
# Power Conversion and Application of Magnetic Components in Solar Energy

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SHENZHEN CODACA ELECTRONIC CO.,LTD

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After long-term technical evolution - especially been stimulated by multiple big crucial topics like environmental crisis and fossil energy dilemma, the solar energy has received enormous break-through on key difficulty indexes from both technological and commercial sides that focusing on conversion efficiency and cost of electricity generation. It is global consensus and also today's fact among economy advanced countries such as US. and EU that the solar power has been widely deployed as key form of renewable and sustainable power infrastructure transforming, as well as the important path for realizing carbon neutralizing propagation. China is also rolling out policy guidelines to significantly increase the number of photovoltaic installations.

Depending on the installation scale of solar energy, the application is often classified into 3 categories: Residential, x100W ~ xKW; Commercial, xKW ~ xMW; Utility, xMW ~ xGW. And because of its extensive scalability the corresponded power conversion of solar power generation has several different schemes as options: in terms of conversion efficiency, there are continuous control units for fitting to the solar irradiation and adjusting output based on battery temperature; meanwhile, considering relative power generation cost and power consumption capacity, there are distributed micro-grids for off-grid power generation and centralized power stations for grid connection, especially when the string of PV panels scales up that the islanding risk to the system and the LVRT (low voltage ride through) ability of the grid-tied equipment makes the configuration scheme of photovoltaic power generation complicated and changeable. On the transformation in the corresponding power, requiring magnetic components such as filter inductor, boost inductor, power transformer, reactor, etc. also have widespread distribution, especially in a typical distributed photovoltaic solutions where magnetic components cost is higher by percentage, selecting the appropriate expansion of magnetic components for photovoltaic power generation and the system performance is more important for greatly broadening solar power's next popularization.

## 1 The principle of photovoltaic power generation and power conversion in the system

### 1.1 Semiconductor foundation

Due to the key requirement of photoelectric conversion efficiency, monocrystal silicon heterojunction (HIT) solar cells (N-type substrate) are currently the key development type (efficiency around 25%), although aluminum backfield (BSF) and PerC-type like such P-type substrate cells (efficiency between 19% and 21.5%) still account for the major share of installed scale. However, with the continuous research and development of equipment and main materials (silicon material and low-temperature silver paste) and the improvement of production capacity, HIT cost will be gradually reduced, and the newly installed solar cells in future will be mainly HIT type.

In intrinsic semiconductors, p-type or N-type semiconductors with sufficient carrier concentration are obtained by doping. Due to their narrow band gap, in the case of external interference, such as illumination electromagnetic radiation, the atoms inside can be excited to produce more electron-hole pairs. When different types of semiconductor form PN junction, n-type terminal will accumulate more electrons under the action of internal diffusion electric field, while p-type terminal will be the contrary case, and eventually formed the driving voltage at both ends and become the power supply, namely the battery. This internal photoelectric effect is called photovoltaic effect. The opposite phenomenon is generating electric light by LED, through the electronic-hole recombination. The working state of the PN junction is forward biased for both the two, but photovoltaic battery is the power supply (optical radiation power an electrical current, low power density), and the LED is load (electric power to produce light, high power density), therefore, photovoltaic cells can provide a large current, while LEDs are limited by their cooling structure and size that can not pass through a large current (burn out). Related diode structures, circuit symbols and equivalent circuits are shown in Fig.1 below:

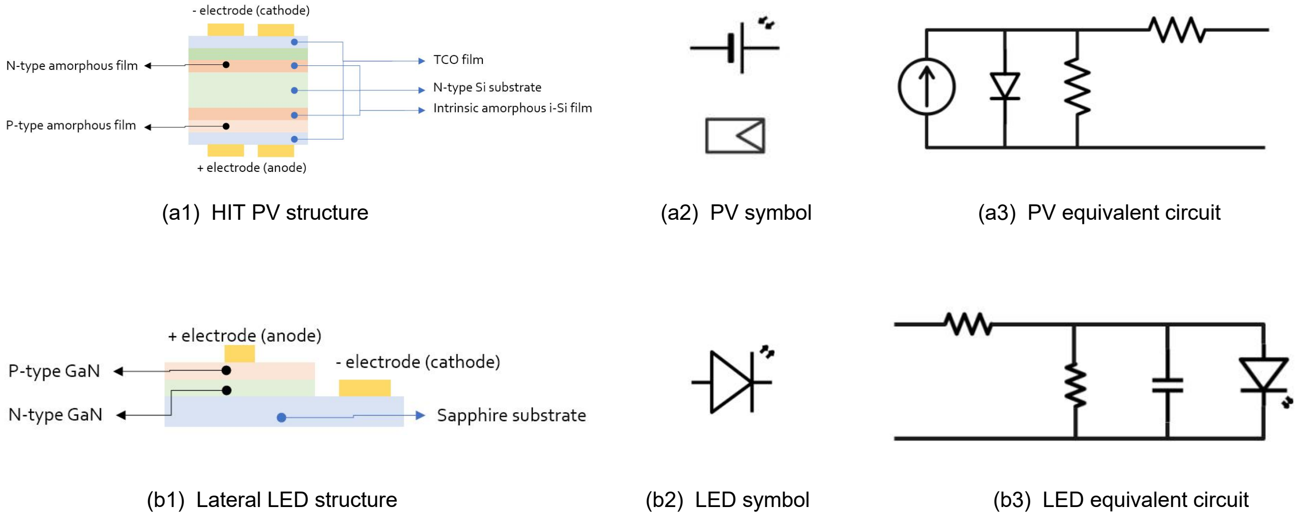



Fig.1 Structure, symbol and equivalent circuit of photovoltaic battery (HIT) and LED

A typical photovoltaic cell (PV) output current is expressed as:

$$i = i_{sc} - i_{Do} \cdot \left(e^{\frac{q(V+i\cdot R_s)}{AKT}} - 1\right) - \frac{V + i \cdot R_s}{R_p}$$

Where:

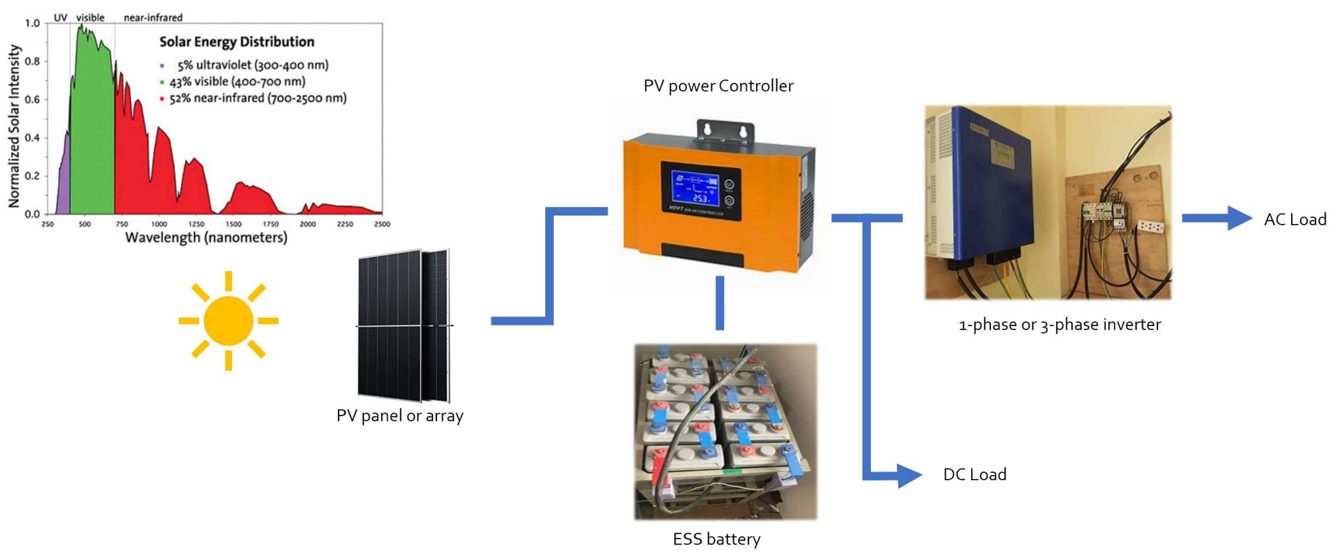
$i_{sc}$ - Excitation current produced by light irradiation;
$i_{Do}$ - Saturation current of PN junction;
$q$ – Electron's charge as $1.6 \times 10^{-19}$C;
$K$ – Boltzmann constant as $1.38 \times 10^{-23}$J/K;
$A$ – Ideal constant between 1~2;
$T$ – Temperature of PN junction.

The $\frac{q}{AKT}$ is weak interaction of the irradiation, it changes with the irradiation intensity; because $R_s$ is generally small and $R_p$ is generally large (>100KΩ), the output voltage and current of photovoltaic cells are mainly affected by the irradiation intensity and temperature, and when the irradiation intensity and temperature are stable, the output current decreases gradually when the output voltage of PV increases. It can be seen that the power output of photovoltaic cells will increase first and then decrease with the increase of output voltage; in order to achieve optimal photovoltaic power generation design, it is necessary to control the output power and maximize the power output through maximum Power point tracking (MPPT) technology.

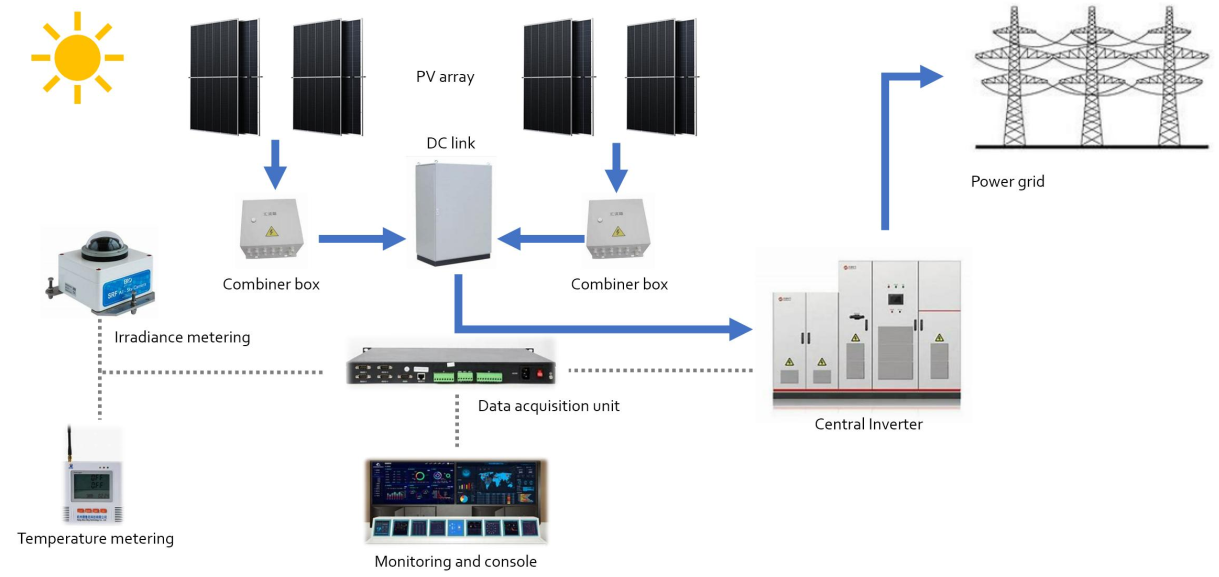
Beside of this, in addition to photovoltaic cells, in the power conversion of photovoltaic power generation, depending on the sit uation, there uses different switching FETs and diodes semiconductor such as: MOS, gallium nitride (GaN), silicon carbide (SiC), IGBT. The main reason of this difference is that under different application conditions (operating voltage, switching frequency, etc.), different types of semiconductors have advantages in terms of cost and performance. As can be seen from the actual photovoltaic application, the control complexity and the cost of different types of switching devices in return affect the choice of specific photovoltaic power conversion schemes (boost and inverter, etc.), and due to the continuous development and change of various factors on these power semiconductors, the technical iteration and commercial promotion of photovoltaic products have been continuously developed.

## 1.2 Main considerations in solar energy system

Grid-connected solar power generation needs to meet specific technical requirements, such as IEEE1547(US.), ENEL 2010 Ed.2.1 (Italy), EN50438 or GB/T 19939-2005, GB/Z 19964-2005 in China. In order to configure appropriate grid-connected inverter, the photovoltaic system needs multi-stage power conversion, efficiency control, complete monitoring associated communication system, and has necessary functions such as islanding detection and power yield prediction, which is generally suitable for medium and large-scale photovoltaic power generation deployment. In the case of local power consumption, distributed off-grid photovoltaic power generation system has lower system configuration difficulty and higher flexibility, usually with microinverter as the main power level, or equipped with energy storage system to achieve effective power scheduling. Typical off-grid and grid-connected photovoltaic power generation systems are shown in Fig.2 below.




(a) Typical off-grid photovoltaic power generation systems




(b) Typical grid-connected photovoltaic power generation systems

Fig.2 Two typical types of photovoltaic systems (Pic. source from network)

Safety is more important than efficiency among the main factors to be considered in grid-connected photovoltaic power generation system, which mainly includes islanding detection, insulation detection, leakage current detection and LVRT, etc. However, because the load of low-density distributed PV often exceeds the power generation capacity, the occurrence probability of islanding risk is very low, so it is generally not configured in this case. In the centralized photovoltaic power plant, active islanding detection is needed to protect it, and the risk brought by photovoltaic power generation can be minimized by controlling voltage and frequency. There are many methods both active and passive solutions, their basic principle is: when the power grid is down, the load of active power and reactive power by the power supply of the photovoltaic inverter output has obvious change occurring, the change of the photovoltaic inverter output voltage will be directly reflected in the load voltage variation at both ends. Similarly, the reactive power of the load (occurs on the equivalent inductance and capacitance) also changes by frequency when the inverter output changes (Fig. 3). As shown, voltage and frequency of load before and after power grid outage are respectively $U_{L1}$ , $U_{L2}$ and $\omega_1$ , $\omega_2$, and their active power and reactive power changes are ΔP and ΔQ respectively, corresponding relationship as follow:

$$U_{L2}^2 - U_{L1}^2 = R \cdot \Delta P$$

$$(\omega_1 - \omega_2) \cdot (1 + \omega_1 \omega_2 \cdot L \cdot C) = \omega_1 \omega_2 \cdot L \cdot \Delta Q / U_{L1}^2$$

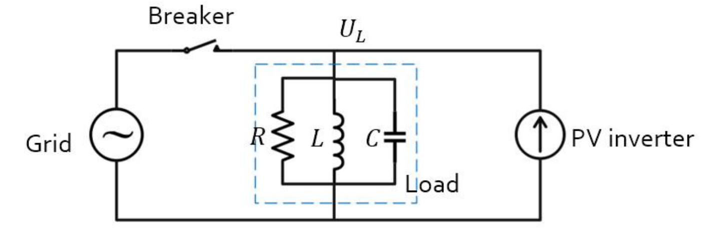



Fig.3 Principle of islanding detection for grid-connected PV power generation (simplified)

As can be seen from the simplified relationship, as long as the changes of ΔP and ΔQ on the load are obvious, the voltage variation and frequency variation of photovoltaic inverter can produce an obvious correlation reaction at the load ends, thus it can detect whether the photovoltaic power generation in the grid system is in islanding state or not. When the change is not obvious, it is necessary to supplement other monitoring schemes such as carrier communication to meet the security requirements actively.

In addition, the installed capacity of photovoltaic power generation systems (photovoltaic modules total nominal power) and the inverter with rated capacity (the total active power rating) have also proportioning ratio (of the two) which defined in performance specification (China NB/T 10394-2020). Improving the capacity matching can persist on stable output power, and the corresponding comprehensive efficiency of system can be improved as well.

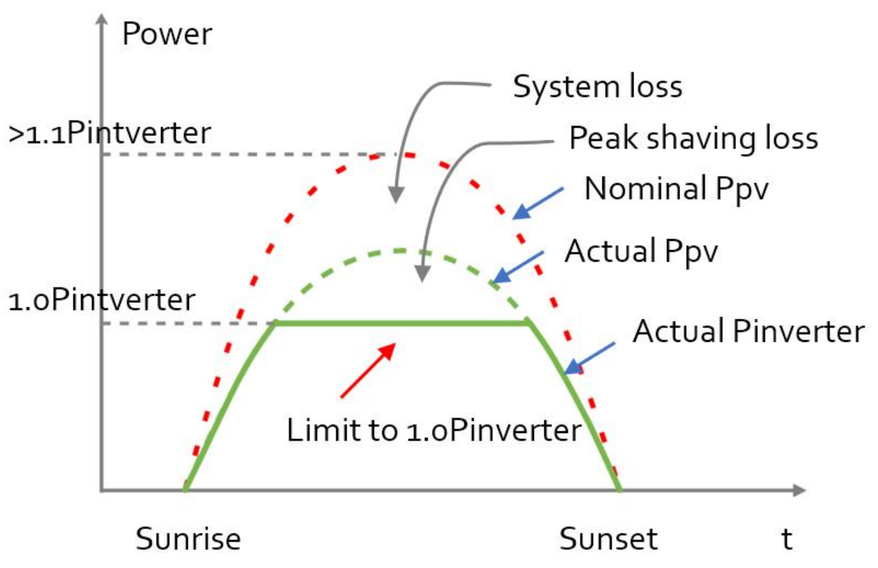



Fig.4 Example of the relationship between PV capacity ratio and the corresponding actual power output

1.3 Main types of power conversion in photovoltaic power generation

Photovoltaic power generation, as a current source, has a fluctuating relationship between its power output and its working voltage, that is, in the actual power conversion, the control of maximum power output needs to be realized first. According to the algorithm of MPPT or Power Optimizer, the fluctuating photovoltaic power is generally converted to DC power at first, that is, DC bus (or DC-link). This process is generally boost conversion. Secondly, according to different power levels, the boost conversion can also achieve better efficiency and cost through interleaved boost or full-bridge control. At the same time, soft switching or other isolated power conversion can be supplemented according to isolation requirements to achieve dc requirements of different voltages. Or according to the application need can be directly supplied to the AC load in the form of full bridge inverter.

In a string inverter or central Inverter, in addition to MPPT or stable DC high voltage after power optimization, there are many complex forms of inverter topology. For example, single-phase or three-phase series inverter can be divided into two or multi-level forms. Because of the configuration flexibility of the string inverters – both technically and cost wise, they gradually become the main development trend these years.

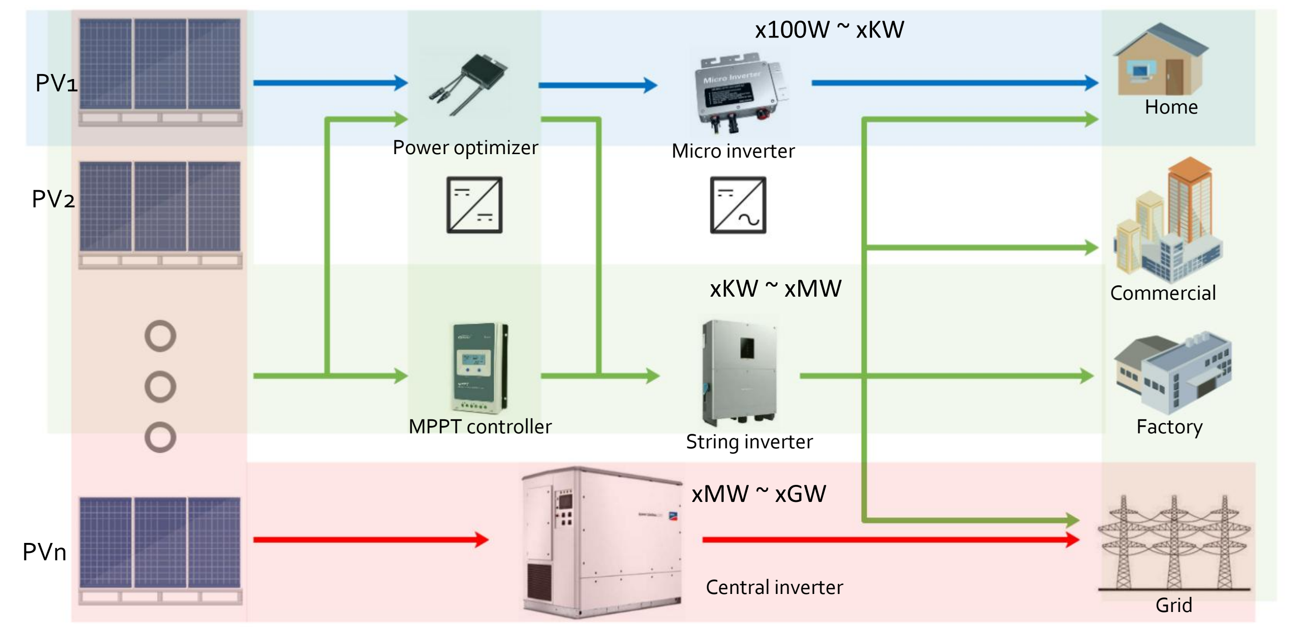


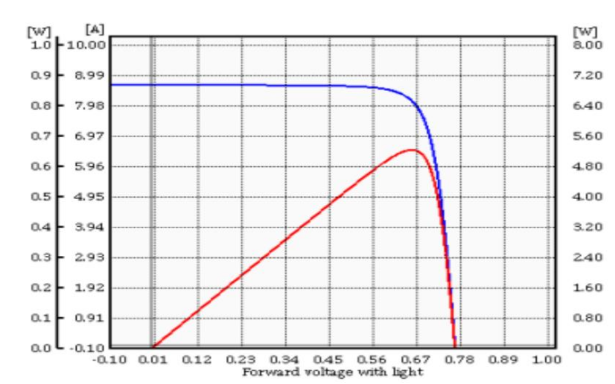

Fig.5 Power conversion in PV power generation:
(Blue) Micro-inverter (Green) String inverter (Red) Centralized inverter

**2 Application of magnetic components in solar energy**

2.1 MPPT (or Power Optimizer)

The development of photovoltaic cells has gone through several technical iterations, in the latest 6.0 era represented by 210 cells (210mmx210mm), a single chip power output of 10~12W can be achieved at an irradiation intensity of $1000W/m^2$ at 25° C. Usually, the specification of the PV will provide the open circuit voltage ($V_{oc}$), short circuit current ($I_{sc}$), voltage of maximum power point ($V_{mp}$) as well as the maximum power point current ($I_{mp}$). When the irradiation intensity decreases, $I_{sc}$ decreases significantly and $V_{oc}$ decreases slightly. As the temperature increases, $V_{oc}$ decreases. Correspondingly, $V_{mp}$ and $I_{mp}$ changes simultaneously. The power limit of PV is obtained by multiplying $I_{sc}$ and $V_{oc}$, and then the ratio of the maximum output power to the power limit is called the filling factor of photovoltaic modules. This value is mainly determined by the internal equivalent resistance and PN junction material, which can be used to measure the battery performance:

$$FF(\%) = \frac{V_{mp} \cdot I_{mp}}{V_{oc} \cdot I_{sc}}$$




(a) TW Solar - TW210Y212A (half-type PV cell) I-V curve

| Code | Eff(%) | Pmpp(W) | Vmpp(V) | Impp(A) | Voc(V) | Isc(A) | FF(%) |
|---|---|---|---|---|---|---|---|
| TW-210M-250 | 25.00 | 5.51 | 0.675 | 8.166 | 0.7487 | 8.573 | 85.89 |
| TW-210M-249 | 24.90 | 5.49 | 0.674 | 8.145 | 0.7484 | 8.560 | 85.78 |
| TW-210M-248 | 24.80 | 5.47 | 0.673 | 8.123 | 0.7482 | 8.554 | 85.47 |
| TW-210M-247 | 24.70 | 5.45 | 0.672 | 8.116 | 0.7478 | 8.553 | 85.24 |
| TW-210M-246 | 24.60 | 5.43 | 0.671 | 8.093 | 0.7472 | 8.542 | 85.11 |
| TW-210M-245 | 24.50 | 5.41 | 0.670 | 8.076 | 0.7470 | 8.541 | 84.80 |
| TW-210M-244 | 24.40 | 5.39 | 0.668 | 8.061 | 0.7469 | 8.541 | 84.46 |
| TW-210M-243 | 24.30 | 5.37 | 0.667 | 8.046 | 0.7465 | 8.536 | 84.24 |
| TW-210M-242 | 24.20 | 5.35 | 0.666 | 8.033 | 0.7461 | 8.530 | 84.01 |
| TW-210M-241 | 24.10 | 5.32 | 0.664 | 8.024 | 0.7456 | 8.526 | 83.76 |

(b) TW Solar - TW210Y212A (half-type PV cell) specification

Fig.6 210 PV cell - (a) I-V curve (b) Specification (TW Solar - TW210Y212A (half-type PV cell))

There are many algorithms to achieve MPPT, the simplest way is the voltage feedback method, that is, test the maximum power point voltage under a specific light intensity in advance, and by adjusting the PV terminal voltage to achieve the maximum power point, but when the environment changes, the efficiency loss is relatively large; The most commonly used method is Perturb and observe, that is, to observe the change of PV output by changing the load and further adjust the output power to the maximum point, but this will cause power loss continuously also. Other methods such as power feedback and incremental conductance have similar ideas.

Although MPPT can be implemented in various ways, and is also called power optimizer for some applications, but from the circuit form, the adjustment mode is basically realized by Boost circuit, because it always works in the state of continuous input current without the need to add a large volume of energy storage capacitor (stable DCDC input voltage) at both ends of PV. In addition, for the DC/AC inverter of the latter stage, it can provide high stable voltage and realize high inverter efficiency. Moreover, one end of the switching FET is convenient to be driven by grounding. The PV output voltage can be controlled by adjusting the duty cycle DC% of boost conversion (Fig.7):

$$U_{pv} = V_o \cdot (1 - DC)$$

The duty cycle (DC%) reaches the lowest when PV voltage reaches $V_{oc}$ (the maximum value). And when DC% increases gradually, PV voltage moves to lower side and finally reaches the maximum power point $V_{mp}$. Generally, the output voltage of distributed photovoltaic panel array is between 60 and 300V. Considering the latter stage DC/AC inverter efficiency, it is generally required to reach 400 to 600V for micro grid-connected inverter (output 220Vac). It reaches 600-800V (typically 700V) for distributed string inverters (output may be 380Vac) and 700-1500V for centralized inverters. For 2-level, 3-level and multi-level single-phase or three-phase inverters in high-power (such as >100KW) series or centralized inverters, the input goes through combiner box and then directly inverts to the grid, so generally there is no MPPT. However, the optimized photovoltaic power generation will set the MPPT function in the current combiner box for balanced control if needed.

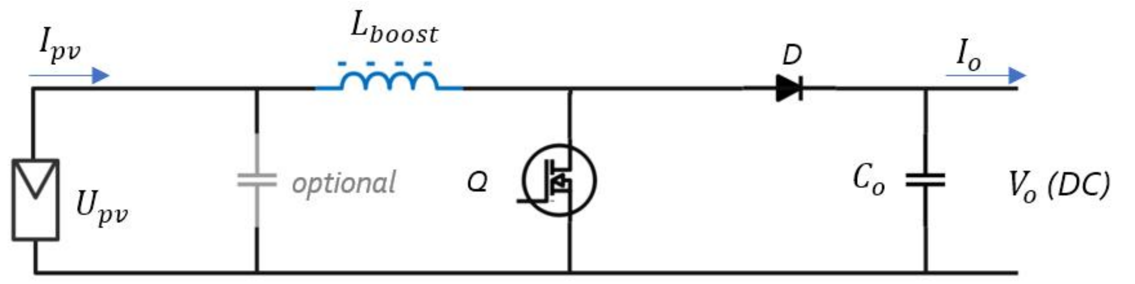



Fig.7 Equivalent Boost stage of MPPT control

The boost inductance $L_{boost}$ required by the MPPT control should meet the requirement that the converter circuit is in CCM operation (continuous inductor current mode) so that PV can work in the best state and the input bypassing capacitor can be reduced at the same time. In addition, the inductance value should be large enough to reduce the influence of switching FET-Q in MPPT control. Its value should be satisfied by:

$$L_{boost} \geq \frac{V_o \cdot DC_{min} \cdot (1 - DC_{min})^2}{2 f_{sw} \cdot I_{o\,min}}$$

Eg.1: When ignoring conversion efficiency, if the DC-link will supply inverting power of 700Vx1A, the maximum power the PV installation can support is at 700W=170Vx4.12A, switching frequency is 20KHz, if the open circuit voltage of the PV cell is Uoc=195V, then:

$$DC_{min} = 1 - \frac{U_{oc}}{V_o} = 1 - \frac{195}{700} = 72.1\%$$

The corresponding minimum inductance required is:

$$L_{boost} \geq \frac{700 \cdot 72.1\% \cdot (1 - 72.1\%)^2}{2 \cdot 20 \cdot 10^3 \cdot 1} \approx 982\ \mu H$$

The maximum inductor current is:

$$I_{L\,max} = 4.12 + \frac{1}{2} \cdot \left(\frac{170 \cdot 0.757}{20 \cdot 10^3 \cdot 982 \cdot 10^{-6}}\right) = 7.4\ A$$

The RMS value of inductor current is:

$$I_{L\,rms} = \sqrt{4.12^2 + \frac{1}{12} \cdot \left(\frac{170 \cdot 0.757}{20 \cdot 10^3 \cdot 982 \cdot 10^{-6}}\right)^2} \approx 4.53\ A$$

Accordingly, the parameters required for the boost inductor can be defined as 1mH, saturation current 9A, and temperature-rise current 7A(40K temperature rise) with appropriate margins. For the boost inductor, the maximum voltage at both ends is the higher value between $V_o - U_{pv}$ and $U_{oc}$, which is 530V and therefore can be set to 600V. For PV terminal circuits, the Category II transient overvoltage range is defined in IEC 62109-1 and is suitable for 2500Vdc transient overvoltage, so the 1.6mm clearance (eg. Pin to pin distance), needs to be met with.

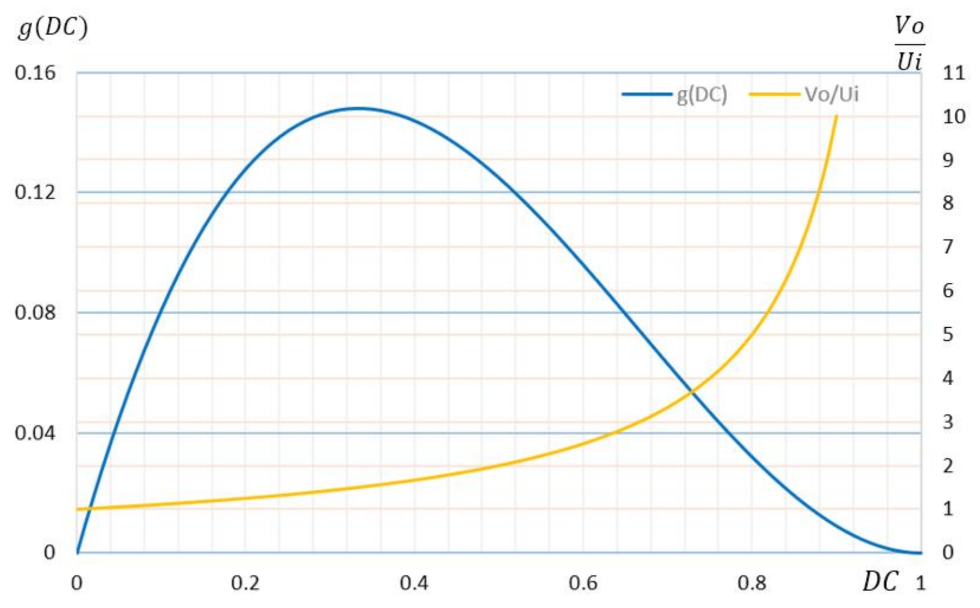



Fig.8 Inductance requirement for boost inductor and voltage gain versus Duty cycle (DC%)

The relationship between the inductance value and DC% is preset in the above minimum inductance value requirement for boost inductor, that is, determined by $g(DC) = DC \cdot (1 - DC)^2$ : the inductance value demand reaches the maximum when $DC = 1/3$, and the inductance demand decreases away from this point. Therefore, for the PV terminal MPPT, the voltage of DC Link is often twice (x2) or even several times higher than that of PV string. Accordingly, the lower the output impedance $Z_o = \frac{V_o}{I_{o\,min}}$ and the higher the switching frequency $f_{sw}$ can reduce the need for inductance. Fig.8 shows the influence of DC% on inductance requirement and its simultaneous influence on voltage gain $\frac{V_o}{U_i}$.

Because the main available switching FETs and Diode on the market are divided into three categories: MOS, SiC and GaN, and the main applicable voltage ranges are shown in Fig.9. : for micro-inverters, the optional boost topologies based on application requirements mainly include full-bridge and single-channel boost or multi-channel boost(including interleaving) which normally voltage applied up to 650V maximum; In addition, for small-to-medium power applications, isolated full-bridge Flyback or LLC topology of soft switching can also be adopted to achieve a more efficient MPPT Stage that meets safety requirements. For the requirement of string inverter medium power MPPT, single-channel boost or multi-channel boost is often adopted where voltage applied up to 1200V. For the centralized high-power inverter, the front-end MPPT is usually double boost or because been directly connected to both ends of the high voltage PV that this part is often omitted.

| Comparison between different FETs | MOSFET | SJ-FET (MOS) | SiC | GaN | IGBT |
|---|---|---|---|---|---|
| Switching freq. (KHz) | ~100 | ~500 | 20~600 | 50~20000 | ~20 |
| Rail voltage. (V) | ~60 | ~600 | 600~1000 | ~600 | 600~1500 |
| Blocking voltage. (V) | 60~150 | ~600 | 600/650/1200 | 600/650 | 650/950/1200/1500 |
| Applicable power (W) | ~x.KW | ~x.10KW | 1~x.100KW | ~10KW | 1~1MW |
| Benefit | Cost-effective | High switching freq. | Better thermal resistivity | 50% less switching loss than SiC | High volt. & low Rdson. |

Fig.9 Comparison of the applicable range of different types of switching FETs

For PV panel below 60V, because MOSFET or higher frequency switching FETs can be used, so the need for inductance value will be greatly reduced, and because the DC bus voltage is higher related to the input PV voltage, such as 400V, it in turn forces DC% rise, the result is a larger input current ripple. Therefore, this low-power MPPT or power optimizer is suitable for high current inductors usually made of flat wire or coarse-diameter round wire.

Eg.2: When ignoring conversion efficiency, if the DC-link will supply inverting power of 400Vx2A, the maximum power the PV installation can support is at 800W=60Vx13.33A， switching frequency is 100KHz， if the open circuit voltage of the PV cell is Uoc=70V, then:

$$DC_{min} = 1 - \frac{U_{oc}}{V_o} = 1 - \frac{70}{400} = 82.5\%$$

The corresponding minimum inductance required is:

$$L_{boost} \geq \frac{400 \cdot 82.5\% \cdot (1 - 82.5\%)^2}{2 \cdot 100 \cdot 10^3 \cdot 2} \approx 25.3\mu H$$

The maximum inductor current is:

$$I_{L\,max} = 13.33 + \frac{1}{2} \cdot \left(\frac{60 \cdot 0.825}{100 \cdot 10^3 \cdot 25.3 \cdot 10^{-6}}\right) = 23.11A$$

The RMS value of inductor current is:

$$I_{L\,rms} = \sqrt{13.33^2 + \frac{1}{12} \cdot \left(\frac{60 \cdot 0.825}{100 \cdot 10^3 \cdot 25.3 \cdot 10^{-6}}\right)^2} \approx 14.48A$$

When considering the inductor design and choice in a limited package size, because the ripple current ratio is:

$$\alpha\% = \frac{60 \cdot 0.825}{100 \cdot 10^3 \cdot 25.3 \cdot 10^{-6}} \cdot \frac{1}{13.33} = 147\%$$

Although the power conversion works in CCM mode, in order to reduce the hysteresis loss of the magnetic core caused by the large ripple current, the ripple ratio must be reduced by increasing the inductance value, or keeping the same inductance but put the peak point of flux density at working smaller: Therefore, in the case of DC%(optimal operating point) determined by MPPT, the optimal inductance value and current ripple ratio need to be redetermined, or increase the number of turns N and lower the permeability of core material to achieve the optimal conversion efficiency η%.

Taking Eg. 2 as an example, it is assumed that the effective cross-sectional area provided by the selected magnetic core is $A_e$ and the effective magnetic circuit length is $l_e$ . If the maximum inductor current allowable at minimum inductance is its saturation current, its maximum working flux density is:

$$B_{max} = \frac{L_{sat.} \cdot (1 + \frac{1}{2}\alpha) \cdot 13.33A}{N \cdot A_e}$$

And the minimum working flux density is:

$$B_{min.} = \frac{L \cdot (1 - \frac{1}{2}\alpha) \cdot 13.33A}{N \cdot A_e}$$

According to core loss $P_{cv}$ $(\frac{mw}{cm^3})$ curve, the core loss will be approximated as:

$$P_{cv} = K \cdot f^a \cdot B^b \;\; (f: KHz;\; B: KGauss;\; K, a, b \; provided\; by\; manufacturer)$$

$$P_{cv\,op} = P_{cv\,Bmax.} - P_{cv\,Bmin.}$$

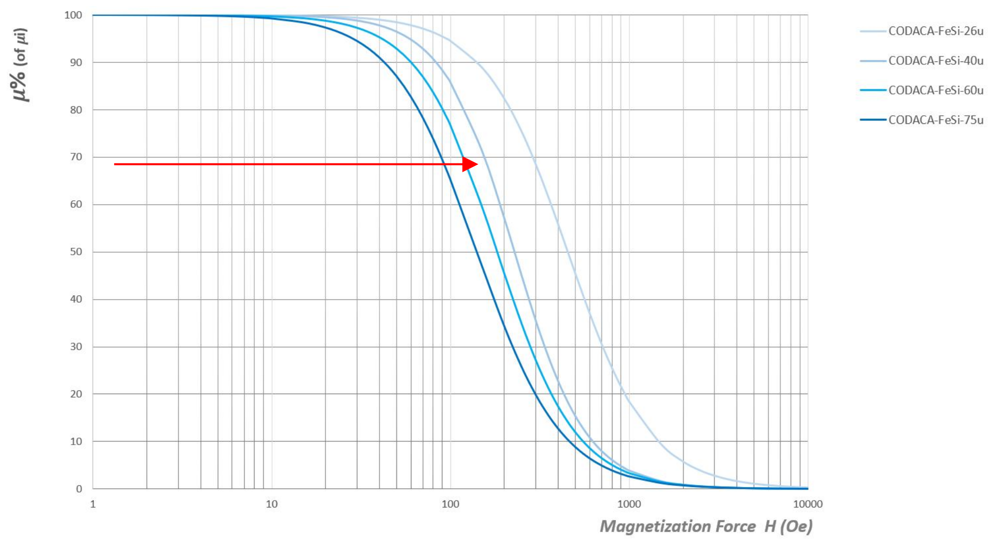
$$P_{core} = \frac{1}{2} P_{cv\,op} \cdot A_e \cdot l_e \;\; (mW)$$

Here, " the maximum inductor current allowable at minimum inductance is its saturation current ", is not always the case; but in actual working circuit it is usually not at the saturation current point in the inductor specification, when ensuring sufficient inductance value and the corresponding ripple current control within the limited range, the selection of this point is relatively simple and safe; In fact, as long as the guaranteed maximum current placed in the core material under DC Bias curve is far from its saturation point (on the corresponding permeability attenuation curve is relatively stable interval, such as the corresponding saturation current is set to the value relative to the falling 30% from initial point), just check the following relationship if it is satisfied or not:

$$H_{op}\ (\mathrm{Oersted}) \le H_{-30\%\ of\ \mu_i}$$

It is therefore more like additional design margin, that taking the maximum possible power loss for evaluation. Besides of core loss, the copper loss will be approximated with only the skin-effect been considered for preliminary evaluation:

$$P_{cu} = I_{L\,rms}{}^2 \cdot ESR$$



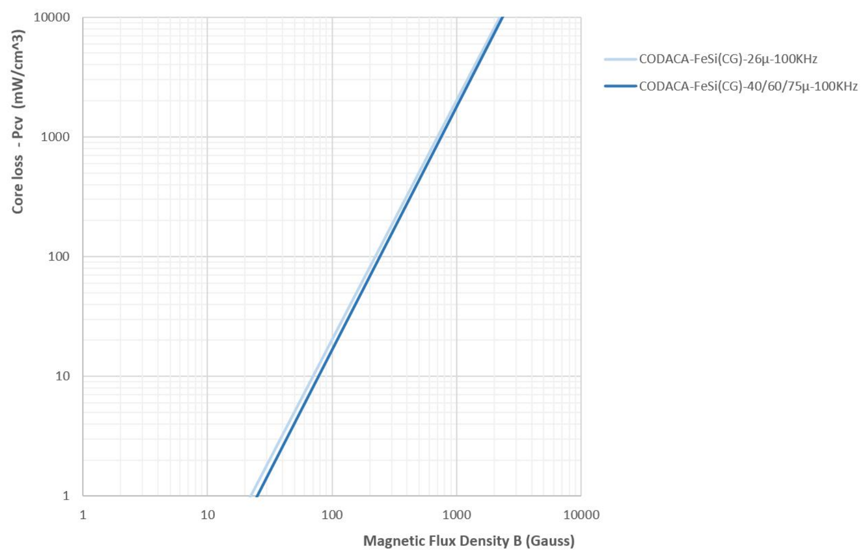




Fig.10 CODACA - FeSi powder core material: DC-bias curve and Core loss curve

Taking example of CODACA inductor CPER3231-101MC for Eg.2，its specification as below listed the key parameters with manufacturer definition:

| Part No. 型 号 | Inductance (μH) 电感值 ※1 | D.C.R. (mΩ) 直流电阻 | | Saturation current (A) 饱和电流 ※2 | Temperature rise current (A) 温升电流 ※3 |
|---|---|---|---|---|---|
| | ±20% | Typical | Max. | Typical | Typical |
| CPER3231-680MC | 68.0 | 7.70 | 9.20 | 27.0 | 28.0 |
| CPER3231-820MC | 82.0 | 8.50 | 10.2 | 25.0 | 26.0 |
| CPER3231-101MC | 100 | 9.02 | 11.0 | 23.0 | 25.0 |

■ All data is tested based on 25℃ ambient temperature.
所有数据基于环境温度 25℃条件下测试。
※1 Inductance measure condition at 100kHz, 0.1V.
电感测试条件为 100kHz, 0.1V。
※2 Saturation current：the actual value of DC current when the inductance decrease 30% of its initial value.
饱和电流：电感值下降其初始值的 30%时所加载的实际直流电流值。
※3 Temperature rise current：the actual value of DC current when the temperature rise is ΔT50℃(Ta=25℃).
温升电流：使产品温度上升到 ΔT50℃时所加载的实际直流电流值(Ta=25℃)。

The corresponding ripple current will be:

$$I_{ripple} = \frac{60 \cdot 0.825}{100 \cdot 10^{3} \cdot 100 \cdot 10^{-6}} = 4.95A$$

The maximum inductor current is:

$$I_{L\,max} = 13.33 + \frac{1}{2} \cdot (4.95) = 15.8A$$

As supposed, when inductance drops by 30% the ripple current will rise 43% and it is $4.95x1.43 = 7.07\ A$ , the corresponding maximum current will be $13.33 + \frac{7.07}{2} = 16.87\ A$. It is smaller than spec. (23A)，the above estimation could be taken as maximum loss condition. The power loss calculation follows as:

$$B_{max} = \frac{L_{sat.} \cdot (1 + \frac{1}{2}\alpha) \cdot 13.33A}{N \cdot A_e} = \frac{100 \cdot 10^{-6} \cdot 0.7 \cdot 16.87}{25.5 \cdot 1.523 \cdot 10^{-4}} = 3.04\ KGauss$$

$$B_{min.} = \frac{L \cdot (1 - \frac{1}{2}\alpha) \cdot 13.33A}{N \cdot A_e} = \frac{100 \cdot 10^{-6} \cdot 10.86}{25.5 \cdot 1.523 \cdot 10^{-4}} = 2.796\ KGauss$$

$$P_{cv\,op} = P_{cv\,Bmax.} - P_{cv\,Bmin.} = 1.79 \cdot 100^{1.5} \cdot (3.04^{2.03} - 2.796^{2.03}) \approx 2672\ mW/cm^3$$

$$P_{core} = \frac{1}{2} P_{cv\,op} \cdot A_e \cdot l_e = \frac{1}{2} \cdot 2672 \frac{mW}{cm^3} \cdot 1.523cm^2 \cdot 7.99cm = 16.26\ W$$

The RMS value of inductor current is now:

$$I_{L\,rms} = \sqrt{13.33^2 + \frac{1}{12} \cdot (4.95)^2} \approx 13.4A$$

$$P_{cu} \approx 13.4^2 \cdot 9.02 \cdot 10^{-3} \approx 1.62\ W$$

Thus, the total loss is 17.88W and the efficiency loss is approximately 2.24%. The core loss is the main type, so the efficiency optimization can be carried out by increasing the number of winding turns N and reducing the permeability of core material $\mu_r$ to reduce the swing of magnetic flux density in operation. However, as the boost ratio from 60V to 400V is a high proportion, the input current must have a large fluctuation range from the perspective of power conservation. Therefore, MPPT at the PV terminal usually loses a lot of efficiency. In order to achieve lower loss, within the limited package size, it is necessary to increase the inductance value as much as possible in order to exchange for lower ripple current amplitude. At the same time, because of the characteristics of DC-bias and the need for better materials, it is necessary to integrate both requirements to design or get the best inductor selection. In this example, the saturation current and temperature-rising current are still large, and space is left for adjusting the number of turns and permeability to meet the requirements of optimal loss: adjustments are made on the basis of existing products: increase the coil turns to N=38.5, and the permeability is reduced to maintain the same L value: (the actual available material is standard 40ur)

$$\mu_{r\,adjusted} = 90 \cdot \left(\frac{25.5}{38.5}\right)^2 = 39.5$$

The corresponding DC resistance is adjusted to approximately (based on same volume of copper):

$$R_{dc\,adjusted} = 9.02 \cdot \left(\frac{38.5}{25.5}\right)^2 = 20.6\ m\Omega$$

Adjusted power loss as below:

$$B_{max} = \frac{L_{sat.} \cdot (1 + \frac{1}{2}\alpha) \cdot 13.33A}{N \cdot A_e} = \frac{100 \cdot 10^{-6} \cdot 0.7 \cdot 16.87}{38.5 \cdot 1.523 \cdot 10^{-4}} = 2.014\ KGauss$$

$$B_{min.} = \frac{L \cdot (1 - \frac{1}{2}\alpha) \cdot 13.33A}{N \cdot A_e} = \frac{100 \cdot 10^{-6} \cdot 10.86}{38.5 \cdot 1.523 \cdot 10^{-4}} = 1.852\ KGauss$$

$$P_{cv\,op} = P_{cv\,Bmax.} - P_{cv\,Bmin.} = 1.79 \cdot 100^{1.5} \cdot (2.014^{2.03} - 1.852^{2.03}) \approx 1160\ mW/cm^3$$

Verify if the core is saturated or not:

$$H_{max.} = \frac{N \cdot I_{L\,max.}}{l_e} = \frac{38.5 \cdot 16.87 \cdot 4\pi}{7.99 \cdot 10^{-2} \cdot 10^3} \approx 102.2\ Oe$$

The core saturation can be determined by the DC-bias curve of the core, and the calculation is valid because the core has not reach saturation point. And then the power loss after adjustment is:

$$P_{core} = \frac{1}{2} P_{cv\,op} \cdot A_e \cdot l_e = \frac{1}{2} \cdot 1160\ \frac{mW}{cm^3} \cdot 1.523cm^2 \cdot 7.99cm = 7.1\ W$$

$$P_{cu} \approx 13.4^2 \cdot 20.6 \cdot 10^{-3} = 3.7\ W$$

Now the total loss is 10.8W and the efficiency loss is 1.35%. Still, based on: 1, the core is still far away from saturation point after decreasing permeability; 2. The relative ratio of copper wire loss is still not high, and the inductor can continue to optimize the loss by increasing the number of turns and decreasing the permeability. Or, leveraging the package size and go with higher inductance value.

Micro-inverter PV applications often plug in local energy storage cells to achieve optimal wave equalization of power, so the voltage of the DC bus can be adjusted according to the connected battery series, such as 12V,24V,48V or higher battery pack voltage. In such applications, the power optimizer (or MPPT) operates at a lower voltage and can be converted at a higher switching frequency, thus requiring a lower inductance, such as 4.7UH, 6.8UH,10uH,22uH, and so on. Correspondingly, since the charging power is not low, the current will be higher. Such applications generally use flat copper wire wound inductors or even molded inductors at lower power levels.

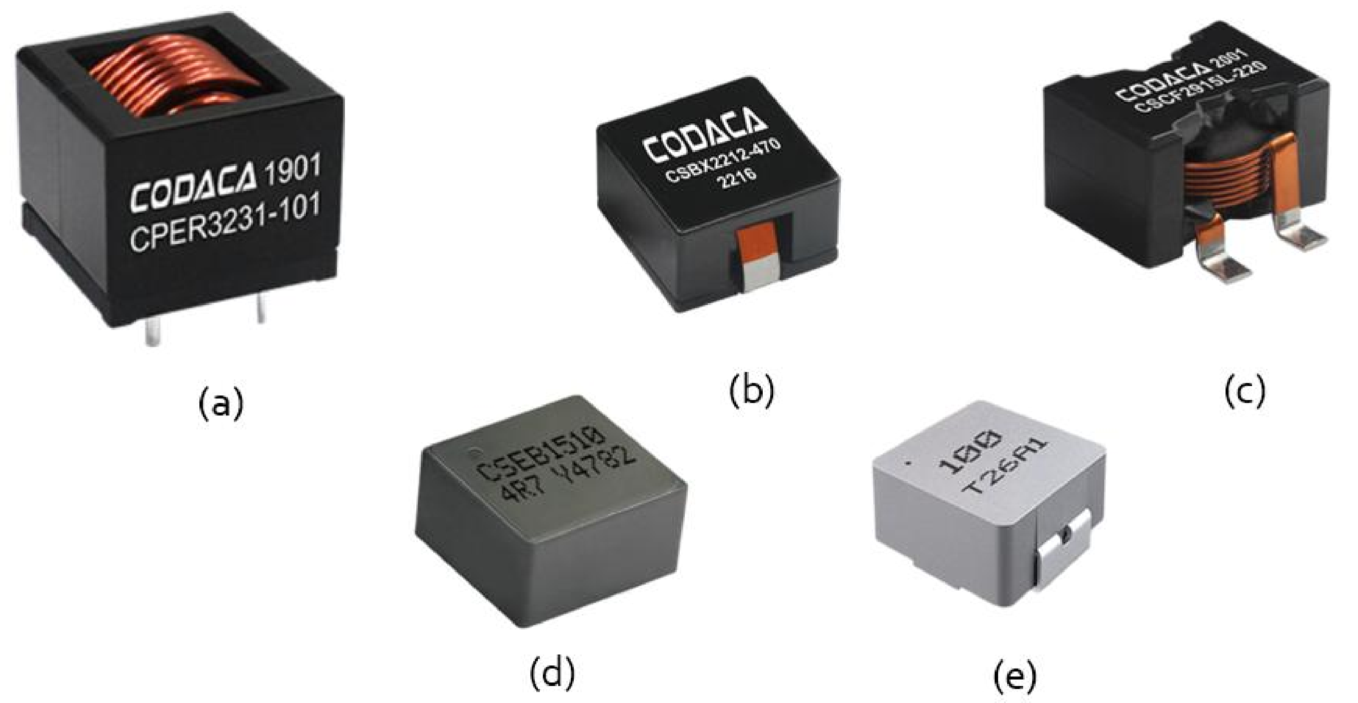



Fig.11 CODACA product series: (a) CPER (b) CSBX (c) CSCF (d) CSEB (f) CSHB

2.2 Other magnetic components in photovoltaic power generation applications

As introduced MPPT mentioned above, for the isolation of photovoltaic inverter application (micro power inverter), flyback or full bridge ZVS soft switching topology, correspondingly need design power transformer and LLC resonant inductor; and in order to reduce the power loss, the material of magnetic core selection generally will adopt MnZn ferrite (air gap), low loss core materials can also be used in some cases (such as FeSiAl, low loss FeSi cores, amorphous, etc.).

In the distributed photovoltaic applications, the voltage has reached several hundred volts or xKV, in order to drive the corresponding switch FETs, must adopt isolation in driver stage: isolators adopting the dielectric isolation is given priority to, but also this can be realized through the use of isolated transformer driver, both can meet the requirements of isolation and satisfies the requirement of system safety. The type of isolated transformer needs to be designed according to the power and gate to drain voltage level requirements of the FETs. The gate drive transformer corresponding to application is basically independently in need of to be designed separately case to case.

In the inverter phase, in order to reduce switching noise and isolate the noise path between PV power generation terminal and power grid, filter inductors with large inductance and large volume, also known as ACL, are usually configured to correspond to DCL inductors used for PV terminal input. In order to achieve a very large inductance value (low filtering frequency), silicon steel or amorphous or multi-air-gap ferrites are often used, since the cross-sectional area is also large so the overall volume is large.

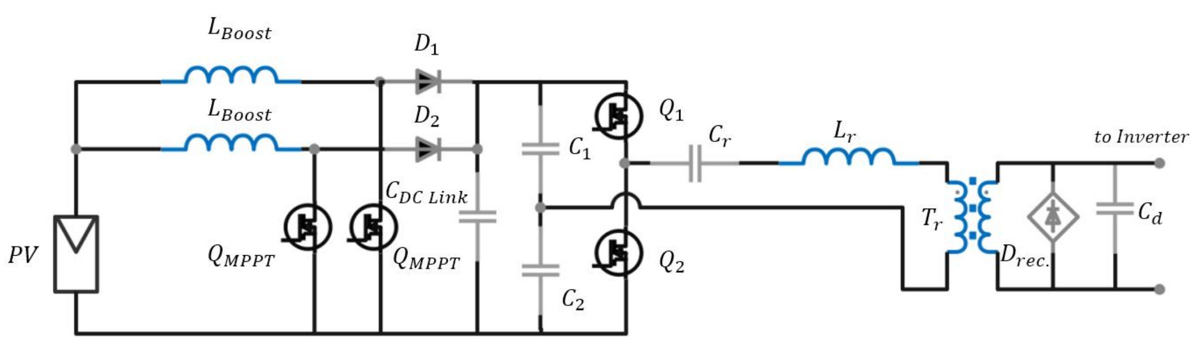



Fig.12 Interleaving boost MPPT plus half-bridge LLC resonant conversion

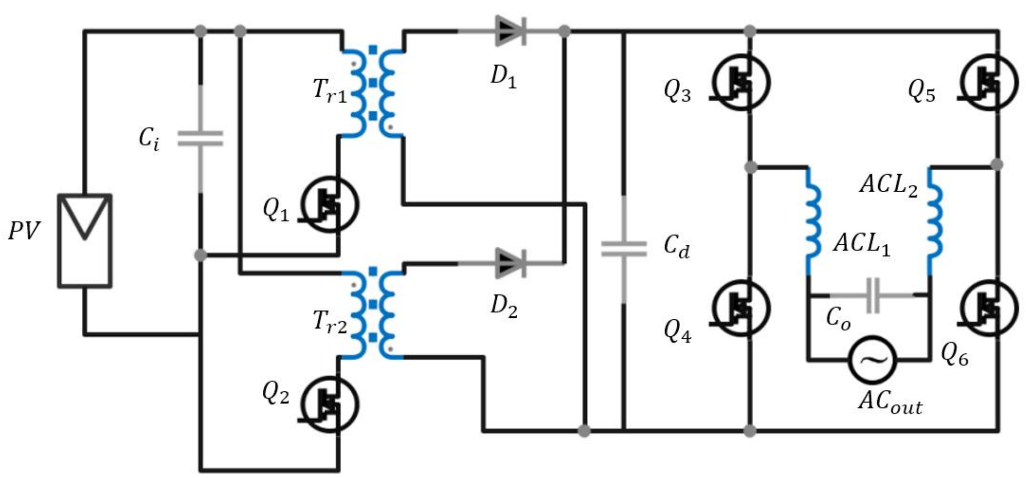



Fig.13 Full-bridge flyback MPPT plus full-bridge inverter for AC output

### 3 CODACA products introduction

Shenzhen CODACA Electronics Co., LTD. (CODACA) , founded in 2001, has been deeply engaged in the market of inductors and magnetic components, with several series of product lines represented by automotive components, high current inductors and molded inductors. In the renewable energy market, represented by photovoltaic, CODACA can provide from magnetic core material to product design, production and test of the whole process which have implementation of autonomous technology. Through continuously meeting with the needs of the customer's new technology or project demands, CODACA has received many industry customer recognition in many application fields. The provided fast delivery and flexible customization service satisfies the actual needs of customers in solar energy market well.

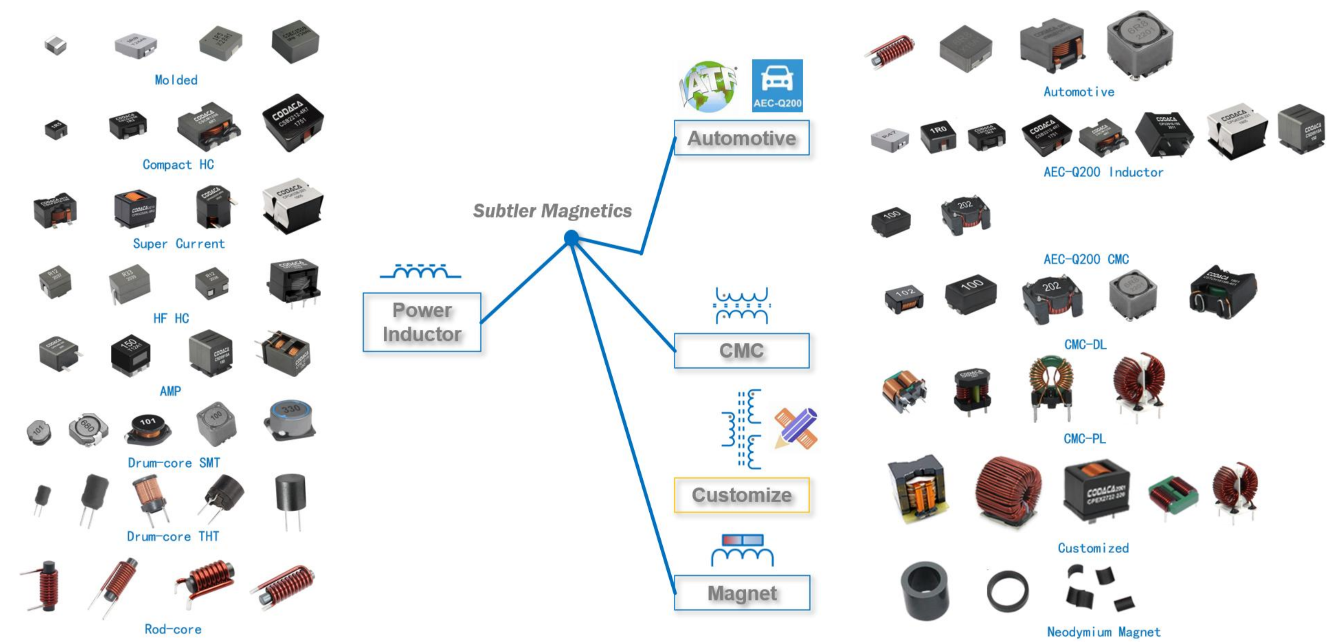



Fig.14 CODACA product lines glance（by June. 2022)

To help customers, especially in photovoltaic applications, to calculate inductor losses easily and quickly, CODACA provides online loss calculation tool as well as product comparison screening tools (www.codaca.com), as powerful support on quick estimation on inductor evaluation.

Related reference：
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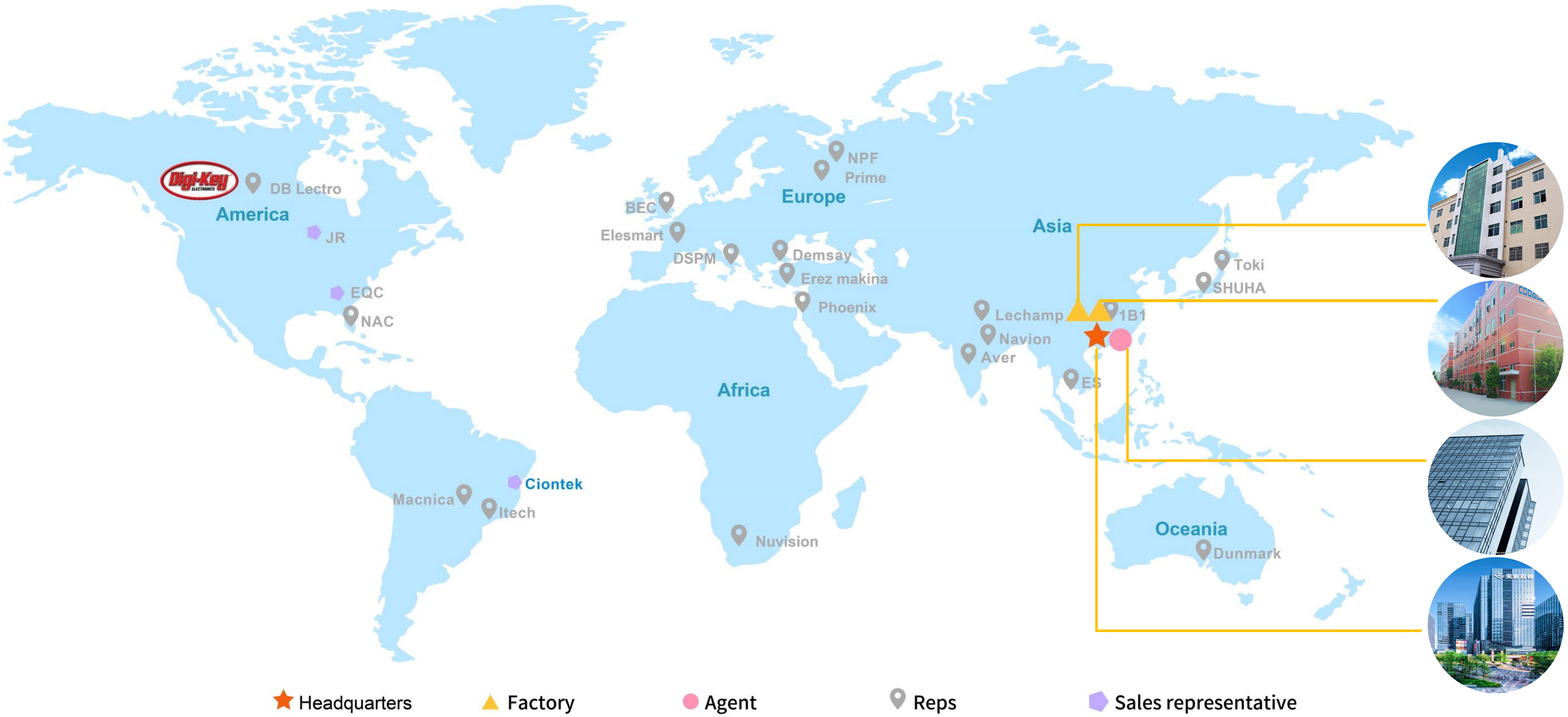


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About CODACA

CODACA has focused on developing and manufacturing quality power inductors to serve tier one global manufacturers for more than 20 years. Through material research and development, CODACA power inductors are built and certified to quickly meet specific customer requirements. CODACA supplies high quality power inductors to these markets: automotive, medical, power supply, industrial, alternative energy, digital amplifier, telecommunications, and motor control.