Design of a dual input energy harvester with independent maximum power point trackers

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- INTRODUCTION

In this thesis I propose one possible system architecture to face the problem of self supplied circuit. This typology of circuit become very important with the exponential growth of the internet of things, infact, the IoT require that our circuit must be able to work in any condition without the possibility of maintenance in an easy way.

Let's consider a Wireless Sensor Network, each node must be designed with a high consideration for the energy consumption and for the energy wasted among the different tasks that our net must execute. In order to increase the lifetime of the nodes and guarantee their functionality, we must provide alternative ways to supply the circuit.

The power supply units that we use could be able to generate energy in independent way, without require the mainteinance of an human operator. This purpose is reached with the energy harvesting, where the node generate in local the amount of energy that it needs, exploiting renewable energy sources. The issue is that each source provide a maximum amount of energy in specific condition that cannot be always available. It can be handled adding more energy sources at our node, in this way we can generate power supply in different condition.

The proposed system will use two different energy sources and will extract the maximum amount of energy. The design is carried forward having in mind three keypoints:

- scalability : we need an architecture able to work with harvester of different power

- simplicity : must be easy to modify and enlarge

- self-supply : the circuit the must able to supply itself

. In the following pages the documentation is reported with the same order used in the design phase : as first of all we need to understand better the problem of the energy harvesting, it follows a wide signal analisys to fix all the component used, after a small signal analisys where I test the circuit and the base algorithm for the MPPT, the design of the printed circuit board and, finally the measurement.

- ENERGY HARVESTING

Our goal is convert the energy in the environment around us in eletrical energy, this is done using different tipologies of harvesters. Each one use a different physical principle and is characterized by different advantages and disadvantages. Here i report an extract of [[1]]. Start from the most mature and used , the light.

- Light

Light is one of the most handling source, we can gain energy from the sun or from the artificial light, indoor or outdoor. It's the most efficient and thanks to the fact that is used from a lot of time, we have a deep consciousness. The best way is catch light directly from the sun and then storage theextra energy in the local batteries. If used in a smart way our node can survive until the next charge. The harvester used is the photovoltaic cell (PV). When a cell is reached by a photon, it absorbs this energy and is transferred to the electrons in the polycrystalline lattice that compound the cell. These electrons will be carried out from the lattice and an electric energy born.The quantity of electricity depends on the cell properties, from its efficiency e from the intensity of light that hit the surface.

- Mechanical

Vibrations, mechanical stress and pressure, strain from the surface of the sensor, high-pressure motors, waste rotational movements, fluid, and force are the effects that we use. The drawback is the unpredictability of these force, but we can control they. The basic idea is to exploit a spring-mass system in order to amplify the effect of the resonance phenomena, increasing the output power. It is implemented with three different techniques:

- Piezoelectric

This type of material are able to accumulate charges when stressed. when a force is applied it deforms the material generating an electric charge on the surface of the deformed material. Most commonly used materials are Piezo-ceramic lead Zirconate Titanate (PZT) and Piezo-polymer Polyvinylidene Fluoride (PVDF). Observe that PZT has good electrical characteristic but it is more weak from the mechanical point of view, in fact it can break under excessive stress, instead PVDF is more roubust but the amount of energy generated is lower.

- Electromagnetic

It's based on the electromagnetic induction, essentially we exploit the relative motion between a coil and a magnetic mass, so a magnetic field induces voltage in a fluctuating magnetic material and after we keep out the generated power.

- Electrostatic

Here the main idea is to change a capacitance of a vibration dependent variable capacitor. When a vibration occur, the plate of the previously charged capacitor change and generate an output power. They are well suited for MEMS (Micro Electro Mechanical System) level type of application, have a good output voltage and are long-lasting. The problem is that it needs an initial quantity of charge to start the process.

- Heat

Theoretically it's the best choice because heat is ubiquitous in the ambient environment. We can exploit the difference of temperature from any heat source to generate electrical energy. Two techniques can be used for this scope:

- Thermoelectricity

The seedback effect (1821) is exploited connecting two semiconductors at two point with different temperature, electrons at the hot junction at higher thermal velocities diffuse to the cold junction and produce an electromagnetic field between the two ends the problem in this technique is the low efficiency and the fact that after an amount of time, when the environment go in a steady heated state the two plate go at the same temperature and the harvester stop to provide energy.

- Pyroelectricity

It's observed at first time in quartz (1824), Pyroelectricity exploits specific materials which when applied with heat modifies the structure of the material which in turn changes polarization of the material, thus creating electric potential. today the material used for this energy conversion are polyvinylidene fluoride trifluoroethylene polymers and lead lanthanum zirconate titanate (PLZT) ceramics. Thanks to the miniaturization, the actual thermal systems are widely used, especially in biomedical implementation where we provide energy from the human body heat.

- Radiofrequency

The total amount of devices that uses radiofrequnecy to communicate fill the environment with a lot of energy carried by radioquency radiations. We are able to stole this energy with rectifying antenna that catch the signals in the etere and accumulate in storage devices. Here the problem is that the energy that is available is not very much, therefore its not widely used.

- Wind

Wind, as heat and solar, is one of the most convenient energy source. Wind can be harvested using turbine that, nowadays, can be very small and efficient. As in the other techniques, wind is unpredictable, it depends on the weather but in the rural environment it can be an efficient source. Summarizing, exists a lot of energy sources, each one with its own pros and cons. In order to design a node of our wireless sensor network truly energetical independent, the challenge is mix together all these sources to generate energy in any conditions of the environment where it will be embedded.

More information, with an higher level of detail about the different power sources can be founded on [2]. Now is necessary an overview of the electrical characteristic of the harvesters to understand which is the better way to combine they.

An interesting overview of the power density and efficiency is given in paper number [3] :

Energy harvesting technique	**Power density**	**Efficiency**
Photovoltaic	Outdoors (direct sun): 15 mW/cm^2 Outdoors (cloudy day): 0.15 mW/cm^2 Indoors: <10 µW/cm^2	Highest: 32 +- 1.5% Typical: 25 +- 1,5%
Thermoelectric	Human: 30 µW/cm^2 Industrial: 1 to 10 mW/cm^2	+- 0,1% +- 3%
Pyroelectric	8.64 µW/cm^2 at the temperature rate of 8.5 ◦ C/s	3,5%
Piezoelectric	250 µW/cm^3	Maximum power and efficiency are source dependent
Electromagnetic	Human motion: 1 to 4 µW/cm^3 Industrial: 306 µW/cm^3 , 800 µW/cm^3	Maximum power and efficiency are source dependent
Electrostatic	50 to 100 µW/cm^3	Maximum power and efficiency are source dependent
RF	GSM 900/1800 MHz: 0.1 µW/cm^2 WiFi 2.4 GHz: 0.01 µW/cm^2	50% Excluding transmission efficiency
Wind	380 µW/cm^3 at the speed of 5 m/s	5%

Table 1 : power density and efficiency of EH sources

An overview on the typical electrical characteristic of each source can be discovered in paper [4] :

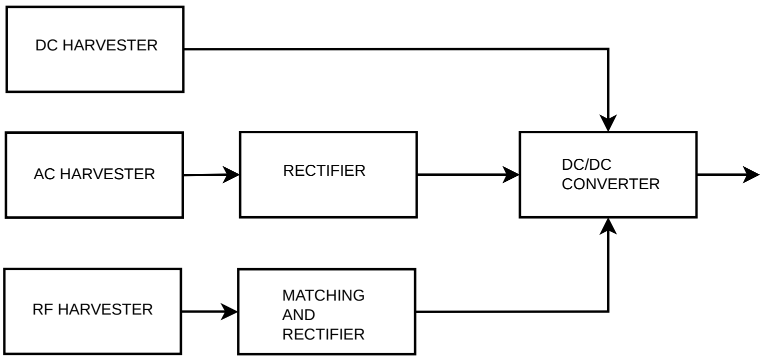
	Photoelectric	Thermoelectric	Piezoelectric	Electrostatic	Electromagnetic	RF
Polarity	DC	DC	AC	AC	AC	AC
Voltage	0.5 V – 5 V	10 mV-10 V	10V-100 V	1V-10V	0.5 V – 5 V	10 mV – 5 V
Power	10uW-100mW	0.5mW-10mW	1uW-10mW	10uW-100mW	10 uW – 100 mW	0.1 uW – 1 mW
Impedance	1kΩ - 100kΩ	1Ω-10kΩ	10kΩ-100kΩ	10kΩ-100kΩ	1kΩ-10kΩ	1kΩ-10kΩ
Challenge	impedance light dependent, indoor much less power	usually only small thermal gradient, efficient heat sink necessary	harvester frequency range fixed, phase shift of current & voltage	variable frequency, phase shift of current & voltage	infrequent short pulses with high energy from some harvesters	high frequency, low power at long distance

Table_2_electrical_characteristics_of_EH_sources

we can observe from the tables that:
- **RF** is not mature as harvesting technologies.
- **photovoltaic cells** must be present in any node, they provide the most efficient and economic energy source.
- **wind** is an optimal energy source when solar is not available and thanks to miniaturization turbine are more and more efficient
- **thermoelectric and electromagnetic** in closed environment, where solar and wind are very low, can be the best choice.

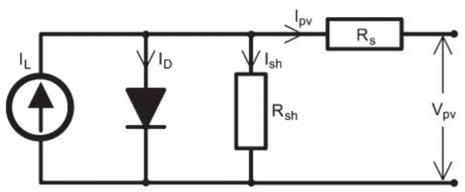
- Generalize the harvesters behaviour

We can generalize the beaviour of all the possible harvesters. The first useful think to note is that exists many energy source with two type of output power, but, if we put an additional blocks on the power path we are able to sum all togheter via a DC/DC converter.

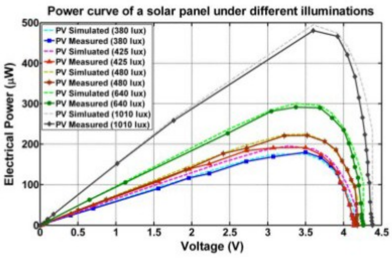


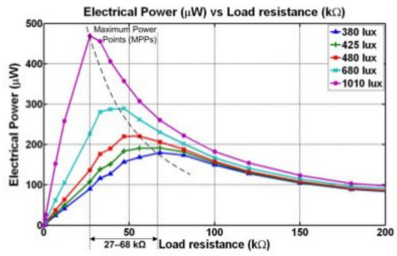
As we seen in the previous table, can be there AC or DC polarity, so, where required a rectifier block must be added. Instead, the radio-frequency harvester need special attention because a matching net must be designed.

Anyway, the truly keypoint is the power curve of each harvester. Let's see different power curve in order to understand how to generalize. From [5] we have a look on photovoltaic cell behaviour :

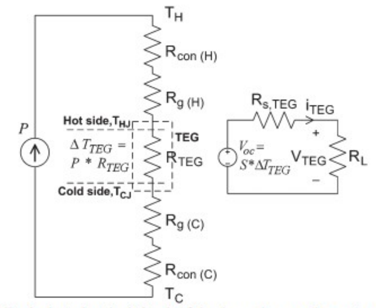


Equivalent electrical circuit for a photovoltaic module.

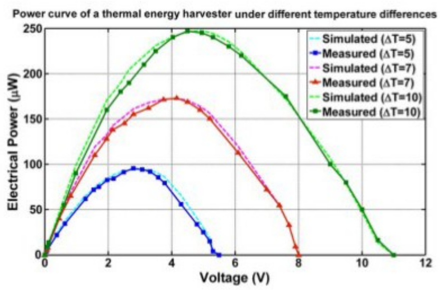


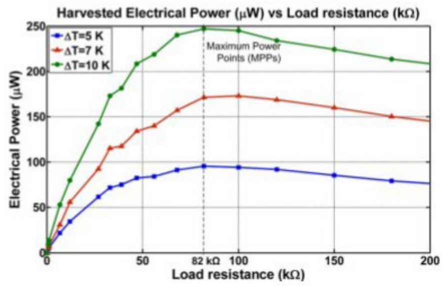


and a thermoelectric generator :

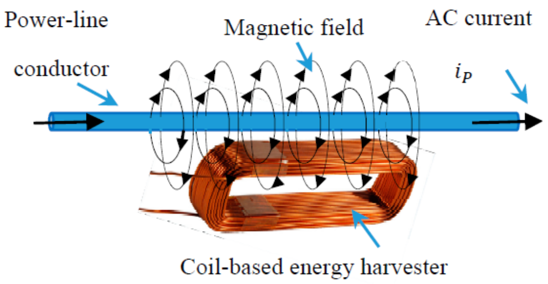


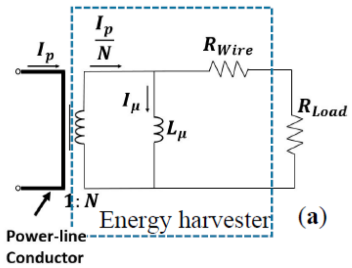
Equivalent electrical circuit of the thermal energy harvester.

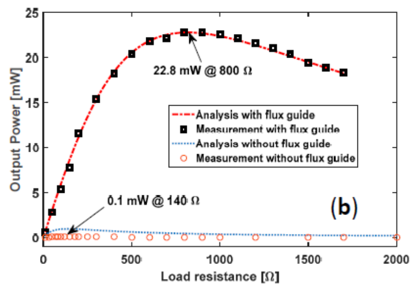




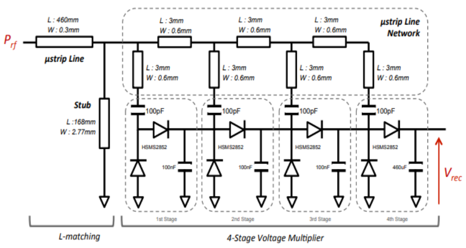
from [6] we can observe the power curve of one coil based harvester :



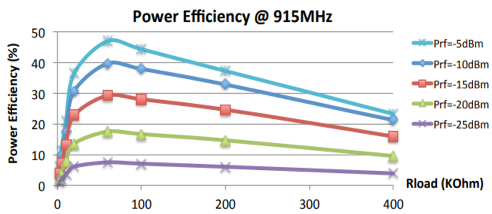


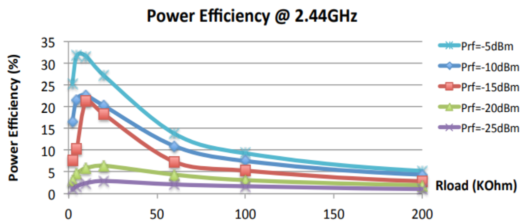


the reference [7] show us the power curve obtained from a dual band RF energy harvester:



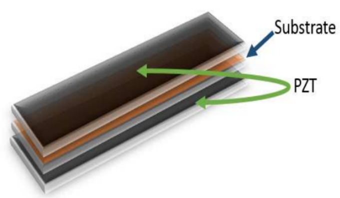
Architecture of the RF to DC converter





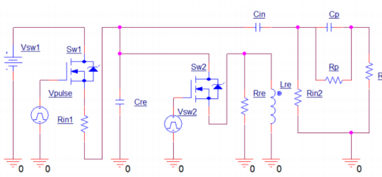
in [8] the authors provide an exaustive analisys of a piezoeletric harvester:

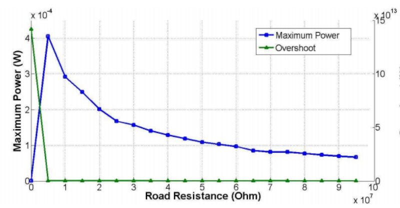
(a)



(b)

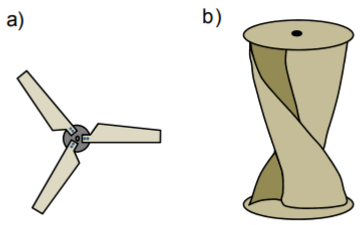
The piezoelectric structure. (a) Actual structure, (b) basic structure


The electromechanical model of the PZT

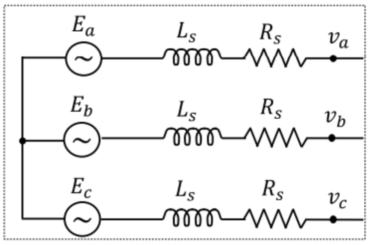


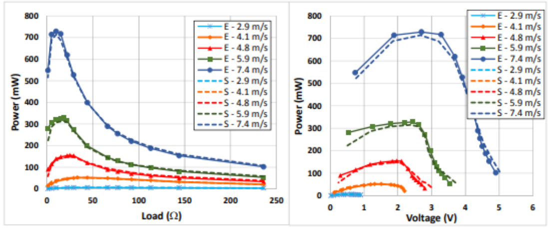
Performance analysis of maximum power and overshoot with variation of load resistance.

the last harvester observed here is a wind turbine with reference from [9]:

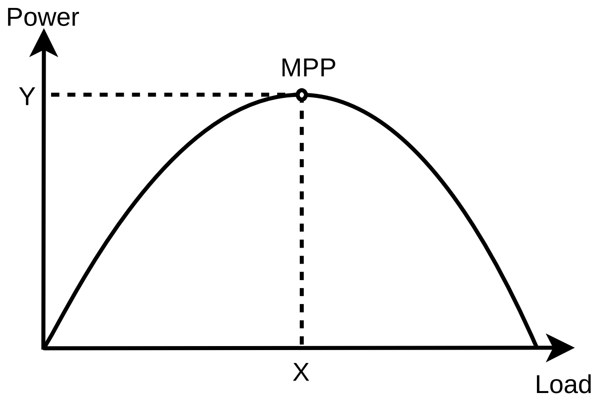


Wind turbines: a) propeller; b) Savonius.





We can easly note that each power versus load (or power versus voltage) curve has a bell shape, where exists only one maximum point that will be called maximum power point (MPP). The main problem is that this MPP is not fixed in a precise position, it can vary for each harvester and for any operating conditions. So, our system must be able to track this MPP indipendently from the energy nature by varing the harvester's load.



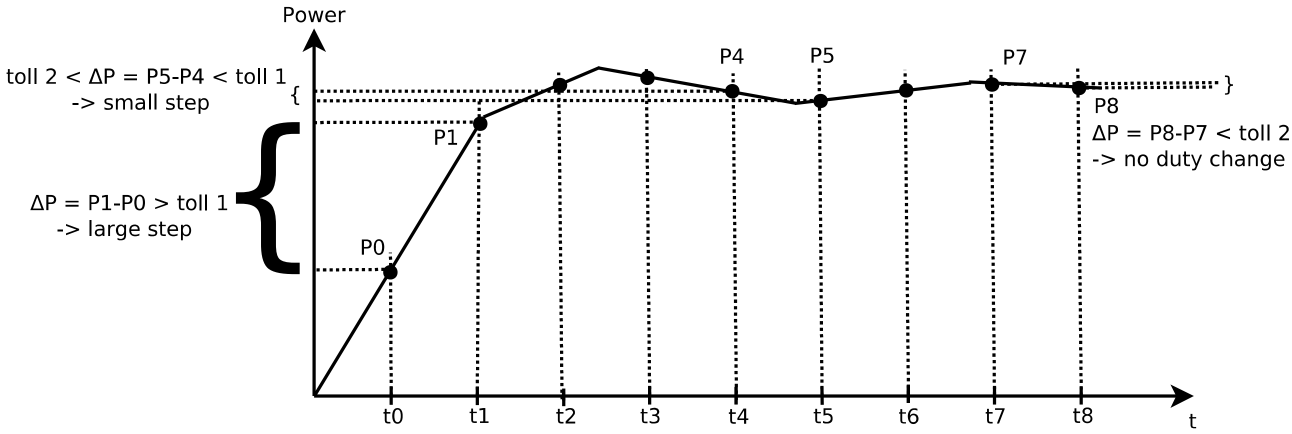
Fortunately, the research about energy harvesting provide many modes to solve this problem, in fact, researchers around the word suggest different maximum power point trackers (MPPTs).

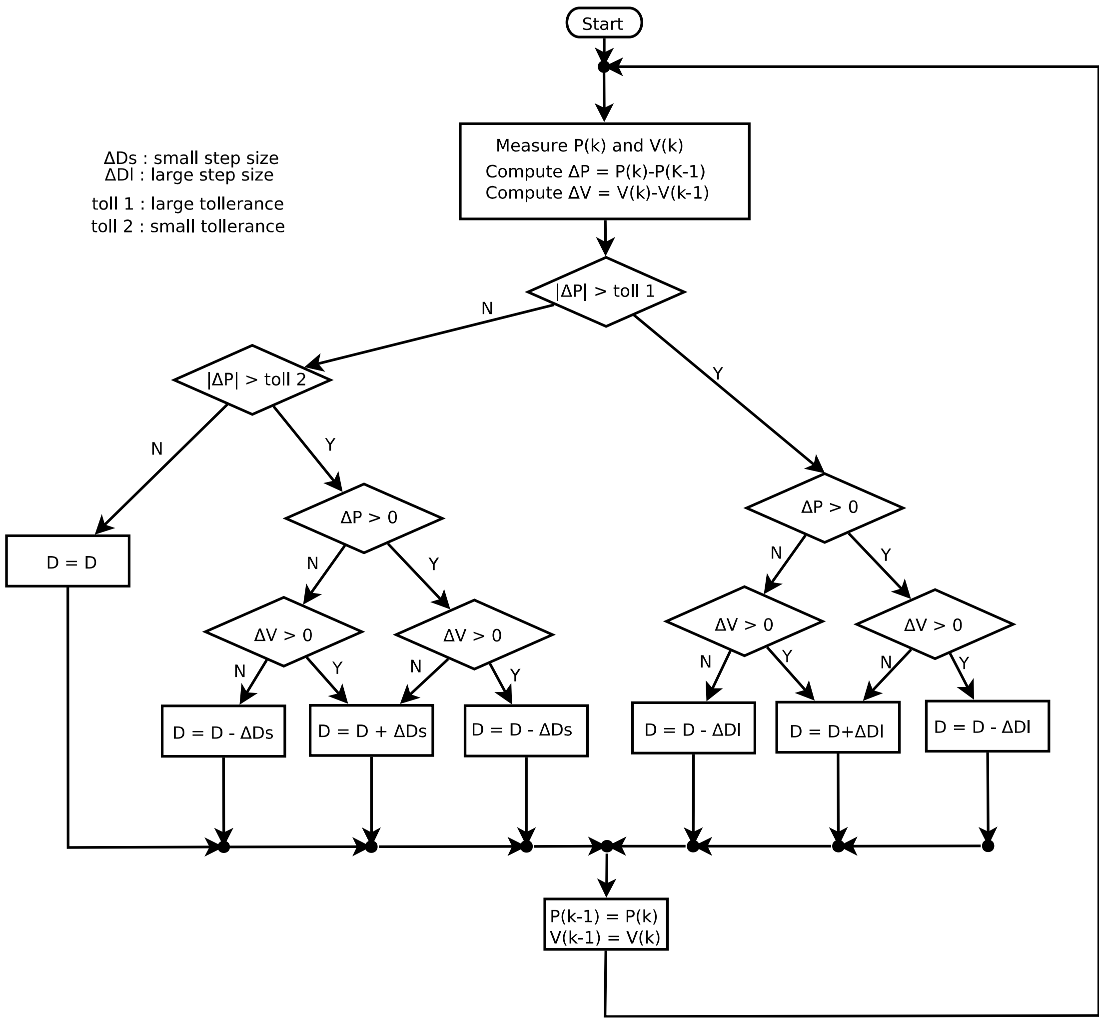
- The proposed MPPT algorithm

Tracker can be done with two different approaches: the analog way or the digital one. The analog implementation of MPPT is called costant voltage scaling (CVS) and consists in the exploitation of a sensor that provide an output voltage similar to the control voltage that must be used in the DC/DC converter to change the duty cycle and, therefore, the load resistance. Two example of CVS applications can be found in the reference [10] and in [11]. The advantage in using CVS is the low energy and hardware requirement that made this MPPT method particularly interesting in low power sensor nodes where we are not able to extract a lot of energy from the enviroment.

The digital implementation has the standard form of a sample data control system. An ADC will be used to sense the state of the harvester, the received data drive the MPPT algorithm that will be implemented on a microcontroller/DSP and a DAC will apply the required changement on the DC/DC forcing the alteration of the duty cycle. The licterature suggest mainly two big classes of algorithms : the incremental condactance (IncC) and the perturb and observe (P&O) method.
With the IncC [13] [12] the system could reach a better level of tracking but it require more resource. Instead, the P&O is preferred thanks to its simplicity and less resource requirement.

In [[14]] we can find a good analisys of the method and in [15] the authors compare seven different P&O variant with an useful focus on the harvested energy. In this thesis I'll use another variant of P&O, the variable step one [16] [17] [18]. The main idea behind the algorithm is the division of the power interval in two smaller one. Thanks to that, the algorithm is able to decide which will be the best step size to use. If the digital control sense that the power variation(P1-P0) is bigger than the high threshold (toll1), it uses a large step (ΔDl) on the duty cycle changement. Instead, if the sensed power variation is between the higher and the lower threshold (P5-P4), a small step will be chosed (ΔDs). Finally, if the power change of an amount that can be considered negligible (toll2, the lower threshold), the algorithm stop to change the duty cycle and the steady state is reached until the harvester don't change the amount of harvested power due to the enviroment conditions. In the next two figure I report the aspected behaviour and the flow chart of the algorithm.





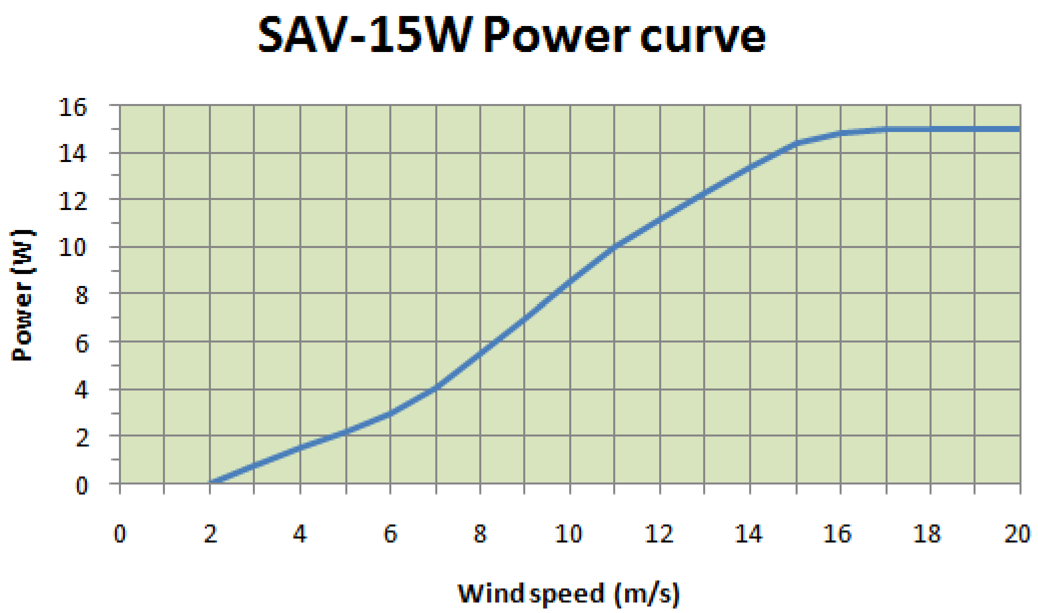
- The used harvesters

Thanks to the analisys previously done, in this project i'll consider one photovoltaic (PV) panelwith a maximum rated power of 10W and a current/voltage at te MPP of 0,55A/18V. The second harvester is a vertical acix wind turbine (VAWT) with a maximum power of 15W characterized by current/voltage at the MPP of 1,25A/12V.

The technical details of the VAWT are in : http://www.saiampower.com/article_read_156.html. here i report an extract :

Technical Specification:

Performance	
Rated power	10W @10m/s
Peak power	15W
Start-up wind speed	2m/s
Working wind speed	3-20m/s
Survival wind speed	35m/s
Noise	≤40dB
Rotor	
Rotor diameter	310mm
Swept area	0.1m2
Blade	5pcs alumimium alloy
Blade length	300mm
Shell material	Erosion resistant aluminum
Rated RPM	400
Weight	2.3KG
Others	
Generator type	3-phase AC PMG
Speed regulation & protection	overvoltage charge controlling
Rated voltage	DC 12V
Suggested battery capacity	1pcs 7AH/12VDC
Suggested tower	3-4m guyed cable tower
Working temperature	-30-50℃

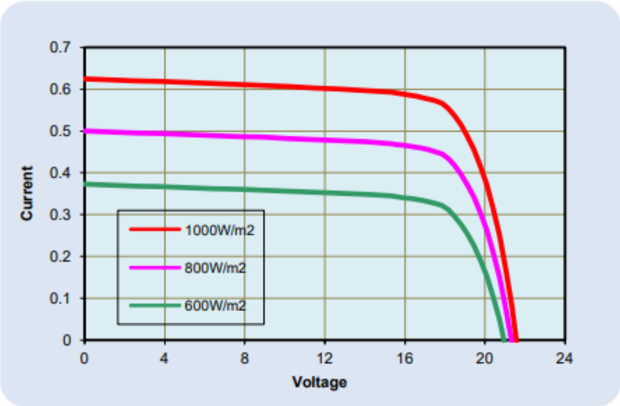


Instead, the PV panel : http://www.alternative-energy-tutorials.com/solar-panel-review/10w-akt-solar-panel.html , with the following charactestics :

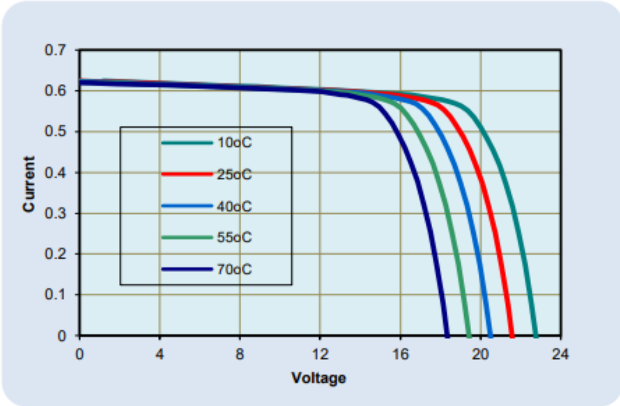
– 36 (4×9) Monocrystalline Solar Cells

- •– Peak Power (Wp): 10W ± 5%
- •– Voltage at maximum power (Vmp): 17.5V
- •– Current at maximum power (Imp): 0.57A
- •– Open circuit voltage (Voc): 21.0V
- •– Short circuit current (Isc): 0.63A
- •– Power allowance range: ± 5%
- •– Dimensions: 300 x 330 x 25mm
- •– Weight: 1.8kg

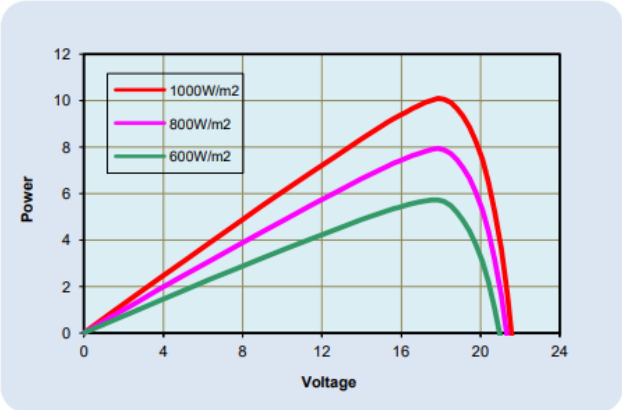
Current-Voltage Relationship, variable light intensity



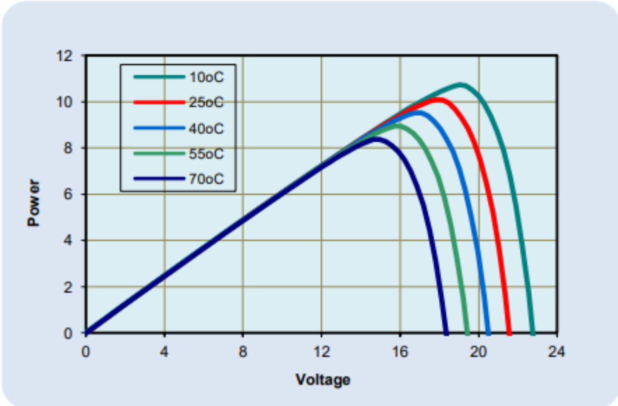
Current-Voltage Relationship, variable temperature



Power-Voltage Relationship, variable light intensity



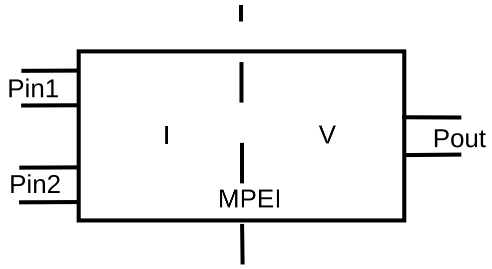
Power-Voltage Relationship, variable temperature



- THE PROPOSED SYSTEM

The system designed in these pages born from a reinterpretation of the one described in [19] and resumed in [20]. The basic idea is to develop a multi port power electronic interface (MPEI) where there is no charge accumulation but only the manipolation of the power flows and the extraction of energy in the most efficient way from different renewable energy sources.Two additional examples of system can be found in [21] [22].

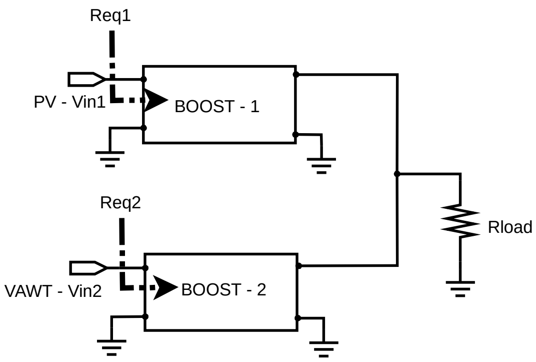
Start from a description with an high level abstraction of the system, we want a circuit that catch the maximum amount of power from the two uncorrelated input harvesters (Pin1 and Pin2) and return this power in output in a reusable form (Pout). Let's define a virtual barrier in the middle of the system that will be useful to divide the system design in two separate parts.

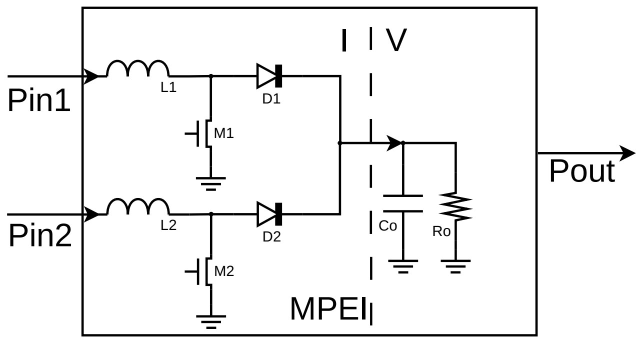


The first half of the MPEI take care of energy extraction and mix the current coming from the two inputs, while the second half of the MPEI should stabilize the output voltage. In this thesis I will work only on the first half but the results can be easly reused to complete the whole design.

The first aspect to fix is the power path architecture. Exists many architecture that should be used, each one with pros and cons. The most interesting alternative are 2 : a double input SEPIC [23][24] or BOOST. The SEPIC converter can be used if we need to harvest power for the entire load range of power versus load curve, on the other hand, the sepic converter require a cut on the direct current path (there is a capacitor in series), this means that the system require an external power source (battery).

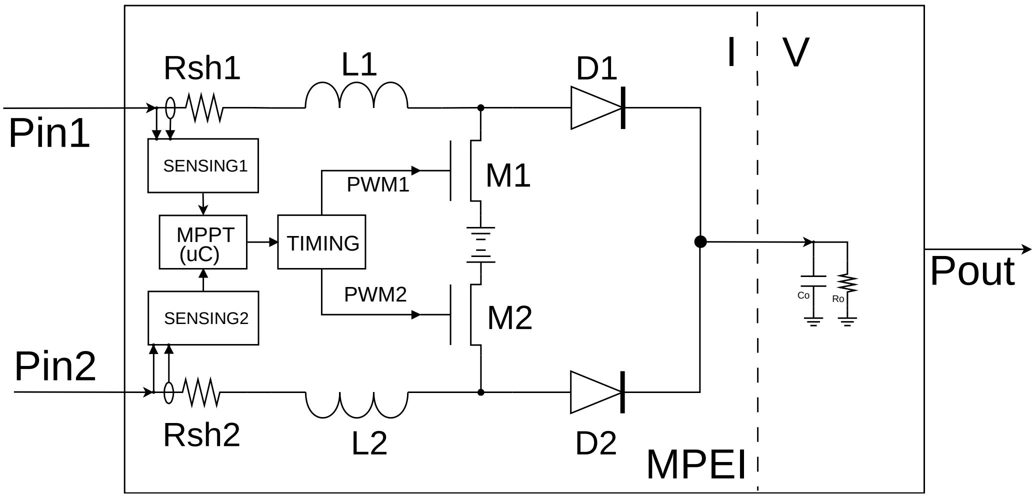
The multi input boost converter seems the right choose. It's simply, ensure the direct current path and can be modified in easy way. The problem is the limitation on the usable power versus load curve of the harvester. Observe the next figure, with a boost architecture we have that the load resistance of each harvester (Req1 and Req2) will be a fractional part of the output resistance (Rload). In particular, the input impedence will be modulate by the duty cycle of each boost. If we impose a limited duty cycle range hence the Req will have a limited values. The problem can be partially ignored if the two power sources has the same characteristic, but if they require nonequivalent input resistance there will be a slight mismatch on the power extraction intervals. The question will be analyzed and solved in the next chapter choosing the load resistance of the MPEI. The figure on the right show the MPEI power path architecture:



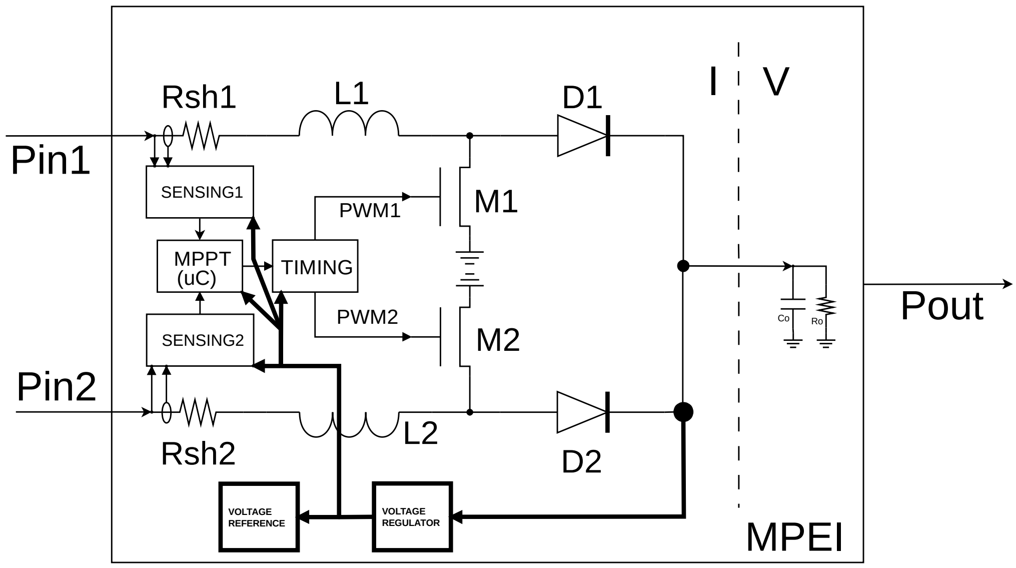


In the double input boost converter each branch will be in continuos conduction mode (CCM) [25] and they will drive the load with current sharing technique [26], in other words, they will provide current on the output load in different time interval not overlapped.

At this point we must think on how apply the MPPT algorithm previously described. The control system architecture used is the classical one who require a sensing net to measure the state of the harvesters, a microcontroller to apply the MPPT algorithm, a timing net used as synchronizer and MOS driver that act on the power MOS to force a specific working point.



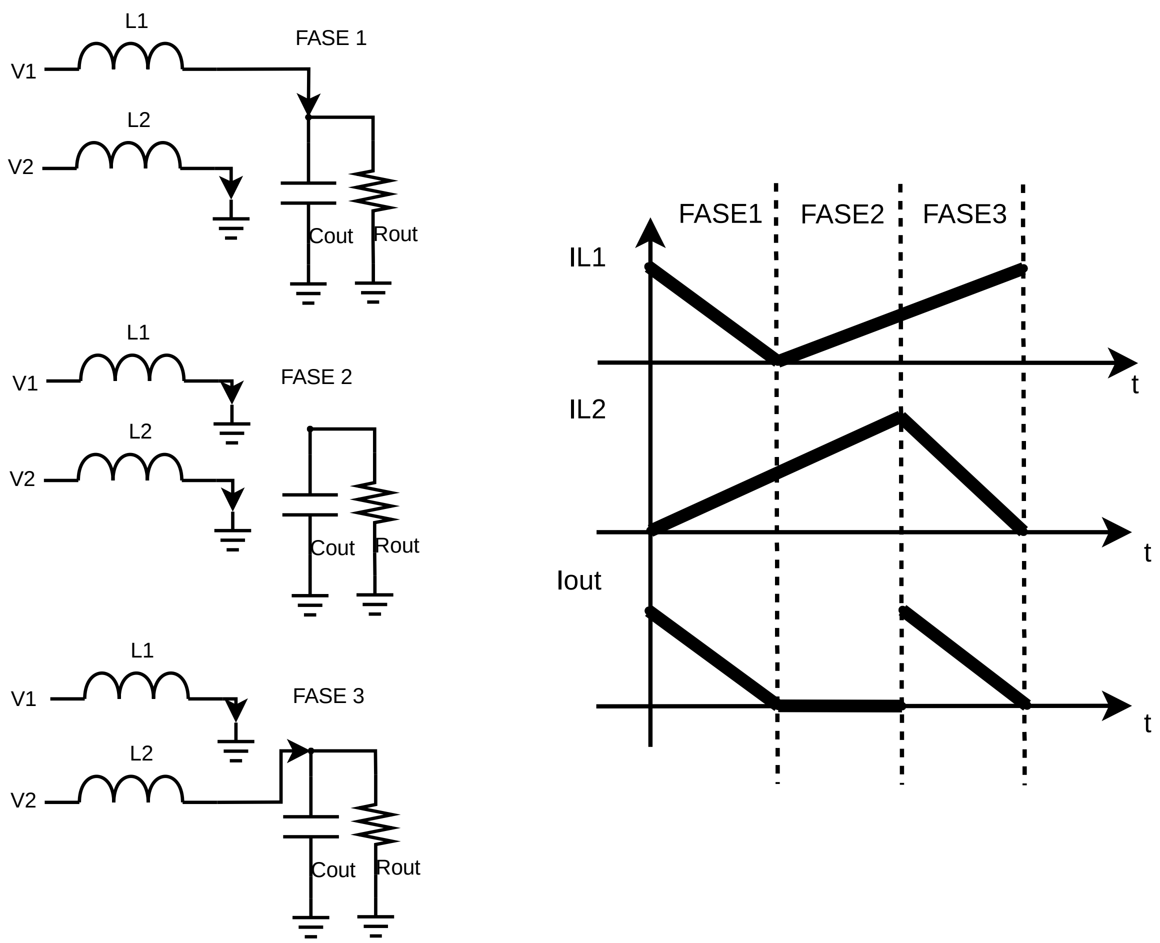
Note that the absence of an external loop that stabilize the output voltage means that this voltage can vary in a limited range. In order to use directly the output power to self-supply the circuit, a wide signal analisys of the circuit must be done to stimate this voltage range. After we can insert a voltage regulator that will supply all the nets.



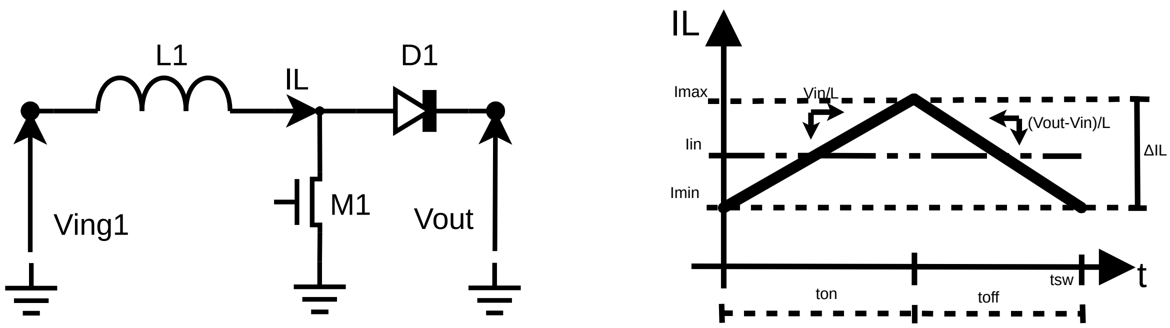
Another keypoint should be observed in this phase, the direct current link. Using two power diodes the DC link will be ensured, therefore, when one of the two input harvester start to generate power, the virtual barrier of the MPEI will be reached by usable electric power that will turn on the voltage regulator and, accordingly, the other circuits among the system.

- WIDE SIGNAL ANALISYS

The analisys start with a generic description of what happen on the current of the two parallel boost. Look at the simplified power path neglecting, just for now, the problem carried by the diodes and the MOSs. As previously said, the circuit will work on charge sharing where each inductor force current on output in intermittent way. The expected behaviour is shown in the the figure, where I suppose three separated phases that can also be only two :



What we are looking for is the average value of the input current. In the phases 1 and 3 the inductors discharge current on the load generating a saw wave. If we focus on the single inductor, we observe that each branch force a specific average current draw from the renewable source. To understand what exactly happens here we can use the theory of [27] [28] [29]. Focus on the inductor current of the single boost :



and do the math :

$$t_1 < t < t_2 \quad during \quad t_{on} \qquad i_{l_{1\,ON}}(t) = I_{min} + t\frac{V_{ing1}}{L_1}$$

$$t_2 < t < t_3 \quad during \quad t_{OFF} \quad i_{l_{1\,OFF}}(t) = I_{MAX1} + t\frac{-V_{out} + V_{ing1}}{L_1}$$

$$for \quad t = t_2 \qquad I_{MAX1} = I_{MIN1} + T_{ON1}\frac{V_{ing1}}{L_1} = i_{L_1}(t_2)$$

hence :

$$I_{MAX1} - I_{MIN1} = T_{ON1}\frac{V_{ING1}}{L_1}$$

instead:

$$for \quad t = t_3 \qquad I_{MIN1} = I_{MAX1} - T_{OFF1}\frac{V_{OUT} - V_{ING1}}{L_1} = i_{L_1}(t_3)$$

therefore :

$$I_{MAX1} - I_{MIN1} \;=\; T_{OFF1}\frac{V_{OUT} - V_{ING1}}{L_1}$$

make equal the two expression of $I_{MAX} - I_{MIN}$ we obtain :

$$T_{ON1}\frac{V_{ING1}}{L_1} \;=\; T_{OFF1}\frac{V_{OUT} - V_{ING1}}{L_1}$$

consequently :

$$V_{OUT} \;=\; V_{ING1}\frac{T_{ON1} + T_{OFF1}}{T_{OFF1}}$$

define :

$$T_{ON1} \;=\; DT_{SW} \quad ; \quad T_{OFF1} \;=\; (1-D)TSW$$

we can compute :

$$M_{CCM} \;=\; \frac{V_{OUT}}{V_{ING1}} \;=\; \frac{1}{1-D_1}$$

supposing that $P_{ING} = P_{OUT}$

$$I_{OUT} = \frac{V_{OUT}}{R_{OUT}} \qquad ; \qquad I_{ING1} = I_{OUT}M_{CCM} = \frac{I_{OUT}}{1-D_1}$$

that are the general equation for the wide signal.

- INDUCTOR

The computation of the critical inductor value that ensure the continuos conduction mode of the boost converter will use the math previously done. Come to observe the current behaviour. In the previous page we find :

$$\frac{I_{MAX1}-I_{MIN1}}{2} = I_{ING1} = I_{OUT} M_{CCM} = \frac{I_{OUT}}{1-D_1} = \frac{V_{OUT}}{R(1-D_1)} \quad average \;\; current \;\; I_{L_1}$$

$$\Delta I_{L_1} = I_{MAX}-I_{MIN} = \frac{V_{ING1}}{L_1}\frac{D_1}{f_{sw}} = \frac{V_{OUT}(1-D_1)D_1}{L_1 f_{sw}} \quad variation \;\; of \;\; i_{L_1}$$

it follow that :

$$I_{MAX}=I_{ING1}+\frac{\Delta I_{L_1}}{2} \qquad I_{MIN}=I_{ING1}-\frac{\Delta I_{L_1}}{2}$$

written in explicit way :

$$I_{MAX}=\frac{V_{OUT}}{R(1-D_1)}+\frac{V_{OUT}(1-D_1)D_1}{2L_1 f_{sw}} \qquad I_{MIN}=\frac{V_{OUT}}{R(1-D_1)}-\frac{V_{OUT}(1-D_1)D_1}{2L_1 f_{sw}}$$

Now, we can use Imin to find the critical value of the inductor. The CCM condition is defined as : the condition where the inductor current never reach the zero, therefore, imposing Imin = 0 we apply this condition :

$$I_{MIN} = 0 = \frac{V_{OUT}}{R(1-D_1)}-\frac{V_{OUT}(1-D_1)D_1}{2L_1 f_{sw}}$$

obtaining :

$$L_{CRITIC} = \frac{R(1-D_1)^2 D_1}{2 f_{sw}}$$

for energy harvesting application, it's more useful know the critical value as source function. So, rewrite the equation:

$$L_{CRITIC} = \frac{V_{OUT}}{I_{OUT}}\frac{(1-D_1)^2 D_1}{2 f_{sw}} = \frac{V_{ING1}}{1-D_1}\frac{1}{I_{ING1}(1-D_1)}\frac{(1-D_1)^2 D_1}{2 f_{sw}} = \frac{V_{ING1}}{I_{ING1}}\frac{D_1}{2 f_{sw}}$$

$$L > L_{CRITIC} = \frac{V_{ING1}}{I_{ING1}}\frac{D_1}{2 f_{sw}}$$

bringing the equation in matlab we can test a set of combination :
for the photovoltaic panel branch (VIN = 18V, Iing @100% = 0,6A)

L_PV	10	20	30	40	50	60	70	80	90	100	% Iing
0,3	1,54E-004	7,68E-005	5,12E-005	3,84E-005	3,07E-005	2,56E-005	2,19E-005	1,92E-005	1,71E-005	1,54E-005	
0,4	2,05E-004	1,02E-004	6,82E-005	5,12E-005	4,09E-005	3,41E-005	2,92E-005	2,56E-005	2,27E-005	2,05E-005	
0,5	2,56E-004	1,28E-004	8,53E-005	6,40E-005	5,12E-005	4,26E-005	3,65E-005	3,20E-005	2,84E-005	2,56E-005	
0,6	3,07E-004	1,54E-004	1,02E-004	7,68E-005	6,14E-005	5,12E-005	4,39E-005	3,84E-005	3,41E-005	3,07E-005	
0,7	3,58E-004	1,79E-004	1,19E-004	8,95E-005	7,16E-005	5,97E-005	5,12E-005	4,48E-005	3,98E-005	3,58E-005	
Duty cycle											

and, for the VAWT branch (VIN = 12V, Iing @100% = 1,25A)

L_VAWT	10	20	30	40	50	60	70	80	90	100	% Iing
0,3	4,80E-005	2,40E-005	1,60E-005	1,20E-005	9,60E-006	8,00E-006	6,86E-006	6,00E-006	5,33E-006	4,80E-006	
0,4	6,40E-005	3,20E-005	2,13E-005	1,60E-005	1,28E-005	1,07E-005	9,14E-006	8,00E-006	7,11E-006	6,40E-006	
0,5	8,00E-005	4,00E-005	2,67E-005	2,00E-005	1,60E-005	1,33E-005	1,14E-005	1,00E-005	8,89E-006	8,00E-006	
0,6	9,60E-005	4,80E-005	3,20E-005	2,40E-005	1,92E-005	1,60E-005	1,37E-005	1,20E-005	1,07E-005	9,60E-006	
0,7	0,000112	5,60E-005	3,73E-005	2,80E-005	2,24E-005	1,87E-005	1,60E-005	1,40E-005	1,24E-005	1,12E-005	
Duty cycle											

a good choice can be made by selecting two inductors offered by the MSS1260 series of Coilcraft.
For our requirement we can choose :
100uH for the VAWT (MSS1260-104ML)
220uH for the PV (MSS1260-224KL)

—- POWER DISSIPATION

The power losses in the inductor are due by the parasitic resistance. The estimation of this wasted energy can be done by calculating the RMS power and so, the RMS current that flow in the inductor.

$$P_{L_{RMS}} = I_{L_{RMS}}^{2} * R_L$$

compute $I_{L_{RMS}}$ using the quadratic current Kirchhoff law, where:

$$I_{L_{RMS}}^{2} = I_{DC}^{2} + I_{AC}^{2} \qquad I_{DC}^{2} = I_{ING}^{2}$$

instead I_{AC}^2 will be done by :

$$I_{AC}^2 = \frac{1}{T}\left[\int_0^{t_1} i_L(t)\,dt + \int_{t_1}^{t_2} i_L(t)\,dt\right]$$

$$I_{AC}^2 = \frac{1}{T}\left[\int_0^{t_1} \frac{\Delta I_L}{2}^2 \frac{t}{t_1}^2 dt + \int_{t_1}^{t_2} \frac{\Delta I_L}{2}^2 \frac{t_2 - t}{t_2 - t_1}^2 dt\right]$$

$$I_{AC}^2 = \frac{1}{T}\frac{\Delta I_L^{2}}{4}\left[\frac{t^3}{3t_1^2}\right]_0^{t_1}$$

$$I_{AC}^2 = \frac{1}{T}\frac{\Delta I_L^{2}}{4}\left[\frac{t_1}{3} + \frac{t_2 - t_1}{3}\right] \qquad with \quad t_2 = T \quad we\ have:$$

$$I_{AC}^2 = \frac{\Delta I_L^{2}}{12}$$

the result is :

$$I_{L_{RMS}}^{2} = I_{DC}^2 + I_{AC}^2 = I_{ING}^{2} + \frac{\Delta I_L^{2}}{12}$$

in the worst case, where $\Delta I_L = 2 * I_{ING}$ we will have :

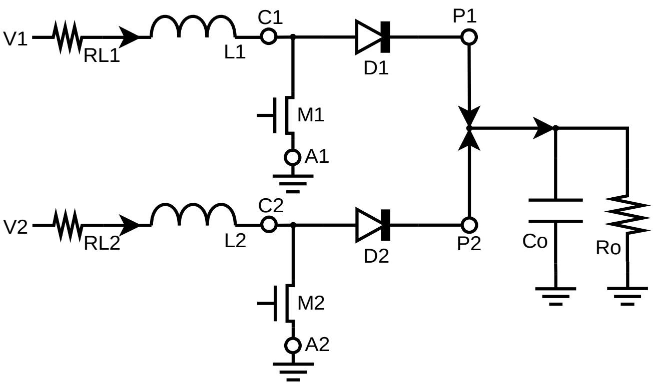
$$I_{L_{RMS}}^{2} = I_{ING}^{2} + \frac{(2 I_{ING})^2}{12} = I_{ING}^{2}\left(1 + \frac{1}{3}\right) = \left(\frac{2}{\sqrt{3}} I_{ING}\right)^2$$

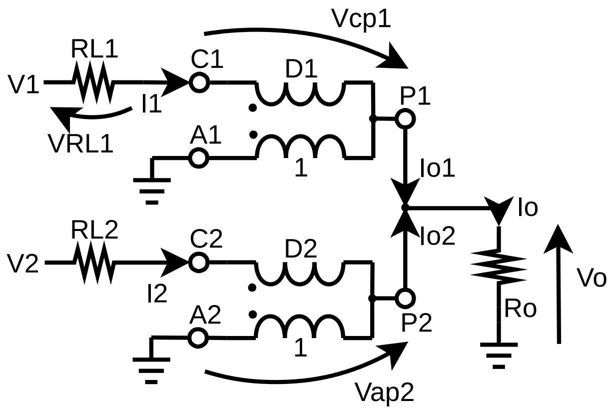
hence, the wasted power will be given by :

$$P_{L_{RMS}} = \frac{4}{3} I_{ING}^{2} R_L$$

- MAXIMUM OUTPUT VOLTAGE

To choose the right components of the circuit, we need to know which is the maximum output voltage that the MPEI can generate; this can be done using the PWM switch model defined by Vorperian in the far '89 [30].





From the model we know that : $V_{CP} = D V_{AP}$ $\quad e \quad$ $I_A = D I_C$

Note that here I am considering only the parasitic resistance of the inductor and neglect the other therms. Start writing the KCL on the output node:

$$I_o = I_{o1} + I_{o2} = I_1 D_1' + I_2 D_2'$$

with :

$$D' = 1 - D$$

and the KVL :

$$\begin{cases} V_1 - V_{R_{L1}} + V_{CP_1} - V_o = 0 \\ V_2 - V_{R_{L2}} + V_{CP_2} - V_o = 0 \end{cases}$$

$$\begin{cases} V_1 - I_1 R_{L1} + D_1 V_{AP1} - V_o = 0 \\ V_2 - I_2 R_{L2} + D_2 V_{AP2} - V_o = 0 \end{cases} \rightarrow \begin{cases} V_1 - I_1 R_{L1} - (1 - D_1) V_o = 0 \\ V_2 - I_2 R_{L2} - (1 - D_2) V_o = 0 \end{cases}$$

$$\begin{cases} I_1 = \dfrac{V_1 - V_O D_1'}{R_{L1}} \\ I_2 = \dfrac{V_2 - V_O D_2'}{R_{L2}} \end{cases} \rightarrow \begin{cases} I_{o1} = \dfrac{V_1 - V_O D_1'}{R_{L1}} D_1' \\ I_{o2} = \dfrac{V_2 - V_O D_2'}{R_{L2}} D_2' \end{cases}$$

substitute the KVL in the KCL:

$$\frac{V_1 - V_o D_1'}{R_{L1}} D' + \frac{V_2 - V_o D_2'}{R_{L2}} D_2' = I_1 D_1' + I_2 D_2'$$

$$V_o \left(\frac{D_1'^2}{R_{L1}} + \frac{D_2'^2}{R_{L2}} \right) = V_1 \frac{D_1'}{R_{L1}} + V_2 \frac{D_2'}{R_{L2}} - I_1 D_1' - I_2 D_2'$$

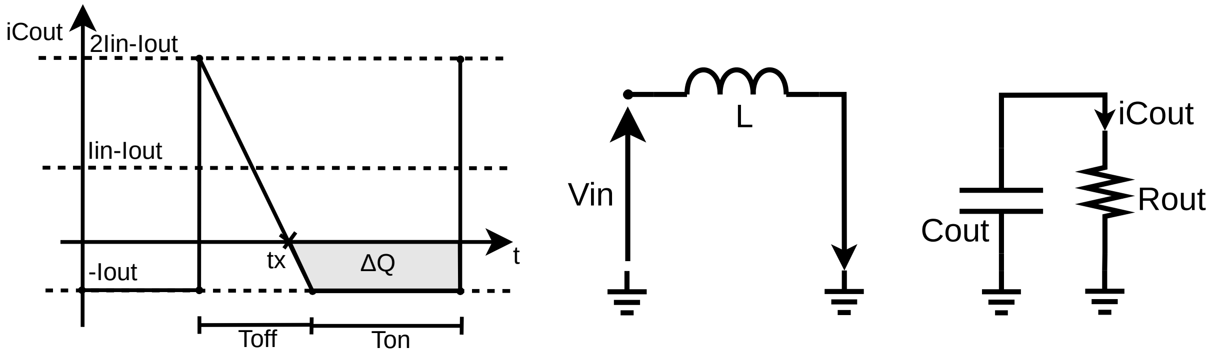
the result is :

$$V_o = \frac{R_{L1} R_{L2}}{D_1'^2 R_{L2} + D_2'^2 R_{L1}} \left(V_1 \frac{D_1'}{R_{L1}} + V_2 \frac{D_2'}{R_{L2}} - I_1 D_1' - I_2 D_2' \right)$$

also here, bringing the obtained equation in MATLAB we have an output voltage of about 50V. Therefore, all the component will be sized taking in account a maximum output voltae of 100V.

- OUTPUT CAPACITOR

The choose of the capacitor follow the analisys done in [28]. The wort case to consider is when only one harvester is on and the capacitor will supply the output when the boost is in charging phase of the inductor.



Imagin a situation where only the VAWT generate power. From its datasheet we know that $P_{MAX_{VAWT}} = 15\,W$ with $V_{out} = 12\,V$ therefore the current that the capacitor must provide on the load is:

$$I_{MAX} = \frac{P_{MAX_{VAWT}}}{V_{OUT}} = \frac{15\,W}{12\,V} = 1{,}25\,A$$

watching the above image we have that the requested charge is ΔQ , thanks to the fact that the time tx is not knowned, I choose of approximate the ΔQ with the area of the remaining rectangle and apply an increasement on the final value of the capacitor.
Remember that :

$$\Delta Q = T_{ON}\, I_{OUT} = D\, T_{SW}\, I_{C_{OUT}} = C\, \Delta V$$

To compute the C value we must fix an accettable ΔV and manipulate the formula :

$$C = \frac{D\, I_{C_{OUT}}}{f_{sw}\, \Delta V_{OUT}}$$

The Matlab computation of this equation provide the following results :

C out	1	2	3	4	5	6	7	8	9	10	Δvout [V]
0,3	1,25E-006	6,25E-007	4,17E-007	3,13E-007	2,50E-007	2,08E-007	1,79E-007	1,56E-007	1,39E-007	1,25E-007	
0,4	1,67E-006	8,33E-007	5,56E-007	4,17E-007	3,33E-007	2,78E-007	2,38E-007	2,08E-007	1,85E-007	1,67E-007	
0,5	2,08E-006	1,04E-006	6,94E-007	5,21E-007	4,17E-007	3,47E-007	2,98E-007	2,60E-007	2,31E-007	2,08E-007	
0,6	2,50E-006	1,25E-006	8,33E-007	6,25E-007	5,00E-007	4,17E-007	3,57E-007	3,13E-007	2,78E-007	2,50E-007	
0,7	2,92E-006	1,46E-006	9,72E-007	7,29E-007	5,83E-007	4,86E-007	4,17E-007	3,65E-007	3,24E-007	2,92E-007	
Duty cycle											

From this analisys we can observe that the output capacitor must have a value bigger than 2,92uF. But, this value will be conditioned also by other factors. First of all from the LDO specifications. Hence, take these 2,92uF has limit value.

- POWER DISSIPATION

As seen in the graph, we know that :

- when the MOS is ON : $i_c(t)=-I_{OUT}$

- when the MOS is OFF : $i_c(t)=i_L(t)-I_{OUT}$

if we assume that the MOS will be ON or OFF for the entire interval we should have:

- when the MOS is ON : $i_c(t)=-I_{OUT}$

- when the MOS is OFF : $I^2_{C_{RMS}}=(I_{ING}-I_{OUT})^2+\frac{1}{12}(2I_{ING})^2 con\, \Delta I_L=2I_{ING}$

the weighted average on the time of these two contribute will give:

$$I^2_{C_{RMS}}=D\,I_{OUT}{}^2+(1-D)(I_{ING}-I_{OUT})^2+\frac{1}{12}(2I_{ING})^2$$

substitute $I_{OUT}=I_{ING}(1-D)$ and simplify the equation :

$$I^2_{C_{RMS}}=D*I_{ING}{}^2*(1-D)^2+(1-D)*(I^2_{ING}*D^2+\frac{1}{3}*I^2_{ING})^2$$

$$I^2_{C_{RMS}} = D\,I_{ING}{}^2(1-D)^2 + (1-D)(I^2_{ING}D^2+\frac{1}{3}I^2_{ING})^2$$

$$I^2_{C_{RMS}}=I_{ING}{}^2*[\frac{-3*D^2+2*D+1}{3}]$$

By developing the partial derivatives with respect to D, the maximum is observed at D = 1/3, therefore :

$$I_{C_{RMS}} = \frac{2}{3}I_{ING} = \frac{1}{3}\frac{I_{OUT}}{(1-D)} = \frac{1}{3}\frac{I_{OUT}}{(1-\frac{1}{3})} = I_{OUT}$$

The result is that, in the worst cas, the power dissipation on the Cout will be :

$$P_{C\,RMS} = I_{CRMS_{MAX}}{}^2 R_{ESR} = I^2_{OUT}R_{ESR}$$

- MOSFET

The choice of the right MOS to use depends from 3 keypoint (deeply explained in [31] [32]): Vds max, Ion max and the power dissipation. For what concer Vdsmax and Ion max, designers follow the golden rule : they must be 1,5/2 times the used one in the circuit.

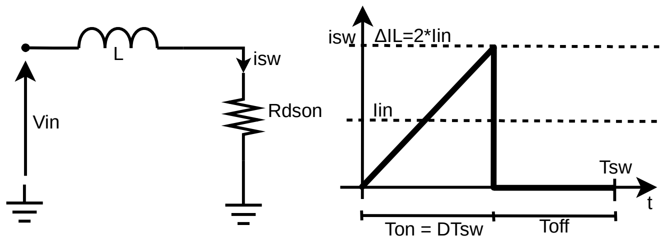
—- WASTED POWER ON THE MOS

The power dissipation of a power MOS require more attention.There are 3 tipe of loss to consider:

- losses in conduction
- losses in commutation
- losses on the gate

- Losses in conduction:

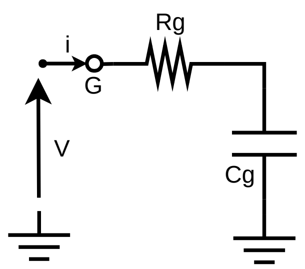
When the MOS is ON and driven in deep triode region, we can assume it as its Ron, hence the wasted power will be:



$$P_{cond} = I_{condRMS}{}^{2} R_{DSon}$$
$$= \left(D I_{ING}^{2} + D\left(\frac{\Delta I_L}{3}\right)^{2}\right)^{2} R_{DSon}$$
$$= \left(D I_{ING}^{2} + D\left(\frac{2 I_{ING}}{3}\right)^{2}\right)^{2} R_{DSon}$$

- Losses on the gate

Seen from the input port, we can modelize the MOS with his gate capacitance that offer on the driver circuit :



$$i(t) = \frac{V}{R} e^{\left(\frac{-t}{RC}\right)}$$
$$P_{diss}(t) = i_{(t)}{}^{2} R$$
$$P_{TOT} = \int_{0}^{inf} \left(\frac{V}{R} e^{\left(\frac{-t}{RC}\right)}\right) 2 R\, dt = \frac{1}{2} C V^{2}$$

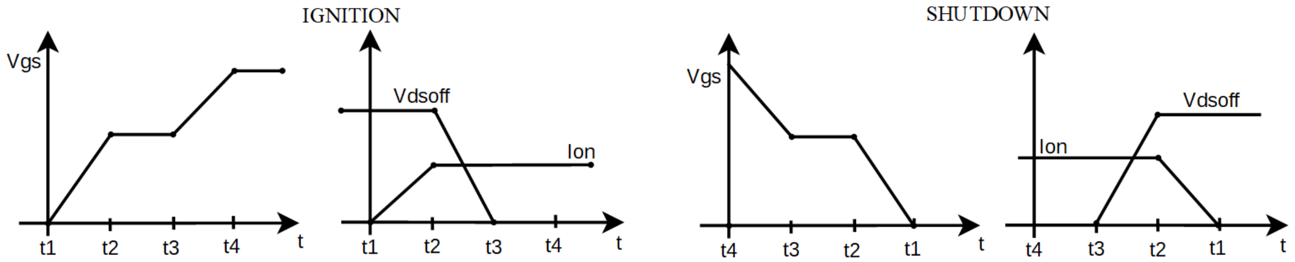
considering also the discharge: $P_{TOT2} = 2 P_{TOT} = C V^2$

charged and discharged at the commutation frequency of fsw: $P_{TOT3} = f_{sw} P_{TOT2} = f_{sw} C V^2$

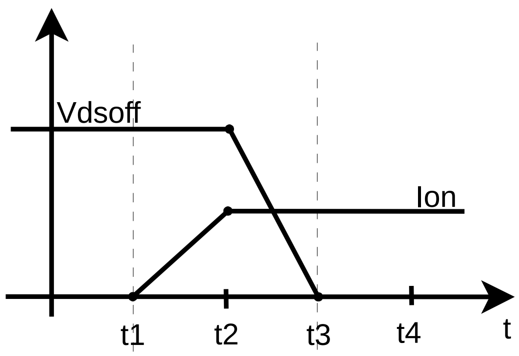
substitute $Q_g = C V$

and the result is the wasted power on the gate : $P_{GATE} = Q_g V f_{sw}$

- Losses on commutation



The main problem is the Miller effect that in the interval $t_2 - t_3$ increase the gate capacitance, requiring more charge at the driver circuit to rise up Vgs and turn on the MOS. The same condition in the shutdown phase. This extra charge will be computed using the information in the datasheet. In the two sequences, the losses are there when an overlapping between Vds and Id happen. Let's focus on the single phase:



To simplify the analisys approximate the waves with a triangular and continue wave :

$$t_1 < t < t_2 \qquad P_{LOSS1} = V_{DSOFF} \frac{\Delta Q}{T_{SW}} = V_{DSOFF} \frac{I_{ON}(t_2 - t_1)}{2 T_{SW}}$$

$$t_2 < t < t_3 \qquad P_{LOSS2} = I_{ON} V_{DS_{MEDIA}} = I_{ON} \frac{V_{DSOFF}(t_3 - t_2)}{2 T_{SW}}$$

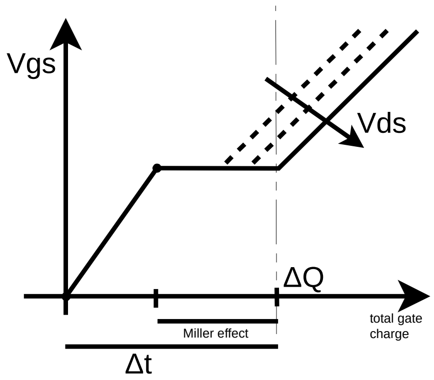
Combine togheter the equations :

$$P_{LOSS} = P_{LOSS1} + P_{LOSS2} = \frac{I_{ON} V_{DSOFF}(t_3 - t_1)}{2 T_{SW}}$$

Taking in account the two phases :

$$P_{COMM} = 2\, P_{LOSS} = \frac{I_{ON}\, V_{DSOFF}\, \Delta t}{T_{SW}} \qquad \text{where } \Delta t = t_3 - t_1$$

- Charge on the gate



The producers supply a graph like the one the figure. From this, designers can extrapolate the maximum value of gate current in order to have a Δt (seen above) of a appropriate value.

With a good approximation we can say that to turn on the MOS it require ΔQ charge on the gate bringing Vgs at a certain value. This charge transfer can be ensured in Δt only if the driver circuit provide a current of :

$$I_{DRIVER_{MAX}} = \frac{\Delta Q}{\Delta t}$$

- CHOICE OF THE MOS

The transistor to use must havethe following characteristics :

- accept at least the double of the input current: 2*0,6 = 1,2A for the PV panel, 2*1,25=2,5A in the case of VAWT.

- accept a Vds voltage of 100V

- threshold voltage lower than 5 V

- the lowest gate charge

- the lowest channel resistance (Rdson).

In the sea of possibility, a good choice can be the **CSD19538Q2**, a power MOSFET designed by texas instruments with the following parameters:

CSD19538Q2	**Absolute Maximum Ratings**	**(TA = 25°C)**	
V DS	Drain-to-Source Voltage	100	V
V GS	Gate-to-Source Voltage	±20	V
	Continuous Drain Current (Package Limited)	14,4	A
I D	Continuous Drain Current (Silicon Limited),	13,1	A
	Continuous Drain Current (1)	4,6	A
P D	Power Dissipation	2,5	W
	Power Dissipation, T C = 25°C	20,2	W
T J	Operating Junction Temperature,	–55 to 150	°C

- DIODE

All information resumed in this paragraph can be found in [33] [34] [35] [36]. There are 4 parameter to observe in order to make a good choice for the diode:

- inverse breakdown voltage : when the MOS in ON, it must survive at the voltage forced from the output $V_{BD} > V_{OUT_{MAx}}$

- maximum current : when the MOS is OFF, the diode will carry current on the output. So, it must be able to support more than the maximum current imposed from the inductor $I_{D_{ON}} > I_{MAX} = 2 * I_{ING}$

- forward voltage : to decrease the power dissipation, the forward voltage must be the lowest as possible. A common choice is to use a Schottky diode because it offer the lowest one.

- reverse recovery time : a diode with low reverse recovery time allow us to limit the charge lost from the output toward the input when the MOS change its state from ON to OFF.

– POWER DISSIPATION

the estimation of wasted power can become particularly hard, I choose to use the model described in [34] where the evaluation is done with a simple model :

$$P_{DIODO} = D\, V_{OUT}\, I_{LEAK} + (1-D)\, V_{FORW}\, I_{FORW}$$

with :

Vout maximum output voltage

Ileak is the inverse leakage current of the diode

Vforw is the forward voltage of the diode

Iforw is the average current that flow in the diode

note that: $I_{FORW} = I_{OUT} = (1-D) I_{ING}$

With all these specifications, a good choice for the diode to use can be **FSV12100V** designed by **Fairchild Semiconductor Corporation**, with the following characteristics :

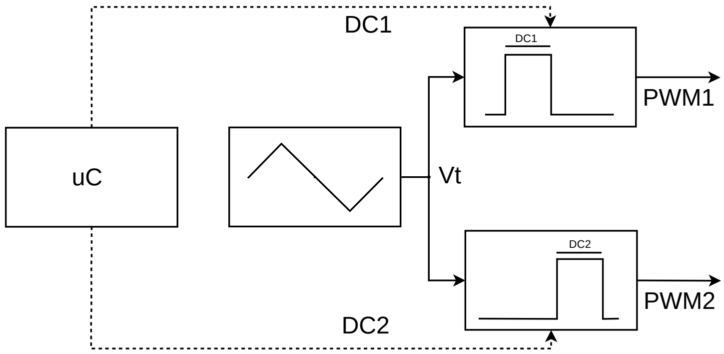
FSV12100V	**Absolute Maximum Ratings**		
V RRM	Peak Repetitive Reverse Voltage	100	V
V RWM	Working Peak Reverse Voltage	100	V
V RMS	RMS Reverse Voltage	70	V
I F(AV)	Average Rectified Peak Forward Surge Current	12	A
I FSM	Non-Repetitive Peak Forward Surge Current	220	A
T J	Operating Junction Temperature Range	-55 to +150	°C

Electrical Characteristics

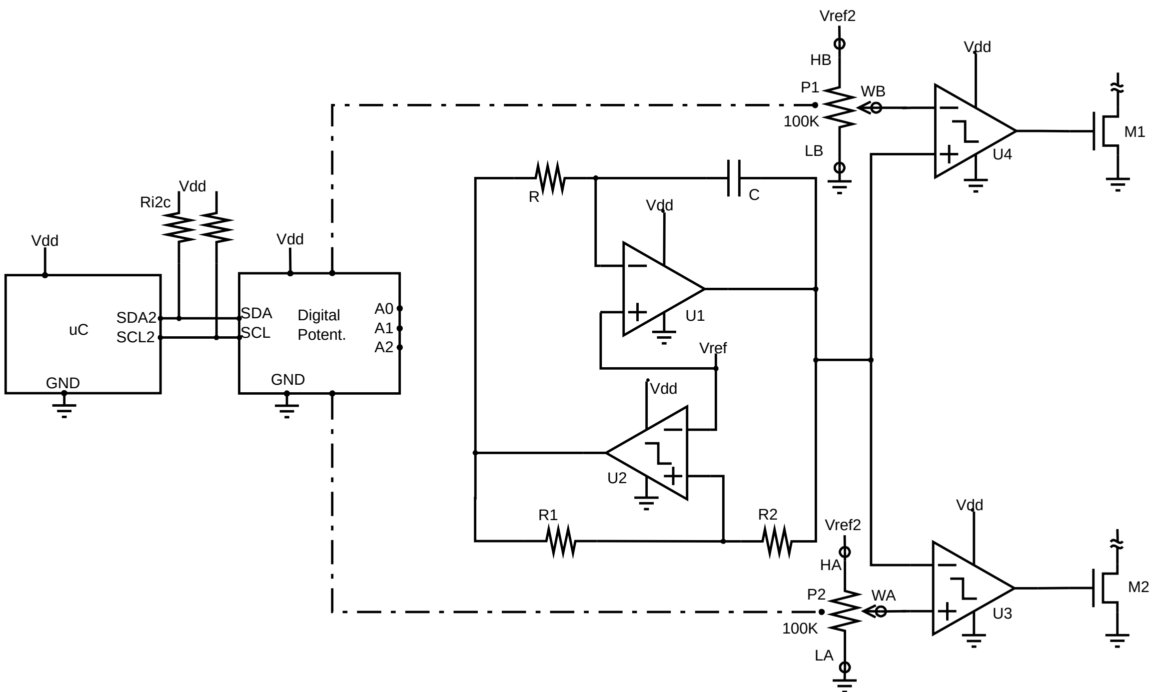
Symbol	**Parameter**	**Conditions**	**min**	**typ**	**max**	
BV R	Breakdown Voltage	I R = 0.5 mA	100			V
V F	Forward Voltage Drop	I F = 5 A		485		mV
		I F = 5 A, TA = 125°C		418		mV
		I F = 12 A		598	670	mV
		I F = 12 A, TA = 125°C		564	600	mV
I R	Reverse Current	V R = 70 V		0,0084		mA
		V R = 70 V, TA = 125°C		9,485		mA
		V R = 100 V		0,0225	0,1	mA
		V R = 100 V, TA = 125°C		16,56	20	mA
T rr	Reverse Recovery Time	I F = 0.5 A, I R = 1 A, I rr = 0.25 A		27,33		ns

- TIMING NET

As previously mentioned, the timing net must be able to receive datas from the microcontroller and use they to generate two square wave with variable duty cycle. A signal of synchronization must be used to avoid a possible overlapping between the two. The basic idea is shown in the figure:



The synchronism signal is a triangular wave where the two square wave will growth around the maximum and minimum peak value. As transducer I will use a couple of digital controlled potentiometer that receive datas from the i2c bus and set the wiper posistion according to the desired position. The hardware translation of what we have just said can be found in the following figure:

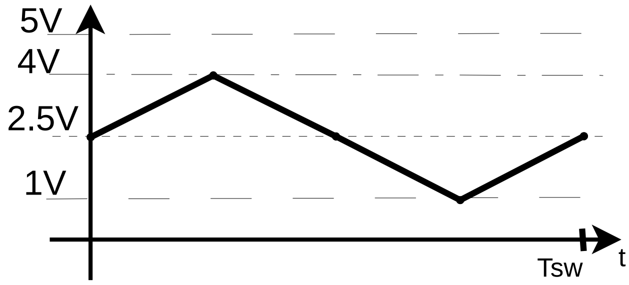


With referenco to [37] and [38] we define all the componets of the proposed circuit starting from the triangular wave generator. Note that in different point of the circuit thare are known voltage: Vdd, the supply voltage is 5V; Vref, reference voltage for the triangular generator is 2,5V and Vref2 is the reference voltage for the two potentiometer (4V).

These choices are dictate by the necessity of separate as more as possible the noise that will be present on the supply line from the two point of particular interest for the correct behaviour of the circuit

(Vref and Vref2). Infact, these voltage will be generated by a bandgap voltage reference.

Don't take care about it in this moment, it will be analized in deep way in the dedicated section (internal supply).



As shown in the figure, the triangular wave must have an average voltage of 2,5V, a maximum voltage of 4V and a peak to peak voltage of 3V with a frequency of 300kHz. The equation used to fix the circuit come directly from [37]:

$$\frac{V_{pp}}{2} = \frac{R_2}{R_1} V_{ref} \rightarrow 1{,}5V = \frac{R_2}{R_1} 2{,}5V \quad with\ R_1 = 5{,}97\ k\Omega,\ therefore\ :$$

$$R_2 = \frac{1{,}5V}{2{,}5V} 5{,}97\,k\Omega = 3582\,\Omega \quad normalized\ at\ the\ E96\ series\ \ R_2 = 3{,}57\,k\Omega$$

$$instead,\ R = \frac{R_1}{4 f_{sw} R_2 C} \quad with\ C = 100\,pF\ \ we\ obtain\ :$$

$$R = \frac{6\,k\Omega}{4\,300\,kHz\,3{,}6\,k\Omega\,100\,pF} = 13{,}9\ k\Omega,\ normalized:\ R = 14\,k\Omega$$

The operational amplifier must be choosen watching the slew rate (SR) limitation and the gain bandwidth product (GBW). The slew rate of the triangular wave is :

$$SR = 4 * \frac{Vpp}{2} * f_{sw} = 4 * 1{,}5V * 300\,kHz = 1800 * 10^3 \frac{V}{s} = 1{,}8 \frac{V}{us}$$

We need an OPAMP with an higher slew rate in order to avoid distortion. For the GBW we must consider that a triangular wave require no less than 10 armonics. Given the fact that the 10th armonic will be at 19 time the foundamental frequency, therefore the minimum GBWwill be:

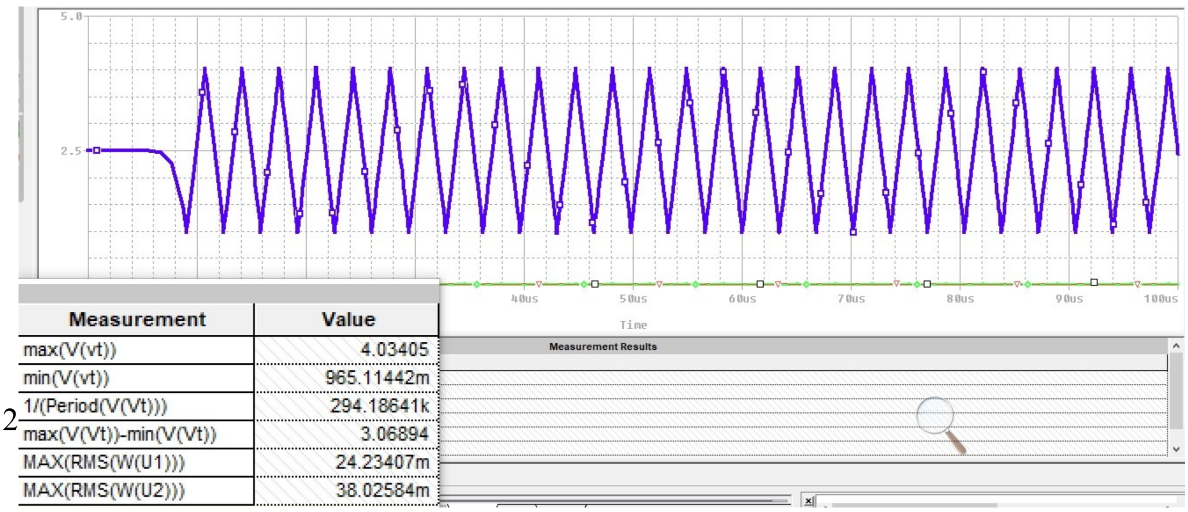
$$GBW_{min} = 19 f_{sw} = 19 * 300\,kHz = 5{,}7\,MHz$$

With these new values, we discover that the opamp used in the reference is a good choice. It's the **OPA365** characterized by FET input stage, GBW = 50MHz,SR = 25V/us and Voff = 200uV.

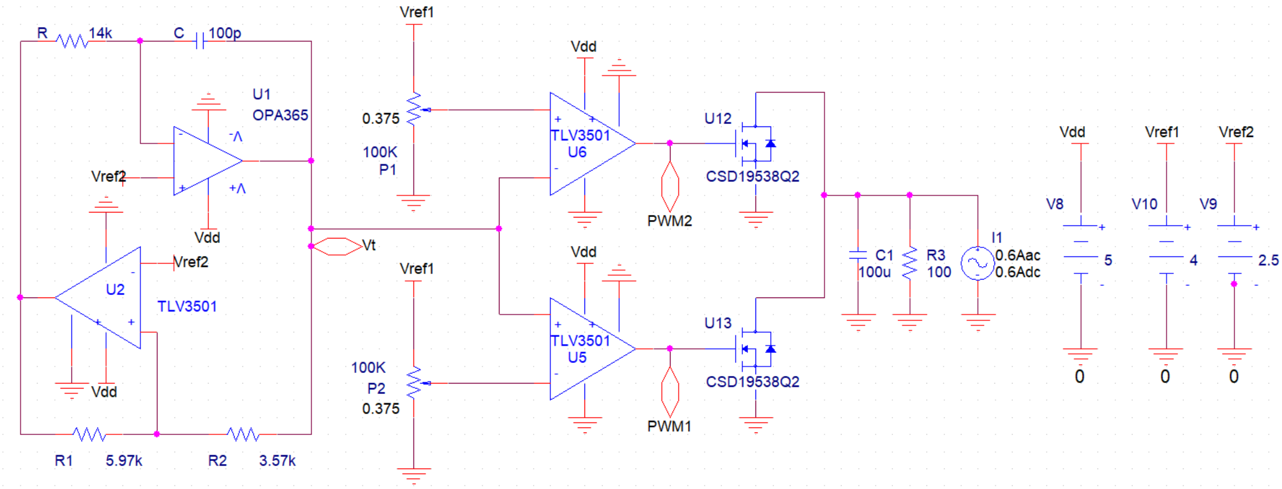
The comparator is chosen by two characteristcs: the ability to drive the load and the introduced delay. In orde to not degrade the performance we need a comparator able to drive the output in active way both in high to low and in low to high transitions, hence a push-pull output is required. On the other hand, the propagation delay must be much less than the PWM period, a golden rule is fix it under the 1/10 times.

With these specifications, texas instruments suggests the **TLV3502** characterized by a push-pull output and a propagation delay of $t_{pd} < 4{,}5\,ns$.

The Pspice simulation confirm what desired :



with the following schematic:



At this point, we can move to fix the other parts of the circuit. In the specific, the comparators that will drive the power MOS. As previously said, the maximum current of the driver will define the behaviour and the power dissipation of the MOS.

From the datasheet of the TLV3502 we can read that the comparator is characterized by an output short circuit current of 74mA. Remembering that the choosen MOS require 2,5nC to put on the gate, theorically the rising commutation, to turn on the MOS, will require a minimum time of:

$$\Delta t = \frac{\Delta Q}{I_{DRIVER_{MAX}}} = \frac{2{,}5\,nC}{74\,mA} = 33.78\,ns$$

instead, the falling commutation should depends from the parasitic component in the link among the two component. Come on Pspice and observe the behaviour of this part of the circuit:

The simulation return a behaviour similar to the supposed one : the rising commutation require about 35ns and the MOS ask no more than 54mA at the comparator. The falling commutation require about 35ns forcing on the comparator a peak current of about 49mA.

These simulation allow us to say that the analisys done in the MOS paragraph is a good worst case due the fact that we approximate the two delay as equal. In other words this means that the estimation done for the power dissipation provide a good approximation ensuring the computation of a minimum efficiency of the DC/DC converter.

- POWER DISSIPATION IN THE TIMING NET

We can evaluate the wasted power in this circuit with the static power consumption of the various chips, therefore theyr bias current multiplied for the supply voltage:

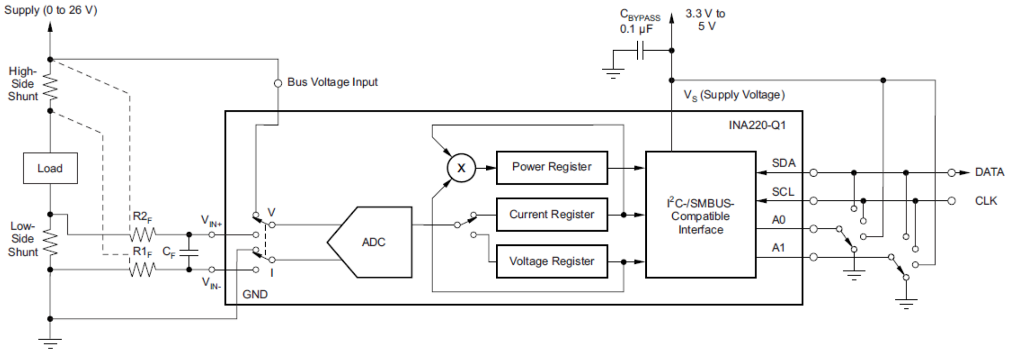
$$\begin{aligned} P_{diss} &= 3I_{Q_{TLV}}V_{DD}+I_{Q_{OPA}}V_{DD}+2V_{REF2}I_{POT}+I_{Q_{DIGPOT}}V_{DD} \\ &= 3I_{Q_{TLV}}V_{DD}+I_{Q_{OPA}}V_{DD}+2V_{REF2}\left(\frac{V_{REF2}}{P_1}\right)+I_{Q_{DIGPOT}}V_{DD} \\ &= 3I_{Q_{TLV}}V_{DD}+I_{Q_{OPA}}V_{DD}+2\frac{(V_{REF2})^2}{P_1}+I_{Q_{DIGPOT}}V_{DD} \\ &= V_{DD}(3I_{Q_{TLV}}+I_{Q_{DIGPOT}}+I_{Q_{OPA}})+2\frac{(V_{REF2})^2}{P_1} \end{aligned}$$

note that, the current necessary to drive the gate is just considered in the analisys of the MOS power dissipation.

- SENSING NET

On the sensing net there is little to say because I use a dedicated chip of texas instruments : the **INA220-Q1**. The only thinks to fix here is the shunt resistance and how to set its internal registers.

From datasheet :



Where, in this project is used for an high-side measure.

INA220-Q1	Absolute Maximum Ratings	min	max	
	supply voltage		6V	
	voltage at Vbus pin	-0,3V	26V	
	voltage at SDA pin	GND-0,3V	6V	

Electrical characteristics	test conditions	min	typ	max
power supply		3		5,5V
quiescent current			0,7mA	1mA
ADC basic resolution			12 bits	
full scale current sense (input) voltage range	PGA = /1	0		±40mV
	PGA = /2	0		±80mV
	PGA = /4	0		±160mV
	PGA = /8	0		±320mV
Bus Voltage	BRNG = 1	0		32V
	BRNG = 0	0		16V

With PGA = 1 we fix a full scale of 40mV on the voltage across the shunt resistance. With BRNG = 1, instead, we fix a maximum voltage on Vbus of 32V. Therefore, the shunt resistance will be:

PV panel PGA	Vmax [mV]	Imax (2*Imp=2*0,6 A)	BRNG	Vinmax	Vbusfs	Rshunt (=Vmax/Imax)
1	**40**	**1,2**	**1**	**18**	**32**	**3,33E-02**
2	80	1,2	1	18	32	6,67E-02
4	160	1,2	1	18	32	1,33E-01
8	320	1,2	1	18	32	2,67E-01

VAWT PGA	Vmax [mV]	Imax (2*Imp=2*1,25 A)	BRNG	Vinmax	Vbusfs	Rshunt (=Vmax/Imax)
1	**40**	**2,5**	**1**	**18**	**32**	**1,60E-02**
2	80	2,5	1	18	32	3,20E-02
4	160	2,5	1	18	32	6,40E-02
8	320	2,5	1	18	32	1,28E-01

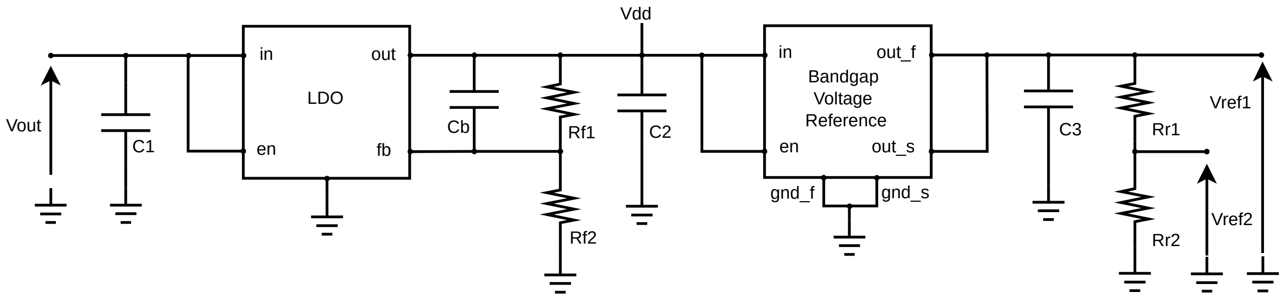
or rather, 33mΩ for the PV panel branch and 16 mΩ for the VAWT branch.

- POWER DISSIPATION

$$P_{SENS}=R_{SHUNT}*(I_{INGRMS})^2+I_Q*V_{DD}$$

- INTERNAL SUPPLY

The internal supply net will stole power from the main path to supply the circuits necessary to the correct work of the system. it must generate 5V used as voltage supply and the other two voltage for the timing net : 4V and 2,5V. The licterature propose many way to do this, the choosed method should be the most roubust and simply; one LDO to generate the 5V and a bandgap voltage reference (BVR) for the other two voltage with the circuit in the lower picture:



The problem is faced in two consecutive steps:

- in the first step the voltage regulator stabilize Vout from the power path and generate Vdd
- an additional stabilization is done from BVR to provide Vref1 and Vref2

The first step is entrusted at an LDO of the automotive world, the **TPS7A4001-100V** with the following characteristics:

TPS7A4001-100V	
7V< Vin < 100V	Iout = 50mA
Vfb < Vout < 90V	Iout limit = 200ma
1,161V < Vfb < 1,185V	Iq = 25uA

From the datasheet we obtaine the suggested values for the capacitors:

$$C_1 = 10uF \ ; \ C_b = 10nF \ ; \ C_2 = 10uF$$

Intead, the two feedback resistors:

$$V_{fb} = V_{dd}\frac{R_{f2}}{R_{f1}+R_{f2}} \rightarrow R_{f1} = R_{f2}\left(\frac{V_{dd}}{V_{fb}}-1\right) \quad with \ V_{dd}=5V \ , \ V_{fb} = 1{,}17V \wedge R_{f2}=53{,}6k\Omega$$

$$R_{f1} = 53{,}6k\left(\frac{5}{1{,}17}-1\right) = 175{,}46k\Omega \ normalized \ at \ the \ E96 \ series \rightarrow R_{f1} = 178k\Omega$$

The result is that when $V_{out}>7V$ the LDO turn on providing $V_{dd}=5V$ on the output.

To extract the two voltage of reference from Vdd, a bandgap voltage reference is used; the **REF3240** designed by texas instruments :

REF3240	
Vout +0,05V < Vin < 5,5V	Iq = 135uA
1,5V < Ven < Vin	Vout = 4,096V

with a short circuit among input and enable terminals, we have that when $V_{dd}>4{,}096V+0{,}05V$ there will be $V_{ref1} = 4{,}096V$. For Vref2 we use a resistive voltage divider:

$$V_{ref2} = V_{ref1}\frac{R_{r2}}{R_{r1}+R_{r2}} \rightarrow R_{r1} = R_{r2}\left(\frac{V_{ref1}}{V_{ref2}}-1\right) \quad with \ V_{ref1}=4{,}096V \ , \ V_{ref2} = 2{,}5V$$

$$R_{r2}=100k\Omega; \ R_{r1} = 100k\left(\frac{4{,}096}{2{,}5}-1\right) = 63{,}8k\Omega \ normalized \ at \ E96 \ serie \rightarrow R_{r1} = 63{,}4k\Omega$$

From datasheet : $C_3 = 0{,}1uF$.

Let pay attention on the power dissipation of the TPS. The regulator must supply the bias current of all the integrated circuits, but, above all the peak current to drive the two power MOSFET. The direct current component of the output current will be mainly the bias current for the comparator, the ADC and here I consider an overhead of 3mA. Hence:

$$I_{DC} = 3I_{Qcomp}+2I_{QADC}+I_{overh}$$
$$=3*5mA+2*1mA+3mA = 20mA$$

the AC component is done by the two peak current of 78mA for 30ns of the MOS driver.

$$I_{AC}=\begin{cases} I_{pk}=78mA & 0<t<2\Delta t \\ 0 & 2\Delta t<t<T_{sw} \end{cases}$$

with these information we can compute the power dissipation by means:

$$P_{LDO} = \Delta V*I_{RMS}+I_Q*V_{OUT} \qquad I_{RMs}^2 = I_{DC}^2+I_{AC}^2 \qquad I_{DC}^2 =(20mA)^2$$

$$I_{AC}^2 = \frac{1}{T_{sw}}\int_0^{2\Delta t} I_{pk}^2\,dt = \frac{1}{T_{sw}}2\Delta t I_{pk}^2 = 2\Delta t f_{sw} I_{pk}^2 = 2*30ns*300kHz*(78{,}5mA)^2 = 109{,}51uA^2$$

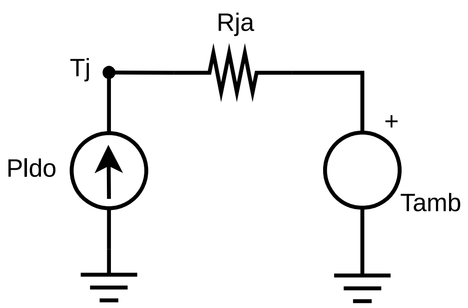
$$I_{RMS} = \sqrt{I_{DC}^2+I_{AC}^2} = \sqrt{(20mA)^2+109{,}51uA^2} = 22{,}57mA$$

as seen in the maximum output voltage analisys, we know that $V_{OUTMAX} = 50V$, that will be our wort case. Therefore :

$$\Delta V = V_{OUT}-V_{dd} = 50v-5V = 45V$$
$$P_{LDO} = 45V*22{,}57mA + 25uA*50V=1{,}017W$$

Following the analisys of [39] and [40] let's analize the thermal equivalent in order to know if it's possible use the LDO without an heatsink.

$$T_j = P_{LDO}*R_{JA}+T_{AMB}$$



where :
- Tj : junction temperature
- Tamb : enviroment temperature
- Pldo : power dissipation
- Rja : thermical equivalent resistance junction-enviroment

From datasheet :
- Rja = 66,7°C/W
- Tjmax = 125°C

If we take as reference the resistance specified on the datasheet, the result is that the chip can work without heatsink until :

$$T_{AMB} = T_J-P_{LDO}*R_{JA}=125-1{,}017*66{,}7=57{,}16°C$$

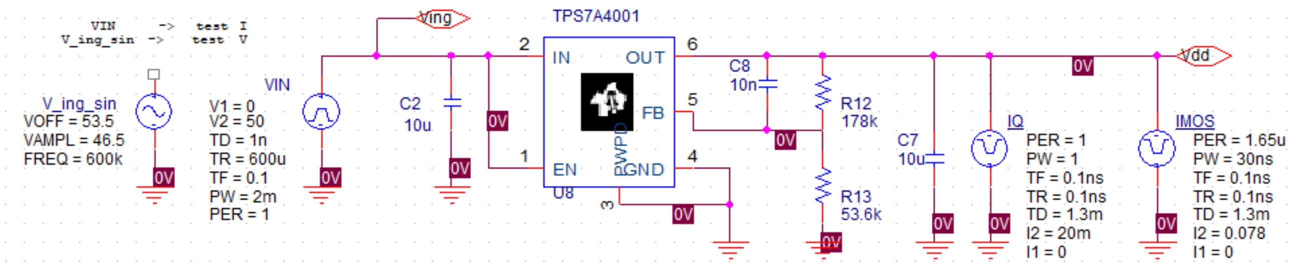
That is supposed to be accettable because the VAWT and the PV panel are generating the maximum amount of power. It means that the wind is of 15m/s, in other words, the heat is carried out, so we can neglect it. Move to analize the case where there is only the PV panle that is ON. In this situaion the MPEI will have only one branch active, so, we can watch at the single boost converter where $V_{OUT}=\frac{V_{ING}}{1-D}$.

If we assume a duty cycle of 0,6 the maximum output voltage will be of 45V, with a dissipated power of 904mW and the critical temperature value is 64,7°C that continue to be accettable.

In conclusion, the heatsink will be not used for the testing phase done in the laboratory, instead, due the low cost of an heatsink and the low temperature margin, an heatsink is suggested if the system will be commercialized.

- SIMULATION

The LDO is tested with two different simulations, the first one is done with an input voltage from 0V to 50V where we have a focus on the circuit current and the power dissipation; with the second test we force an input sinusoidal voltage with a maximum peak of 100V where I test the stability of the Vdd. Both the tests will have two current generator on the output : the first one simulate the bias currents (20mA) and the second one simulate the charge required to drive the MOS, 78mA for 30ns each Tsw/2 (=1,65us) time.

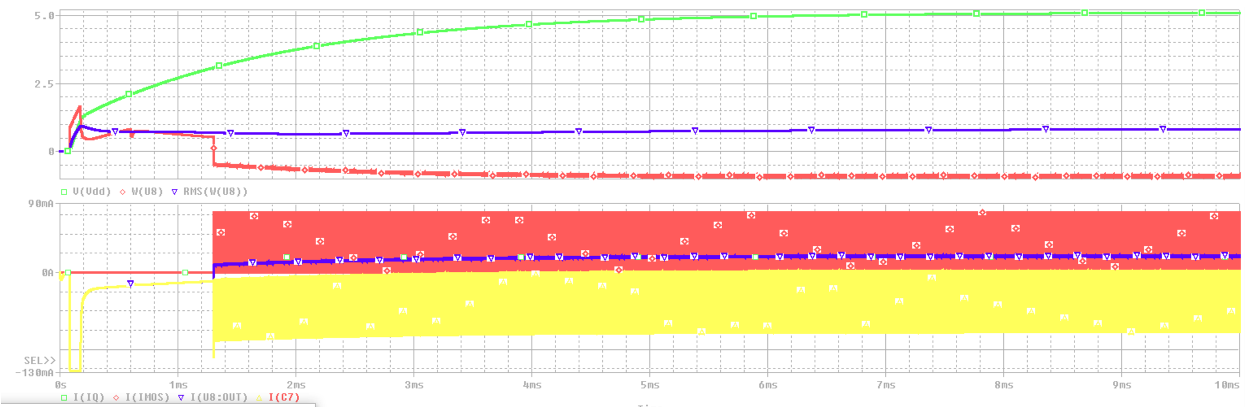


there are 3 phases in the simulation:

- a first phase of "wake up", where Vdd<3V required from the circuit to work correctly (simulated by the delay of current generator with TD = 1,3m). Here LDO is charging C7. Note the peak on the dissipated power is related to the peak current required to charge the capacitor.

- the second phase of ignition of the circuit. After 1,3ms, Vdd>3V the circuit start to be supplied and beginning to request current from the power line.

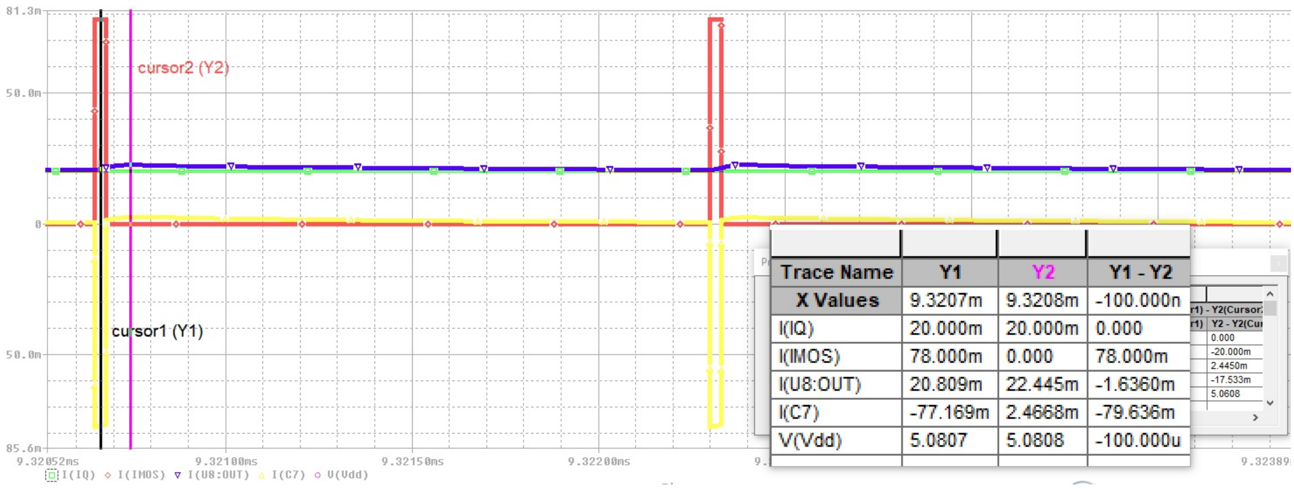
- steady operation.



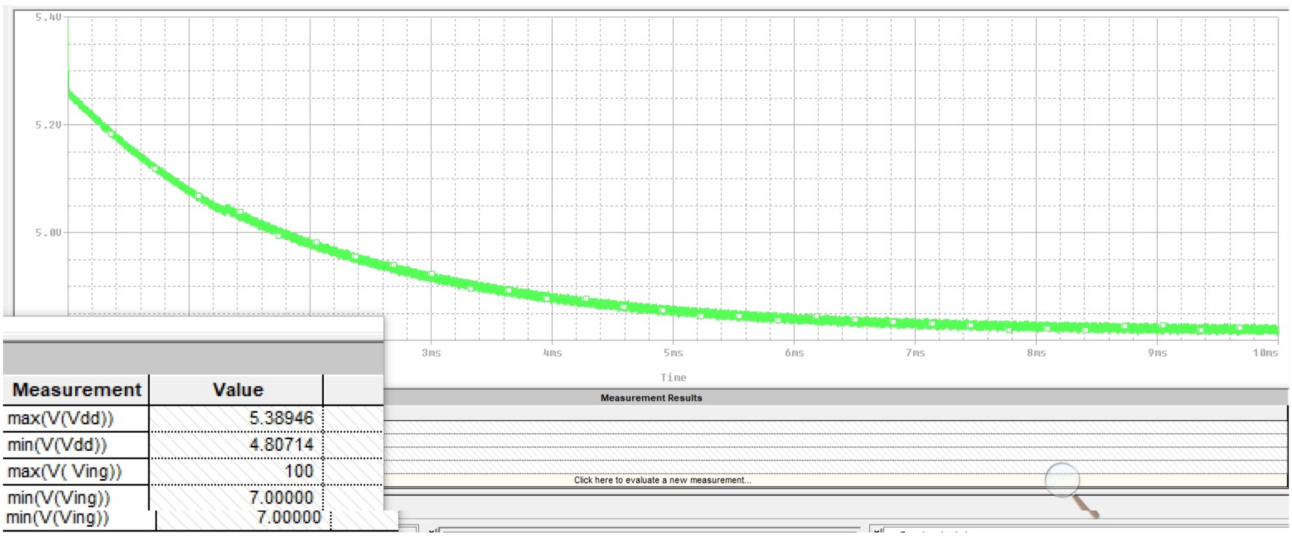
max(V(Vdd))	5.08766
max(V(Ving))	50
max(RMS(W(U8)))	951.67044m
max(W(U8))	1.69578
max(I(U8:OUT))	22.49911m
max(I(IQ))	20m

A first look on the obtained values show us an output current and a power dissipation slightly lower than the one computed in the previous page.

Let's go into detail of the steady state current with the next figure. We can note that the current peaks (of 78mA) are taken from the capacitor C7 and then recharged during the period.

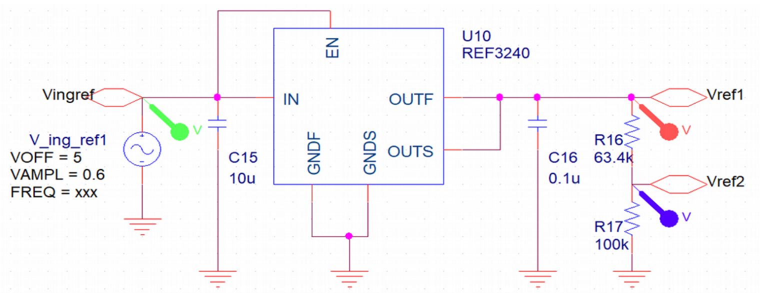


The second test is done by changing the input generator. The used one is V_ing_sin that apply a sinusoidal signal on the input forcing a voltage that swipe from 7V to 100V. The results are reported in the next figure:



The registered output voltage swipe can be considered as accettable, infact the simulation return a voltage swing from 4,52V to 5,10V; remeber that all our integrated circuits accepts a supply voltage from 3V to 5,5V and the REF3240 accept from 4,1V to 5,5V.

In order to analyze a critical worst case, I use these information about the swing of the Vdd voltage (4,5V to 5,5V) to set up a sinusoidal generator that will drive the bandgap voltage reference and test a set of frequencies:



From the datasheet we know that the REF3240 has a good PSRR at low frequencies that drop out at higher frequencies. In the next figure the PSRR versus frequency is display:

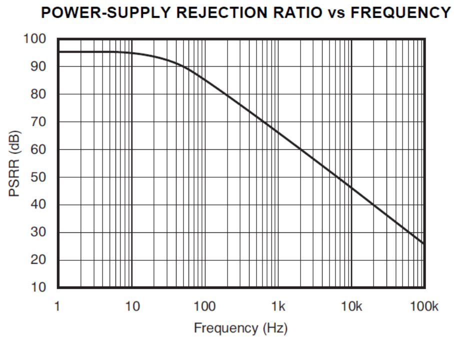
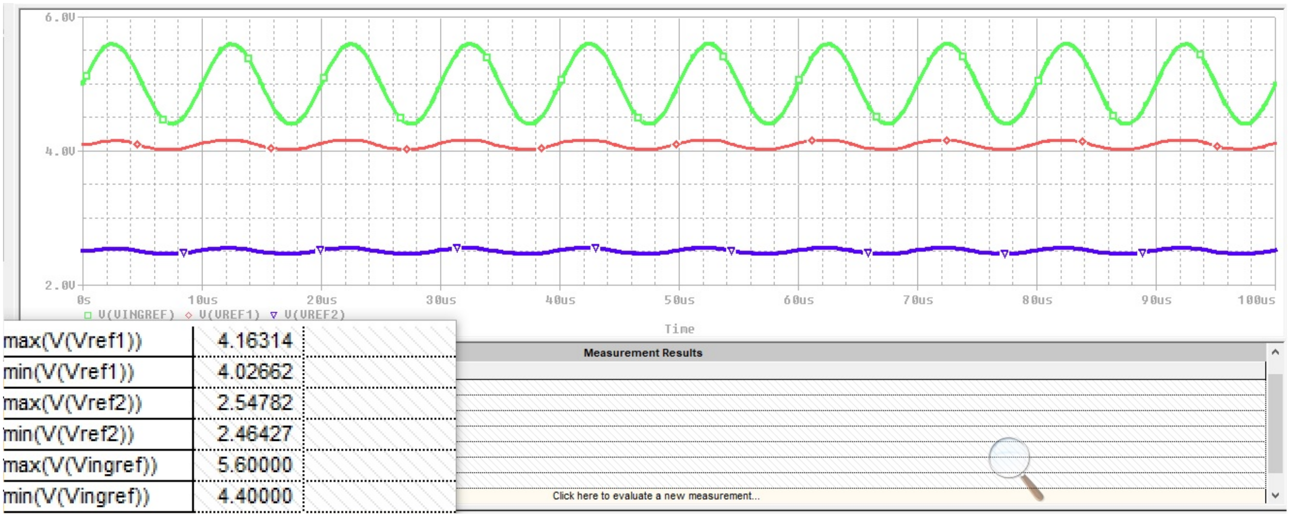


Figure 6.

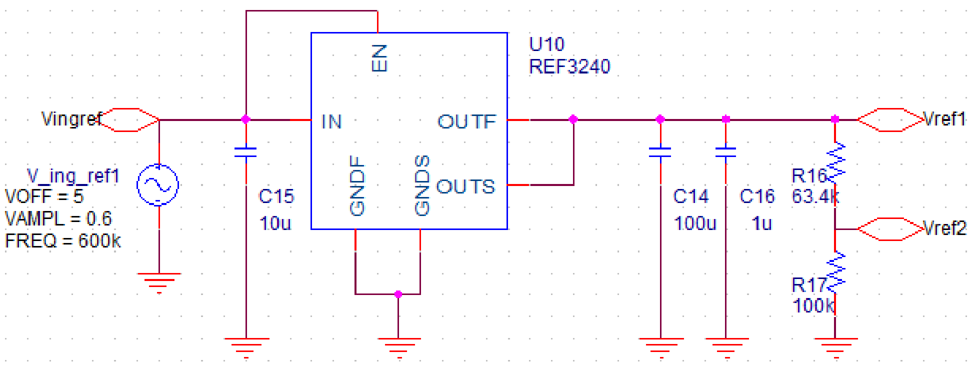
therefore, start the simulation to observe what happens with the spice model supplied from texas instruments. If we force an input signal at 100kHz the result is:



As the image shows, the Vref swing is of about 0,1V that is unacceptable; to kill the noise/swing we can use a typical trick used in electronics : two bypass capacitors on the Vref line. The choosed capacitor are 1uF and 100uF. A set of additional test are done, in the next table are summerized all the results of interest:

			max(Vref1)-min(Vref1)			max(Vref1)-min(Vref1)
f	**max(Vref1)**	**min(Vref1)**		**max(Vref2)**	**min(Vref2)**	
1k Hz	4,10072	4,09121	0,00951	2,50962	2,5038	0,00582
10K Hz	4,09989	4,0941	0,00579	2,50911	2,50557	0,00354
50k Hz	4,09764	4,09636	0,00128	2,50774	2,50695	0,00079
100k Hz	4,09736	4,09661	0,00075	2,50756	2,50711	0,00045
200k Hz	4,09726	4,09671	0,00055	2,5075	2,50716	0,00034
600k Hz	4,09715	4,0968	0,00035	2,50744	2,50722	0,00022

the swing become of about mV instead of 100mV, so the circuit become:



- POWER DISSIPATION

The amount of power wasted in to the circuit is computed in MATLAB with the following code:

```
format shortEng
clear all
clc
%% DATA ******************************************************************
Iin1 = 0.6; % average current of L1
Iin2 = 1.25;
Rind1 = 335e-3; % parastic resistance of L1
Rind2 = 146e-3;
D1 = 0.5; % duty cycle
D2 = 0.5;
deltaIl1 = 2*Iin1;
deltaIl2 = 2*Iin2;
%% Cout
Resr = 88e-3;
Ioutmax = 1.25;
%% N-MOS : CDS19538Q2 (ti)
Qgate = 2.5e-9;
Rdson = 70e-3;
Fsw = 300e+03;
Ion1 = Iin1;
Ion2 = Iin2;
%%  TLV3502 (ti)
Vdd = 5;
Vdrive = 5;
Idrivermax = 78e-3;
Iqcomp = 5e-3;
%% diodo FSV12100V
Vf = 0.485; %forward voltage of schottky;
Ileakage = 8.4e-6; % leakage
%% otuput voltage
Vx = 50;
Vinldo = Vx;
Vdsoff1 = Vx;
Vdsoff2 = Vx;
Voutmax = Vx;
%% LDO TPS7A4001 (ti)
Voutldo = Vdd;
Iinldo = 50e-3;
Iqldo = 0;
%% ADC INA220-Q1 (ti)
Pi2c = 0;
Iqina = 1e-3;
%% OP AMP : OPA2365 (ti)
Iqopa = 0;
Iqdigpot = 1e-6;
Vref2 = 4;
P=100e+3;
%% POWER DISSIPATION ****************************************************
%% Rshunt
Rshunt1 = 33e-3;
Rshunt2 = 16e-3;
Prshunt1 = (4/3)*Rshunt1*(Iin1)^2
Prshunt2 = (4/3)*Rshunt2*(Iin2)^2
Ptemp = Prshunt1+Prshunt2;
Pbranch1 = Prshunt1;
Pbranch2 = Prshunt2;
```

```
%% inductor
Plind1 = (4/3)*Rind1*(Iin1)^2
Plind2 = (4/3)*Rind2*(Iin2)^2
Ptemp = Ptemp + Plind1+Plind2;
Pbranch1 = Pbranch1+Plind1;
Pbranch2 = Pbranch2+Plind2;
%% output capacitor
PCout = Resr*Ioutmax^2
Ptemp = Ptemp + PCout;
Pbranch1 = Pbranch1+PCout;
Pbranch2 = Pbranch2+PCout;
%% MOSFET
deltaT = Qgate/Idrivermax;
Pconduzione1 = ((D1*Iin1^2+(D1)*(deltaIl1/3)^2)^2)*Rdson
Pconduzione2 = ((D2*Iin2^2+(D2)*(deltaIl2/3)^2)^2)*Rdson
Pgate = Qgate*Vdrive*Fsw
Pcommutazione1 = Ion1*Vdsoff1*deltaT*Fsw
Pcommutazione2 = Ion2*Vdsoff2*deltaT*Fsw
Pmos1 =Pconduzione1+Pgate+Pcommutazione1
Pmos2 =Pconduzione2+Pgate+Pcommutazione2
Ptemp = Ptemp + Pmos1 + Pmos2;
Pbranch1 = Pbranch1+Pmos1;
Pbranch2 = Pbranch2+Pmos2;
%% diode
Pdiodo1 = D1*Voutmax*Ileakage+(1-D1)*Vf*Iin1
Pdiodo2 = D2*Voutmax*Ileakage+(1-D2)*Vf*Iin2
Ptemp = Ptemp + Pdiodo1+Pdiodo2;
Pbranch1 = Pbranch1+Pdiodo1;
Pbranch2 = Pbranch2+Pdiodo2;
%% timing net
Ptim = Vdd*(3*Iqcomp+Iqopa+Iqdigpot)+2*(Vref2^2)/P
Ptemp = Ptemp +Ptim;
Pbranch1 = Pbranch1+Ptim;
Pbranch2 = Pbranch2+Ptim;
%% sensing net
Psensing = 2*Iqina*Vdd
Ptemp = Ptemp + Psensing;
Pbranch1 = Pbranch1+Psensing;
Pbranch2 = Pbranch2+Psensing;
%% LDO
Iover = 3e-3;
Ipk = 78e-3;
deltat = 30e-9;
Ildorms = sqrt((3*Iqcomp+2*Iqina+Iover)^2+(2*deltat*Fsw*(Ipk^2)));
Pldo = Ildorms*(Vinldo-Vdd)+Iqldo*Vinldo
Ptemp = Ptemp + Pldo
Pbranch1 = Pbranch1+Pldo
Pbranch2 = Pbranch2+Pldo
%% resume
Ptot = Ptemp;
Pmax = 25;
PPV = 10;
PVAWT = 15;
efficiency_both = (Pmax-Ptot)/Pmax
efficiency_PV = (PPV-Pbranch1)/PPV
efficiency_VAWT = (PVAWT-Pbranch2)/PVAWT
```

with the following results on the terminal:

Prshunt1 = 15.8400e-003

Prshunt2 = 33.3333e-003
Plind1 = 160.8000e-003
Plind2 = 304.1667e-003
PCout = 137.5000e-003
Pconduzione1 = 4.7320e-003
Pconduzione2 = 89.1415e-003
Pgate = 3.7500e-003
Pcommutazione1 = 288.4615e-003
Pcommutazione2 = 600.9615e-003
Pmos1 = 296.9435e-003
Pmos2 = 693.8530e-003
Pdiodo1 = 145.7100e-003
Pdiodo2 = 303.3350e-003
Ptim = 75.3250e-003
Psensing = 10.0000e-003
Pldo = 1.0158e+000
Ptemp = 3.1926e+000
Pbranch1 = 1.8579e+000
Pbranch2 = 2.5733e+000
efficiency_both = 872.2975e-003
efficiency_PV = 814.2125e-003
efficiency_VAWT = 828.4487e-003

The results are not so good. When both the harvester are working there is a power dissipation of 3,2W and the MPEI has an efficiency of 87%. the situation gets worse if only one harvester is active (where we hypotize that the output is stable at the maximum value of 50V):

- if only the PV panel is ON, the power dissipation is 1,86W with an efficiency of 81%
- if only the VAWT is ON, the power dissipation is 2,57W with an efficiency of 83%

As we can see from the MATLAB results, the main actor who waste energy in the circuit are the diodes, the LDO and the MOS due to miller effect. The efficiency can be raised working on these components:

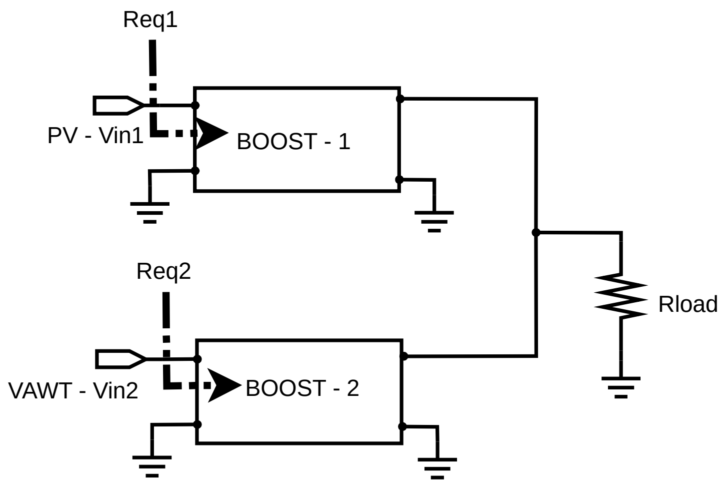
- MOS : we should search a transistor with lower charge request on the gate to reduce the time where Vds and Ids are overlapped, or, substitute the comparator with a miller killer able to force more than 78mA on the gate.

- DIODE : we can't substitute the diodes because they ensure the direct current path that is essential for the self supply of the circuit. The only action available here is to search a better schottky diode.

- LDO : the best idea is substitute the LDO with a DCDC buck converter able to work in the same way.

- OUTPUT RESISTANCE

Recalling what we say in the proposed system chapter, the value of the output resistance has a particular impact on the harvesting operating range; the main problem is that the two harvesters has different operating point, therefore they need different equivalent load resistance. From the power electronics theory we know that the input resistance of a boost converter will be computed from the following circuit:



where :

$$V_{OUT} = \frac{V_{ing}}{1-D} \quad \wedge \quad I_{OUT} = (1-D) I_{ING}$$

$$R_{EQ} = \frac{V_{ING}}{I_{ING}} = \frac{(1-D)V_{OUT}}{\frac{I_{OUT}}{1-D}} = (1-D)^2 \frac{V_{OUT}}{I_{OUT}} = (1-D)^2 R_{LOAD}$$

so, each equivalent input resistance applied on each harvester will be moduled from the duty cycle imposed on the MOS:

$$R_{EQ1} = (1-D_1)^2 \ R_{LOAD}$$
$$R_{EQ2} = (1-D_2)^2 \ R_{LOAD}$$

in the case of the maximum power point, the load resistance on the solar panel (Req1) and on the wind turbine (Req2) must be of:

$$R_{EQ1_{MIN}} = \frac{V_{mp1_{MAX}}}{I_{mp1_{MAX}}} = \frac{18 \ V}{0{,}5 \ A} = 36 \ \Omega$$

$$R_{EQ2_{MIN}} = \frac{V_{mp2_{MAX}}}{I_{mp2_{MAX}}} = \frac{12 \ V}{1{,}25 \ A} = 9{,}6 \ \Omega$$

the problem become to search one output resistance that allow us to harvester the as wide as possible range of renewable energy sources. To compute this value trust in MATLAB. Start with the definition of initial parameter that carry accettable resistance values :

```
Vmp2 = 12;  Imp2 = 1.25;    perc_I2= 10/100;    DeltaV2 = 3;    D2_max = 0.73;  D2_min = 0.2;
Vmp1 = 18;  Imp1 = 0.5;     perc_I1= 10/100;    DeltaV1 = 3;    D1_max = 0.7;  D1_min = 0.2;
```

After compute the maximum and minimum resistance that these value involves :

```
Rdes2_min = floor(Vmp2/Imp2);
Rdes1_min = floor(Vmp1/Imp1);
Rdes2_max = floor((Vmp2-DeltaV2)/(Imp2*perc_I2));
Rdes1_max = floor((Vmp1-DeltaV1)/(Imp1*perc_I1));
```

Compute the duty cycle that each branch must impose on the MOS:

```
D = zeros(7561,5);
i=1;
for Rdes2 = Rdes2_min:9:Rdes2_max
for Rdes1 = Rdes1_min:10:Rdes1_max
    for Rload =60:10:400
        D(i,1) = 1-sqrt(Rdes1/Rload);
        D(i,2) = Rdes1;
        D(i,3) = 1-sqrt(Rdes2/Rload);
        D(i,4) = Rdes2;
        D(i,5) = Rload;
        i=i+1;
    end
end
end
```

at least erase the duty cycle values considered inappropriate :

```
[start_val,tmp]= size(D);
for i = start_val:-1:1
    if (D(i,1)<=D1_min)||(D(i,1)>=D1_max)
        D(i,:)=[];
    end
end
[start_val,tmp]= size(D);
for i = start_val:-1:1
    if (D(i,3)<=D2_min)||(D(i,3)>=D2_max)
        D(i,:)=[];
    end
end
```

The result is a big matrix with all the required information. The next goal is extrapolate these information in an usable form in order to obtain one possible value of resistance. What we need now is a new matrix where, for each value take in account, give us information on how wide is the useful range that we can harvest:

```
[start_val,tmp]= size(D);
R_matrix = zeros(36,6);
R_matrix(:,4)=1000;
R_matrix(:,6)=1000;
i=1;
    for Rload =60:10:400
        R_matrix(i,1)=Rload;
        i=i+1;
    end
for i = start_val:-1:1
   for j = 1:36
         if (D(i,5)==R_matrix(j,1))
                R_matrix(j,2)=R_matrix(j,2)+1;
            if(D(i,2)>R_matrix(j,3))
                R_matrix(j,3) = D(i,2);
            end
            if(D(i,2)<R_matrix(j,4))
```

```
                R_matrix(j,4) = D(i,2);
            end
            if(D(i,4)>R_matrix(j,5))
                R_matrix(j,5) = D(i,4);
            end
            if(D(i,4)<R_matrix(j,6))
                R_matrix(j,6) = D(i,4);
            end
        end
    end
end
```

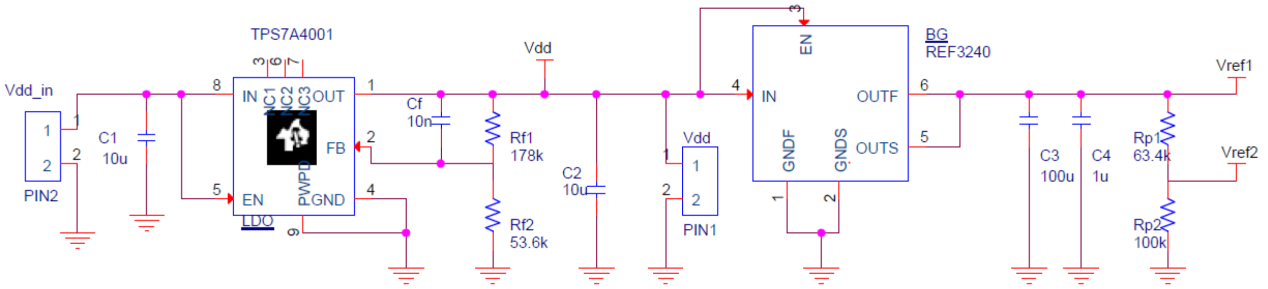
R_matrix contains (on the below table):
- first column : value of the output resistance take in consideration
- second column : how many times the relative value is present in the D matrix previously computed
- third and fourth column : maximum and minimum resistance that we can impose on the solar panel keeping accettable values of duty cycle.
- fifth and sixth column : maximum and minimum resistance that we can impose on the wind turbine keeping accettable values of duty cycle..

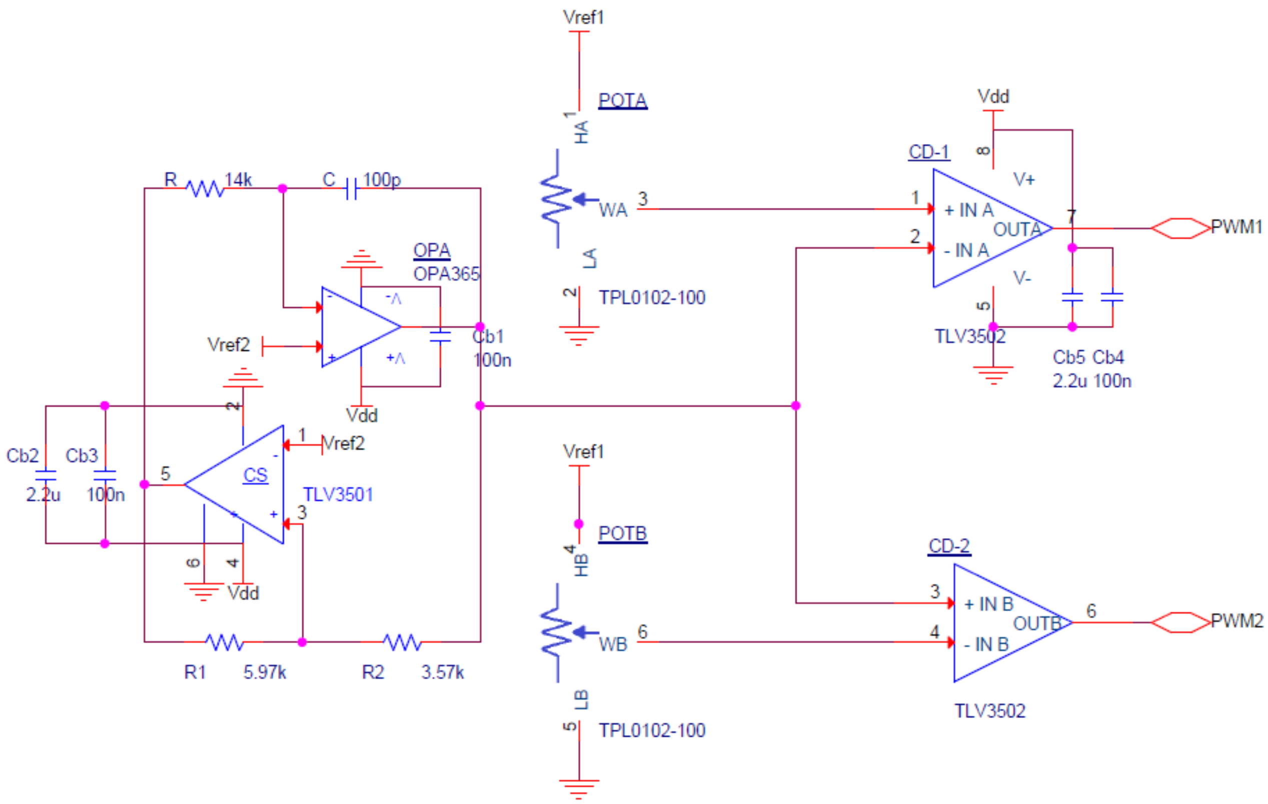
R_LOAD		MAX	MIN	MAX	MIN
60	4	36	36	36	9
70	4	36	36	36	9
80	10	46	36	45	9
90	18	56	36	54	9
100	21	56	36	63	9
110	28	66	36	63	9
120	40	76	36	72	9
130	35	76	36	72	18
140	42	86	36	72	18
150	42	86	36	72	18
160	49	96	36	72	18
170	56	106	36	72	18
180	56	106	36	72	18
190	63	116	36	72	18
200	70	126	36	72	18
210	70	126	36	72	18
220	77	136	36	72	18
230	84	146	36	72	18
240	84	146	36	72	18
250	78	156	36	72	27
260	84	166	36	72	27
270	84	166	36	72	27
280	90	176	36	72	27
290	90	176	36	72	27
300	96	186	36	72	27
310	102	196	36	72	27
320	102	196	36	72	27
330	108	206	36	72	27
340	114	216	36	72	27
350	114	216	36	72	27
360	120	226	36	72	27
370	126	236	36	72	27
380	105	236	36	72	36
390	110	246	36	72	36
400	105	246	46	72	36

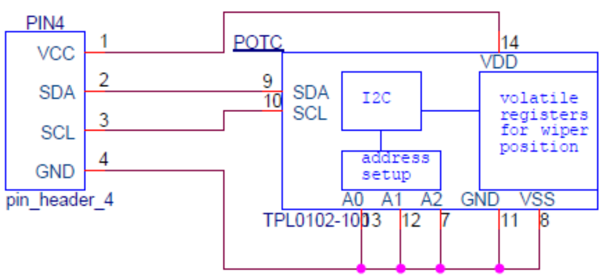
With a double check on the market availability I choose 100 ohm as ideal value:

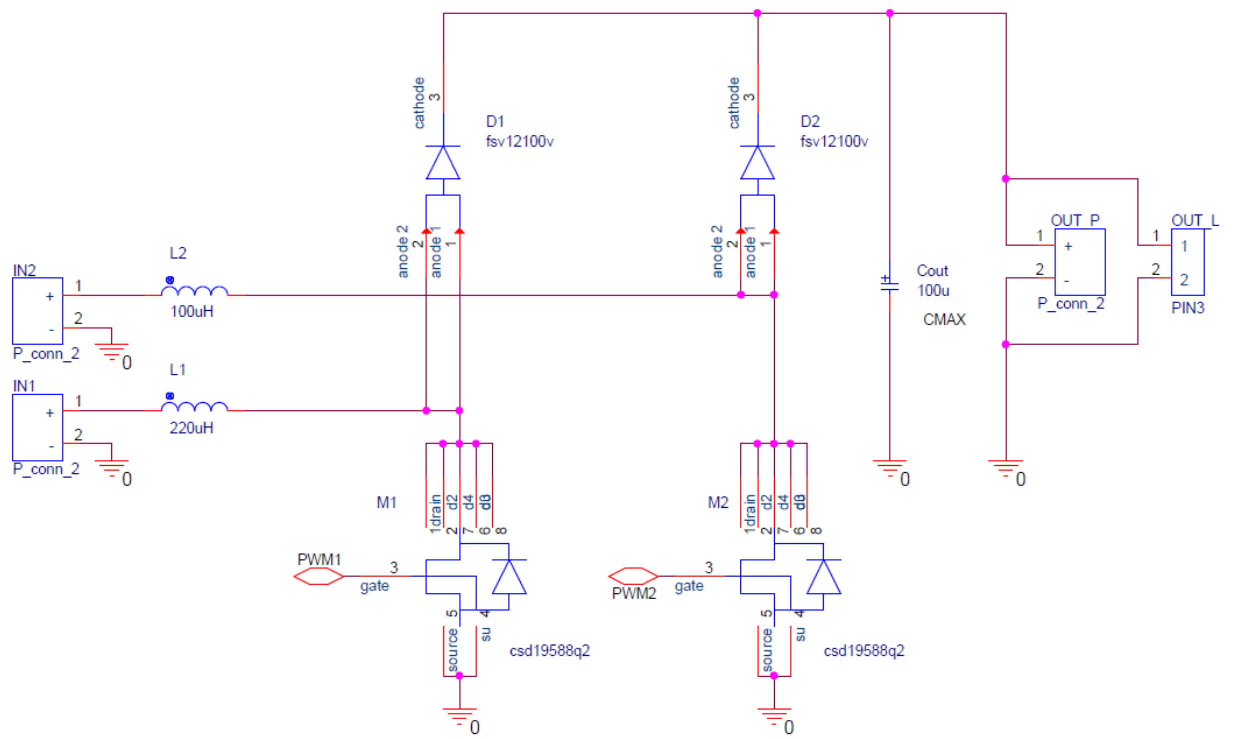
- on the PV panel we are in the range of 56-36 ohm
- on the VAWT we are in the range of 63- 9 ohm.

- SCHEMATIC AND BOM
- POWER BOARD

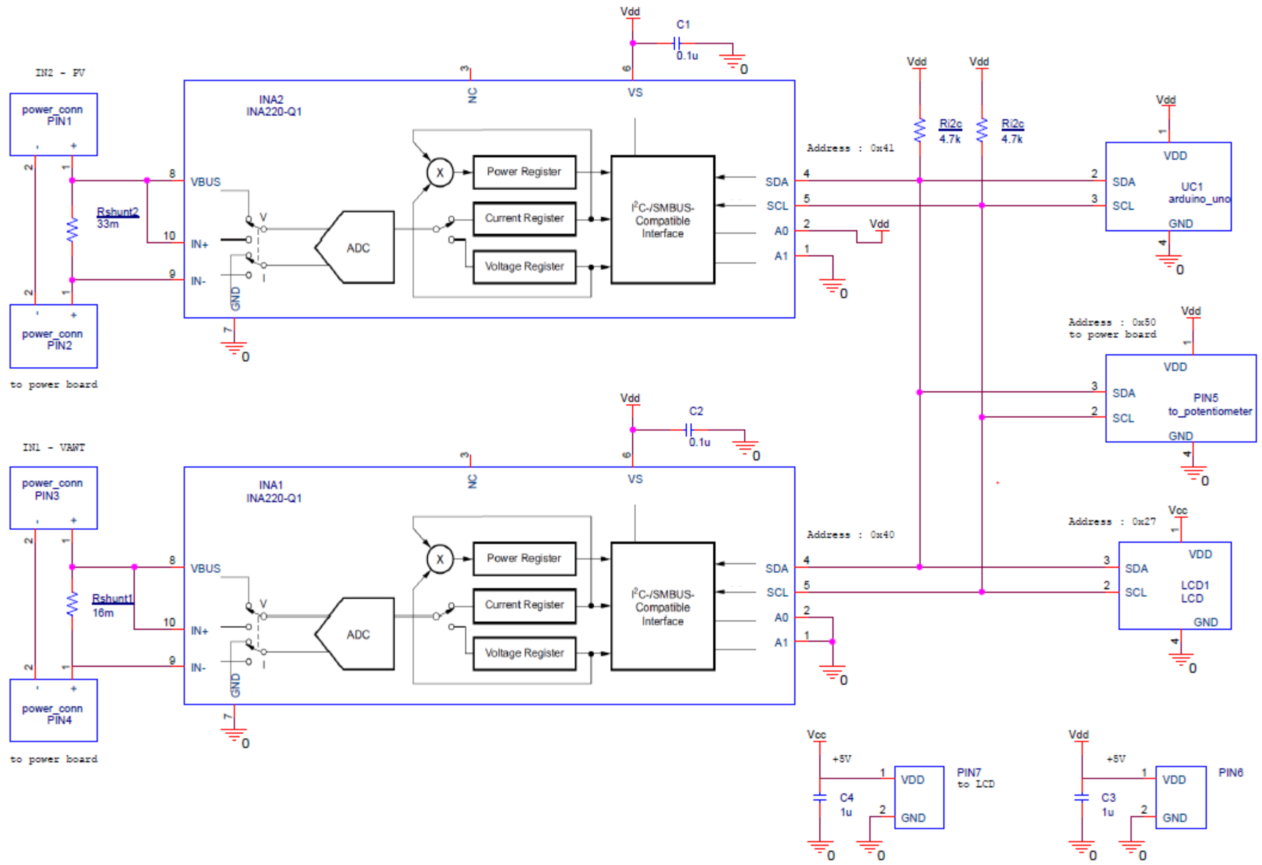




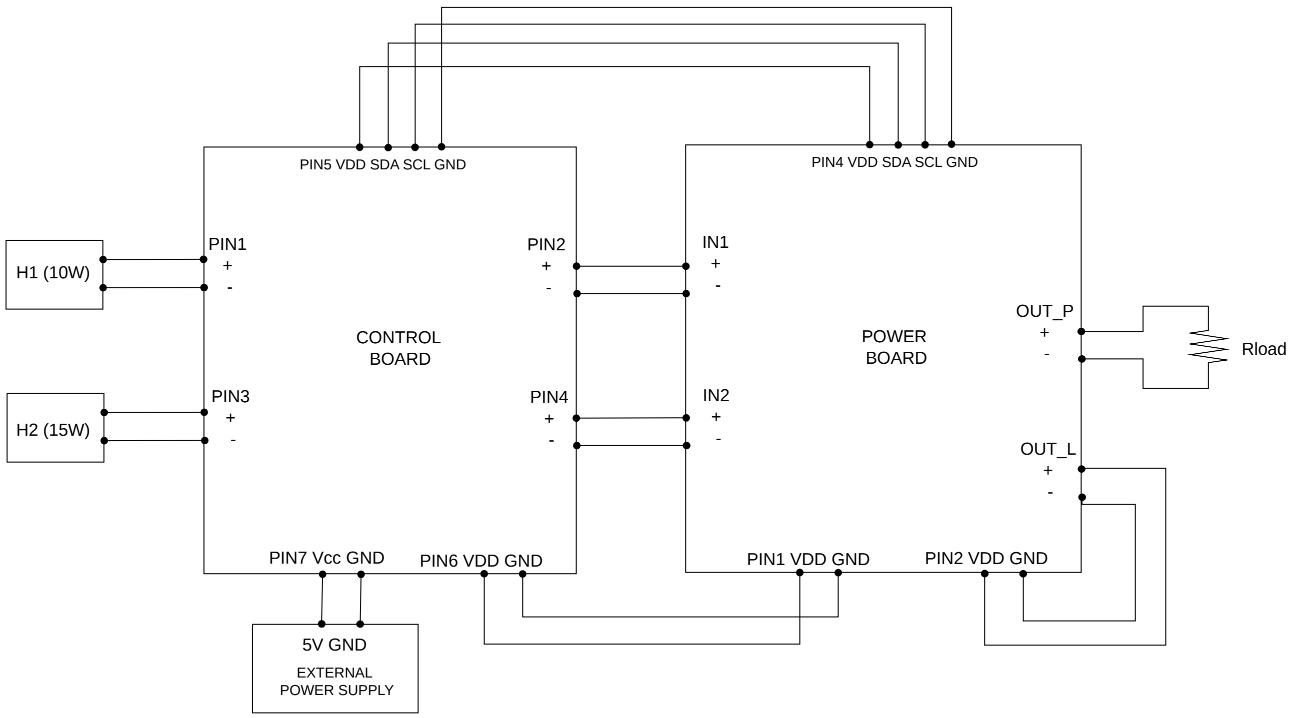




- CONTROL BOARD



- WIRING DIAGRAM

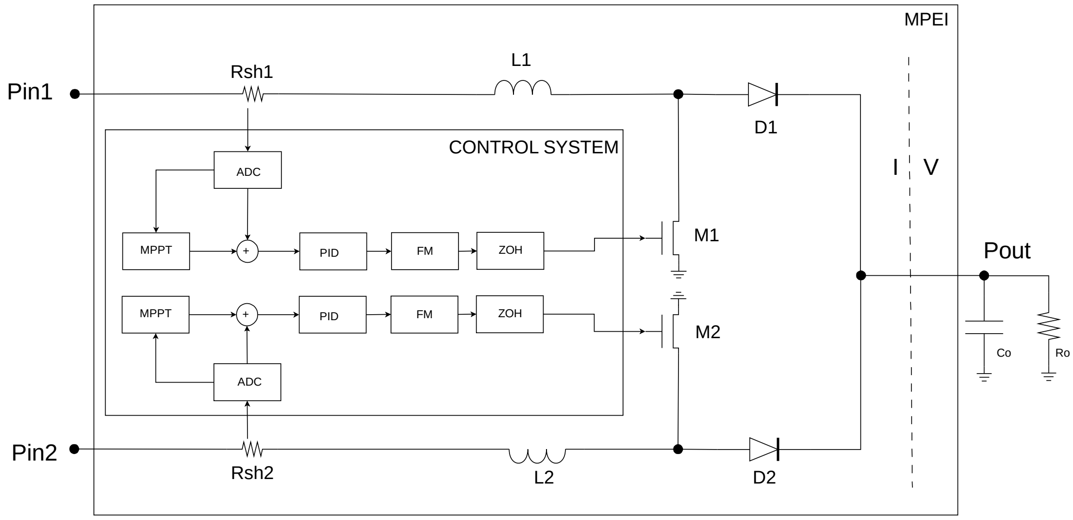


- BOM

	pcs	value	productor	code vendor
power path				
L1	1	220uH	Coilcraft	994-MSS1260-224KLD
L2	1	100uH	Coilcraft	994-MSS1260-104MLD
D1-D2	2	FSV12100V	Fairchild Semiconductor	512-FSV12100V
M1-M2	2	CSD19538Q2	texas instuments	595-CSD19538Q2
Cout	1	100uF	Nichicon	647-UHW2A101MPD1TD
Conn1/2/3	3	2 pin	Phoenix Contact	651-1985865
timing				
R	1	14k ohm	Vishay/Dale	71-RN55C1402B/R
C	1	100pF	TDK	810-FA24NP2W101JNU06
R1	1	5,97k ohm	Vishay/Dale	71-RN55C-B-5.97K
R2	1	3,57k ohm	Vishay/Dale	71-RN55C-B-3.57K
U1	1	OPA365	texas instuments	595-OPA365AIDBVR
U2	1	TLV3501	texas instuments	595-TLV3501AQDBVRQ1
U3A/B	1	TLV3502	texas instuments	595-TLV3502AIDR
Cb1,3,4	3	100nF	AVX	581-0805YC104KAT4A
Cb2,5	2	2,2uF	AVX	581-12065D225KAT2A
Conn4/5/6/7	4	pin header	Molex	538-90120-1082
internal supply				
C1	1	10uF	KEMET	80-ESL106M100AE3AA
Cf	1	10nF	TDK	810-FG18C0G2A103JRT6
C2	1	10uF	Nichicon	647-USA1E100MCA
C3	1	100uF	KEMET	80-A750EK107M1CAAE18
C4	1	1uF	TDK	810-FA11X7R1H10500
Rf1	1	178k ohm	Vishay/Dale	71-RN55C1783BB14
Rf2	1	53,6k ohm	Vishay/Dale	71-RN55E-D-53.6K/R
Rp1	1	63,4k	Vishay/Dale	71-RN55E6342B/R
Rp2	1	100k	Vishay/Dale	71-RN55C-B-100K
U4	1	TPS7A4001	texas instuments	595-TPS7A4001DGNR
U5	1	REF3240	texas instuments	595-REF3240AIDBVR
control board				
POT	1	TPL0102	texas instuments	595-TPL0102-100PWR
ADC	2	INA220-Q1	texas instuments	595-INA220BQDGSRQ1
Rsh1	1	33m ohm	Panasonic	667-ERJ-8CWFR033V
Rsh2	1	16m ohm	Panasonic	667-ERJ-6CWFR016V
Ri2c	2	4,7k ohm	xicon	291-4.7K-RC

- SMALL SIGNAL ANALISYS AND SIMULINK MODEL

In the small signal analisys we will study the bheaviour of the system. A method to close the existing loop will be suggested and after tested on simulink. Recall the high level view of the system introduced in the proposed system chapter and convert it in :



This trasformation use the classical transfer function disposition of a closed loop system. In particular, we can distinguish:

- **ADC :** the tranfer functon that translate the phisical quantities to observe in numerical code
- **MPPT :** it's the algorithm that follow the maximum power point. It request datas from the ADC and act on the choosen control variable on output.
- **+ :** adder node where the system apply the feedback.
- **PID :** the controller to use in order to stabilize the loop function.
- **FM :** transfer function of the frequency modulator.
- **ZOH :** modelize the step bheaviour introduced by the data sampled system.

Two good synthesis of all the transfer functions are in [41] [42]. Instead, the theoretical consideration are in [43] [44].

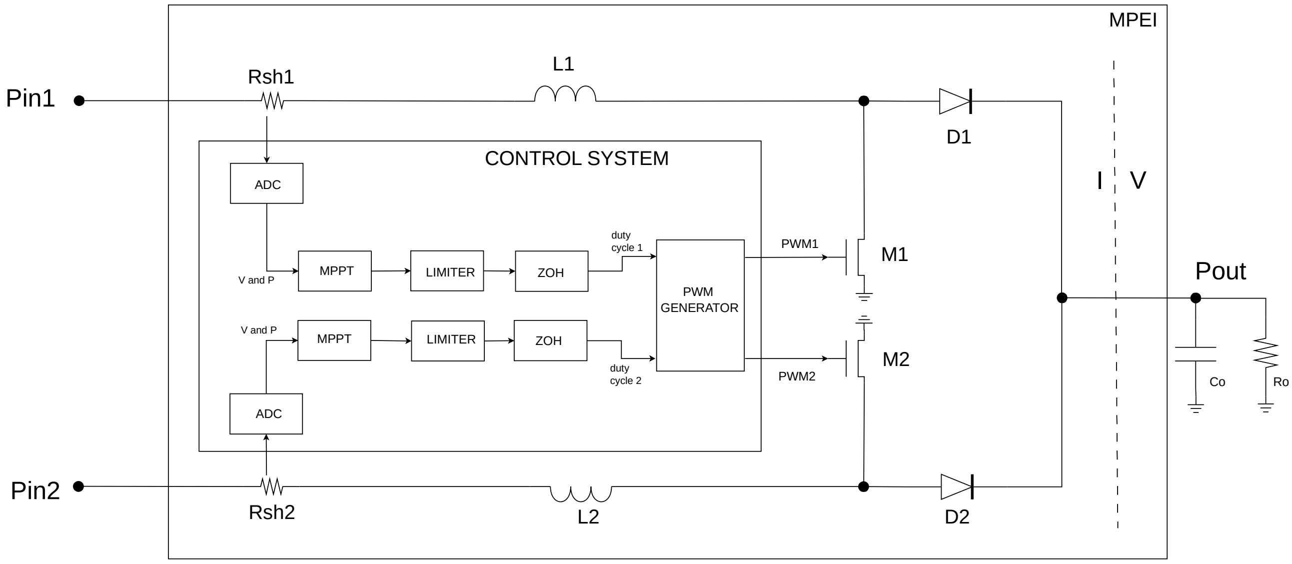
A focus on the control variable driven by MPPT is particularly useful, it will have big impact on the design of the two loops. Accordling with [45], we can choose to apply the perturn and observ algorithm on three different reference variables:

- **Reference voltage perturbation :** in this variant the control variable is the voltage on the harvester. Typically a PID network is used to stabilize the loop.
- **Reference current perturbation:** The variable is the current that flow in the inductor. It's the least used version because it is affected by more problems and it require that loops must be very fast. It can be done with a DSP that run the MPPT algorithm.
- **Direct duty ratio pertubation:** it's the simplest version. The MPP control is done in open loop thanks to the fact that the MPPT act directly on the duty cycle, forcing it on the modulator. Due the open loop condition, this method represent a worst case regarding the reaction time of the circuit.

Remember that our prefixed goal is to design a system as simple as possible, therefore the right choose seem be the direct duty ratio perturbation. In addition, due the intrinsic nature of the harvester and the nature of the algorithm, the system will be surely convergent.

In literature we can find system where the authors implement the P&O algorithm with duty perturbation in closed loop and then design a PID net to stabilize the loop. In this thesis the algorithm optimization is done introducing a variable step on the duty cycle perturbation. The advantage is the lower design complexity that ensure a simple optimization who can be reiterare adding more steps.

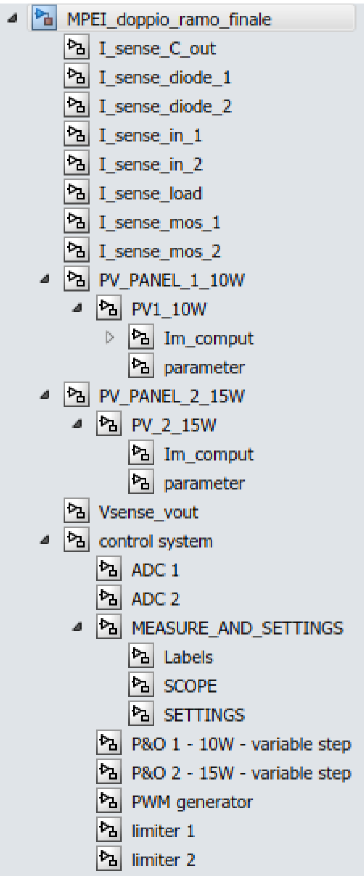
Hence, the proposed control system is:



In the following pages of this chapter each block will be analyzed and modeled in simulink with the appropriate simulation at the end.

To simplify the work, the two harvesters considered will be modelized with two solar panel with opportune characteristics, instead of use one PV panel model and one VAWT model; with reference of what said in the energy harvesting chapter, this will not introduce limitations or falsification of the simulations. Note that the two PV panel models are setted to provide the same electrical characteristics used until now.

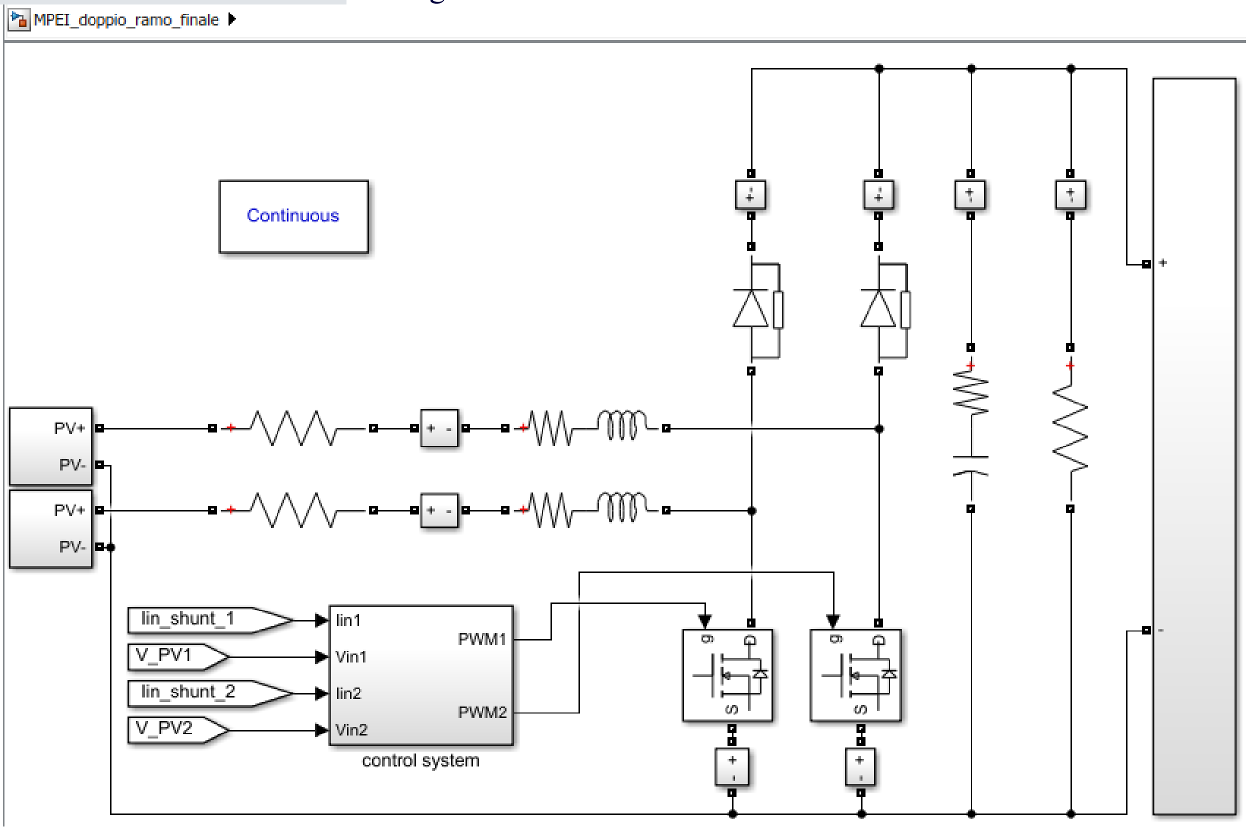
- SYSTEM



The image report the model browser of the whole simulink model developed, where each subystem containe :

- subsystems of measure **I_sense_XXX** used to observe the currents in the circuit.
- models of PV panels: **PV_PANEL_X_XXX**
- **control system**: it contains the model of the subsystem previously described. Inside this block we have:
- **ADC_X** : models used for the ADCs on the two branches.
- **MEASURE_AND_SETTINGS** : include the control panel, the used labels and all the scope of the model. It's the subsystem of interface.
- **P&O_X_XX_-_variable_step** : the model of MPPT algorithm.
- **PWM_GENERATOR** : performs the transformation from duty cycle (numerical value) to non-overlapping square waves.
- **limiter_X** : fixes the duty cycle dynamics and imposes the maximum and minimum values that this can reach.

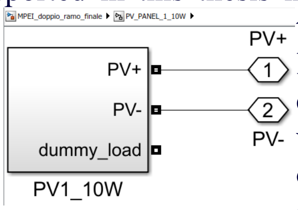
The higher level block containe :



where all the used components (R,L,C) use the parameters seen in the wide signal analisys.

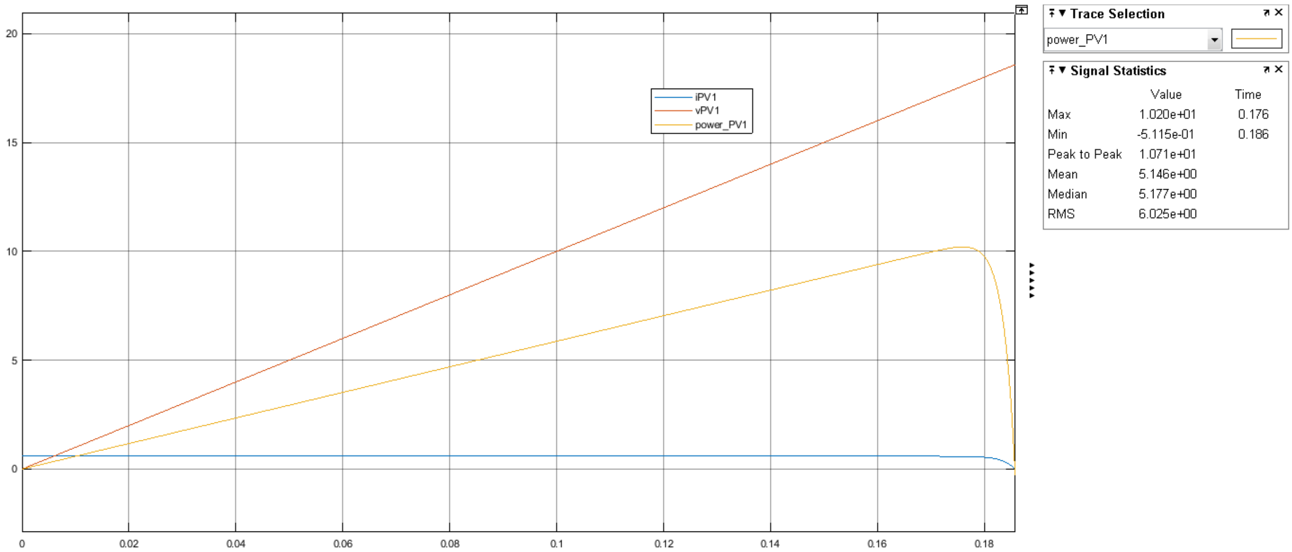
- PV PANEL

The model used for the PV panels is the one described in [46] with light changement and is reported in this thesis in APPENDIX 1. the next two figures shown the simulation done in the tuning phase of the model thanks to the auxiliary port inserted (dummy load):

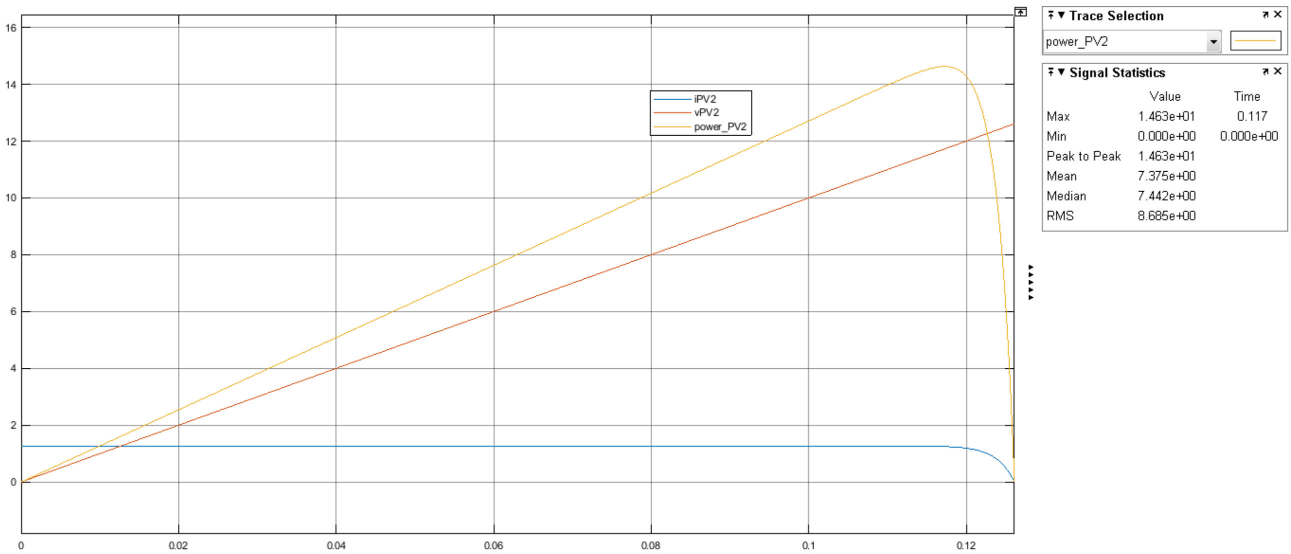


connecting the port dummy_load with PV+, we force a voltage generator voltage controlled as load. This generator swipe for the entire voltage range of the PV panel allowing us to observe the power curve (power_Pvi), the current versus voltage characteristic (iPVi) and also shows the applied load (vPVi).

-10W PANEL SIMULATION



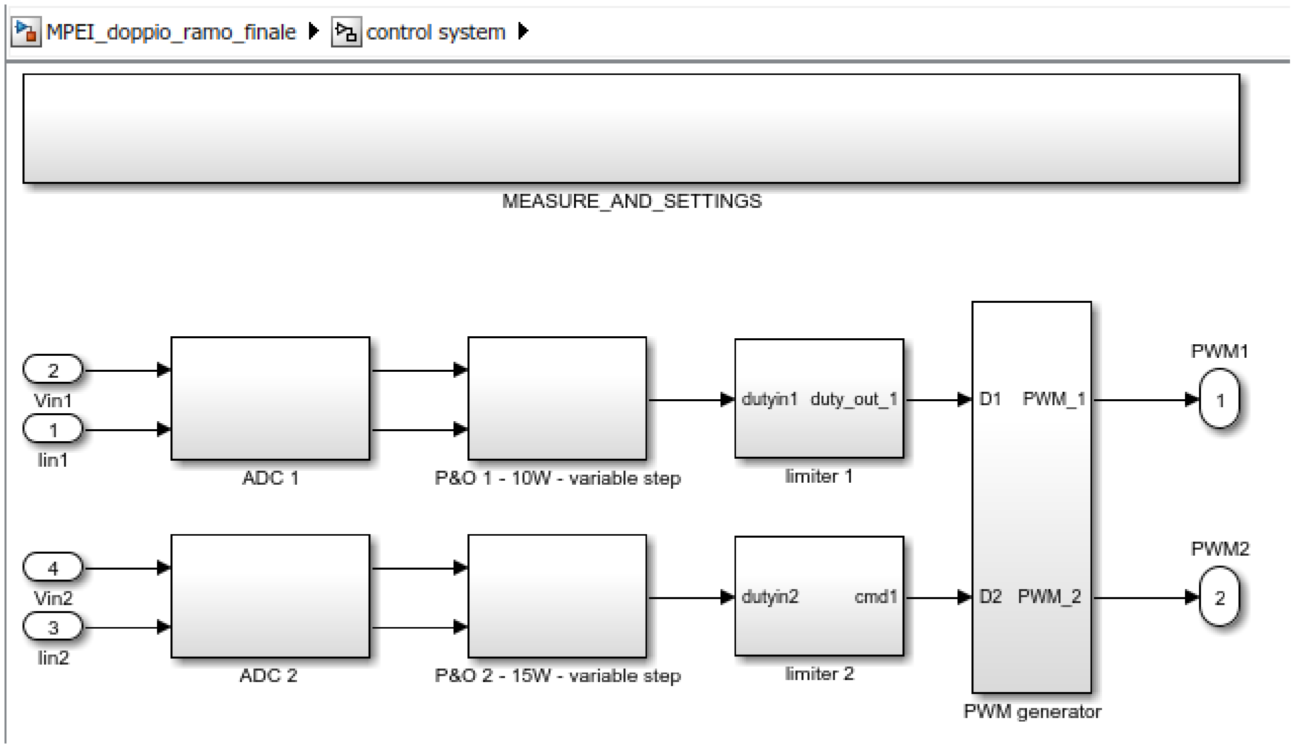
-15W PANEL SIMULATION



Note that, when the forced voltage exceeds the open circuit voltage of the PV panel, the model reports a negative currents therefore a negative power. This detail has an impact on the final simulation (with variable temperature and irradiation) creating " holes on the output power" that will be observed in the dedicated paragraph.

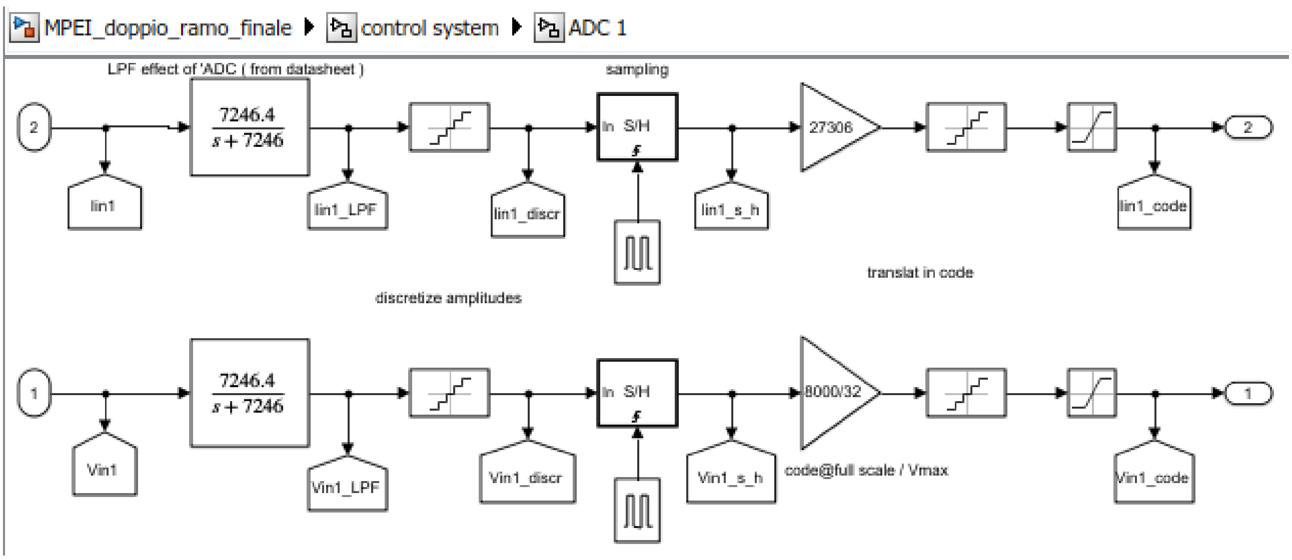
- CONTROL SYSTEM

the simulink translation of the control system is:



- ADC

Since the models for the ADCs are equal, here is reported only one:



This model has a wide usage of elementary blocks typical of the automatic control world. More attention is requested from the first block that modelize the low pass filter effect of the ADC. In order to have a model as acccurate as possible, we must analyze e modelize also this characteristic. On the datasheet, texas instruments provide this transfer function :

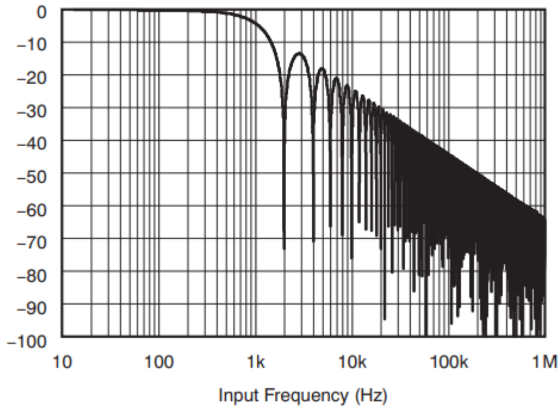
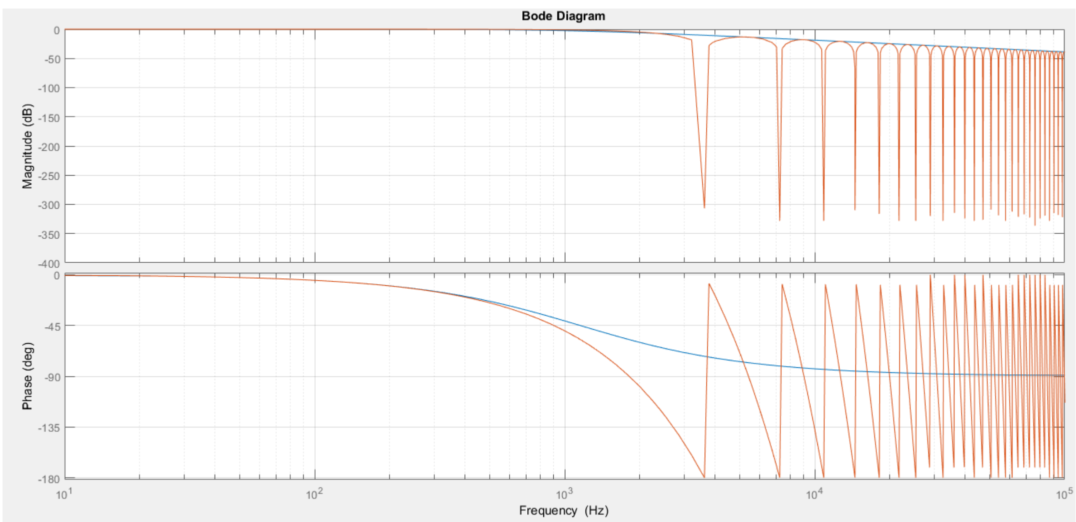


Figure 1. Frequency Response

with a second look on the graph we can observe that it has a behaviour similar to the zero order hold function. Osservando il grafico in questione ci accorgiamo che ha un andamento molto simile a quello della funzione zero order hold, since it contains a delay term that can not be introduced into a linear system, we approximate this function with the padè approximation used to approximate nonlinear functions in the complex field as shown in [47]. The analisys is done with the following MATLAB code:

```
s = tf('s');
opts = bodeoptions('cstprefs');
opts.FreqUnits = 'Hz';
Ts_adc1 = 276e-6;%sampling period
R_PV_gain =1;% 27306;
%% ADC completo :
R_PV_S = (1-(exp(-s*Ts_adc1)))/(s*Ts_adc1); % funz ZOH
R_comp = R_PV_gain*R_PV_S;
%% ADC approximation with padè
R_PV_del_temp = (exp(-s*Ts_adc1));
R_PV_PADE = pade(R_PV_del_temp);
R_PV_del = (1-R_PV_PADE)/(s*Ts_adc1);
 R_PV = zpk(minreal(R_PV_gain*R_PV_del))
 %% PLOT
  figure
  bode(R_PV,opts)
  hold on
  bode(R_comp,opts)
  grid on
```

the bode diagram plotted:



and on terminal:

R_PV = 7246.4

(s+7246)

that is the transfer function used on the model. Downline of filter there are a quantizer and one sample and hold block.
The following block is the gain introduced from the ADC on the output code. With this block we have this conversion:

$$CURRENT_{CODE} = I_L * GAIN$$

the computation of this gain is done with the information reported on the ADC datasheet (INA220-Q1), in other words, we must do all the math on the chain of the setted registers. Remember that:

$$\begin{cases} R_{shuntPV} = 33\,m\Omega \\ R_{shuntVAWT} = 16\,m\Omega \end{cases} \wedge \begin{cases} I_{inPV} = 0{,}6\,A \\ I_{inVAWT} = 1{,}25\,A \end{cases}$$

Assume 2*Iin as maximum value of current, therefore :

$$with \quad CURRENT_{LSB} = \frac{MAX\,I_{ING}}{2^{15}} \rightarrow \begin{cases} CURRENT_{LSBPV} = \frac{2*Iin}{2^{15}} = \frac{1{,}2}{2^{15}} = 36{,}6\,uA \\ CURRENT_{LSBVAWT} = \frac{2*Iin}{2^{15}} = \frac{2{,}5}{2^{15}} = 76{,}294\,uA \end{cases}$$

$$with \quad CALIBRATION_{REG\,PV/VAWT} = TRUNC\left[\frac{0{,}04096}{CURRENT_{LSB\,PV/VAWT} * R_{SHUNT\,PV/VAWT}}\right]$$

$$\rightarrow \begin{cases} CALIBRATION_{REGPV} = 33893 \\ CALIBRATION_{REGVAWT} = 33554 \end{cases}$$

the voltage on the shunt register :

$$V_{SHUNT} = I_L * R_{SHUNT}$$

$$V_{SHUNT_{REG}} = \frac{V_{SHUNT}}{V_{SHUNT\,LSB}} = \frac{I_L R_{SHUNT}}{10\,uV}$$

so, in the current registers we'll find :

$$CURRENT_{REG\,PV/VAWT} = V_{SHUNT\,REG} \frac{CALIBRATION_{REG\,PV/VAWT}}{4096} = I_L \frac{R_{SHUNT}}{V_{SHUNT\,LSB}} \frac{CALIBRATION_{REG\,PV/VAWT}}{4096}$$

finally :

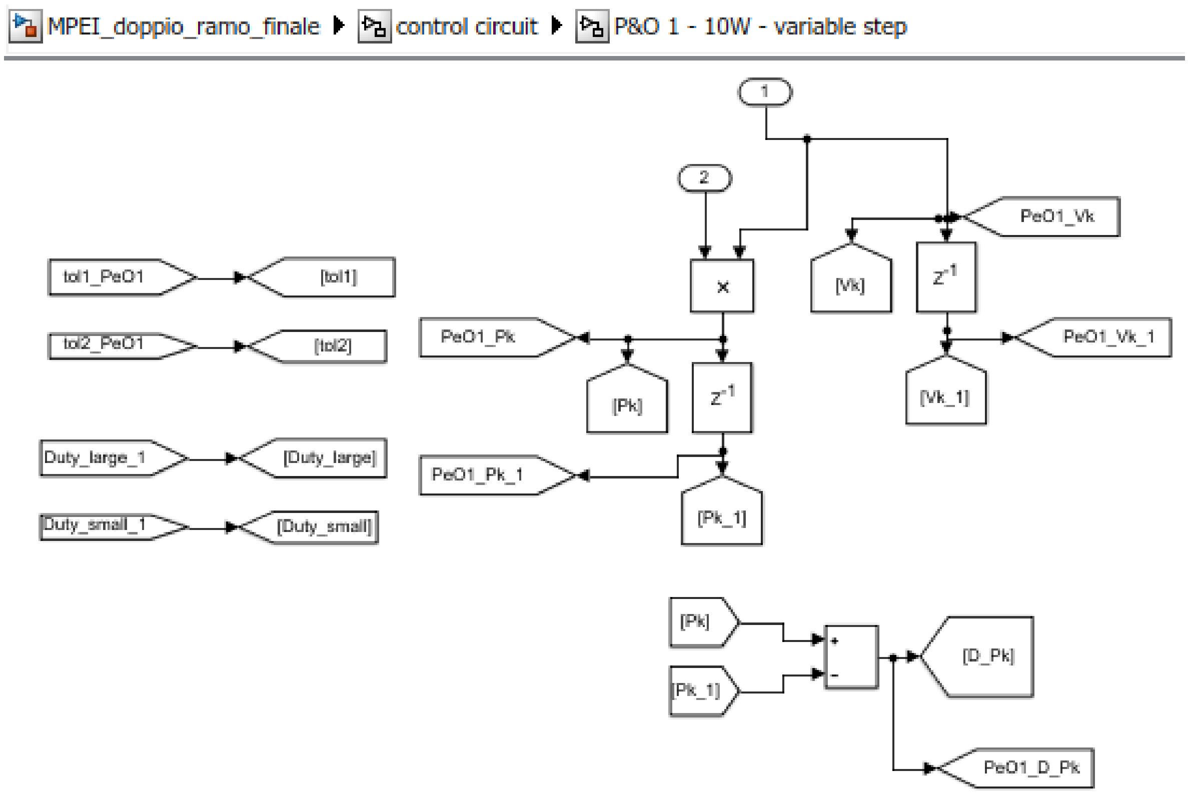
$$CURRENT_{REG\,PV} = I_{LPV} \frac{33*10^{-3}}{10*10^{-6}} \frac{33893}{4096} = I_{LPV} * 27306$$

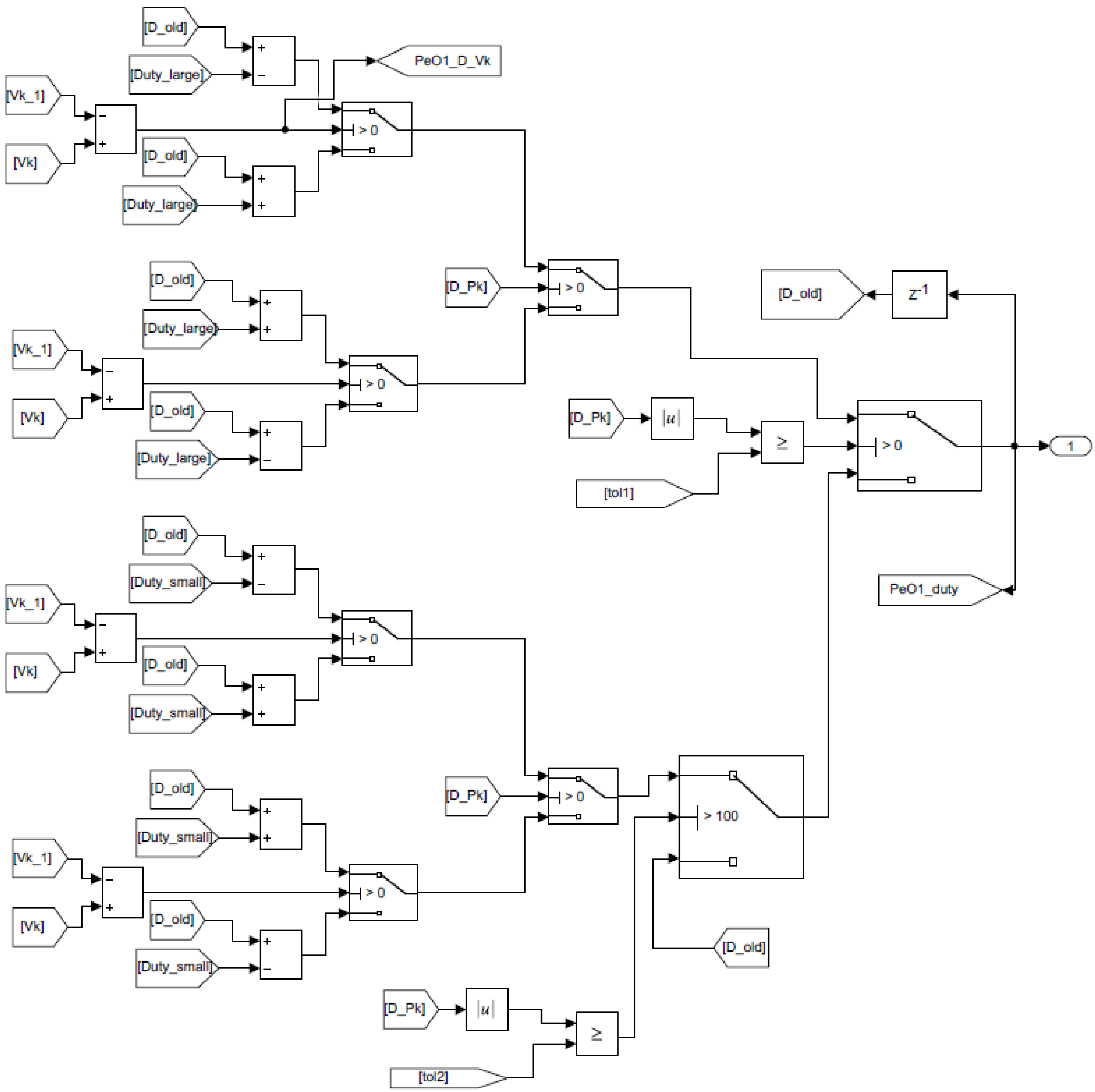
$$CURRENT_{REG\,VAWT} = I_{LVAWT} \frac{16*10^{-3}}{10*10^{-6}} \frac{33554}{4096} = I_{LVAWT} * 13107$$

- MPPT

The next two figures reports the simulink translation of the perturb and observe with variable step algorithm.

Observe that the model used here consider a slightly different case of the one used in the microcontroller. In this part of model a direct multiplication on the numerical code generated by ADCs is done and the algorithm settings (toll1,toll2...) are tuned with reference on this digital values. In reality the microcontroller receive directly the power and the voltage from the ADCs without perform the multiplication.

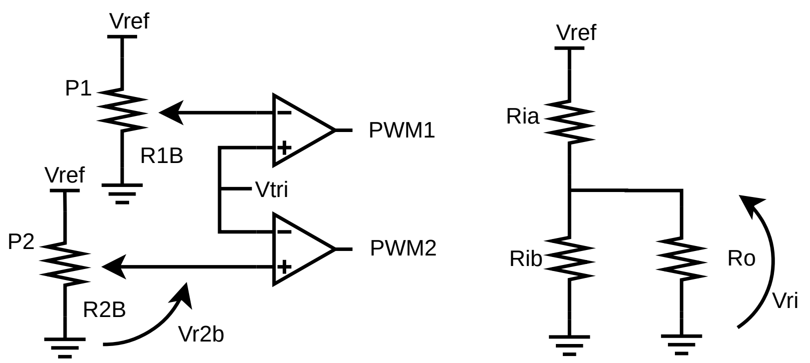




[D_old]
[Duty_large]
PeO1_D_Vk
[Vk_1]
[Vk]
> 0
[D_Pk]
z-1
[Duty_small]
|u|
≥
[tol1]
[tol2]
> 100
1
PeO1_duty

- LIMITER

in this section we need to justify the parameter used (191). We must analyze the behavior of the duty cycle as function of the digital control potentiometer changes.



Where Ro modelize the impedence seen on the OPAMP port. Ria and Rib are the two resistance in which the potentiometer is partitioned by moving the cursor.

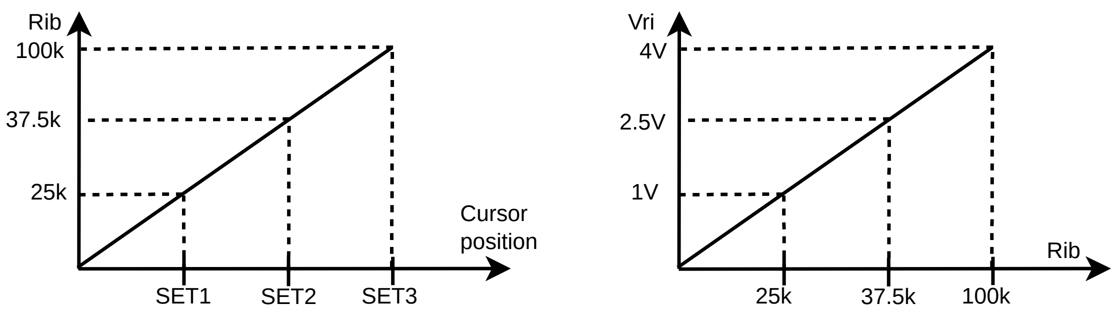
$$with \;\; R_o \gg R_{ib} \;\; then\, V_{Ri} \;=\; Vref \frac{R_{ib}}{R_{ib}+R_{ia}} \;=\; \frac{Vref}{P_i} R_{ib}$$

remember that :

- when Vr1 > Vtri hence D1 = LOW
- when Vr2 > Vtri hence D2 = HIGH

and that the triangular wave is between 1V and 4V. So, we can find three known points:

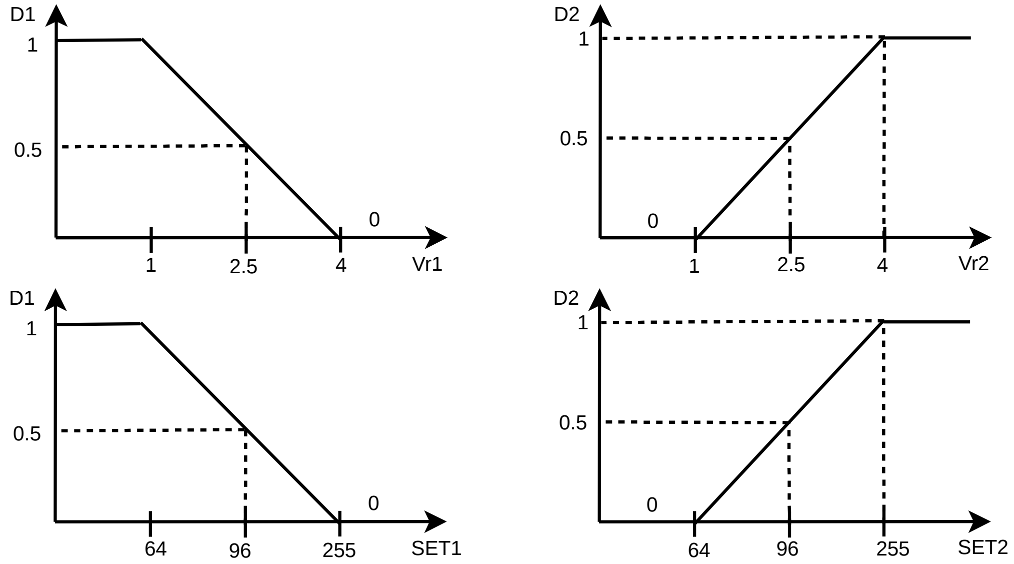
D1	Vr1	R1b	D2	Vr2	R2b
0	>4V	100k	0	<1V	25k
0,5	2,5V	37,5k	0,5	2,5V	37,5k
1	<1V	25k	1	>4V	100k



Let's look at the trends in the various graphs:remeber also that we are using the TPL0102 as digital control potentiometer, from datasheet we can read :

Cursor position	Rib	STEP
SET1	25k	64
SET2	37,5k	96
SET3	99,61k	255

We want that the two duty cycle have the following curve trend:



compute the rect functions on the range of interest 64 < SETi < 255:

$$D1 \rightarrow \frac{x-x_1}{x_2-x_1}=\frac{y-y_1}{y_2-y_1} \rightarrow \frac{x-SET_1}{SET_3-SET_1}=\frac{y-1}{0-1} \rightarrow \frac{x-64}{255-64}=\frac{y-1}{-1} \rightarrow D1 = -\frac{SET1}{191} + \frac{255}{191}$$

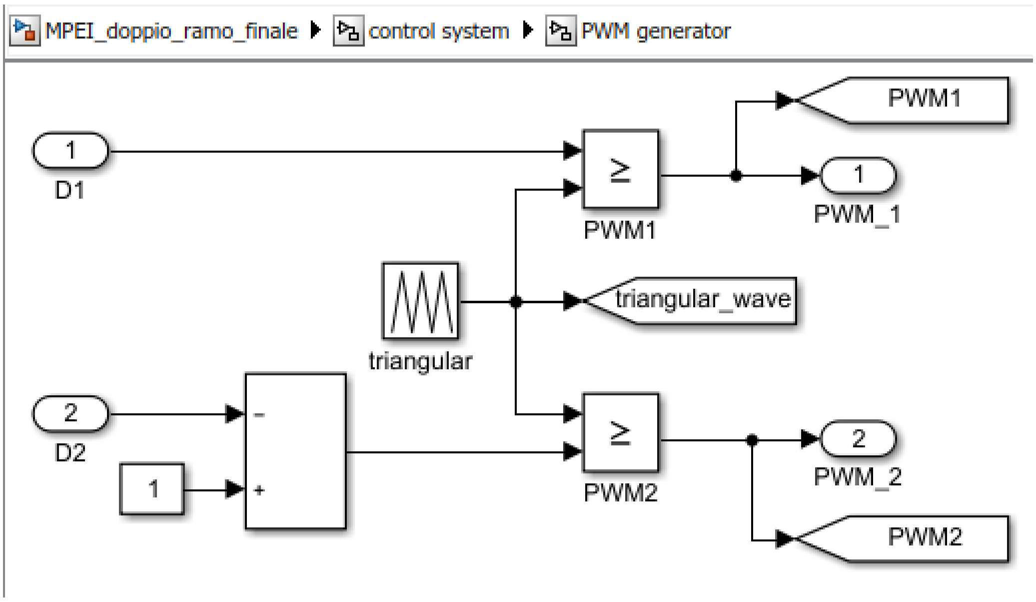
$$D2 \rightarrow \frac{x-64}{191}=y \rightarrow D2 = \frac{SET2}{191} - \frac{64}{191}$$

apply a change of variables to simplify the conversion:

$$\begin{cases} SET1=255-CMD1 \\ SET2=64+CMD2 \end{cases} \rightarrow \begin{cases} D1=\dfrac{CMD1}{191} \\ D2=\dfrac{CMD2}{191} \end{cases} \rightarrow \quad with \;\; CMDi \in [0;191]$$

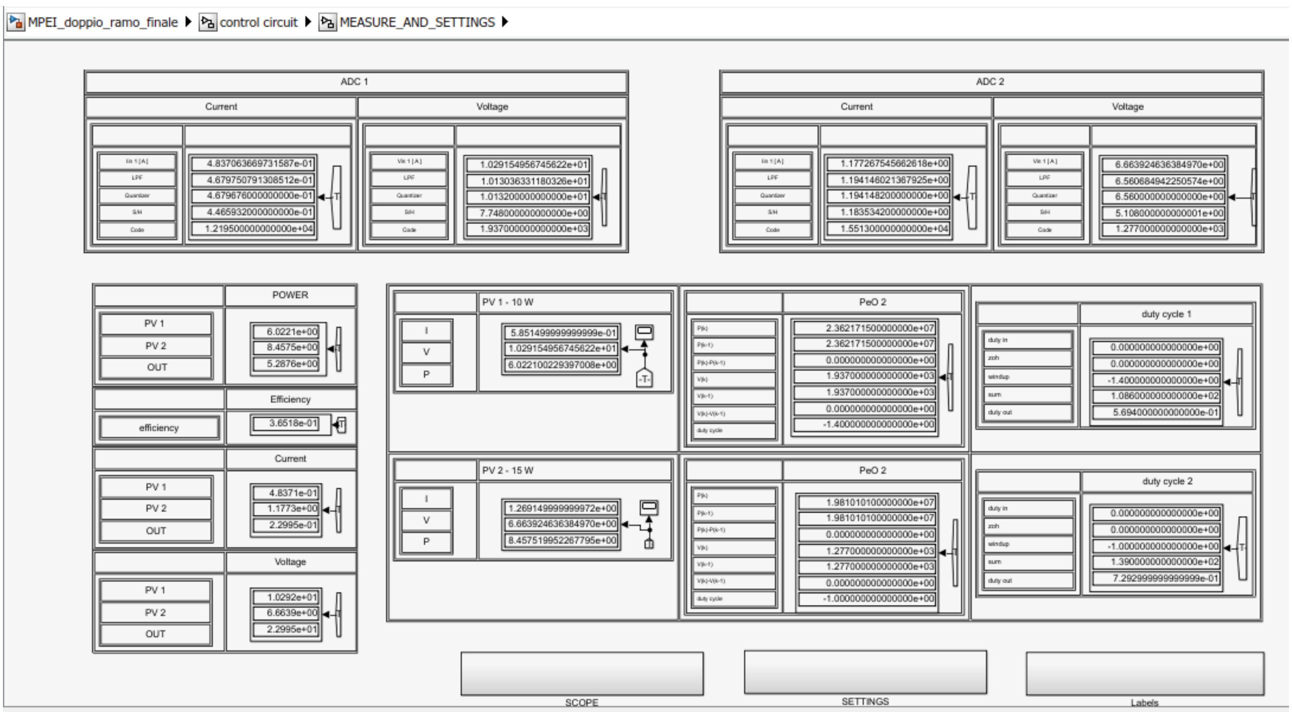
that is the 191 used in the model. Note that : the equation for SET1 and SET2 will be directly used in the microcontroller code to drive the potentiometers wiper.

- PWM GENERATOR



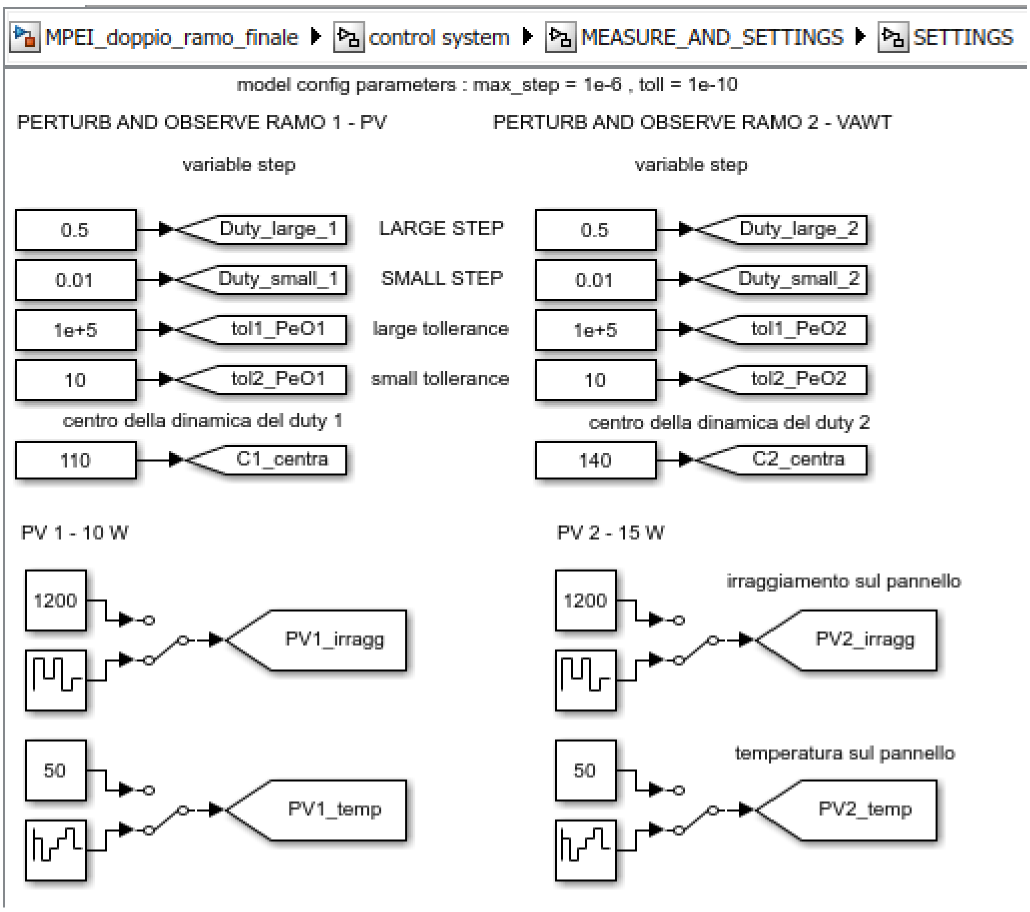
- MEASURE AND SETTING

containe the control panel where we can observe the system evolution and other 3 subsystem useful for the right operation of the whole system.

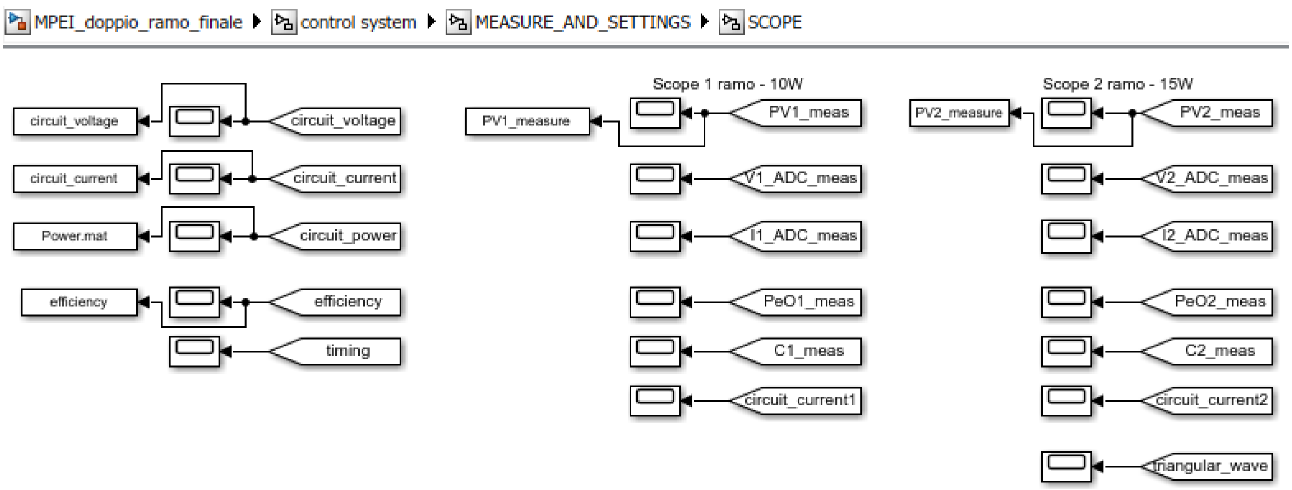


- MEASURE AND SETTINGS

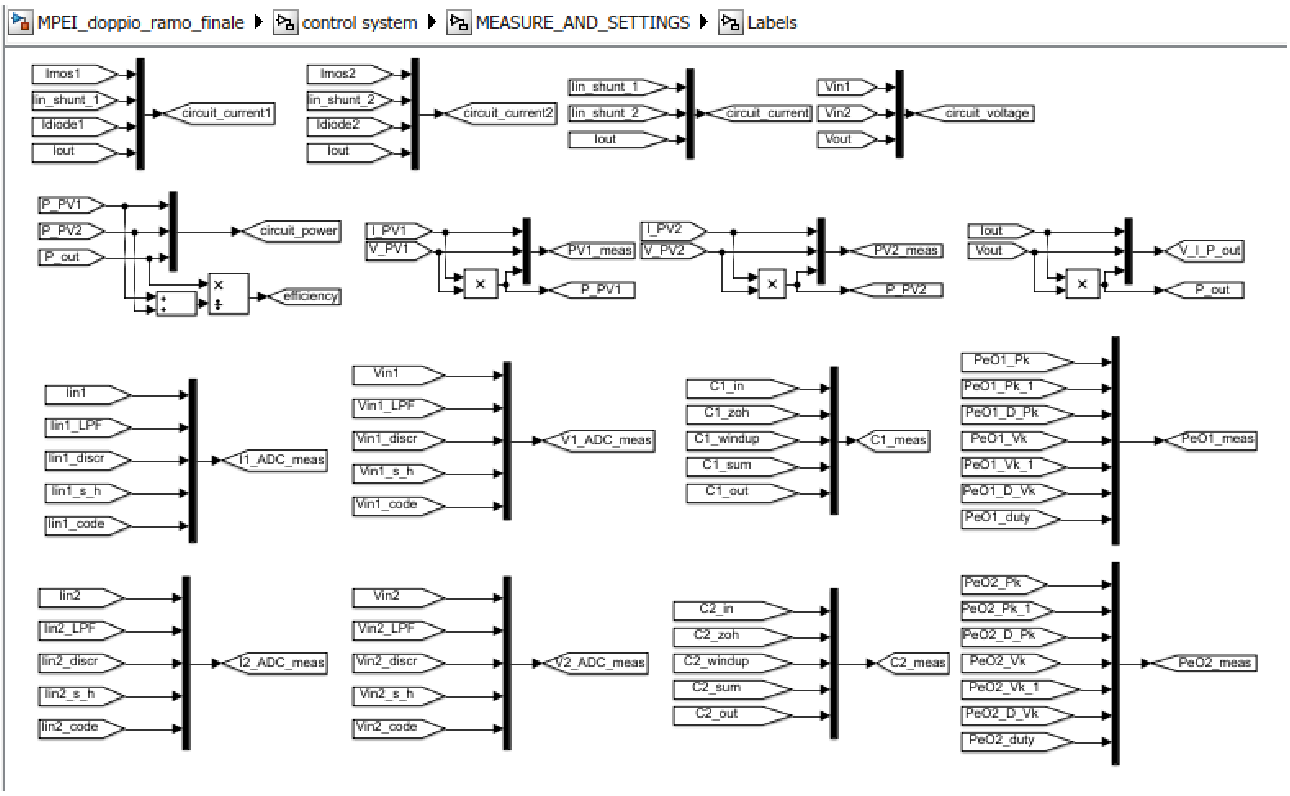
Here are there all the parameters required from the MPPT, the initial value of the duty cycle and the settings for temperature and irradiation.



- SCOPE



- LABELS
combine all the labels on the system and then send the compact form to the control panel:

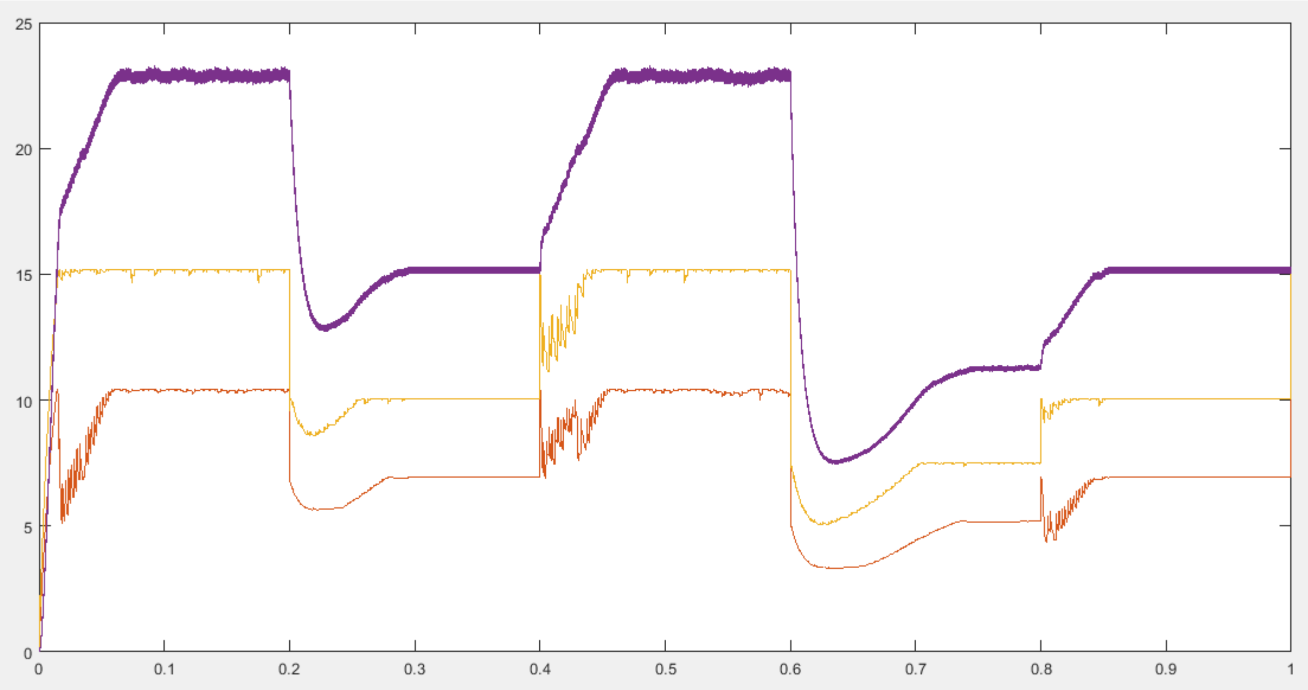


- SIMULATIONS

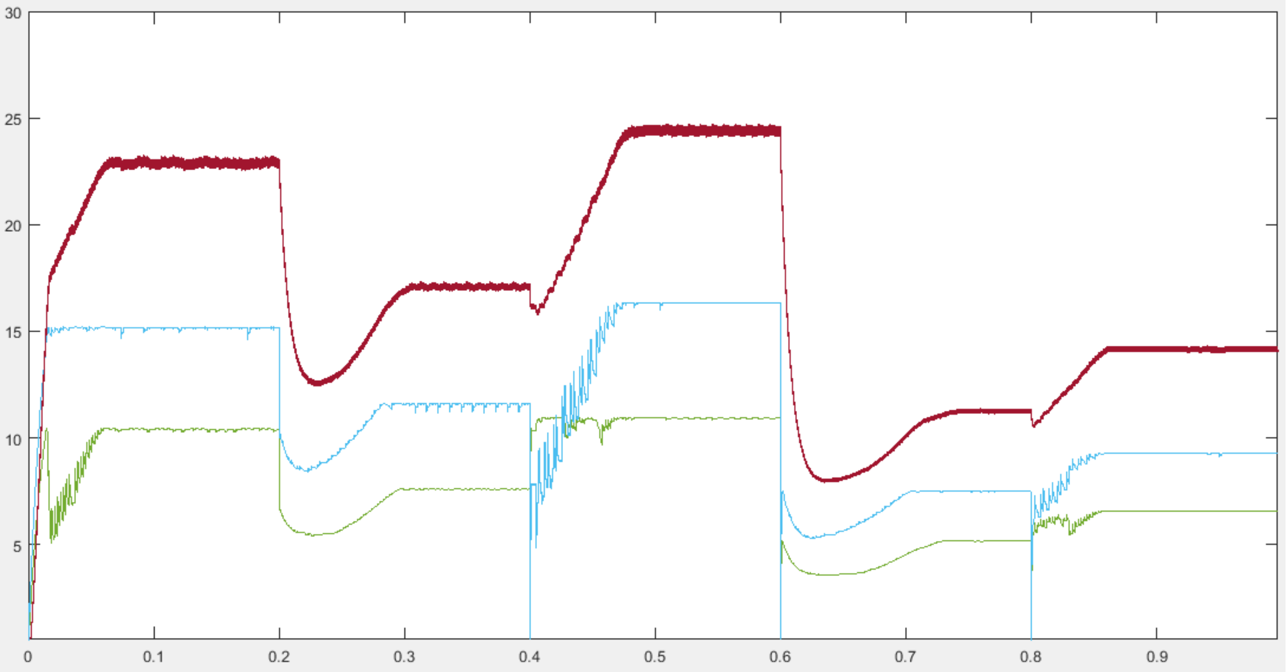
Among the many tests conducted, the most interesting are the two that will be repeated in the next figures. In the first one is shown the bheaviour of the system when a variable irradiation is applied, instead, in the second test both irradiation and temperature will change.

In detail, in the first test the irradiation reach the values of : 1200, 800, 1200, 600, 800 W/m^2 switching among the values each 0,2 s. The second test force the same irradiation swipe but, additionally, apply a temperature variation of : 50, 30, 40, 50 ,60, 40 °C each 0,2s. In both graph there are the output power of MPEI (violet and red), the power extracted from the first panel of 10W (orange and green) and the output power of the 15 W panel (yellow and blue).

The wave obtained from the first test :



and from the second test:



in both cases simulations reports a delay on the MPP pursuit between 30ms and 150ms, also observe that the system is stable and functional even if the temperature change with small variation on the bheaviour.

As already mentioned in the paragraph relating to solar panels, due to inaccuracies of the mathematical model used for the panel and the infinite slope variation required at the temperature (change from one value to another in zero time) on the input powers is observed an abrupt decline which is considered a negligible problem in this thesis.

- MICROCONTROLLER CODE

```
/***************** INCLUDE ******************/
#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <INA219.h>
/***************** DEFINE ******************/
/* PeO parameters*/
#define centro1 140//- VAWT
#define centro2 140//- PV
#define toll1 1
#define toll2 0.00001
double duty_small;
double duty_large;
#define duty_small_1 0.005
#define duty_large_1 0.05
#define duty_small_2 0.005
#define duty_large_2 0.05
#define loop_delay 0

/************************************************************/
#define ADD_POT  0x50 //80
#define ADD_LCD  0x27 //39
#define ADD_ADC1 0x40 //64   - VAWT
#define ADD_ADC2 0x41 //65   - PV
#define POTA 0x00
#define initial_delay 1000
#define i2c_check_delay 1000
#define upper_val 216
#define lower_val 1
#define TEST_MODE 2 // 0 : normal mode, 1 TEST mode i2c, 2 PWM test, 3 testing of single
branch
#define chirp_step 1 // step di incremento del cursore per TEST_MODE =2
#define max_value_swipe 256
#define min_value_swipe 0
#define delay_swipe 50
#define branch_test_3 2 // 1-> ina1 (VAWT) 2-> ina (PV)
#define DEBUG 1 // 1 -> printf attive
#define busVoltagecorrection 32.76
/***************** ISTANCE ******************/
INA219 ADC1;
INA219 ADC2;
LiquidCrystal_I2C lcd(ADD_LCD,16,2);
/***************** GLOBAL VARIABLE ******************/
double duty1 = 0;
double duty2 = 0;
double duty1old = 0;
double duty2old = 0;
double P1,P2,V1,V2,I1,I2;
double P1old = 0;
double P2old = 0;
```

```
double V1old = 0;
double V2old = 0;
double deltaP1,deltaP2,deltaV1,deltaV2;
int set1,set2,intestazione =0;
byte value_2=0;
String buffer = "";
/**********************SETUP*********************************/
void setup(void)
{
 /**LCD***/   lcd.init();
 /**LCD***/   lcd.backlight();
 /**LCD***/   lcd.print("     power on  ");
 /**LCD***/   lcd.setCursor(0,1);
 /**LCD***/   lcd.print(" initializing ...");
             delay(initial_delay);
 /**i2c***/   Wire.begin();
             if(DEBUG ==1)
 /*SERIAL*/  {
             Serial.begin(9600);
             Serial.flush();
             Serial.println("start");
             }
 /**ADC1**/   ADC1.begin(ADD_ADC1);
 /**ADC2**/   ADC2.begin(ADD_ADC2);
/**********  temp = monitor.configure(range, gain, bus adc, shunt adc, mode);*/
 /**ADC1**/   ADC1.configure(1,0,2,2,7);
 /**ADC2**/   ADC2.configure(1,0,2,2,7);
/**********  temp =  monitor.calibrate(shunt_val,v_shunt_max,v_bus_max,i_max_expected)*/
 /**ADC1**/   ADC1.calibrate(0.016,0.04,15,2);
 /**ADC2**/   ADC2.calibrate(0.033,0.04,20,2);
 /**LCD***/   pulisci_schermo();
 /**LCD***/   lcd.setCursor(0,1);
 /**LCD***/   lcd.print("   setup end ");
             delay(initial_delay);
}
/
*************************************LOOP***********************************
*********/
void loop(void)
{
if(TEST_MODE ==0)
{/************************ACQ P e V****************************/
 /**ADC1**/  V1   = ADC1.busVoltage();     //V
 /*wrapping correction */             if( V1 < 0) {V1 = V1 + busVoltagecorrection; }
 /**ADC1**/  P1   = ADC1.busPower();  //W
            //I1   = ADC1.shuntCurrent() * 1000;
 /**ADC2**/  V2   = ADC2.busVoltage();//mV
 /*wrapping correction */              if( V2 < 0){V2 = V2 + busVoltagecorrection; }
 /**ADC2**/  P2   = ADC2.busPower();
            //I2   = ADC2.shuntCurrent() * 1000;
```

```
/************************ CALC delta ************************/
  deltaP1 = P1-P1old;
  deltaV1 = V1-V1old;
  deltaP2 = P2-P2old;
  deltaV2 = V2-V2old;
/************************* MPPT ******************************/
  duty_small = duty_small_1;
  duty_large = duty_large_1;
  duty1 = mppt(deltaP1,deltaV1,duty1old);
  duty_small = duty_small_2;
  duty_large = duty_large_2;
  duty2 = mppt(deltaP2,deltaV2,duty2old);
/********************** STAMPA SU LCD **********************/
  // print_on_screen("I2:",I2," P2:",P2,"I1:", I1," P1:",P1);
/************************ AGGIORNA **************************/
  duty1old = duty1;  P1old = P1; V1old = V1;
  duty2old = duty2;  P2old = P2; V2old = V2;
/******************** APPLICA LIMITATORE *********************/
  duty1 = limiter(duty1,centro1)+centro1;
  duty2 = limiter(duty2,centro2)+centro2;
/*************** CALCOLA POSIZIONE CURSORI *******************/
   set1 = (int)(39+ duty1);
   set2 = (int)( 255-duty2);
  if(DEBUG ==1)
  {   if(intestazione==0)
      {
   buffer += "parameter \n centro1 "; buffer.concat(centro1);
   buffer += "centro2 "; buffer.concat(centro2);
   buffer += " toll1 "; buffer.concat(toll1);
   buffer += " toll2 "; buffer.concat(toll2);
   buffer += " DL1 "; buffer.concat(duty_large_1);
   buffer += " DS1 "; buffer.concat(duty_small_1);
   buffer += " DL2 "; buffer.concat(duty_large_2);
   buffer += " DS2 "; buffer.concat(duty_small_2);
    Serial.println(buffer);
       Serial.println(" first branch : VAWT (15W) \t    second branch branch : PV (10W) ");
       Serial.print("   P   ");   Serial.print("   V   ");   Serial.print("   duty ");   Serial.print(" set ");
       Serial.print("   P   ");   Serial.print("   V   ");   Serial.print("   duty "); Serial.println(" set ");
     intestazione++;
    }
   buffer.concat(P1);    buffer += " ";    buffer.concat(V1);    buffer += " ";    buffer.concat(duty1);
buffer += " ";    buffer.concat(set1);    buffer += " ";
   buffer.concat(P2);    buffer += " ";    buffer.concat(V2);    buffer += " ";    buffer.concat(duty2);
buffer += " ";    buffer.concat(set2);
    Serial.println(buffer);    buffer = "";
  }
  delay(loop_delay);
/************ UPDATE VALORI CURSORI NEI POT ******************/
/**POT***/  scrivi_i2c(ADD_POT,POTA,set1,set2);
}
```

```
if(TEST_MODE ==1){ check_i2c_slave(ADD_POT,ADD_LCD,ADD_ADC1,ADD_ADC2);}
if(TEST_MODE ==2)
{   /**POT***/ scrivi_i2c(ADD_POT,POTA,set1,set2);
           value_2 = swipe_cursor(value_2);
           pulisci_tutto_schermo();
             lcd.setCursor(0,0);  lcd.print("swipe cursor.");
             lcd.setCursor(0,1);  lcd.print("position :   ");
             lcd.print((int)value_2);
               set1 = (int)(39+ value_2);
               set2 = (int)( 255-value_2);
                 set1 = limiter(set1,centro1)+centro1;
                set2 = limiter(set2,centro2)+centro2;
}
if(TEST_MODE ==3)
{
 if (branch_test_3 == 1)
 {/**ADC1**/  V1   = ADC1.busVoltage();        // V
            if( V1 < 0) {V1 = V1 + busVoltagecorrection; }
  /**ADC1**/  P1   = ADC1.shuntVoltage() * 1000; // mV
  /**ADC1**/  V2   = ADC1.busPower();          // W
  /**ADC1**/  P2   = ADC1.shuntCurrent() * 1000; // mA
  print_on_screen("Vb:",V1," Vs:",P1,"P2:",V2," Is:",P2);
 }
 if(branch_test_3 == 2 )
 {/**ADC2**/  V1   = ADC2.busVoltage();    //V
           if( V1 < 0) {V1 = V1 + busVoltagecorrection; }
           if( DEBUG==1)
           {Serial.println(V1,5);}
  /**ADC2**/  P1   = ADC2.shuntVoltage() * 1000;
  /**ADC2**/  V2   = ADC2.busPower();
  /**ADC2**/  P2   = ADC2.shuntCurrent() * 1000;
  print_on_screen("Vb :",V1,"Vs :",P1,"P2 :",V2,"Is :",P2);
 }
 delay(200);
 if(DEBUG==1){Serial.flush();}
}
}
void print_on_screen(char string1[6], double data1, char string2[6], double data2, char string3[6],
double data3, char string4[6], double data4)
{
  pulisci_schermo();
  lcd.setCursor(0,0);
  lcd.print(string1);
  lcd.print(data1);   // input voltage
  lcd.print(string2);
  lcd.print(data2);   // mV voltage on shunt resistor
  lcd.setCursor(0,1);
  lcd.print(string3);
  lcd.print(data3); //W
  lcd.print(string4);
```

```
  lcd.print(data4); //mA
}

/* LIMITER */
double limiter(double duty,int centro)
{
 if(duty > (upper_val -centro))
 {return (double)(upper_val-centro);}
 if(duty < (lower_val -centro))
 {return (double)(lower_val-centro);}
 return duty;
}
/*MPPT*/
double mppt(double deltaP,double deltaV, double duty)
{
 if(abs(deltaP)>toll1)
 {return peo(duty,duty_large,deltaP,deltaV);}
 else
 {
  if(abs(deltaP)>toll2)
   {return peo(duty,duty_small,deltaP,deltaV);}
  else
   {return duty;}
 }
}
/*PEO*/
double peo(double duty,double duty_step,double deltaP,double deltaV)
{
 if(deltaP>0)
 {
  if(deltaV>0)
   {return duty - duty_step;}
   else
   {return duty + duty_step;}
 }
 else
 {
  if(deltaV>0)
 {return duty + duty_step;}
   else
   {return duty - duty_step;}
 }
}
/* GESTIONE LCD
*******************************************************************************
*************************************/
/* stampa_lcd : stampa su lcd potenza e tensione dei due harvester
******************************************************************/
void stampa_lcd(double V1_lcd, double P1_lcd, double V2_lcd, double P2_lcd)
{  pulisci_schermo();
```

```
   lcd.setCursor(0,0);
   lcd.print("V:");
   lcd.print(V1_lcd);
   lcd.print(" P:");
   lcd.print(P1_lcd);
   lcd.setCursor(0,1);
   lcd.print("V:");
   lcd.print(V2_lcd);
   lcd.print(" P:");
   lcd.print(P2_lcd);
}
/* pulisci_schermo : elimino i caratteri sull'lcd per cancellare i refusi
************************************************************/
void pulisci_schermo(void)
{ lcd.setCursor(15,0);
  lcd.print("   ");
    lcd.setCursor(15,1);
  lcd.print("   ");
}
/* cancella tutti i caratteri a schemro */
void pulisci_tutto_schermo(void)
{
lcd.setCursor(0,0);
   lcd.print("                ");
    lcd.setCursor(0,1);
   lcd.print("                ");
}
/
******************************************************************************************
***********************************************************/
/* SCRIVI_i2c :    scrive due byte in successione all indirizzo address_pot. con address pot =
indirizzo i2c potenziometro TPL0102 */
void scrivi_i2c (byte address_pot, byte reg_potA, byte value_potA,byte value_potB)
{
  // scrittura consecutiva sui due registri.
  //  0 - inizia trasmissione
  //  1 - manda indirizzo device
  //  2 - manda indirizzo primo registro
  //  3 - manda valore per primo registro (IVRA)
  //  4 - manda valore per secondo registro (IVRA+1 = IVRB)
  //  5 - chiudi il bus
  Wire.beginTransmission(address_pot);
  Wire.write(reg_potA);
  Wire.write(value_potA);
  Wire.write(value_potB);
  Wire.endTransmission();
}
/* controlla se sul bus ci sono tutti gli slave */
void check_i2c_slave(int ADD1, int ADD2, int ADD3, int ADD4)
{  int address_to_check,error,count=0,i;
```

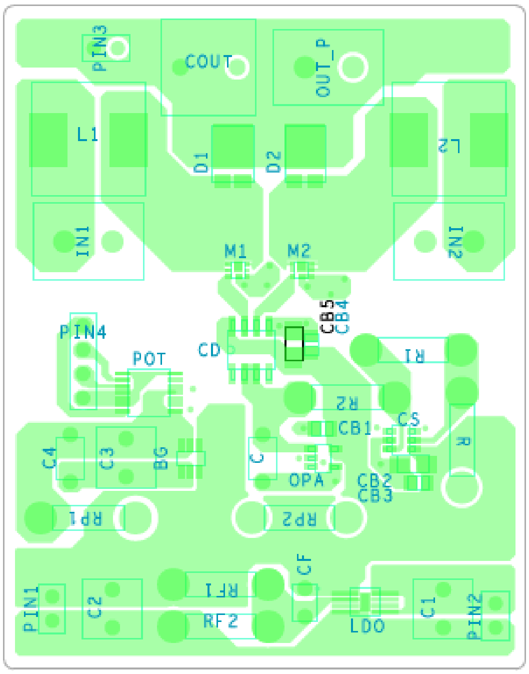
```
pulisci_tutto_schermo();
lcd.setCursor(0,0);
lcd.print("Scanning i2c bus, address:");
  for(i=0; i<4;i++)
  {
     switch (i)
     { case 0:
       address_to_check = ADD1;
       break;
       case 1:
       address_to_check = ADD2;
       break;
       case 2:
       address_to_check = ADD3;
       break;
       case 3:
       address_to_check = ADD4;
       break;
     }
       Wire.beginTransmission(address_to_check);
       error = Wire.endTransmission();
         if(error ==0)
         {
          lcd.setCursor(3*i,1);
          lcd.print(address_to_check);
        delay(i2c_check_delay);
         }
         if(error !=0)
         { pulisci_tutto_schermo();
           count++;
           lcd.setCursor(0,0);
           lcd.print("ERROR:");
           if(count !=0)
            {
           lcd.setCursor(4+count*3,0);
           lcd.print(address_to_check);
            }
          delay(i2c_check_delay);
          }
  }
  if(count!=0)
  {
  pulisci_tutto_schermo();
  lcd.setCursor(0,1);
  lcd.print("DAMAGED BUS!!! ");    }
  else
  {
  lcd.setCursor(11,1);
  lcd.print(" OK!");}
  delay(i2c_check_delay);
```

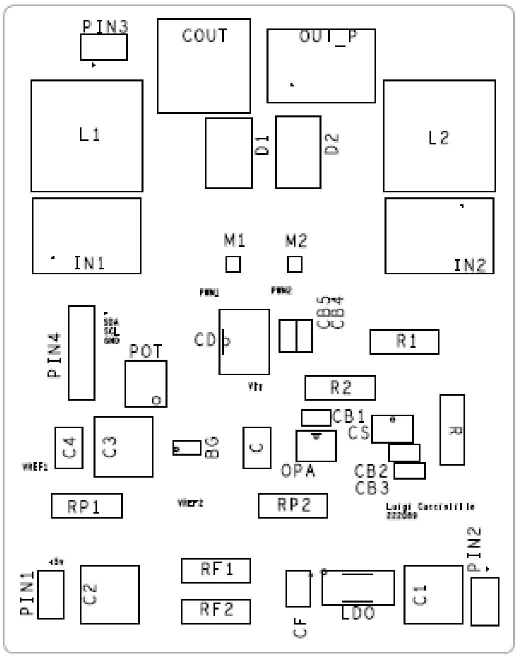
```
}
/* muovo il cursore dei potenziometri per testare variazioni duty cycle**/
byte swipe_cursor(byte value)
{
   value=value+chirp_step;        // increment value
  if (value >= max_value_swipe) { // if reached 64th position (max)
    value = min_value_swipe;    // start over from lowest value
  }
  delay(delay_swipe);
  return value;
}
```

- PCB

ART FILM - TOP

ART FILM - SILKSCREEN_TOP

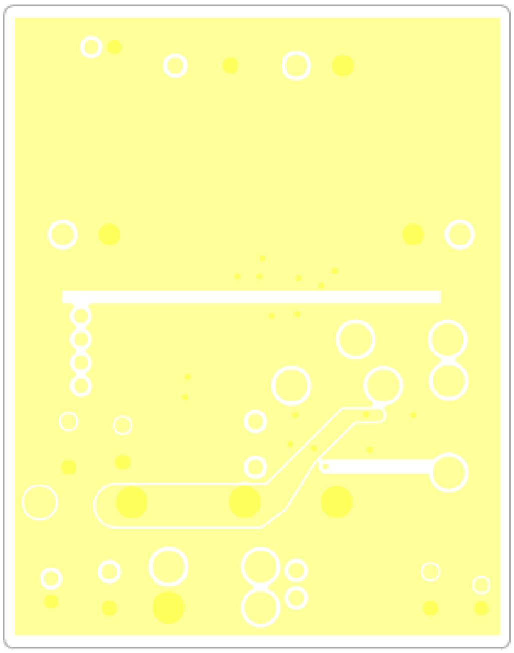


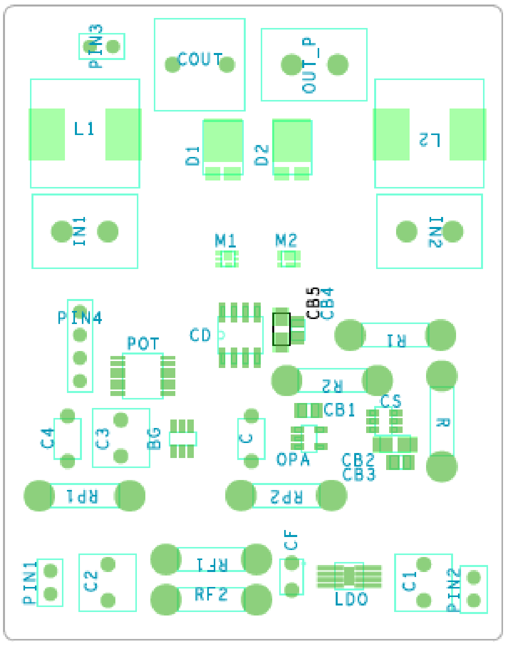


ART FILM - BOTTOM

ART FILM - SILKSCREEN_TOP

ART FILM - SOLDER_MASK_TOP



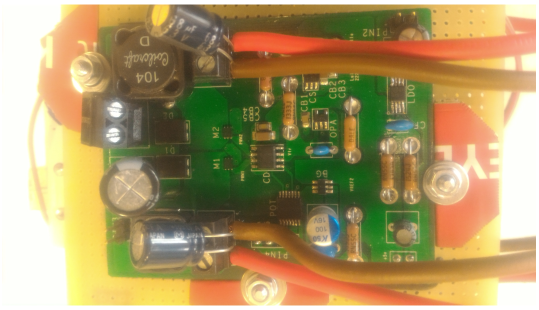


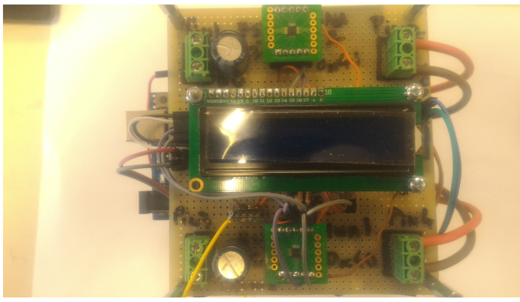
ART FILM - BOTTOM

ART FILM - SOLDER_MASK_TOP

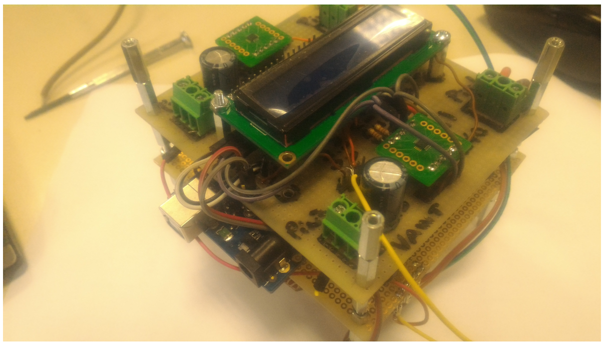
- MEASURE AND VALIDATION

The manufactured system is shown in the following pictures. On the right the control system, on the left the power board and below all togheter.





Before of start with practical tests, we will execute the 3 test modes in the microcontroller code:



- with the first test mode the i2c bus is tested
- check the measure capability with the test mode 3
- test the timing net with the test mode 2.

with the oscilloscope we observe that the triangular wave is a bit different from the one designed. The maximum value is at 4,24V and the minimum voltage is at 640mV. Hence, we must set the algorithm parameters:

knowing that Vpwmi = 0 if Vrib < 640mv, therefore

$$V_R = \frac{4{,}096\,V}{100\,k\Omega} R_{ib} \rightarrow R_{ib} = 15{,}625\,k\Omega$$

the minimum value that the duty cycle can reach is:

$$15{,}625\,k : X = 100\,k : 255 \rightarrow X = 39$$

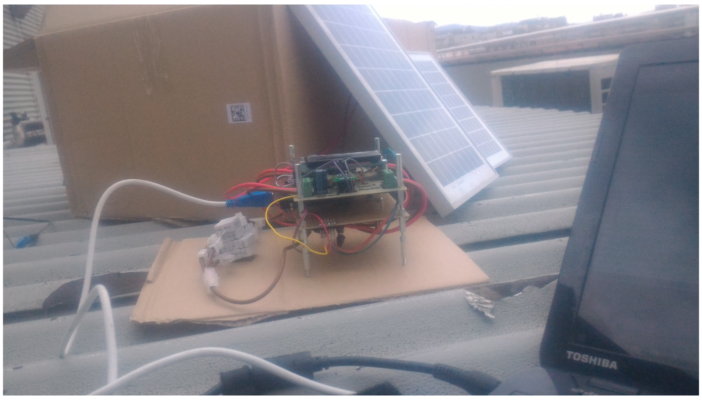
and, the useful dinamyc in which the duty cycle can vary is 216.

WE must also consider that the two harvesters available in the laboratory are different from the two used in the design phase. Instead of VAWT i will use a PV panel of 10 W with Vmp = 18,36V and Imp = 0,54A; the solar panel will be replace by a PV panel from 5W with Vmp = 18,36V and Imp = 0,29A.

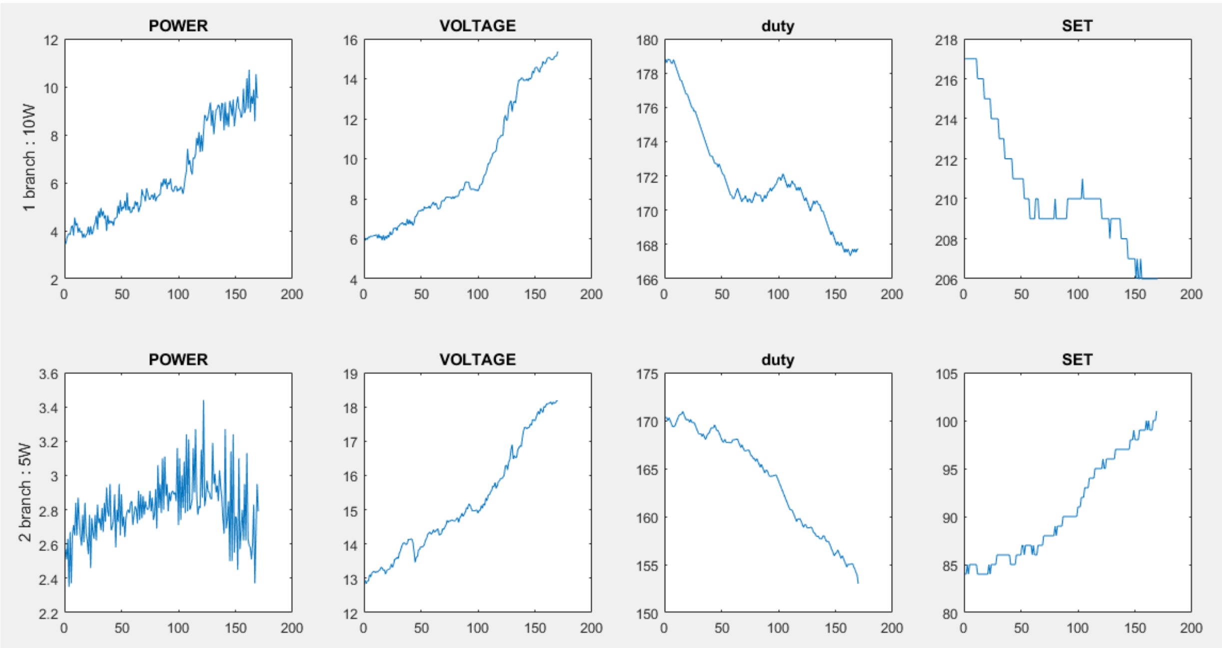
This replacement also forces us to review the load to be used at the exit of the MPEI. Using the MATLAB code already used in the section for calculating the output resistance, we obtain that a useful load capable of making us cover a large part of the useful dynamic of the solar panels is 400 ohms. Having to improvise with the components available in the laboratory, through the use of resistive dividers, we will use a 455 ohm load.

The system is tested on the 5th floor of the electronics department of the Politecnico di Torino on 2 April 2018 over a period of time ranging from 13 to 17.30. in this time the sky provided a good test condition, starting from the absence of clouds at 13:00 until the first clouds appeared at 2.30 pm, becoming completely covered with clouds at about 17.00.

The data were collected using directly those supplied by the arduino serial monitor that arrive from the two ADCs on board and then plotted through MATLAB.



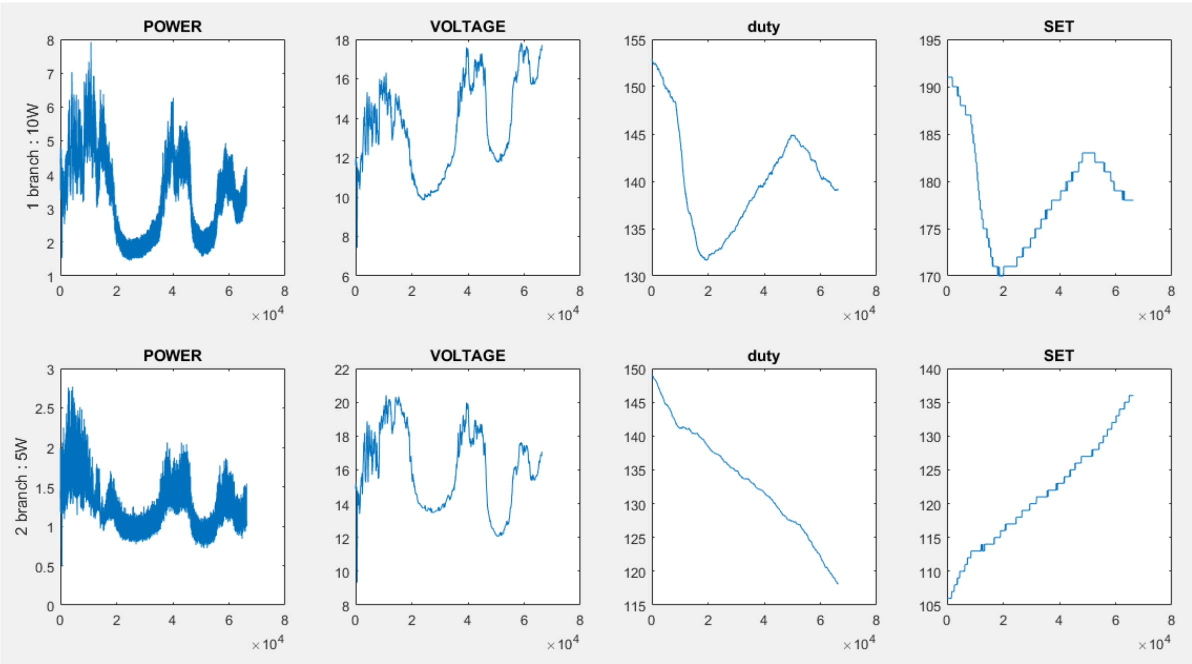
Three different measures will be proposed. The first one is carried out around 13:00 where the maximum recoverable power from the two solar panels is observed. The second measure, carried out at about 2.30 pm, observes the behavior of the system when two clouds pass. The third measure at 4.30 pm where all the behavior of the MPE is recorded at a decidedly unfavorable condition.



the first measure. we note that:

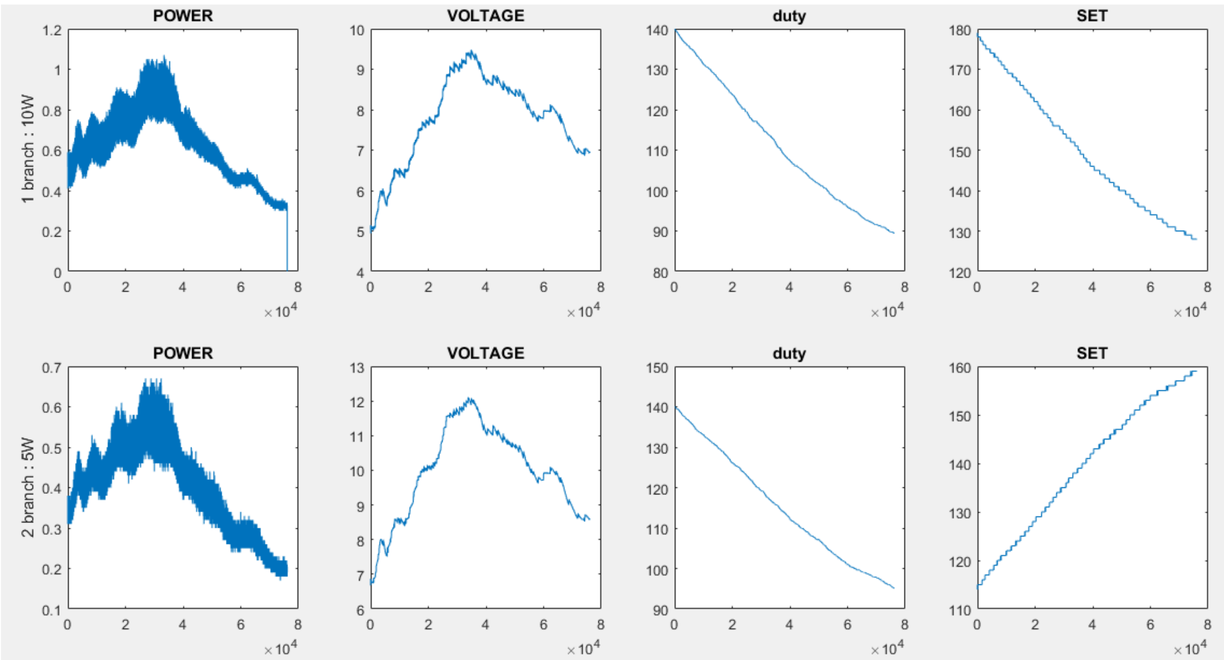
- the 5W promised by the manufacturer are not real. With a total load voltage excursion, they are recorded at more than 3.4W.
- the 10W of the first solar panel are at about Vmp = 15V.
- once the maximum power point is reached, the perturb and observe algorithm tries to impose a certain load in order to return to the maximum power position. Due to the long application times of the algorithm, there is no instant tracking

The second measure shows the passage of two clouds:



- the two harvester are not at maximum power as the system had just been turned on and had yet to be fully operational.
- when the system receives the sharp drop given by the first cloud, the first immediately begins to counter-react, raising the duty cycle. This gains control of the output voltage and the second branch tries to adapt by lowering its duty cycle more slowly.
- when the second cloud no longer influences the irradiation on the two panels, the first branch starts to decrease again, looking for the maximum power point. In the same way the second branch decreases the duty cycle faster

In the third measure the system is turned on at 4:30 pm, the starting point that is imposed by the algorithm's parameters places it to the left of the MPP



P & O tries to reach a maximum point of power, but the sky begins to completely cover itself bringing a loss of power that the system can not contrast.

- CONCLUSION

The behavior observed in the previous pages is similar to the expected one but much lower than the expectations announced by the model developed on simulink. To improve the features, better tuning of the algorithm and measurement parameters will be necessary without the use of serial communication which introduces a further delay in convergence.

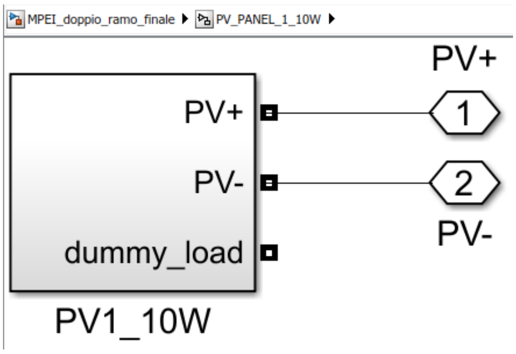
However, the work done remains a good starting point in the design of a similar system with better characteristics. The options available to future developers are different:

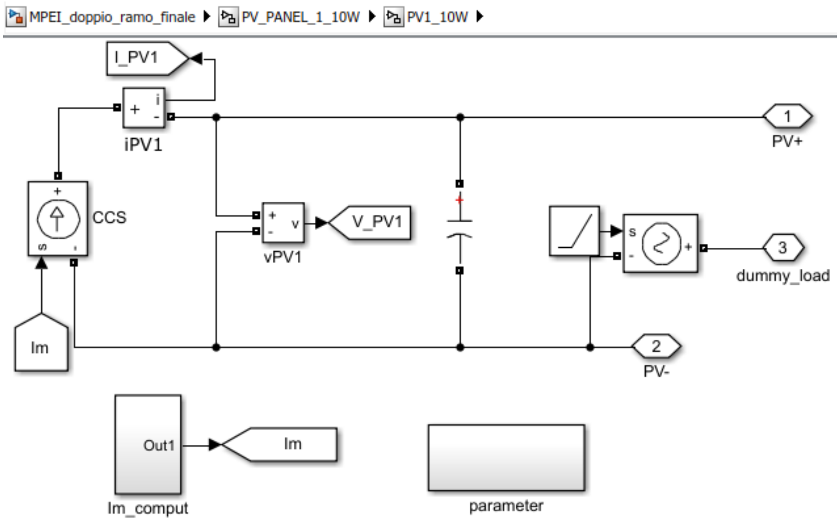
-if a system that is not greedy for resources is desired, the MPPT can be applied using an analogue method, so use constant voltage scaling. It will be enough to eliminate the sub-control system proposed here and to pilot the comparators on the timing network through sensors (photodiodes for the solar panel, anenometers for the VAWT) connected through a special conditioning circuit that will provide a medium voltage to be chased to the comparators closed in feedback as proposed in [11] and [37]

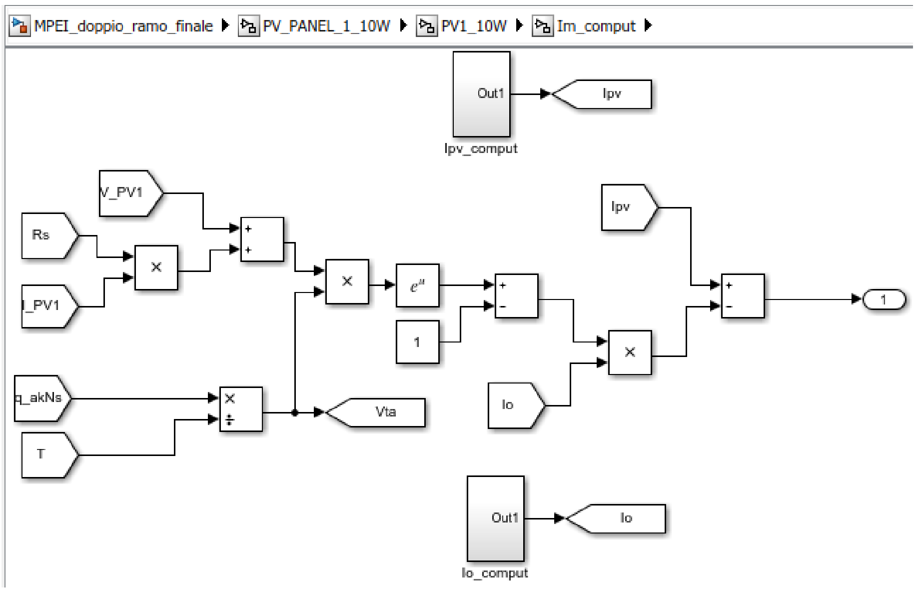
- for a quicker MPP tracking, the digital control potentiometer can be eliminated and the reference voltage is generated directly to the microcontroller, eliminating the constraints of the 3ms setting time required by the potentiometer to move the cursor.

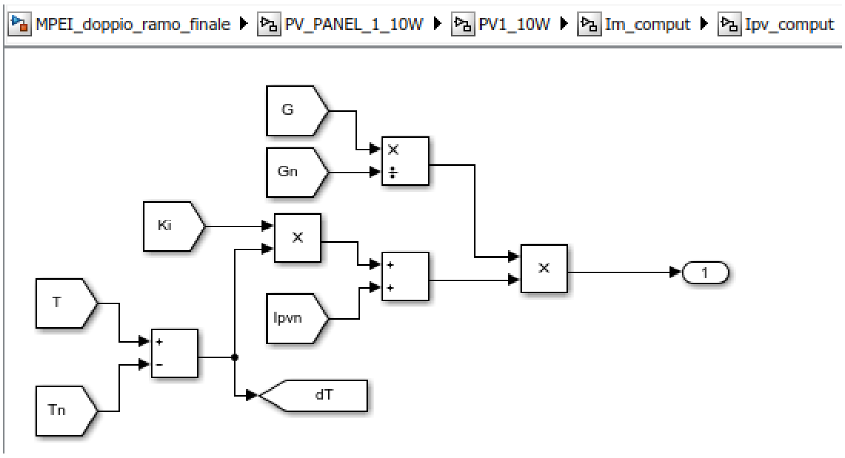
- to bring the tracking time to the minimum possible one can use a DSP or even an FPGA of the microsemi (igloo nano) characterized by power dissipation of the order in which to run the algorithm and to generate the reference voltages.

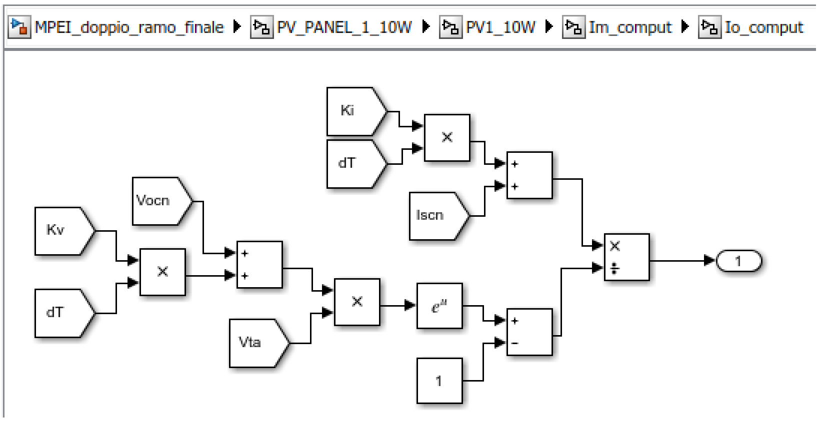
APPENDIX PV PANEL MODEL








MPEI_doppio_ramo_finale ▶ PV_PANEL_1_10W ▶ PV1_10W ▶ Im_comput ▶ Ipv_comput
G
Gn
Ki
T
Tn
Ipvn
dT
1


MPEI_doppio_ramo_finale ▶ PV_PANEL_1_10W ▶ PV1_10W ▶ Im_comput ▶ Io_comput
Ki
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Iscn
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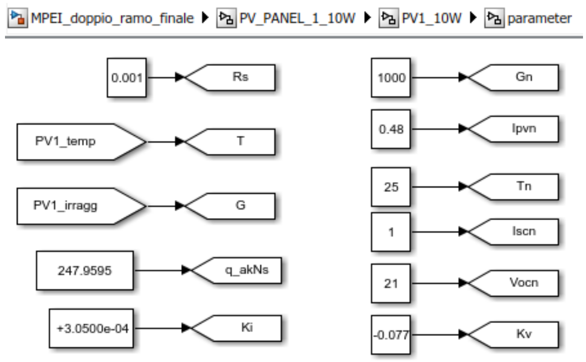
dT
Vta
1
1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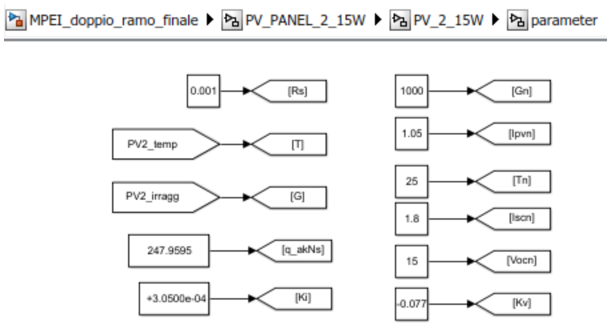
PV1_temp
T
PV1_irragg
G
247.9595
q_akNs
+3.0500e-04
Ki
1000
Gn
0.48
Ipvn
25
Tn
1
Iscn
21
Vocn
-0.077
Kv


MPEI_doppio_ramo_finale ▶ PV_PANEL_2_15W ▶ PV_2_15W ▶ parameter
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[Rs]
PV2_temp
[T]
PV2_irragg
[G]
247.9595
[q_akNs]
+3.0500e-04
[Ki]
1000
[Gn]
1.05
[Ipvn]
25
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1.8
[Iscn]
15
[Vocn]
-0.077
[Kv]

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