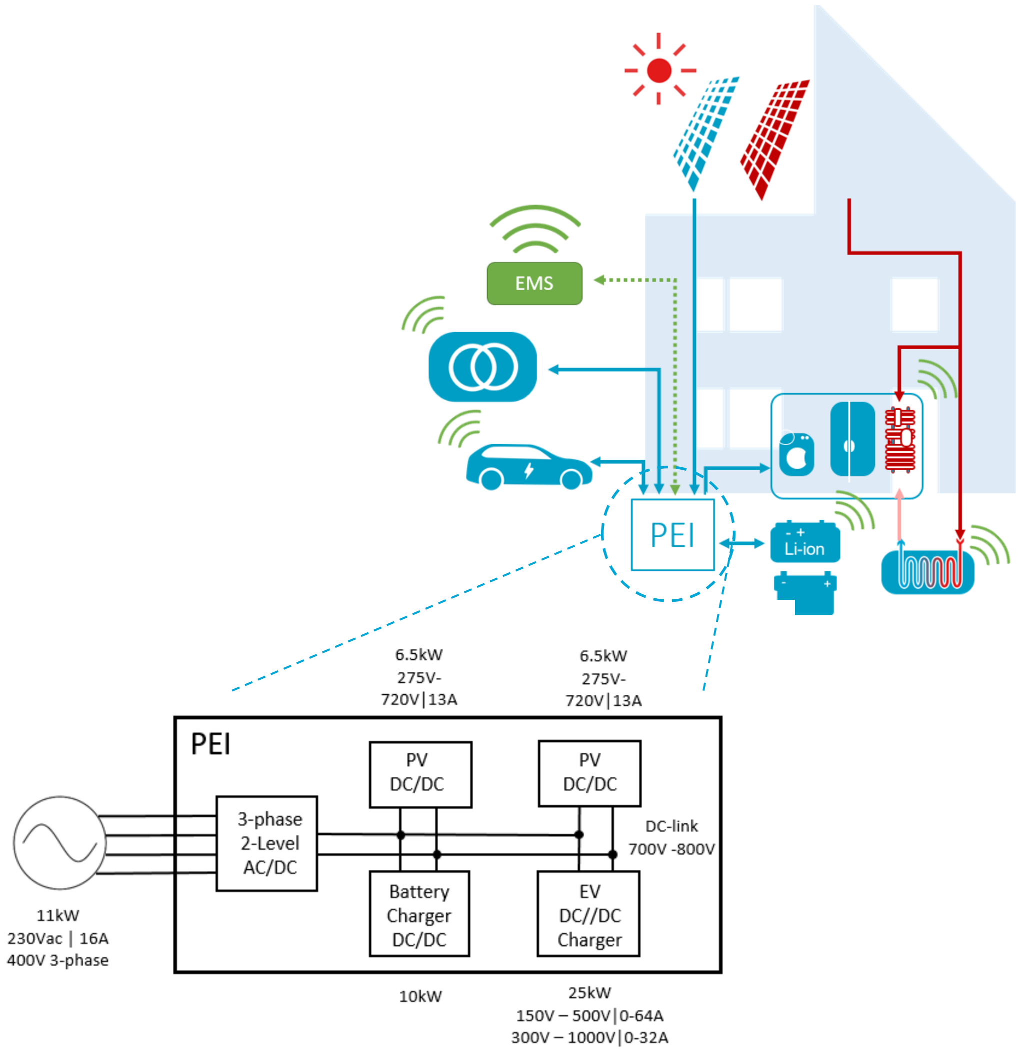

Figure 1: FLEXINet system

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FLEXINet

- Power Electronic Interface (PEI) is the **multiport converter** with **DC-coupled** architecture.
  - 3-phase 4-line, 11 kW grid-tied inverter.
  - Two PV DCDC converters, each 6.5 kW.
  - 25 kW EV DCDC converter .
  - 10 kW battery charger DCDC converter.

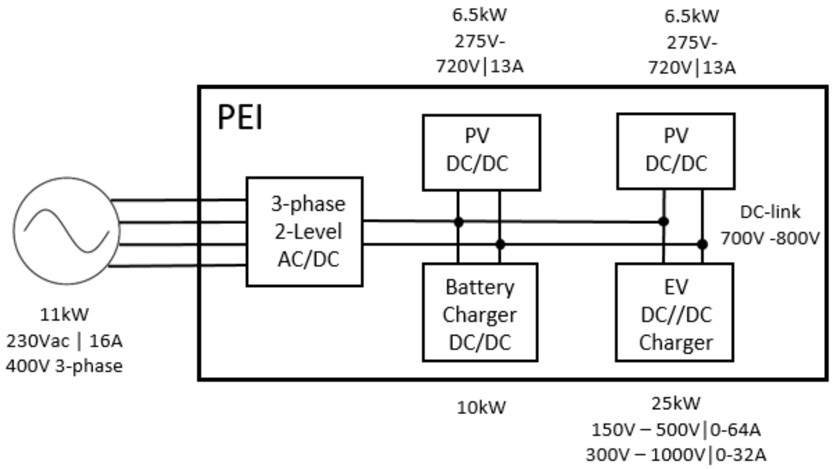

Figure 2: Power Electronics Interface

Problem Definition

- Due to enclosed space underground, typical **forced air convection cooling** is **ineffective**.
- Whereas **liquid convection cooling** is **expensive** and consumes **higher power** due to the presence of the pump to move fluid through pipes and cold plates.
- Therefore **cost-effective**, **low-maintenance** cooling solution for the underground multiport converter is necessary.

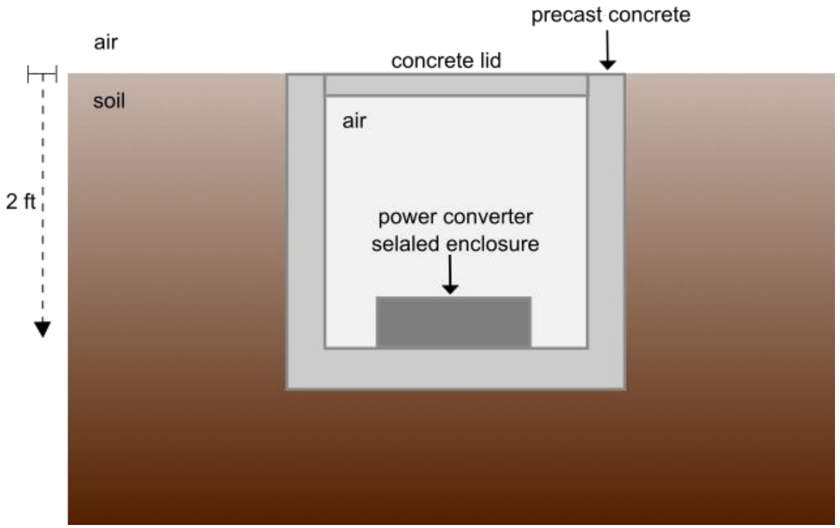

Figure 3: Power Electronics Interface placed undergound

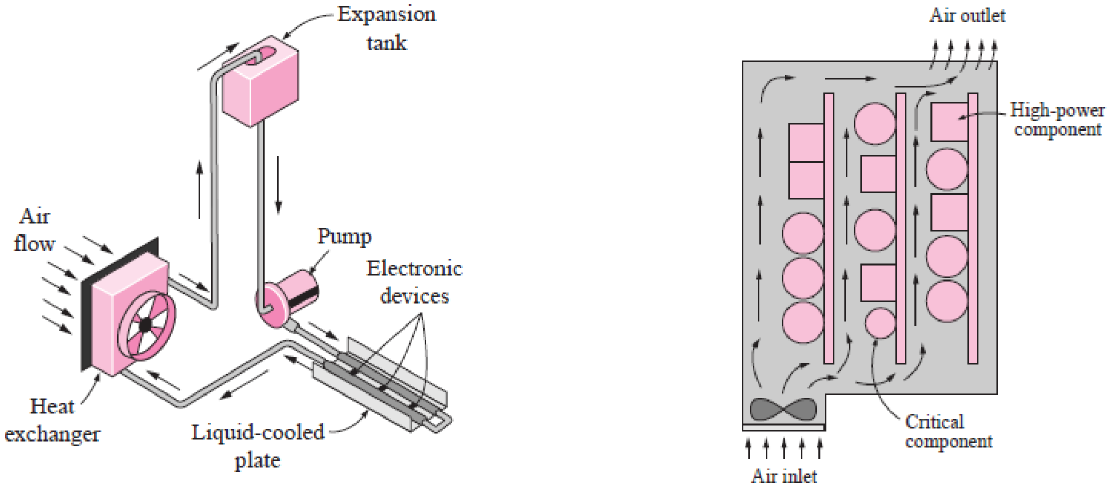

Figure 4: Forced liquid convective cooling and forced air convective cooling [1]

[1] *Heat and Mass Transfer A Practical Approach, 3rd Edition by Cengel*. (n.d.).

Research Goal

Research Goal

- The research aims to demonstrate how **subsurface soil** can **dissipate the heat from a power electronics converter** and how to **design a heat sink**.
- The research will also exhibit how the DCDC converter **modulation techniques** and **component packaging can improve the converter's cooling**.

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Topologies for underground power electronics

Toplogy

- Application-specific requirements of DCDC EV charger:

1. 25 kW output power.
2. Wide output voltage variation: 150V to 1000V.
3. Bi-directional power flow.

- Thermal management requirement of EV charger:

1. Design airless cooling solution.
2. The cooling solution must be cost-effective and low-maintenance.

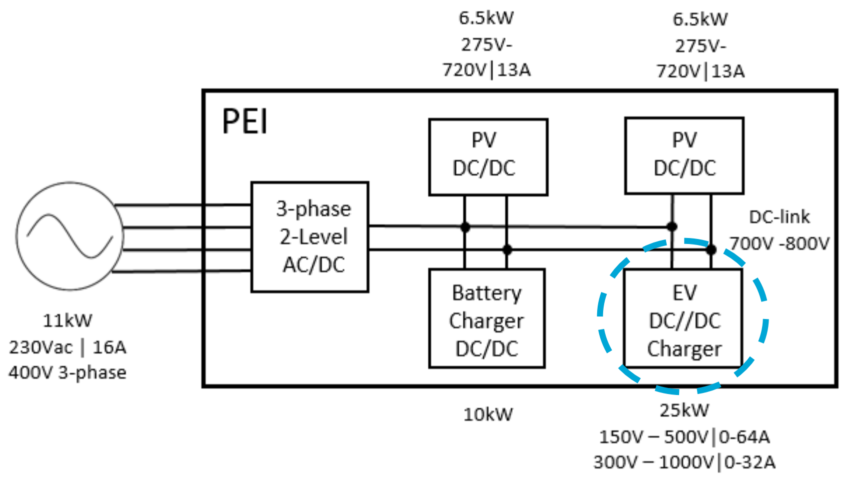

Figure : Power Electronics Interface

Parameters	Quantities
Output power	25 kW
Output voltage	150V-500V / 300V-1000V
Output current	0A-64A / 0A-32A
Input voltage	700V-800V

Table : Specification of the converter

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Toplogy

- For EV charging and V2G operation, the two most commonly used topologies found in the literature are:
  - **CLLC** resonant converter
  - **Dual active bridge** (DAB) converter

- These topologies have:
- **Soft-switching, therefore high, efficiency**
- **buck-boost capability**
- **bidirectional power flow capability**
- **Electrical Isolation**

Power Flow

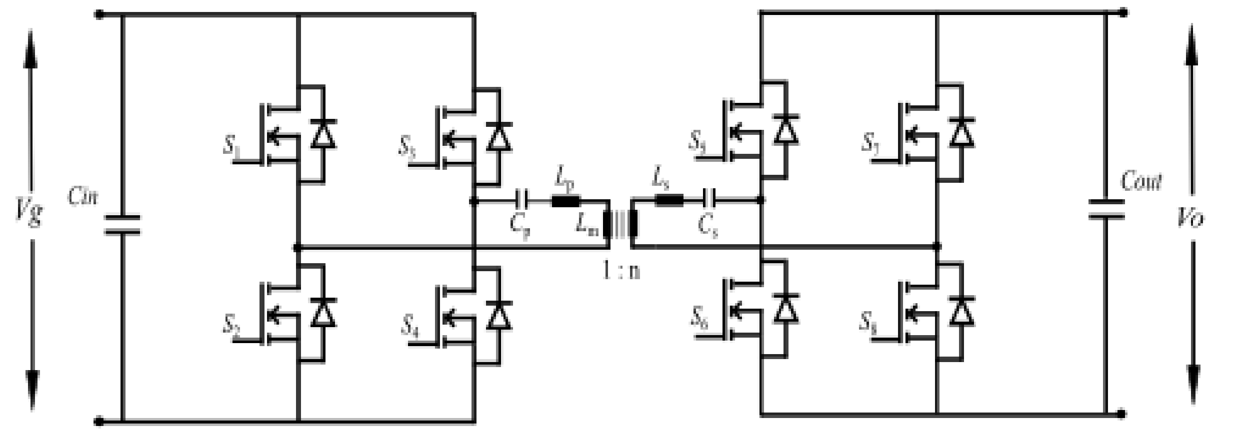

Figure: Symmetric CLLC converter

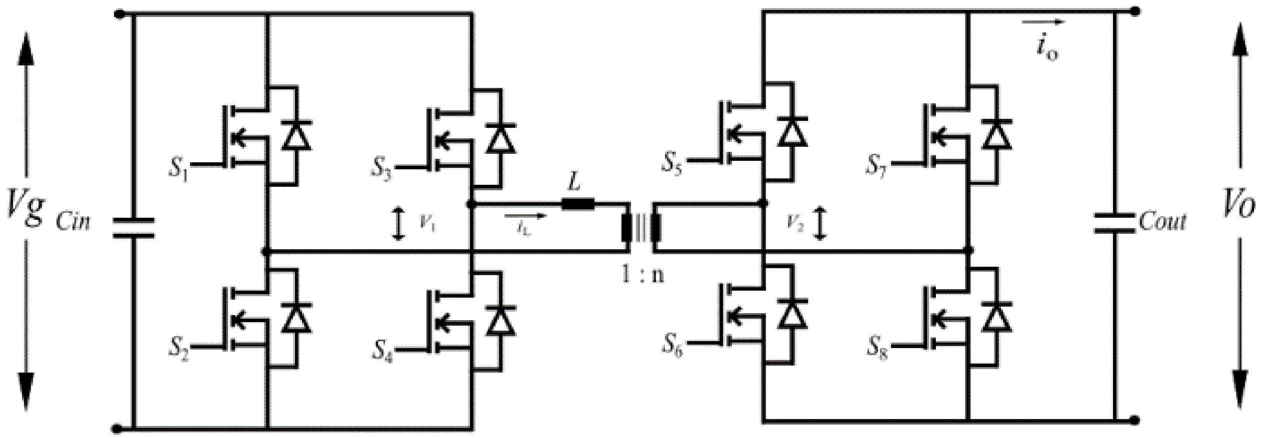

Figure: Dual Active Bridge converter

Toplogy

- Power electronics for underground application requires **minimum losses at higher power** to **reduce thermal management system size** and **cost**.
- DAB has less losses at full load than CLLC converter and, therefore, can be used in undergound application utilizing sub-surface soil for cooling.
- **Modular approach** will be considered in this research due to wide output voltage variation.
- Advantages of modular approach:
  - **Control flexibility**
  - Reducing current ripple by **interleaving** modules
  - Helps in reducing the **concentration** of **heat flux**.

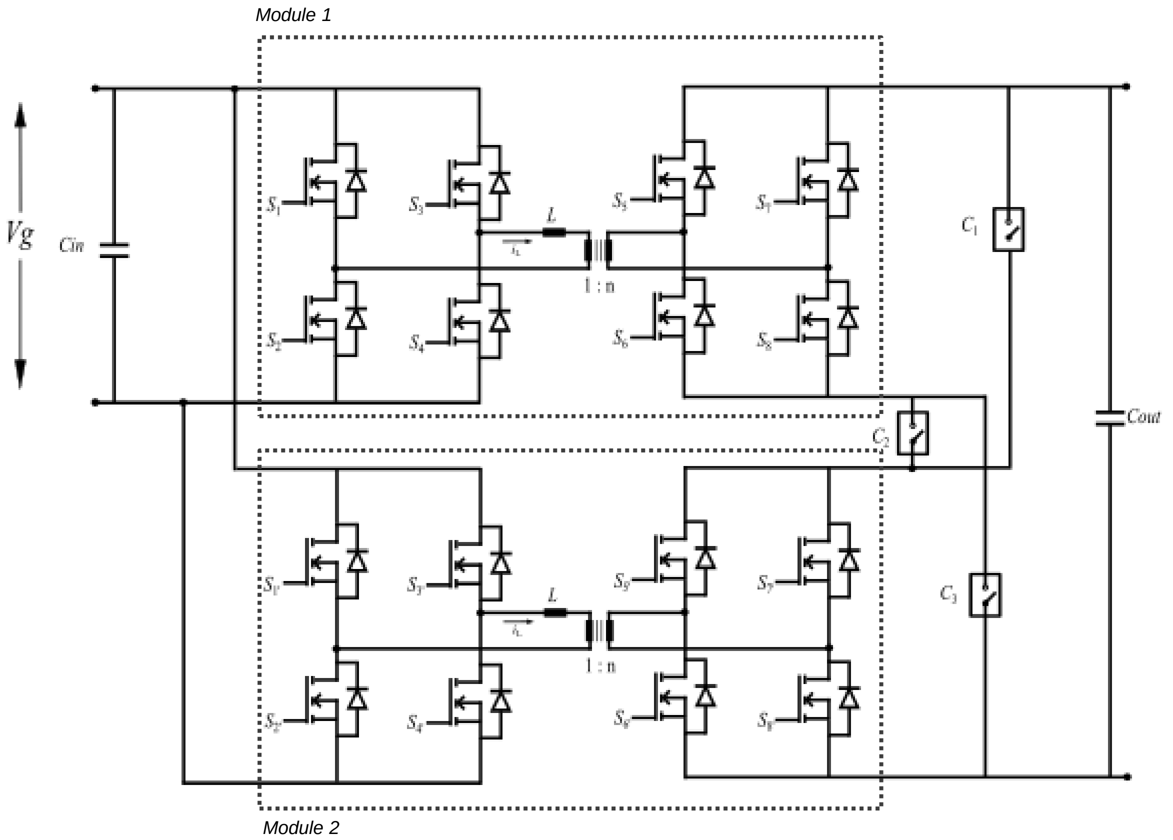

Figure: Parallel input and series/parallel output Dual Active Bridge converter

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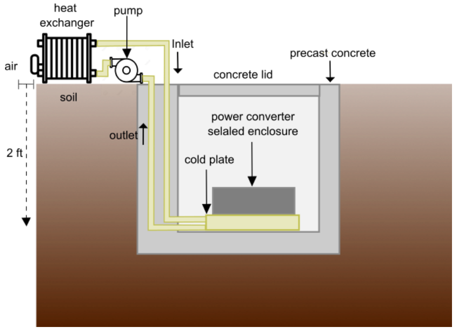
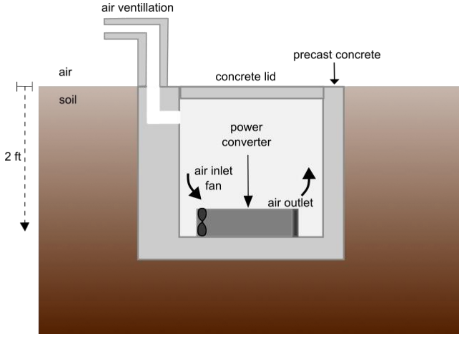
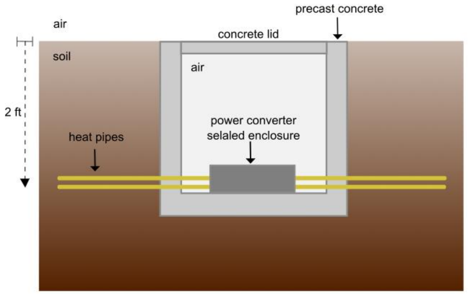
Soil as a heatsink

Heat sink design







Criteria	**Heat sink design using water convection cooling.**	**Heat sink using forced air convection cooling**	**Heat sink design using conductive cooling**
Maintenance cost	High maintenance cost	Moderate maintenance cost	**low maintenance cost**
Infrastructure cost	High infrastructure cost	Moderate infrastructure cost	High Infrastructure cost
Protection against the harsh environmental conditions	Strong protection, since the sealing of the converter is possible	Weak protection since vents is required, sealing of the converter is not possible.	**Strong protection, since the sealing of the converter is possible**
Cost of the heat sink	Very expensive due to loop piping and pumps	Cheaper than other alternatives	Moderate expensive, cost of several heat pipes and thermal interface assembly for conductive cooling.
Power required for cooling	Power is required to run the pump to move the working fluid through the pipes	power is required to run the fans for forced convective cooling	**No power is required for the heat pipes-based conductive cooling.**

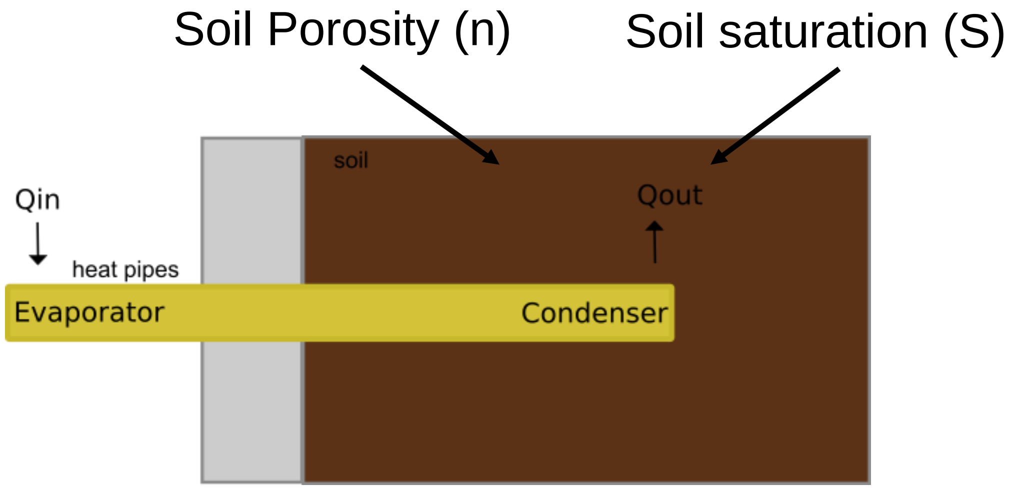
Table 2: underground power converter heatsink design

Soil as a Heat sink

- Heat conduction in the soil cannot be considered under stead state condition because the **temperature in the soil can vary with time and position**.
- It can be approximated by **one dimensional transient heat conduction** analysis.
- Transient one dimension equation:

$$\frac{\partial}{\partial t} = (D_T \frac{\partial^2 T}{\partial^2 x})$$

- Therfore, the properties of the soil required to study for heat transfer in the soil:
  - Thermal diffusivity $(D_T) = k/C$
  - Volumetric heat capcity (C)
  - Thermal conductivity (k)



$$C = \sum f_m C_m + f_o C_o + f_w C_w$$

Figure: Heatpipe soil interface

$$C_{soil} = (1-n)\sum_i f_{solid,i} C_{solid,i} + nSC_{water} + n(1-S)C_{air}$$

$$k_{soil} = \left(\prod_i k_{solid,i}^{(1-n)f_{solid,i}}\right)\left(k_{water}^{nS} k_{air}^{n(1-S)}\right)$$

Where f denotes the volume fraction of each phase: mineral matter (m), organic matter (o), and water (w)

Soil Properties

- Desired soil properties
  - **Higher thermal conductivity**
  - **Lower Thermal heat capcity**
  - **Higher thermal diffusivity**

- **Saturated Sand** has the most desirable thermal properties for heat transfer.

soil type	n $[m^3/m^3]$	S $[m^3/m^3]$	κ $[W/m.K]$	C $[MJ/m^3.K]$	ρ $[Kg/m^3]$	c_p $[J/Kg.K]$	α $[mm^2/s]$
Dry sand	0.4	0.2	1.07	1.50	1679.6	892.5	0.714
Saturated sand	0.4	1	2.92	2.82	1994.8	1413.7	1.037
Dry clay	0.4	0.8	1.20	2.60	1910	1360.1	0.462
Dry clay (surface)	0.6	0.8	0.77	2.84	1540	1842	0.273
Saturated clay	0.4	1	1.54	2.93	1988.8	1472.2	0.527
Saturated clay (surface)	0.6	1	1.13	3.33	1658.2	2099.4	0.338

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Soil Properties

- Heating of the soil by the buried pipe results in **drying of the soil** adjacent to the heat pipe.
- This lower the thermal conductivity of the soil.
- This instability in soil properties is casued due to **moisture migration.**
- To consider the constant thermal properties of the soil, surface heat transfer rates of the heat pipe need to be small.
- Therfore in one dimensional transient heat analysis, **Thermal diffusivity** cannot be considered constant in case of mosture migration :

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial x}(D_T \frac{\partial T}{\partial x})$$

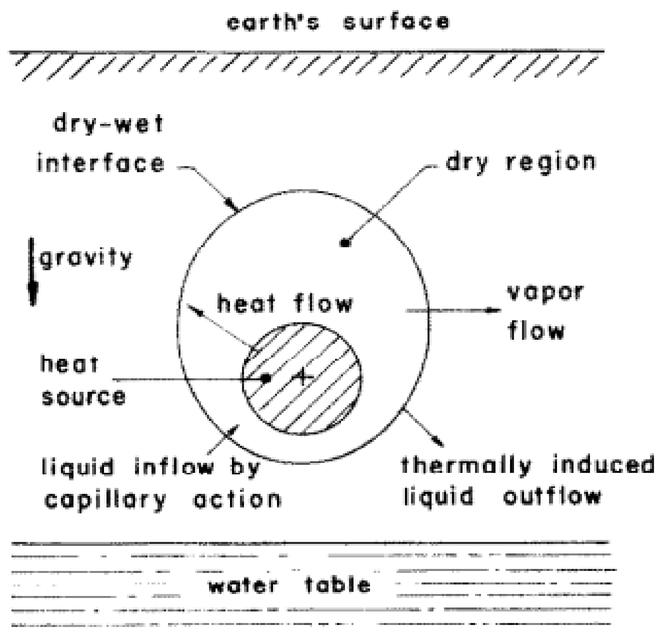

Figure: Moisture migration in soil [2]

[2] Baladi, J. Y., Ayers, D. L., & Schoenhals, R. J. (n.d.). AND MASS TRANSFER IN SOILS

Soil properties

- The **damping depth** is the depth at which the amplitude of the temperature fluctuations at the surface decreases to the fraction of 1/e(0.37).

- Equations shows the combined effect of the annual and diurnal variation in soil temperature.

$$T(z,t) = \bar{T}_y + A_y[sin(\omega_y t - z/d_y)]e^{z/d_y}$$
$$A_d[sin(\omega_d t - z/d_y)]e^{z/d_d}$$

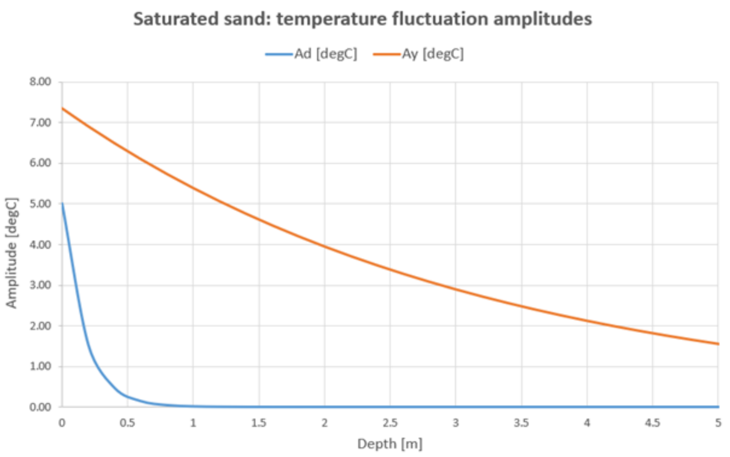

Figure: Annual and daily damping of temerpature with the soil depth

Soil properties

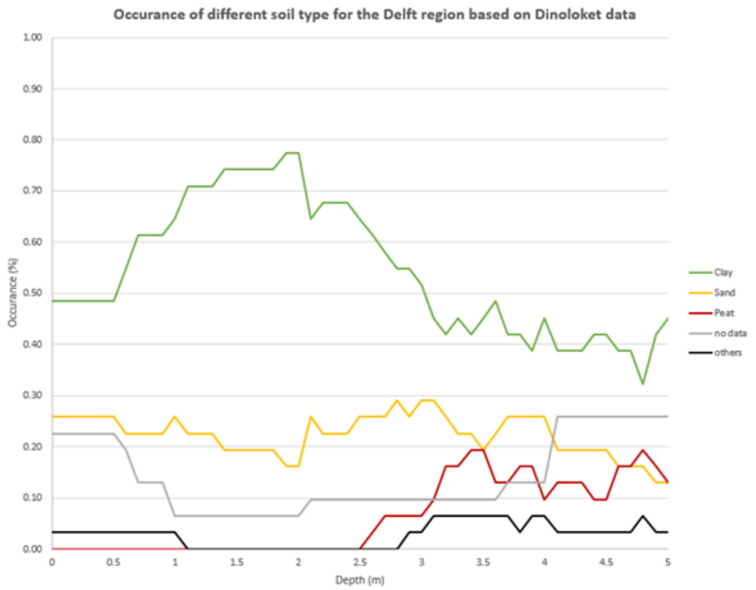

Figure: Soil types found in Delft

Packaging of power electronics

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Packaging of DCDC converter

- Heat pipe assembly with PCB and Chassis
- Heat can be transported to soil with the **arrays** of **heat pipes**.
- The critical parameter to consider while designing heat pipe interface in soil:
  - Power capacity of each heat pipe
  - Diameter of heat pipes
  - Length of the heat pipe
  - Orientation of heat pipe
  - Placement of heat pipes
- To avoid **moisture migration** in the soil, heat pipe power and distance between the heat pipe are important.

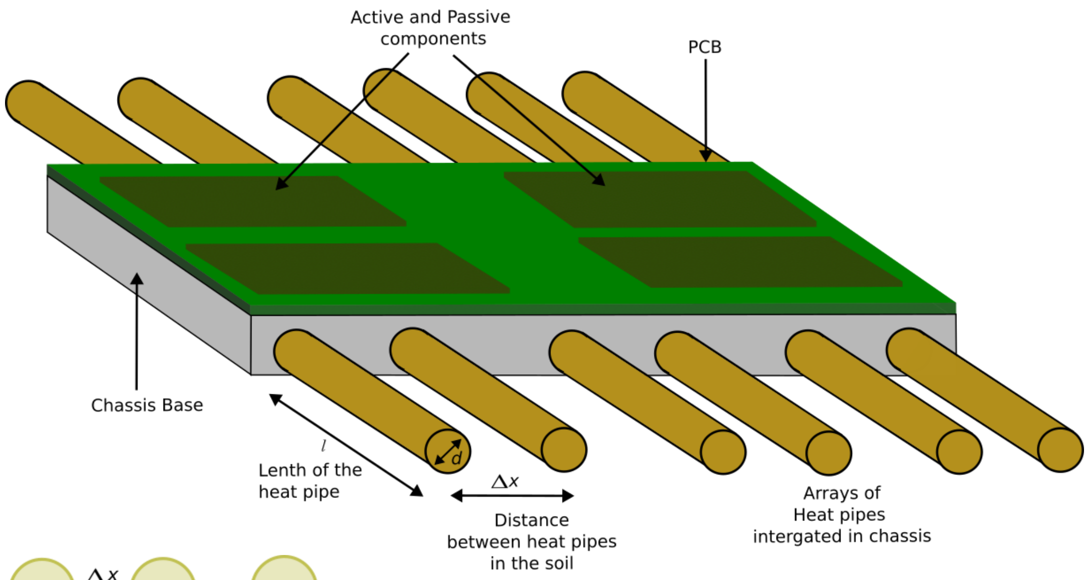

Figure: Heat pipe integrated chassis and PCB assembly

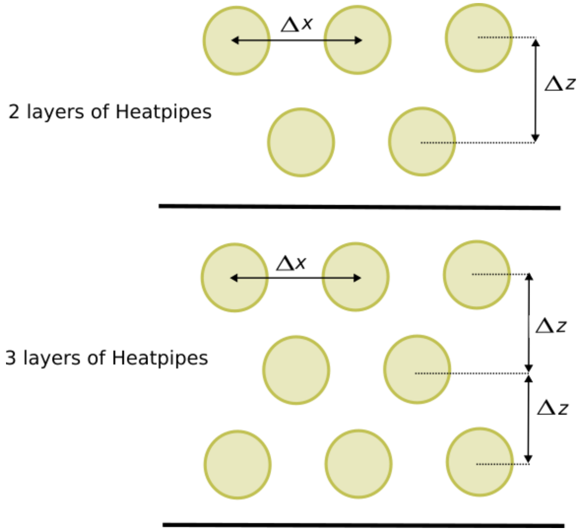

Figure: Layers of Heat pipe is soil

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Packaging of DCDC converter

- The heat pipe is a self-contained structure that achieves high thermal energy conductance utilizing **two-phase fluid** flow with **capillary circulation.**

- The heat pipe's thermal conductivity is several thousand times that of copper.

- The performance of the heat pipe depends on the following:

  - Compatibility of materials
  - Operating temperature range
  - Heat transport limitation
  - Operating orientation
  - Length and diameter of the pipe

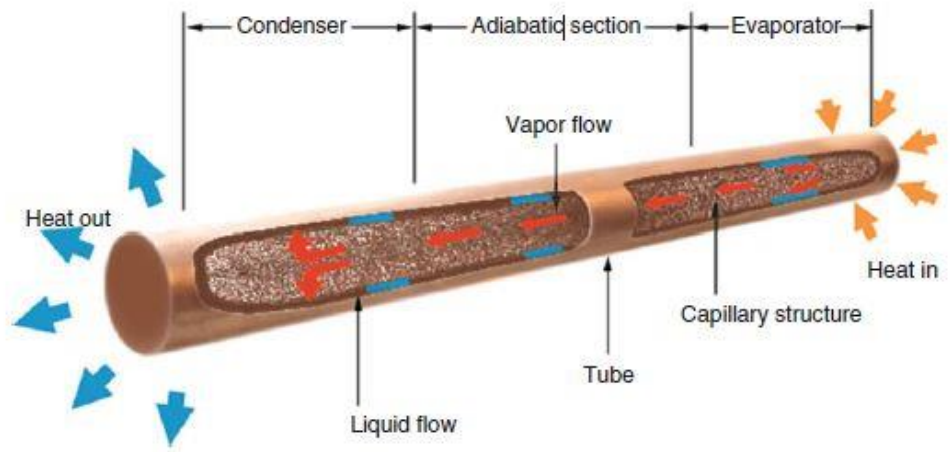

Figure : Heat pipe working [3]

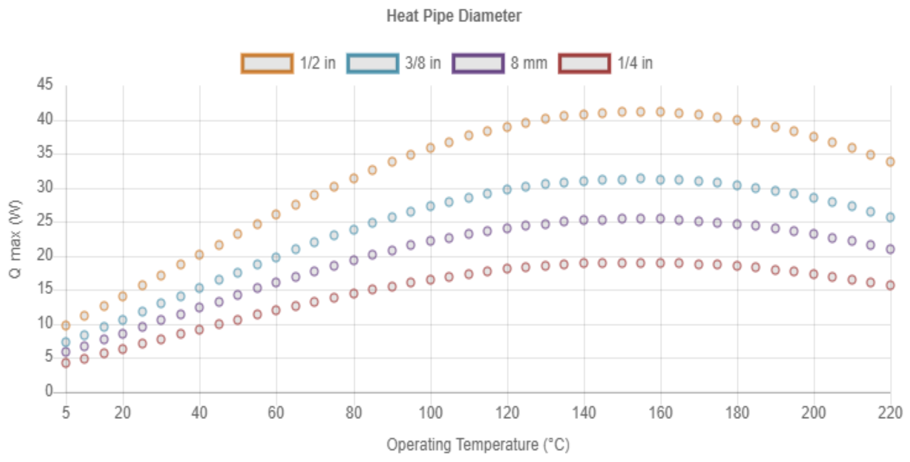

Figure: Heat pipe design tool [4]

Limits for copper/water heat pipe:

- 1000 mm long
- 100 mm evaporator
- 500 mm condenser
- operating 0 deg against gravity

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[3] Zohuri, B. (2016). Heat pipe design and technology: Modern applications for practical thermal management.
[4] https://www.1-act.com/resources/heat-pipe-calculator/

Packaging of DCDC converter

- The Thermal coupling between components and heatpipe is very important for transferring heat to the soil.

- Packaging of the components will allow **maximum power transfer** via **conductive coupling,** and only a few watts of the power is allowed for convection cooling.

- Convection cooling can be done using the **case of the enclosure** and by **heat pipe** with the help of the **fan re-circulating** the air inside the enclosure.

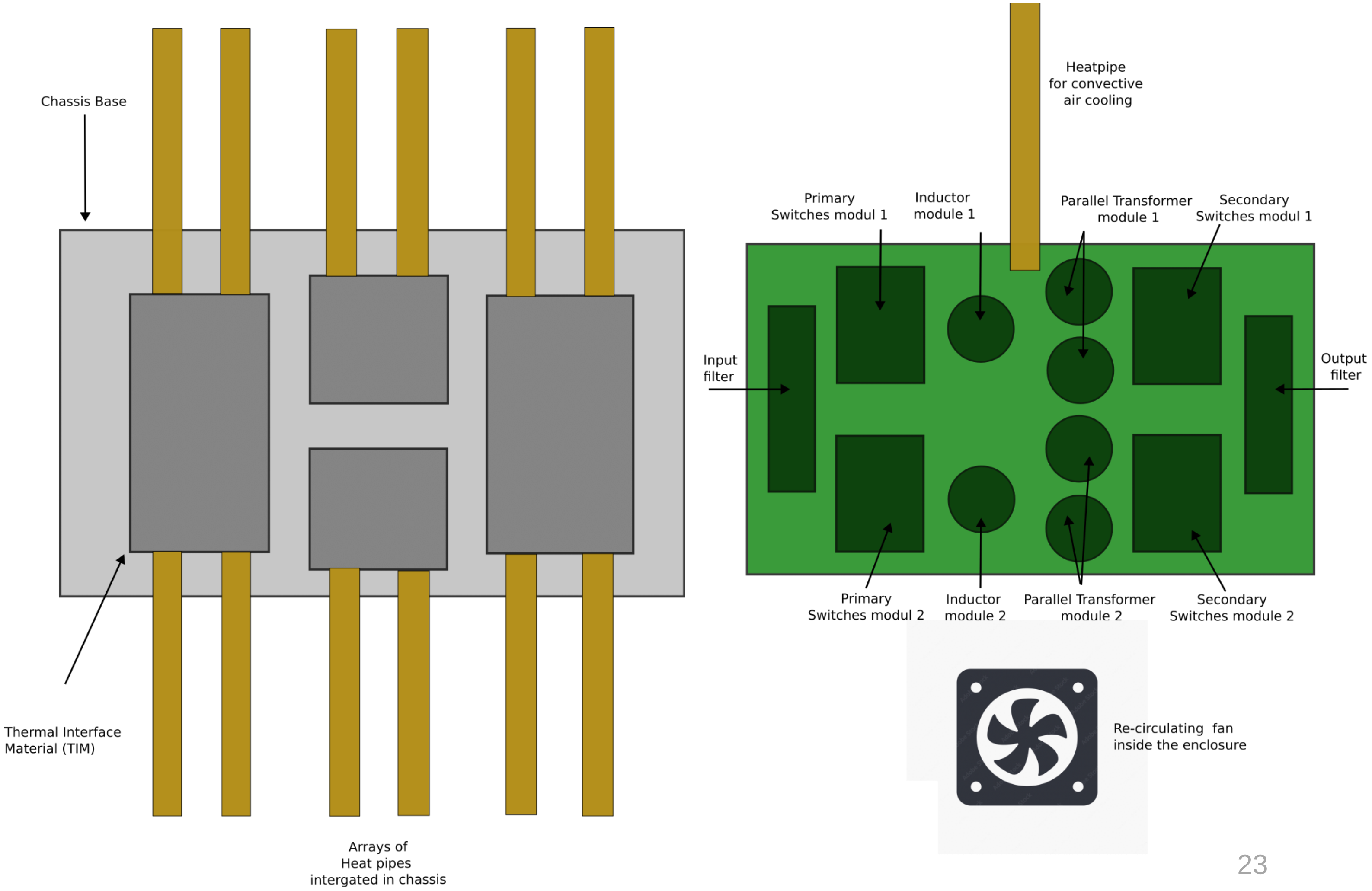

Figure 18: Heatpipe integrated chassis and PCB assembly

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Conclusion

- It is possible to dissipate heat in the soil conductively and operate the converter **without performance loss**.
- The sizing and number of heat pipes in the soil make the system **bulkier** and **harder to install**.
- Complete separation of heat source from the heat sink, allowing **easy sealing of power electronics** enclosure to prevent damage from water and dirt.
- It can improve cooling **system reliability** by removing the need for exterior fans exposed to harsh environments.
- Additionally, **significantly less power** is required to recirculate the air inside the enclosure, which can be dissipated using heat pipes.

Thank you