MISPS

Module Integrated Solar Position Sensor for Concentration Photovoltaics

U.S. Provisional Patent Application

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1 Background

In the development of CPV systems (Concentration Photovoltaics) there have been many different approaches for the fine tuning of solar tracking control systems.

CPV systems work under high concentration (normally more than 100 suns) and therefore require following the sun in two axis with high accuracy.

Some concentration tracking systems only work in open loop, but the vast majority of them follow a hybrid or purely closed loop tracking algorithm using feedback signals or images coming from some sort of solar position sensor or camera.

The existing feed-back sensors are not integrated into the CPV modules, and therefore constitute an independent optical and mechanical system which is brought together with the CPV modules and trackers on the field installations.

These external sensors need a precise alignment with the CPV modules optical axis in order to work properly. As the objective of the tracker system is to align with the sun the CPV modules, it is obvious that any slight mechanical misalignment between the sensor and the modules downgrades the overall CPV system performance.

The requirement for field alignment increases deployment costs and increases the probability of having recurrent problems. If the sensor has to be calibrated to each tracking system then this procedure is critical and it can be prone to develop mechanical misalignment, requiring periodical maintenance.

Another common problem for solar position sensors is that they can be fooled by clouds or ground reflections, therefore misleading the tracking control algorithm actually making it follow other objects, and therefore losing energy productivity.

Additionally, external solar sensors must rely on small aperture optics in order to minimize its impact on the overall CPV module’s solar aperture, so that they are prone to be affected by dirt stains or soiling.

Also, these external sensors constitute completely redundant optical systems working in parallel with the CPV module optics. Having a different optical system makes it difficult to match CPV module’s characteristics and implies a redundancy of components which is not optimal and increases system costs.

The present invention aims at solving these problems, increasing tracking system reliability and reducing manufacturing, commissioning and operation and maintenance costs.

2 Summary of the Invention

The MISPS is a solar position sensor which is integrated into a concentrated photovoltaic (thereafter CPV) module having refractive, diffractive or hybrid primary imaging optics, or even more generically, imaging optics in which the primary lies between the sun and the CPV receiver.

In principle, it is more appropriate for CPV systems having a secondary optical element (thereafter SOE) on top of the CPV cell.

This sensor's main purpose is to be used as a fine tuning device for a hybrid continuous tracking system, which will normally work on an open loop speed setting algorithm following astronomical calculations, which will eventually be corrected using the value of the sensor signals when lack of alignment is detected.

Therefore, one of the characteristics of the MISPS concept is that it is only influencing the tracking algorithm whenever a certain degree of misalignment is detected. Its function can be described as negative signal generation, changing the tracking speed in opposite sense to the detected misalignment.

This sensor concept can also be used for hybrid intermittent tracking systems, where MISPS signal reaching a minimum threshold would trigger the transition from normal open-loop astronomical based operation into closed-loop sensor based operation.

The MISPS sensor introduces the novelty of being module integrated, thus avoiding the need of complex sensor to module alignment procedures which are needed for systems relying on an external (i.e. non module integrated) solar position sensor.

Eliminating the need for such calibration procedures reduces CPV system installation and commissioning costs.

It also increases system reliability, as there is no accidental misalignment possibility between sensor and CPV modules.

Also, because it is integrated in the module, it uses the primary optical element (thereafter POE) of one of the CPV receivers for the positioning function and the module enclosure for the device protection, thus reducing component redundancy and cost.

Another advantage is that the sensor works under concentrated light, so that its working illumination threshold can be correlated to significant direct normal irradiance (thereafter DNI) conditions, in such a way that its function is not disturbed by cloud reflections or diffuse light.

Another advantage is that it uses the full POE area and optics creating an image of the sun in the focal plane, so that even if dirt partially obscures the POE aperture, it will still work and thus its function will be less prone to be affected by soiling or dirt stains.

Another advantage is that the MISPS is made of silicon photovoltaic cells which can be obtained from standard mono or poly crystalline wafers, therefore having a very low cost.

Another advantage is that its configuration, divided in two sensor areas, delivers a very good sensitivity to small deviations combined with a wide acceptance angle.

The central section of the sensor, made of small cells, provides good response to small deviations while the very large area of the peripheral section of the sensor provides the large acceptance angle. For instance, for a f1 optical system it is expected to offer a 0,1 to 17 degrees response range.

A wide sensor acceptance will allow relaxing installation and commissioning alignment requirements and will help the tracking system to recover more easily from different kinds of incidences.

3 Detailed Description

Figure 1 shows the MISPS sensor 1 inside a CPV module, between a panel composed of a pluralilty of POE elements 2 and a receiver panel 3 containing a plurality of CPV receivers 4. For simplicity the CPV module walls have been obviated.

Figure 2 depicts an explosion of the sensor components and figure 3 is a cross section view.

MISPS sensor 1 is installed on top of one of the CPV receivers 4.

The MISPS sensor (1) is actually divided in two sections: a central section (5) and a peripheral section (6). Both sensor sections are arranged in such a way that they jointly cover a surface area close to that of the POE aperture.

Central section 5 consists of four triangular photovoltaic cells 7 placed in a cross arrangement mounted on an insulated metal substrate (IMS) circuit, although other substrates can be used alternatively.

This circuit has the four cells (9) connected to four shunt resistors, in order to allow measurement of the short circuit current of each sensor cell. The shunt resistors and any other electronic circuitry are arranged around the four solar cells.

The central section substrate circuit has a square hole (7) in its centre (thereafter diaphragm), of a width which is just a bit larger than the diameter of the sun image on the POE focal plane (thereafter sun spot).

Each cell 9 is triangular in shape with a truncated corner. The four cells when mounted leave a square empty area between them which must be coincident with the diaphragm aperture on the IMS circuit.

Central section 5 has four standoff inserts 11, and is bolted through them to the CPV module back plate 3. It is mounted coplanar to the CPV module back plate, centred on one of its receivers 4, in such a way that receiver’s SOE geometrical and sensor diaphragm centres are aligned.

The IMS circuit is mounted so that its upper surface (the sensor cells) is as close as possible to the POE focal plane.

Peripheral section 6 surrounds the central section and is mounted on top of it.

It also consists of four triangular photovoltaic cells (10) placed in a diagonal cross arrangement, but these cells are significantly larger than the ones in the central section and the substrate on top of which are mounted can be for instance a FR4 printed circuit board instead of an IMS board.

The four cells are truncated in such a way that the dead space left between them in the centre is coincident with a square aperture on the peripheral circuit board which is of the same area as the central section sensor area.

Peripheral section 6 also has its four cells connected to four shunt resistors to allow measurement of the short circuit currents and it is mounted through mechanical and electrical connectors on top of the central section, so that voltage signals coming from the central section are connected to the peripheral section through these mounting connectors.

It is implemented using a double sided circuit, so that the shunt resistors and remaining electronics can be SMD mounted on the back side of the board while the sensor cells are mounted on the front side.

Connectors transmitting the voltage signals to the control electronics are placed on the edge of the back side of the peripheral sensor.

In principle the kind of cells to be used can be obtained from a standard mono-crystalline silicon wafer but the concept can be implemented using any kind photovoltaic cell which tolerates high current densities.

For an optimal operation, an increased metallization density is desirable, much higher than the standard metallization for silicon photovoltaic cells designed to work at one sun, as the cell has to work under concentrated irradiance and its photocurrent conversion efficiency is of no interest because it is used as a sensor and not as a power generator.

An increased metallisation density will reduce series resistance and recombination losses originated by extreme current densities, avoiding current saturation effects which would originate a non-lineal current response to irradiance: The higher the metallization density the lower the amount of photons that will be converted and the lower the series resistance of fingers.

Desired metallization pattern consists in a busbar parallel to the longest side of the sensor cell and fingers running perpendicular to it.

Additionally, the MISPS aperture is surrounded by four light blocking walls (12), normal to the POE focal and aperture planes, in such a way that these walls are of a height similar to the POE focal length and of a width similar to the POE square solar aperture.

Figure 2 shows only two of the four walls surrounding the MISPS sensors.

The function of these walls is to avoid interference between the MISPS and light coming from POEs corresponding to other receivers. The walls should be as black as possible in order to avoid reflections which could mislead the sensor.

The receiver 4 on which the sensor is centred is better to be one close to the systems mechanical centre, thus being more representative of the mean mechanical alignment vector of all system receivers.

The way the sensor works is depicted in figure 5.

POE 2 creates an image of the sun on its focal plane.

When the CPV system is perfectly aligned, the sun spot lies in the centre of the SOE aperture, and therefore within central section 5 diaphragm aperture (figure 5A).

As soon as there is misalignment, the sun spot will move away from the centre of the SOE aperture, and eventually will start to hit the surface of one or two of the four sensor cells on central section 5 (figure 5B).

If the deviation increases the sun spot will eventually move away from the central section (5) to the peripheral section 6 (figure 5C).

The short current generated by each of the eight sensor cells (four on the central section and four on the peripheral section) is continuously monitored. These signals are used as a measure of the amount of DNI reaching each cell surface.

Whenever the current reaches a certain threshold, the open-loop tracking operating mode will be modified by the sensor signal.

The intensity of the signals (voltages) will be used to change the tracking speed for each axis.

The reason to have two sensor sections is to allow for a larger sensitivity (gain) of the central section.

We must take into account that any of the sensor areas will normally (i.e. when no deviation occurs) be illuminated by stray rays coming from the primary optics, with an illumination distribution similar to the equivalent of diffuse radiation per sensor area.

This diffuse illumination means that the sensor cells will actually generate photocurrent proportional to its area and to diffuse radiation.

A desired characteristic of the MISPS is that it must be very sensitive to slight deviations, in the 0.1 degrees range. This small deviation will only partially place the sun spot within one of the central section sensor cells, in such a way that the increase of current is also small.

The smaller is the central sensor cell area the lower the diffuse radiation generated current (noise) and the larger the capacity for the control algorithm to discriminate an increase of signal due to a small deviation.

At the same time, having large area cells for the peripheral section provides for a very large acceptance sensor. Under very large deviations the sun spot will completely lay outside of the diaphragm and the full DNI illumination will make enough difference to discriminate noise from the larger peripheral sensor cells.

So, reducing the central section area increases sensor sensitivity to small deviations and enlarging the peripheral section area broadens the sensor acceptance angle.

Therefore, dividing the sensor in two areas allows the MISPS to combine high sensitivity with large acceptance.

We want the control algorithm to be able to read the eight sensor signals simultaneously, in order for it to be able to discriminate the several possible deviation scenarios.

Figure 4 is a top view showing the division of the sensor in two sections (central and peripheral) with four quadrants (up, down, left and right), making up a total of eight sensor areas: central up (CUP), peripheral up (PUP), central down (CDN), peripheral down (PDN), central left (CLF), peripheral left (PLF), central right (CRT) and peripheral right (PRT).

The MISPS is designed to be used by a continuous tracking system, and not an intermittent one. This means that the tracking speed and direction of each axis is periodically reviewed, instead of the absolute position.

Under perfect conditions, if no misalignment appears, the MISPS will never generate a strong enough signal in order to affect the open-loop mode, but when this happens, the action will be to increase or decrease the tracking speed of the affected axis.

The main running algorithm for the tracking system using the MISPS will then be similar to this:

```
forever {
      while time < dawn do nothing
      initial position = calculate astronomical sun position
      move to initial position
      while time < sunset {
            periphery = false
            read MISPS signals into PUP, PDN, PLF, PRT, CUP, CDN, CLF, CRT
            if PUP > peripheral threshold
                  speed A = - hunt speed; periphery = true
            if PDN > peripheral threshold
                  speed A = + hunt speed; periphery = true
            if PLF > peripheral threshold
                  speed B = - hunt speed; periphery = true
            if PRT > peripheral threshold
                  speed B = + hunt speed; periphery = true
            if ! periphery {
                  speed A = calculate astronomical speed A axis
                  speed B = calculate astronomical speed B axis
                  if PUP > central threshold
                        speed A = speed A - tune increment
                  if PDN > central threshold
                        speed A = speed A + tune increment
                  if PLF > central threshold
                        speed B = speed B - tune increment
                  if PRT > central threshold
                        speed B = speed B + tune increment
            }
            set speed A axis ( speed A )
            set speed B axis ( speed B )
            wait periode milliseconds
      }
}
```

Please notice that the speed will be recalculated every `periode` milliseconds.

When the sun spot is detected in the peripheral section then the algorithm hunts the sun at constant speed.

When the sun spot is detected in the central section, the speed tracking algorithm is essentially hybrid, and there is actually no significant machine state change between the perfectly aligned and the slightly misaligned situations.

Please notice how sign convention affects the whole algorithm.

For instance, for the B axis, assuming an alt-azimuth tracker on the northern hemisphere, when the sun spot enters the right quadrant it means that the sun is actually faster than the tracker in its east-west (left-right) azimuth speed, leaving the tracker behind. The tracking speed for B axis must therefore be increased in order to allow the tracker to catch up with the sun. Given the sign convention shown in table 1, we must add `k * inc B` to `speed B` in order to actually increase the tracking speed. Also please notice that B axis speed has a sign stating the direction and that the convention is positive for east-west azimuth.

Imagine now that on a similar northern hemisphere alt-azimuth system, tracking before solar noon (positive astronomic elevation speed), the sun spot enters the down quadrant, this meaning that the tracker has overtaken the sun in its upwards A axis trajectory. The solution must be to lower the elevation tracking speed proportionally to `inc A`, and thus its sign must be also negative.

Fig. 1

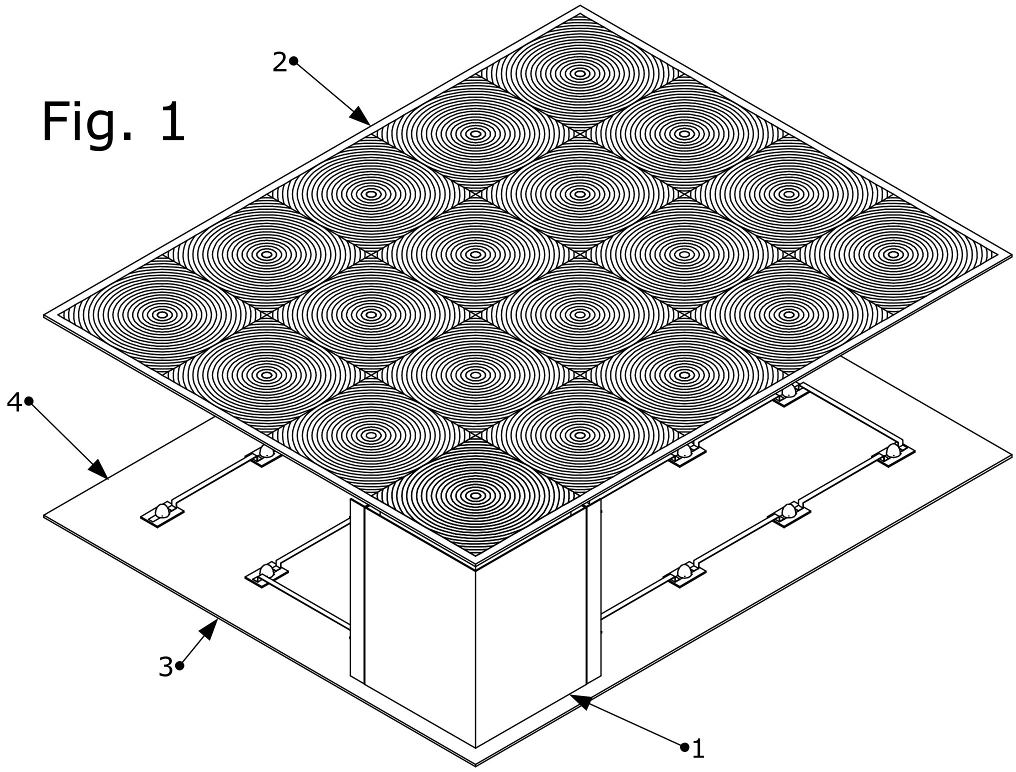

Fig. 2

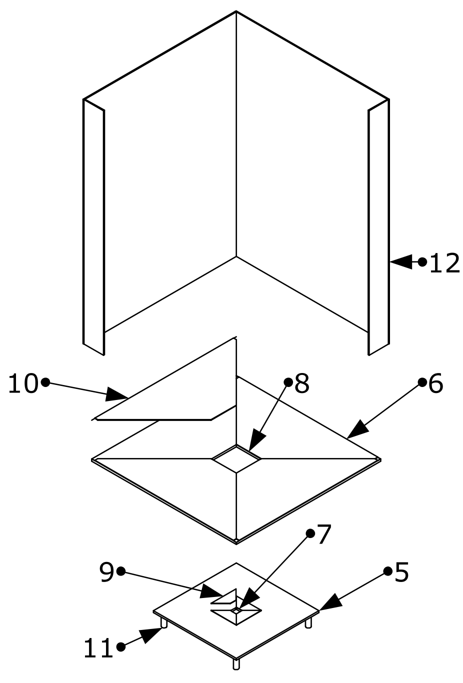

Fig. 3

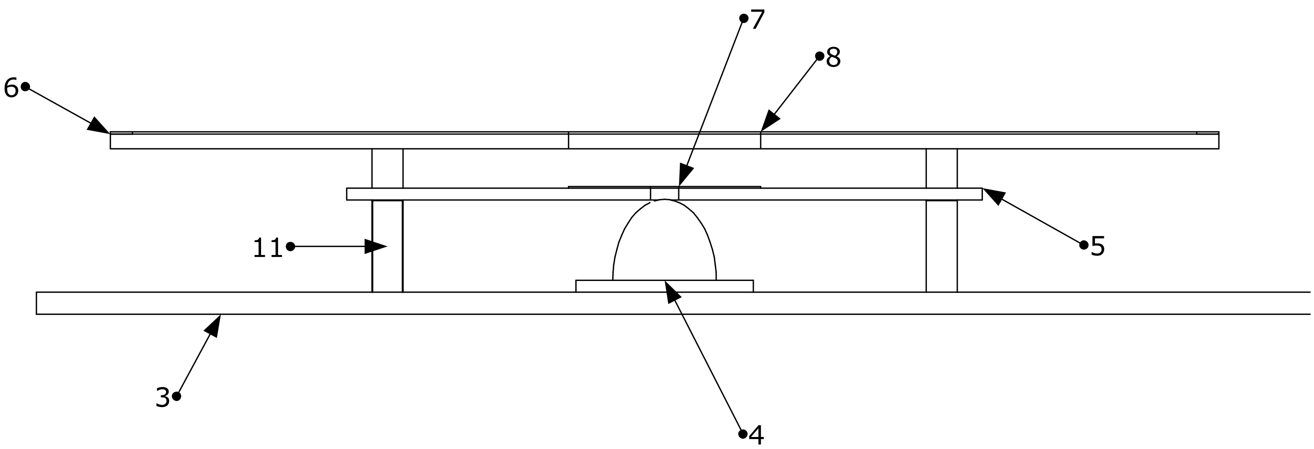

Fig. 4

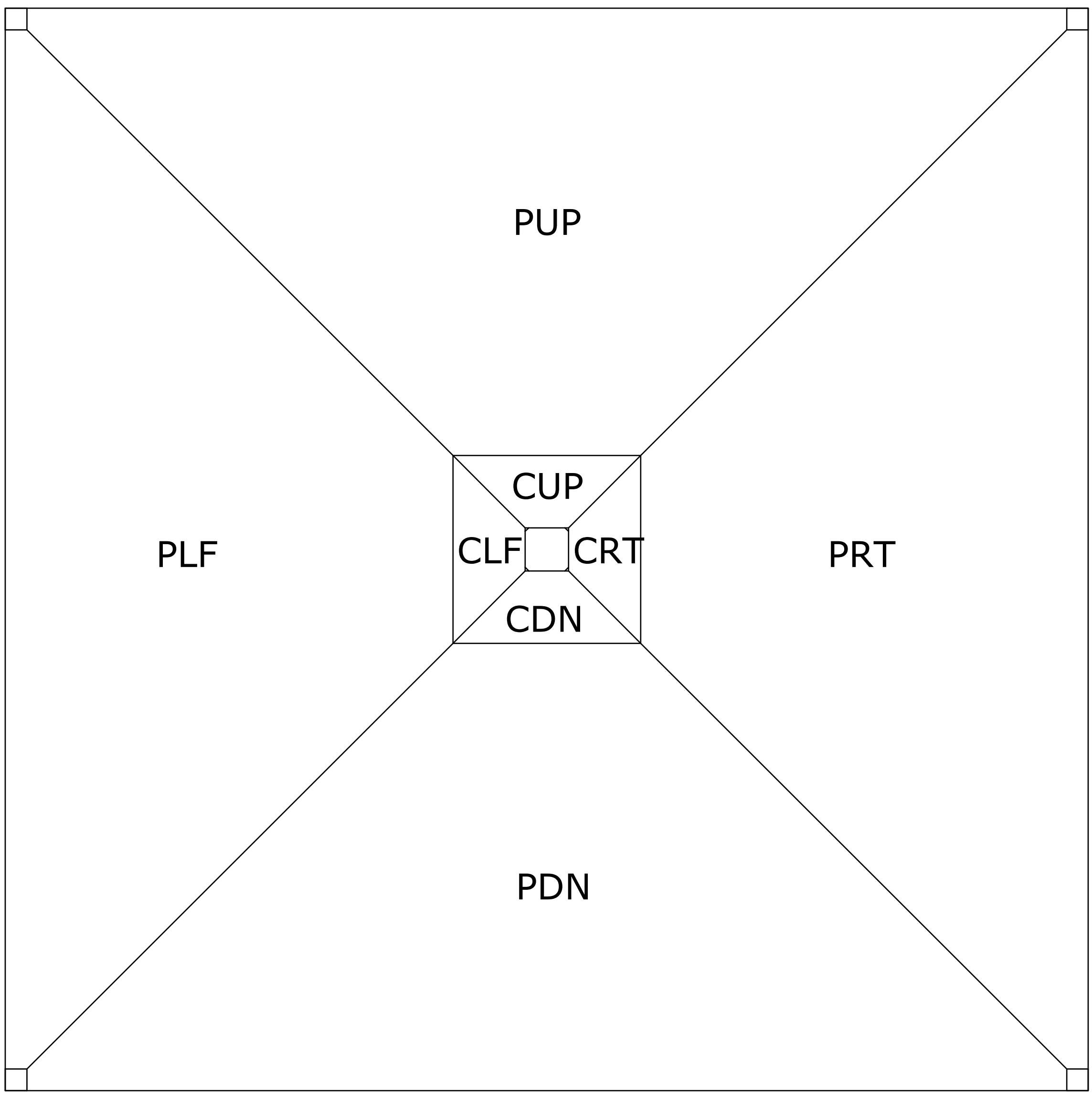

Fig. 5

A

B

C