Principles of residential solar electrical energy systems

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ABSTRACT

Today it is increasingly common for private residences to be equipped with solar electrical energy generating systems (photovoltaic systems). This article discusses a number of technical matters for such systems.

Considerable attention is given to the matter of the *maximum power point* (MPP) of a photovoltaic panel, and the schemes and systems used to exploit it.

Also discussed is the matter of various architectures of residential solar electrical power systems.

The article also discuses the matter of *net metering* arrangements between the solar system user and the local electrical power utility.

Special arrangements for minimizing the risk to technical workers from the high voltages involved in the photovoltaic panel “strings” are also discussed.

The roles of *production metering* and *consumption metering* in these systems are also discussed.

Several appendixes elaborate on various of the topics involved.

Photos illustrating portions of a typical installed system are included.

1 INTRODUCTION

Today it is increasingly common for private residences to be equipped with solar electrical energy generating systems (photovoltaic systems). These often substantially improve the economics of the acquisition of the electrical energy upon which many of us are dependent in a big way, as well as providing significant ecological benefits to society. Today’s systems are extraordinarily complex and sophisticated. Here we will look into many aspects of their operation.

2 DISCLAIMERS

Many of the details of system operation I describe in later sections of this article are not as revealed by information from the various manufacturers, but to some degree have been imputed by logical analysis from the limited information I do have. Readers who know differently are urged to contact me.

Here and there I may refer to a certain approach as being known to me as used by a certain manufacturer of some system component. This is not in any way to be considered an endorsement of that manufacturer or their approach compared to others.

3 THE SOLAR PANEL

What is often spoken of as a *solar panel* is most specifically described as a *photovoltaic* (PV) *panel*. The term reminds us that it converts light energy into electrical energy.

4 QUANTITIES AND UNITS

4.1 Solar radiometry

The "stuff" of solar radiation, from a power standpoint, is *solar flux*. This is quite parallel to the quantity *luminous flux*, which we encounter in illumination design, photography, and the like, except the latter is defined in terms of the response of the human visual system to the "light", whereas solar flux is defined in terms of the actual power contained. Not surprisingly, then, solar flux is denominated in the unit <u>watt</u> (W).

The "potency" of solar radiation arriving at a certain spot is its *solar flux density*, which is the amount of solar flux passing across a unit area of a hypothetical plane perpendicular to the direction of propagation of the solar radiation at the point. The SI unit of this is the <u>watt per square meter</u> (W/m^2).

The "impact" of solar radiation on an actual surface (for example, on the receptive surface of a PV panel) is quantified as the *[solar] irradiance* (the qualifier "solar" often being omitted when the context is clear). It is also defined in terms of power per unit area, the "unit area" now being reckoned on the actual receiving surface (rather than the arbitrary hypothetical surface involved in the definition of solar flux density). The SI unit again is the <u>watt per square meter</u> (W/m^2).

Just as in the wholly parallel situation in photometry, the irradiance is the flux density times the cosine of the angle between the direction of arrival of the solar radiation and the "normal to the surface" (a line perpendicular to the surface).

4.2 Energy and power

Power in physics (electrical or otherwise) is the time rate of flow of *energy*. Conversely, *energy* is the time integral of *power*.

The SI unit of energy is the joule (J), and the SI unit of power is the watt (W). A joule is one watt-second; a watt is one joule per second.

In dealing with electrical energy and power in the context of electrical service, the unit of power is still the watt, of course with the various SI prefixes used, a common one leading to the unit kilowatt (kW). And the unit of energy usually used in this context is the watt hour (wH), again with SI prefixes used where appropriate, often leading to the unit kilowatt hour (kWh). One kilowatt hour is precisely 3.6 megajoules.

5 PV PANEL CURRENT, VOLTAGE, AND POWER

5.1 Open-circuit voltage and short-circuit current

For a given PV panel, receiving a certain irradiance, if we draw no current from it, it will exhibit a certain voltage at its output terminals. Since we would have this situation if in fact the output terminals were just open-circuited, that "zero current" voltage is often spoken of as the *open-circuit voltage* (V_{OC}).

If we then begin to draw current from the panel, the output voltage will decrease, although not necessarily in a proportional way. The limit of this is for a current so great that the voltage declines to zero.

We could actually produce that situation by short-circuiting the output terminals (in which case the voltage would necessarily be zero). Because of that, the current would result in zero voltage is often spoken of as the *short-circuit current* (I_{SC}).

Of course, at intermediate values of current the voltage takes on intermediate values, and we can plot this relationship (typically as current *vs* voltage, I *vs*. V, and usually called a "V-I" plot). Remember that a certain plot pertains to a certain panel operating under a certain solar irradiance, E.

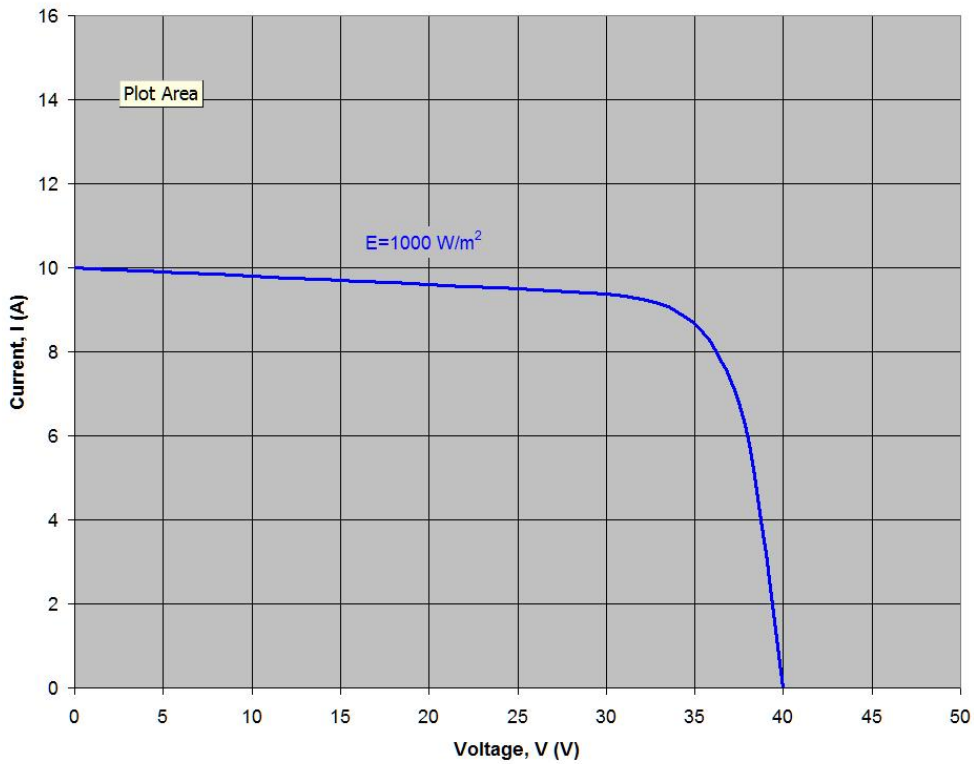

Figure 1. Hypothetical PV panel

Figure 1 shows a plot of the current vs. voltage for a hypothetical panel at an assumed irradiance, E, of 1000 W/m^2. This curve is artificially generated but evocative of the curves for actual panels of the type I am assuming. We note that it is far from a linear relationship.

5.2 Power

Of course, for operation at any given current (and the resulting voltage), the power being delivered by the panel is the product of the current and the voltage.

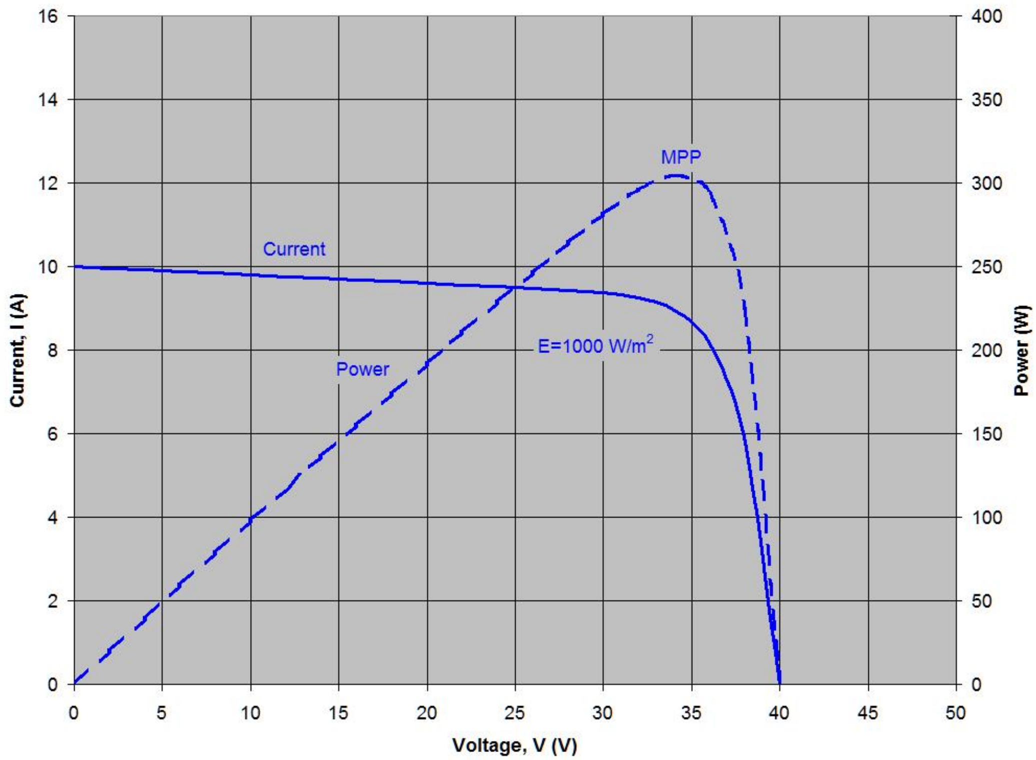

Figure 2. Hypothetical PV panel

On Figure 2, we also see the curve of power vs. voltage (the dashed curve) for the hypothetical panel discussed just above).

Not surprisingly, the power is zero for the situation of zero current (and thus maximum voltage), or for the situation of zero voltage (and thus maximum current). In both those situations the product of voltage and current is zero (since one of the factors is zero). But the output power is at a maximum for a situation between those extremes, at a certain voltage and the current that leads to. That operating point is called the *maximum power point* (MPP).

Of course, if this same panel received a lesser irradiance, E, than was assumed for that graph (perhaps 500 W/m^2), there will be another current vs. voltage curve, and thus another power vs. voltage curve.

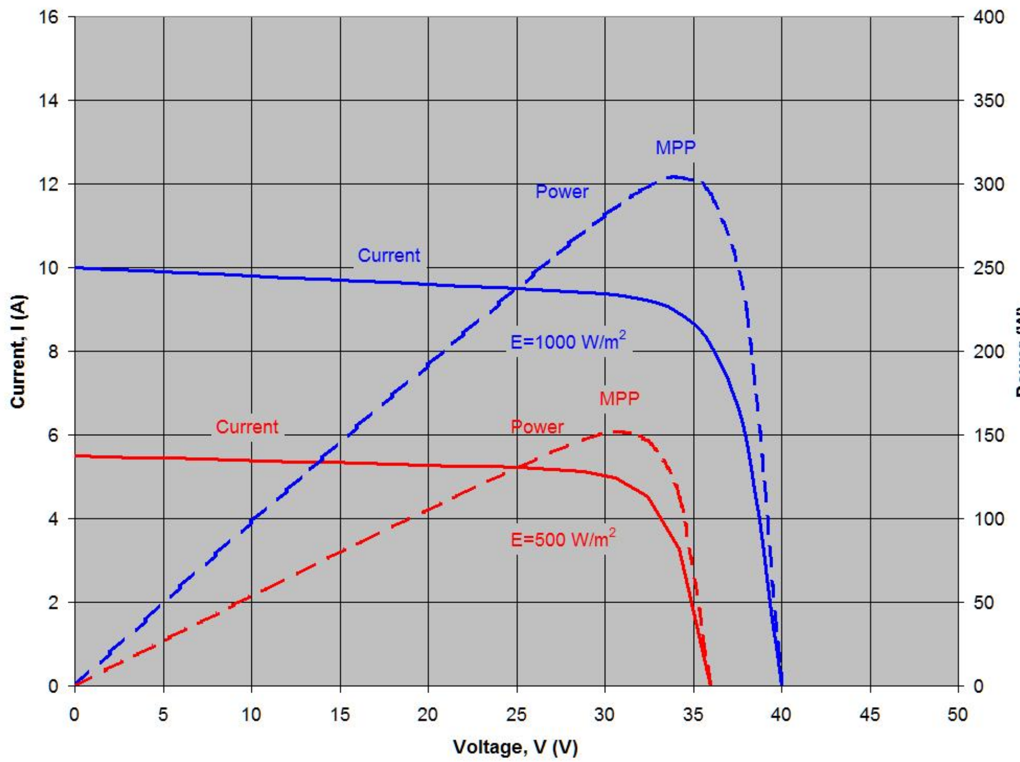

Figure 3. Hypothetical PV panel—two irradiance values

We see those added to our graph in Figure 3. For each irradiance, the power curve is the dashed one.

Not surprisingly, the maximum power is less than for the original (greater) irradiance, and it occurs at a lower current (and a slightly lower voltage)..

Here I have arbitrarily made the ratio between the two maximum powers the same as the ratio between the two irradiances. As we will see later, this linear relationship between irradiance and maximum power does not usually exactly occur in practice, but it is handy for our purposes here.

6 FOR AN ACTUAL COMMERCIAL PANEL

Figure 4 shows the current *vs*. voltage and power *vs*. voltage curves for different solar irradiation levels for an actual commercial PV panel, as published by its manufacturer (JinkoSolar).

This shows, as I had earlier suggested, that in this real panel the maximum power output is not linear with the solar irradiance level.

For example, at an irradiance of 200 W/m^2, the maximum power output is about 70 W, whereas at an irradiance of 1000 W/m^2 (5 times as much) the maximum power output is about 390 W (about

5.6 times as much). This can be thought of as the energy conversion efficiency of the panel being greater at larger irradiance values.

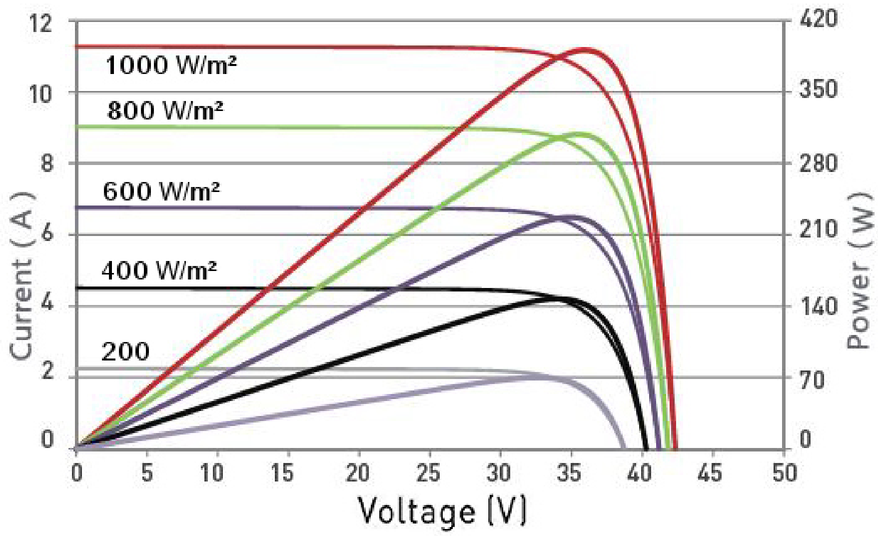

Figure 4. JinkoSolar Eagle "390 W" PV panel—V-I and V-P curves

Often the "nameplate" power output rating of a panel ("390 W", for this one) is the maximum power generated for a solar irradiance of 1000 W/m^2 and a temperature of the panel cells of 25ºC[1] (the maximum power output typically varies with that temperature).

Note also that for this panel, for lower irradiance the maximum power point occurs for a very slightly lower voltage.

[1] This irradiance and cell temperature are often used as reference test conditions.

7 SYSTEM ARCHITECTURE AND OPERATION

7.1 Typical "little" system

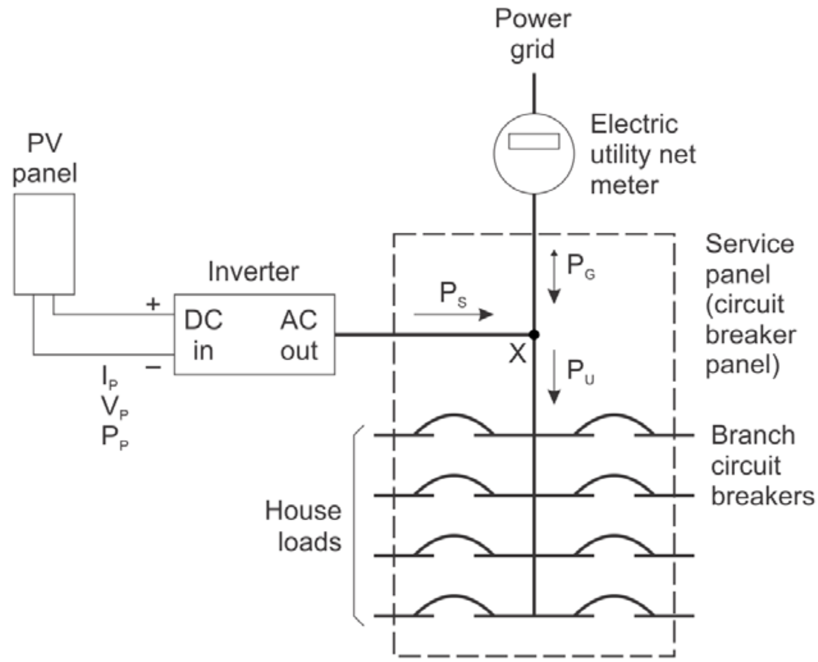

Figure 5. Typical "little" system block diagram

Figure 5 shows a simplified block diagram for a typical "little" residential solar energy installation.

In almost all actual installations, there will actually be several PV panels, but to allow one aspect of system operation to be most clearly seen, I have shown a system with a single panel. I have also simplified here some details of the service panel (circuit breaker panel); the omitted details are not pivotal to the discussion here. Note that here the convention on the AC side of the inverter is "single-line drawing", where one line represents an entire electrical circuit, actually comprising two (or in this case often three) conductors.

The inverter takes DC power from the PV panel, with a voltage of perhaps 5-40 V, and converts it to 120/240 V AC, with its frequency and phase locked to that of the voltage of the grid. Modern inverters do this with efficiencies of typically over 99%.

This figure has symbols for the DC current, voltage, and power at the DC input to the inverter, and various powers on the AC side, even though here we will not in general be working with actual numerical values for these quantities.

From here on, I will assume an inverter efficiency of 100%, so I can speak of its input power and output power as being the same, this simplifying some of the narrative.

The inverter can vary the ratio between its DC input voltage and its AC output voltage as required for it to play its role in the complex drama I am about to describe.

Normally the inverter input will draw from the panel the current that corresponds to the MPP of the panel (at its present irradiance; I will mostly omit this parenthetical reminder from here on), so the DC power taken from the panel is the maximum it can create under the present solar irradiance.

Under our assumed inverter efficiency of 100%, that will also be the AC power delivered by the inverter, here designated P_S (the "S" being evocative of "solar"), which is fed to point "X". The power being used by the house loads at the moment is P_U ("U" for "usage"). The power being extracted, at the moment, from the power grid is designated P_G. We can see that P_G must equal $P_U - P_S$.

I noted earlier that P_S is normally always the maximum that can be created from the incident solar energy on the panel at the moment, not dependent on the present usage by the house. Thus, at some times P_S will be greater than P_U, and then P_G will be negative, which implies the flow of power back into the grid.

Note that the arrows show the "positive" direction convention for current flow, and do not necessary imply that the flow will always be in that direction. But in this case, only for P_G can the power flow actually be in either direction. I have put a little arrowhead on the tail of the P_G arrow as a reminder of that.

Note that I have labeled the familiar power utility watthour meter as the "net" meter to reflect the implications of this situation (as will be discussed next).

7.2 The "net metering" plan

7.2.1 *Introduction and the utility meter*

I discuss here a today-common arrangement with the homeowner's power utility company that is often described as "net metering".[2]

This scheme depends on the utility meter being truly bidirectional; that is, it runs either forward or backward, depending on the instantaneous direction of energy flow, in both cases at the correct "count": 1 per kWh of energy.

[2] Note that various other arrangements may be found in practice. (See also section 7.2.5.)

Note that the traditional electromechanical watthour meter would, conceptually, fulfill this requirement, but for technical reasons its "constant" is usually not identical for forward and reverse "counting" to the accuracy required of meters that govern the price charged for energy. Thus in almost all modern solar installations, the utility meter must be of the modern electronic type which can be precisely calibrated for both directions of "count".

7.2.2 *System block diagram, simplified*

In Figure 6, I have simplified the entire system so we can concentrate on the matters of this section.

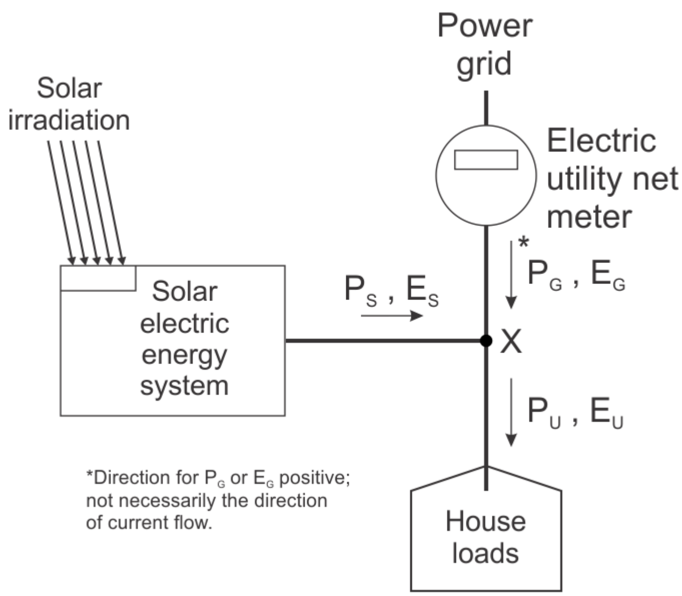

Figure 6.

As we already saw in Figure 5, the icon for the utility meter I use here is meant to evoke an "electronic/digital" one, with a digital display, rather than the traditional electromechanical kind (most commonly with a "dial register").

I have followed the prior notation regarding the different powers (P): the subscript "S" for the power from the solar energy system, "U" for the power used by the home, and "G" for the power to or from the power grid.

But here, I have accompanied the labeling of each flow arrow with an "E" quantity, for the *energy* involved over some period of time, as it is energy that we will be accounting for in the discussion to follow. In fact, here the period of interest will be the electric utility company billing period, typically approximately one month in duration.

The arrows indicate the convention for the values of P and E being positive; it does not necessarily indicate that the flow of power/energy is always in that physical direction. But I chose those positive directions so that for P_D and P_U those values will inevitably be positive, and P_U would be positive for the direction of flow absent a solar energy system.

Given the assigned conventions, the equations for power flow "to" infamous point "X" are:

$$P_S - P_U + P_G = 0 \qquad (1)$$

which we can rewrite as:

$$P_G = P_U - P_S \qquad (2)$$

That is, if at some instant, the power delivered by the solar energy system is greater than the power being then used by the load in the home, P_G will be negative; that is, the flow of power then will be into the grid. (So I had to use algebra for that?)

for energy:

$$E_S - E_U + E_G = 0 \qquad (3)$$

which we can rewrite as:

$$E_G = E_U - E_S \qquad (4)$$

That is, for let's say a certain utility billing period, the energy delivered by the solar energy system is greater than the energy used by the load in the home, E_G will be negative; that is, the net flow of energy for that period will be into the grid. And it that net flow of energy that is shown by the *meter increment* (the change of the reading at the end of the period against the reading at the beginning). The unit, by the way, is the kilowatt hour (kWh).

7.2.3 *The net metering plan*

In the specific plan I discuss here, if during any billing period the meter increment is **positive** (the net energy flow over that period of energy is **from** the grid), the consumer is charged for that amount of energy according to the regular rate schedule.

If the meter increment is **negative** (there was a "net export" of energy **to** the grid for the period), that amount is in effect "banked" for the customer (on a kWh, not dollar, basis), and (hopefully) will be returned in later billing periods as "free energy" from the grid.

For the billing period, the consumption will first be considered to be from that "free energy".

If the total net consumption from the grid that period is greater than the total that was "in the bank", the remainder is charged for under the regular rate schedule just as if that was the whole consumption for the month. Any amount "left in the bank" after this reckoning remains there for future use.

Given this scheme, it is to the benefit of the customer to have the solar energy system develop as much power as it can at each moment (which of course depends on the irradiance at the moment). Ideally, all the energy generated by the PV panels will all be "used" in the home, now or later, directly or indirectly.

7.2.4 *The "revenue meter" or "billing meter"*

Often the watthour meter I describe as the "net meter" may be spoken of as the "revenue meter" or the "billing meter". It is distinct from another watthour meter we will hear of later.

7.2.5 *Caveat lector*

The reader is cautioned that often the plans offered by an electrical utility that are spoken of as "net metering" plans might differ in important ways from what I described above. Discussions of those differences or of totally different plans is beyond the scope of this article.

7.3 Operation at MPP–how do it know[3]

Back to the MPP. How does the inverter know what the current is for the MPP for the panel under the present irradiance on the panel (whatever that is)? Many different techniques are used, but most are variations on the following theme.

Every so often, the inverter temporarily decreases the current it is taking from the panel by a small amount. It notes the new voltage, calculates the new power, and if that is less than the power before this maneuver, decides that the MPP is not at a lower current. So then it temporarily makes the current drawn slightly greater than before that maneuver, and again sees if the power is greater. If it is, it performs this latter maneuver again, until it finds a point at which a small increase in the current drawn reduces the power.

So then it knows that the current drawn just before this last maneuver puts the system at the present MPP of the panel.

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[3] Apologies to the Thermos bottle in the famous gag line.

Of course, since the irradiance is usually continually changing, the inverter repeats this scenario frequently.

This overall strategy of the inverter is sometimes described as *power optimization*.

7.4 Multi-panel systems

In almost any real system of appreciable size, there are several panels, often connected together (usually in series) in a "string". In Figure 7, we see such a system in its simplest form.

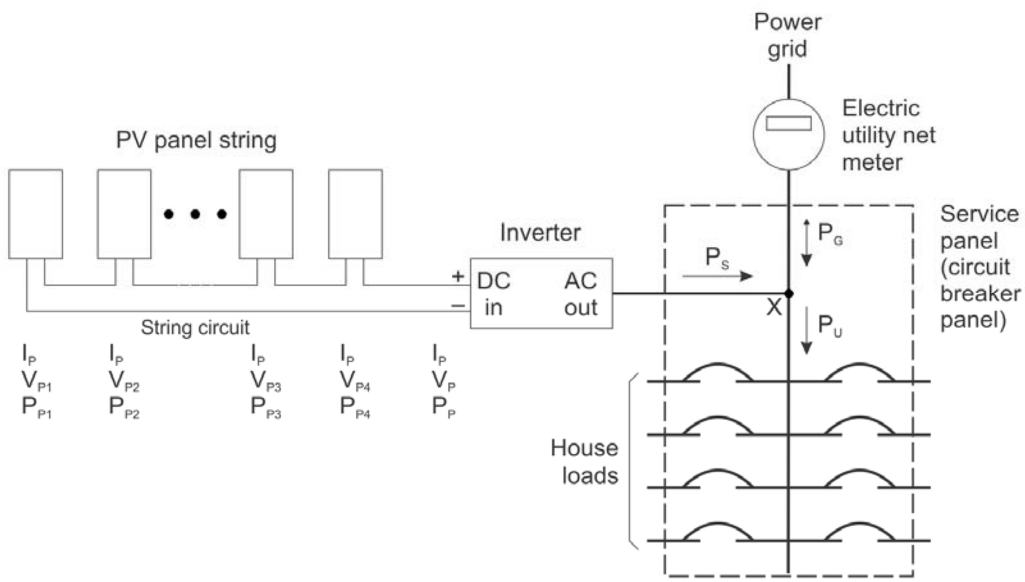

Figure 7. Multi-panel string system

We will assume for the moment that all the panels are identical (and thus have identical V-I curves for any irradiance), and that all receive the same irradiance at any moment. Since the current is, by definition, the same in all the panels (they being connected in series), at the current that operates one of them at its MPP, all the others will be at their MPPs.

So if the inverter searches for the MPP as previously described, the current that it finally decides to draw will put all the panels in the MPP condition, and thus the entire string will be made to deliver the maximum power available under the current irradiance.[4]

Note that in a typical residential system, the string voltage (V_P) can reach 700-1000 V. Thus great care must be taken to avoid electrical hazards to persons working on a system.

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[4] Subject to the fact that the inverter limits this process to its rated output power.

7.5 A fly in the ointment

But in reality, those assumptions may not all be met. Even if all the panels are of the same model, their V-I curves may not be exactly identical. In some cases (perhaps based on architectural constraints), different sizes of panels may be included in the overall arsenal. Architectural constraints may dictate that some panels are mounted pointing in a different orientation. And if there is any shading by trees (true in many cases), not all the panels will be equally shaded at a given moment. Thus, at any instant, even identical panels will receive different irradiances, and thus their V-I curves will be different, and in turn their MPP points will be different.

If we operate such a "real" system as suggested in Figure 7, whatever current the inverter decides is appropriate to draw from the string will not necessarily operate all the panels at their individual MPPs. Some will be delivering less than they might be able to at the moment. Thus the overall string will not deliver the total power of which it is potentially capable at the present irradiance situation.

7.6 Power optimizers

7.6.1 *Per panel*

There are several techniques used to overcome this situation. One class of scheme involves an accessory circuit often called a *power optimizer* [5], and in fact, one popular plan uses one of those with each panel.[6] We see this arrangement in Figure 8.

[5] These are sometimes spoken of as "MPLE", for *module level power electronics*.

[6] This approach is used, for example, in solar power systems revolving around inverters and power optimizers made by SolarEdge.

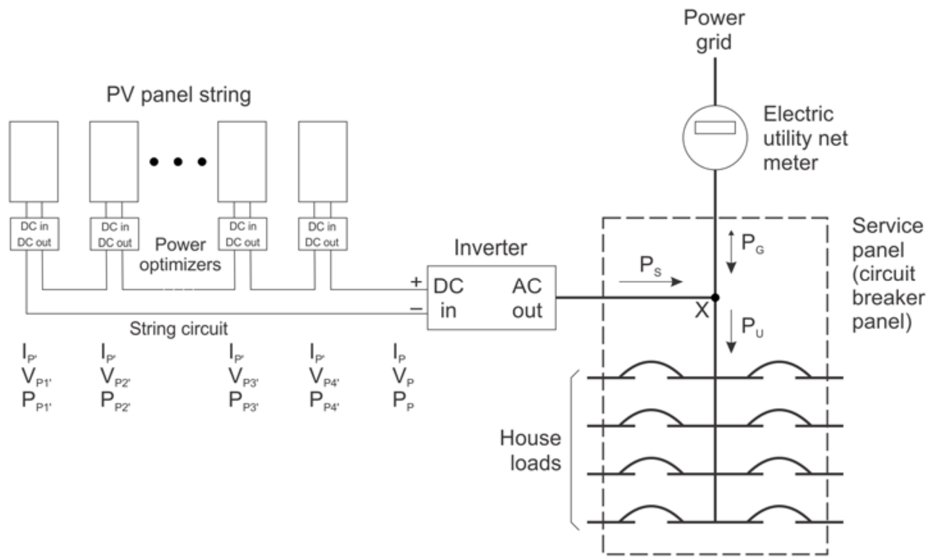

Figure 8. Per-panel power optimizers

The power optimizers are DC-to-DC converters[7]. They can take a DC input voltage at a value over a fairly wide range and convert it to a DC output voltage at a different voltage, also over a fairly wide range. They typically do this with an efficiency of about 99% (but, here, as for the inverter, I will assume they have efficiency of 100%, as it makes the discussion simpler).

For each panel, its power optimizer will arrange its input to draw from the panel the current that operates the panel at its MPP for its present illuminance. (It probably figures this out the same way the inverter did as described in section 7.3.) That means that the power extracted from the panel by its optimizer is the greatest power the panel can deliver under its current irradiance. And of course, the optimizer must get rid of that power into the string circuit. We'll see shortly how that happens.

The power optimizers use in the system seen in Figure 8 are typically quite small (perhaps about 6″ × 5″ × 1.25″), and are often mounted by way of a bracket on the frame of the associated PV panel.

7.6.2 *How does all this work?*

In one scheme[8], the inverter DC input is operated a constant voltage, that having been determined by the designers of that inverter[9]. That is

[7] Often of the "buck-boost" type.

[8] Used in inverters and power optimizers made by SolarEdge, and likely by the systems of other manufacturers as well. The details described here are the author's elaboration of a description given by SolarEdge.

likely the voltage at which the inverter is most efficient (at least at higher power throughputs), but limited to the highest voltage (perhaps less than that ideal) considered safe from a personal and equipment safety standpoint.

In any case, the inverter, as to its DC input side, is that rarity in electrical engineering theory, a *constant voltage sink*.

The inverter actually accomplishes this behavior by, at any instant, controlling the current drawn from the input circuit until the circuit voltage is that target voltage.

As mentioned just above, each of the optimizers, as to its input side, determines the MPP of the associated panel, and draws from the panel the corresponding current. The output voltage of the panel will then be the one associated with the MPP. That panel current and voltage together define the power drawn from the panel by the optimizer input (which is the maximum power that panel can deliver under the present illuminance).

The optimizer has to "get rid of" that power through its output into the string circuit. The current through that circuit is that which the inverter is drawing to cause the string voltage to be the established value. The optimizer knows it must generate the output voltage that, combined with the observed current in the string circuit (which it cannot directly control), will make the power delivered into the string circuit the amount that the optimizer must "get rid of".

Of course, as an individual optimizer changes its output voltage so as to arrange for the output of the needed power, that will change the total string voltage, which, as seen by the inverter, will no longer be the target value established for the inverter input. So the inverter will change its current draw from the string circuit until the string voltage is again the established value.

This change in string circuit current causes every power optimizer to reconsider the voltage it needs to develop so it "gets rid of" the power it is drawing from the panel (which it does in accordance with the present MPP for the panel).

And of course the resulting change in the string voltage causes the inverter to again change its current draw from the string circuit to bring the string voltage back to the established value. And then all the optimizers will again have to rework their situation of disposing, into

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[9] In one series of inverters made by SolarEdge, that value is 380 V.

the string circuit, of the amount of power available from the associated panel. But that will. . ..

By virtue of appropriate algorithms in the inverter and in the power optimizers[10], this "circular sounding" situation will in fact converge on a steady state in which the string circuit current is such that, when all optimizers generate the output voltage they must to dispose of the power they draw from the associated panel (at that string current), all those voltages add up to the established inverter input voltage–an amazing ""dance".

Thus this system will, at any given moment, extract from the cadre of panels all the power they are collectively able to generate at the moment, while operating the inverter at the desired input voltage. As we saw earlier, this is the most desirable overall situation, economically, for the user.

Appendix A, using a "fanciful" model of system operation, gives further insight into the inner workings of this "dance"

7.6.3 *Panel-to-ground voltage*

Commonly, the power optimizers are not "isolating". That is, one of the output terminals and one of the input terminals are essentially in common.

As a consequence, the voltage to ground of either panel output terminal, and either power optimizer output terminal, will depend on where that panel and its power optimizer are in the string circuit and the distribution of power optimizer output voltages along the string circuit.

Those voltages can be quite high. Accordingly, the cell array proper within the panel must be insulated from the panel metal frame (customarily grounded for safety) with insulation able to withstand a quite high voltage across it. (The specifications for a solar PV panel often specify that this insulation is suitable for a voltage-to-ground of up to a certain limit. A limit of 1000 V is common for that.)

7.6.4 *Per substring power optimizers*

If the overall array of panels can be divided into *substrings*, each comprising nominally identical panels, of identical orientation, and unshaded, so that they all have the same irradiance at any moment, a

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[10] The collaboration between the two algorithms is quite tricky, and at the present time (late 2023) essentially requires that the inverter and power optimizers have been designed and made by the same entity.

single power optimizer may be used for each substring rather than using one per panel). We see this in Figure 9.

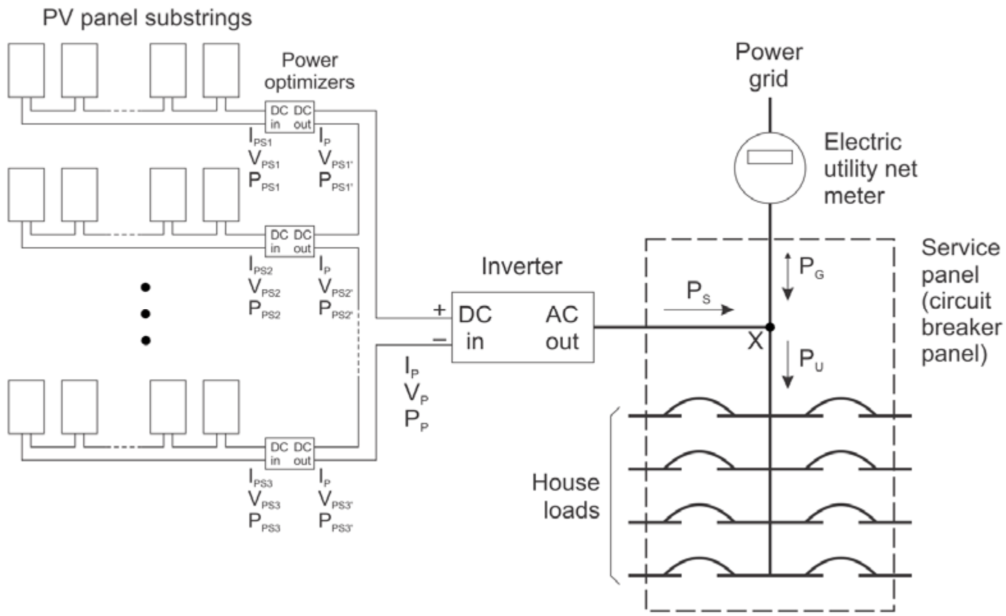

Figure 9. Per substring power optimizers

The overall concept and operation are essentially the same as described above for a per-panel application of power optimizers. Each substring essentially behaves as a single panel, and when that "panel" is operated at its apparent MPP, all the constituent panels will be operating at their individual MPPs.

7.6.5 *Safety in "shut down", and then "restart"*

Note that the development of an output voltage by a solar panel string is essentially beyond our control (if we exclude the possibility of putting an opaque blanket over each panel in the system). Thus, even if we were to shut down the inverter, we would still possibly have high (and thus dangerous) voltages to ground along the panel string.

But, typically in modern systems using this scheme, if the inverter DC input circuit is disconnected (by a "DC safety disconnect switch"), the string circuit current perforce becomes zero, regardless of what output voltages the various power optimizers try to develop. All the power optimizers recognize this zero current situation, and go into a mode in which they only develop a voltage of perhaps one volt each. (We will see shortly why this is not zero volts.) We might then shut the inverter down for some kind of maintenance.

Thus the total voltage on the string circuit is now very low (and thus the voltage-to-ground of any panel terminals is very low), making it safe for a technician to, for example, check the connections or even replace a power optimizer or an entire panel.

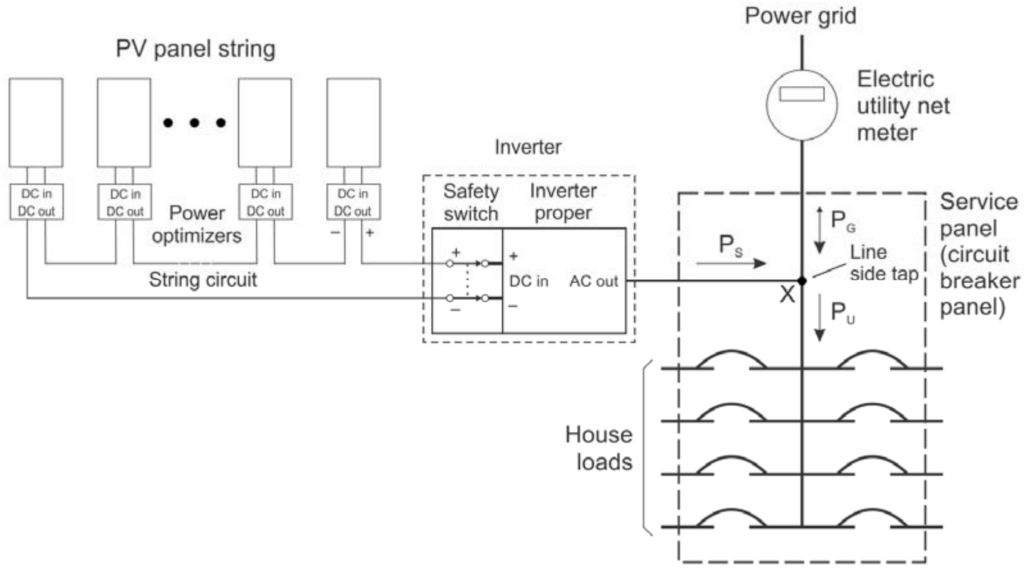

Figure 10.

In Figure 10 I explicitly show the DC safety disconnect switch (just "safety switch" on the figure, for conciseness).

When the work is finished, and the inverter is turned back on, if it was off, and the DC safety switch closed, the inverter input circuit at first exhibits an arbitrary low constant current mode. The small voltage from each power optimizer, added up along the string, causes a current to flow in the string circuit into the inverter DC input. This informs the power optimizers that the panel string is back "on the air", and they resume their normal behavior, seeking the equilibrium discussed earlier.

Of course, as this process proceeds, the inverter follows its normal instinct (to ultimately become a "constant voltage sink") so as to properly participate as the host for that equilibrium "dance" among all the power optimizers as the system settles into a steady state.

Note that, for some manufacturers, when a DC safety switch is involved, the term "inverter" means a factory-assembled unit comprising both what I call the *inverter proper* and the *safety switch*. In many of the figures to follow, I will show this "greater inverter" just as one box.

7.6.6 *In the night season*

Typically, at night, the maximum power output of all the PV panels in a system is negligible. Thus the scenarios described above cannot really be followed, and the system in effect goes into a "night mode". The inverter generates no AC output power, and consumes just a few watts of AC from the grid to keep its circuitry operating, awaiting the dawn. Startup then follows essentially the scenario described in section 7.6.5 for restart after a period of inverter shutdown.

7.6.7 *Multiple strings*

As mentioned earlier, for larger systems (with many PV panels), the string voltage could reach perhaps 700-1000 V. This can be undesirable, not only from a personnel and equipment safety standpoint but also requiring that the solid-state components in the inverter be suitable for operation at such voltages.

As a consequence, the arrangement seen in Figure 11 is quite common in medium to large size residential solar energy systems.

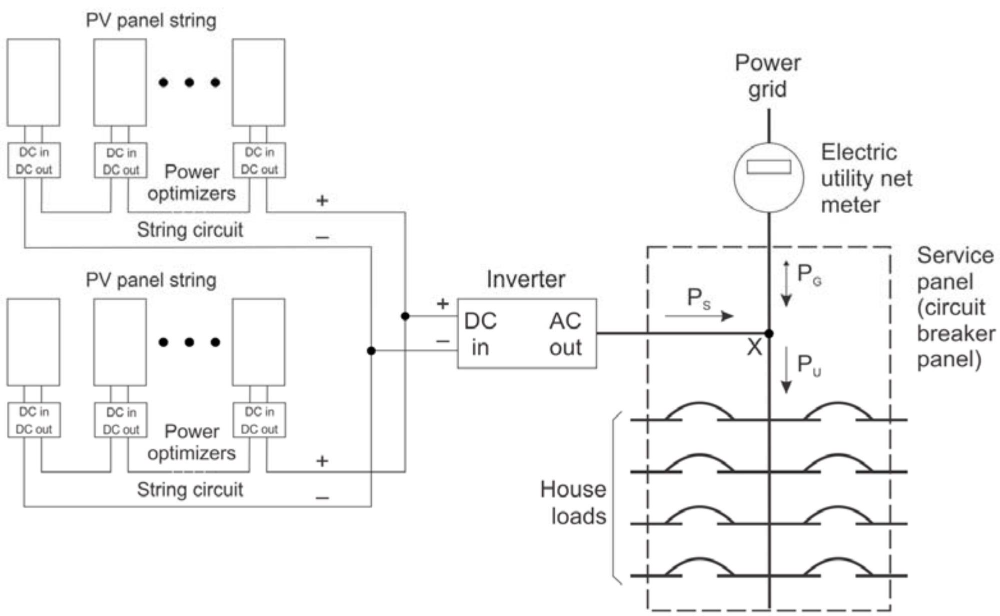

Figure 11. Multiple strings

Here the two string circuits are connected in parallel (sometimes physically at the DC input terminal strips in the inverter).

The intricate “dance” described earlier between the power optimizers and the inverter is able to be successfully performed in this configuration.

The key is that the inverter is a “constant voltage sink”. Thus each string circuit sees a constant voltage destination, and the “dance” as the power optimzers on the string manage to settle into an appropriate equilibrium for the delivery, into the string circuit, of the total power generated by their panels proceeds just as described earlier.

In a common inverter family[11], in the case of inverters rated at a maximum output power of 10 kW or greater, as many as three strings can be connected in parallel, two springs for inverters with lower output power ratings.

7.7 Micro inverters

An alternate approach uses a *micro inverter* per panel. We see the concept, in an simple form, in Figure12.

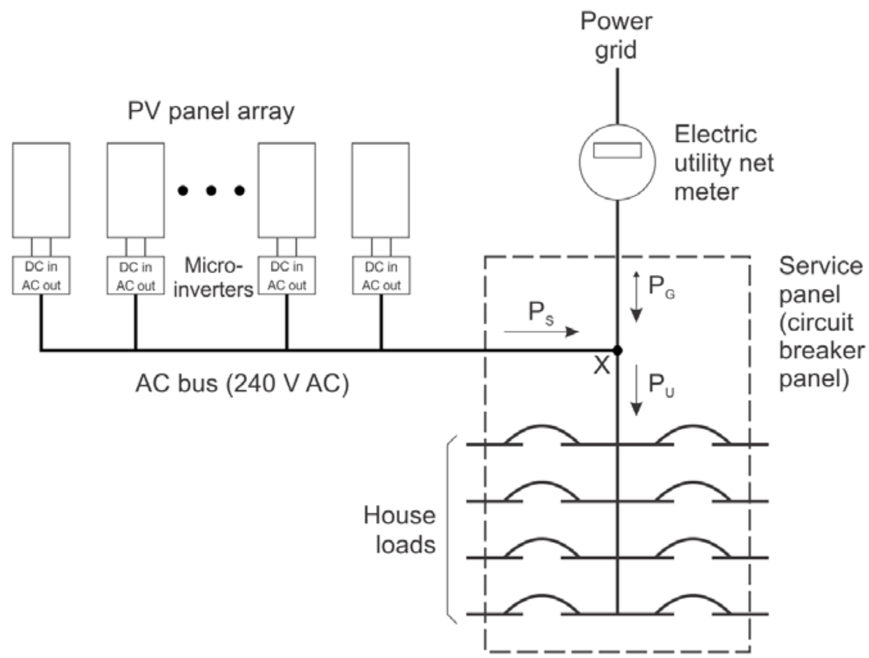

Figure 12. Micro inverter system

The AC outputs of the micro inverters (240 V AC) are connected in parallel to the AC bus.

The inverters all act to follow the frequency and phase cues given by connection to the grid, and deliver the available energy (at the time) from their panel, transformed to AC, into the bus[12].

Each micro inverter, like the system-wide inverter discussed in section 7.4, performs the power optimizer function, in this case on behalf of its own panel.

The mediation between (a) the 2-wire 240 V AC circuit developed by the solar system and (b) the 3-wire 120/240 V AC circuit on which the residence power distribution is predicated is actually done by the

[11] Made by SolarEdge

[12] Up to the power output rating of the micro inverter.

secondary of the power utility distribution transformer (not even seen on this figure). [13]

The further details of operation of this system are beyond the scope of this article.

8 OTHER FEATURES

8.1 Production meter

As briefly mentioned earlier, it is often important for various reasons for the power utility involved in a residential solar electrical power system to know accurately the total amount of electrical energy **generated** by the solar system during each utility billing period.

This is often the role of a separate *production mete*r included in the system. This matter is discussed in some detail in Appendix B.

8.2 The consumption meter

It is often of interest to know, on a more or less real time basis, the actual consumption of electrical energy by the host home. This is often the role of a separate *consumption mete*ring subsystem included in the system. This matter is discussed in some detail in Appendix C.

8.3 Reality at the circuit breaker panel

In much of this article I have given that item short shrift to the circuit breaker panel, generally portraying it in an illustrative way since its details are not the main story here.

But the realities of that area can have a significant impact on the topology and construction of the solar energy system. In Appendix D I discuss some of these realities and the way they may be accommodated in a real solar energy system.

9 A WHOLE SYSTEM

Appendix E shows the overall block diagram of a perfectly-realistic system residential solar electrical energy system that incorporates almost all the features described in this article. It also shows photos of the important parts of a real solar energy system.

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[13] It actually has always performed that same function with regard to, at any time, the imbalance of loads on the two 120 V “sides” of the house distribution system.

Appendix A
The "dance" of the power optimizers and the inverter

A.1 INTRODUCTION

In section 7.6.2, I discussed the amazing "dance" by which the power optimzers and the inverter interact to produce a situation in which each power optimizer delivers to the string circuit (and thus to the inverter DC input) the maximum power that can be, at the moment, extracted from the associated PV panel, in such a way that all the power optimizer output voltages add up to the voltage at which the inverter prefers to operated.

This all happens without the players conspiring over a separate data channel or such.

In reality, the maximum output of any panel does not change "instantaneously", and the overall transition to the eventual new steady state involves many iterations of tiny changes in the various voltages and current. But it can be hard to visualize just how this works.

In this appendix, I will give a fanciful description of this dance, to lend insight into how it works.[14] In this description, I will assume that, at some instant, the maximum output of one panel changes instantaneously. I then will adopt the conceit that, when some action has changed some electrical value, the system does not at first, overall, completely react to it, but rather reacts in separable steps. I will separately describe these fanciful "steps" This will be rather a "stop motion cartoon" description of what, in reality, is a smooth overall process of convergence to a new operating state.

I will assume, for convenience, that the power optimizers and the inverter both operate with 100% efficiency (and that is not very far from the typical reality).

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[14] The details described here are the author's elaboration of a description given by SolarEdge. There is no guarantee that these details are exactly correct.

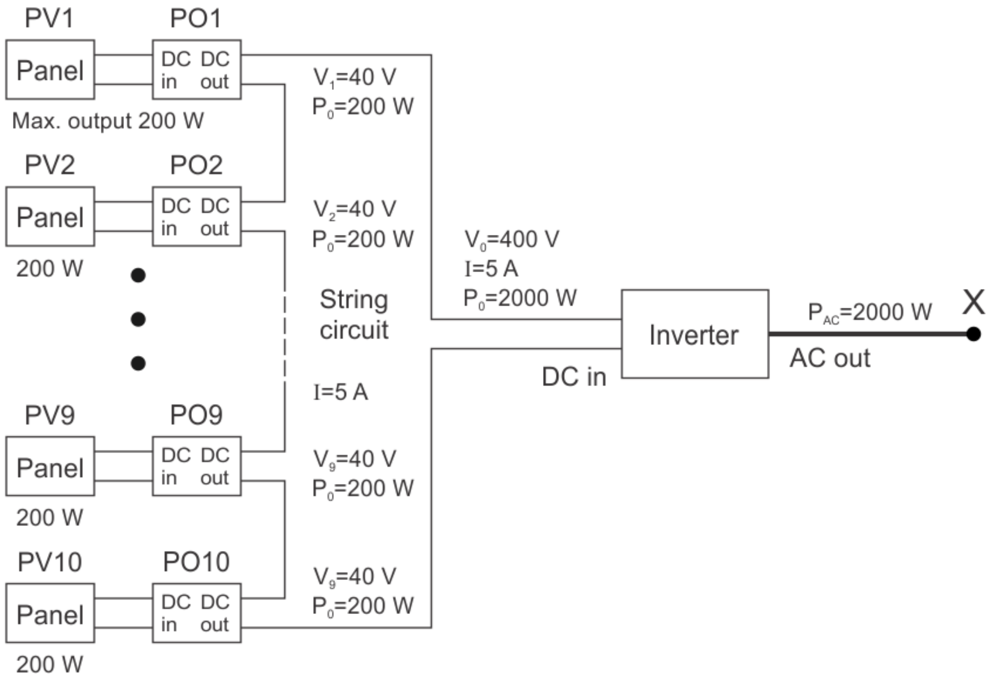

Figure 13. Hypothetical system—Initial steady state

A.2 THE PLAYERS

A.2.1 General

Figure 13 shows the system whose operation I will describe. It comprises 10 identical solar PV panels, each with a power optimizer (PO- on the figure). The power optimizer outputs are connected in series to form the string circuit, which goes to the inverter DC input. The inverter AC output goes to point "X", the node shared by the house loads and the path to the power grid.

On this figure are also shown the symbols for the electrical quantities of interest (I hope that the notation is self-explanatory).

A.2.2 The inverter's constant input voltage

As initially mentioned in section 7.6.2, in this scheme, the inverter aspires to (with the collaboration of the power optimizers) manage the entire ensemble so that, in steady state, its input voltage is a fixed value, chosen by the designers.

In this example, we assume that to be 400 V (within the range of the values commonly seen).

A.3 THE DANCE

A.3.1 Initial conditions

We assume that we encounter the system in a stable steady state. Do not yet try and imagine how it attained that; it is this matter we will pursue here. Figure 13 shows the electrical values in that state.

We assume that at the initial moment all PV panels receive equal solar irradiance and thus could deliver identical output power (at the right balance of voltage and current). We assume that output power to be 200 W for each panel, a total of 2000 W for the entire array (P_0).

We assume that this model of inverter prefers a DC input voltage of 400 V (in the general range of values seemingly used today), and in fact we find that in effect in the initial conditions.

Since we have assumed a total power optimizer output of 2000 W, the input current to the inverter (the current in the string circuit), I, must be 5 A.

And of course, we assume that the AC output power of the inverter, P_{AC}, led to point "X", is also 2000 W.

Since the current I is 5 A, then at the output of each power optimizer, where the power being delivered to the inverter input circuit is assumed to be 200 W, the output voltage must be 40 V.

Again, we do not (yet) know how the inverter and its chorus of POs collaborated to bring this about. That happened before we got there.

A.3.2 About the inverter

Strategically, the inverter aspires to have its DC input voltage at 400 V. Tactically, it tries to bring this about by controlling the current it draws from its DC input circuit. It is that oddity in electrical engineering theory, a **constant voltage sink**.

But in this fanciful presentation, I will assume that, at any instant, the inverter is a **constant current sink**, but where that current value is manipulated by a "hand" in the inverter so that, over any longer (albeit still miniscule) time interval the inverter input actually behaves as a constant voltage sink.

A.3.3 A perturbation to the system

Now suppose that somehow (perhaps a tiny passing cloud), at a certain instance, the solar irradiance on panel 9 **instantaneously** drops by 25% so that the potential power output of the panel drops from 200 W to 150 W (suggested by the shading on the panel icon). Note that the total potential power output of the overall array is now 1950 W.

In response, PO9, as to its input side, adjusts the current it draws from the panel to cause the operating point of the panel to be the maximum power point for this new irradiance. That maximum power turns out to be, of course, 150 W.

On its output side, PO9, considering the present value of the current in the string circuit (5 A) to be "string circuit current of the moment", changes its output voltage (to 30 V) so as to deliver to the circuit that power: 150 W.

The string voltage (presented to the inverter DC input) is now 390 V, and of course the inverter notes that.

Momentarily, the current in the inverter DC input circuit does not change (for the reason described in section A.3.2), and so the power into the inverter is now 1950 W (as we know is must be). And of course the inverter notes that.

We see the system. frozen in that "stage" of the process, in Figure 14. In this figure, and those to follow, I show in bold all electrical values that changed since the immediately prior figure.

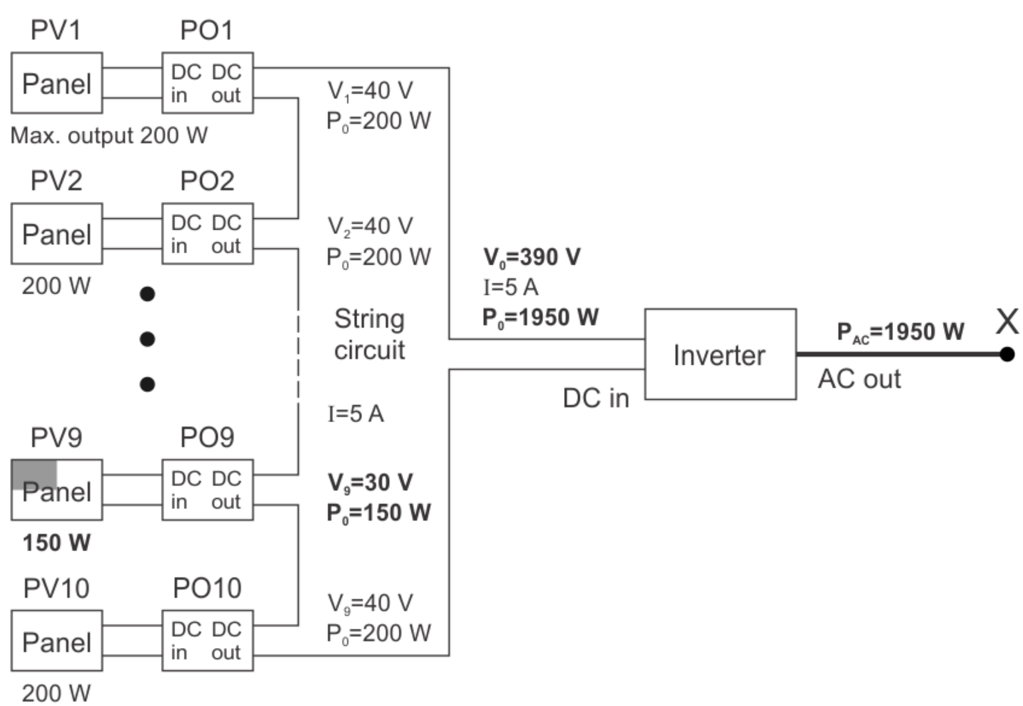

Figure 14. Panel 9 output drops, PO9 responds

The inverter, however, prefers that its input voltage be 400 V. It knows that the present joint output of the string is 1950 W

(5 A × 390 V), but at the desired input voltage of 400 V that would require a current of 4.875 A.

So the inverter sets its constant current mechanism to draw 4.875 A from the DC input circuit.

We see the system, frozen in that "stage" of the process, in Figure 15.

Momentarily (as we assume in our "stop motion cartoon" scenario), the output voltages of the POs do not change, and so with the new circuit current (0.875 A), their output power contributions decrease, as seen. The result would be, for the instant, a total DC input power to the inverter of about 1901 W.

Note that, for this instant, the power taken from each panel is less than its "potential" under the current solar irradiation.

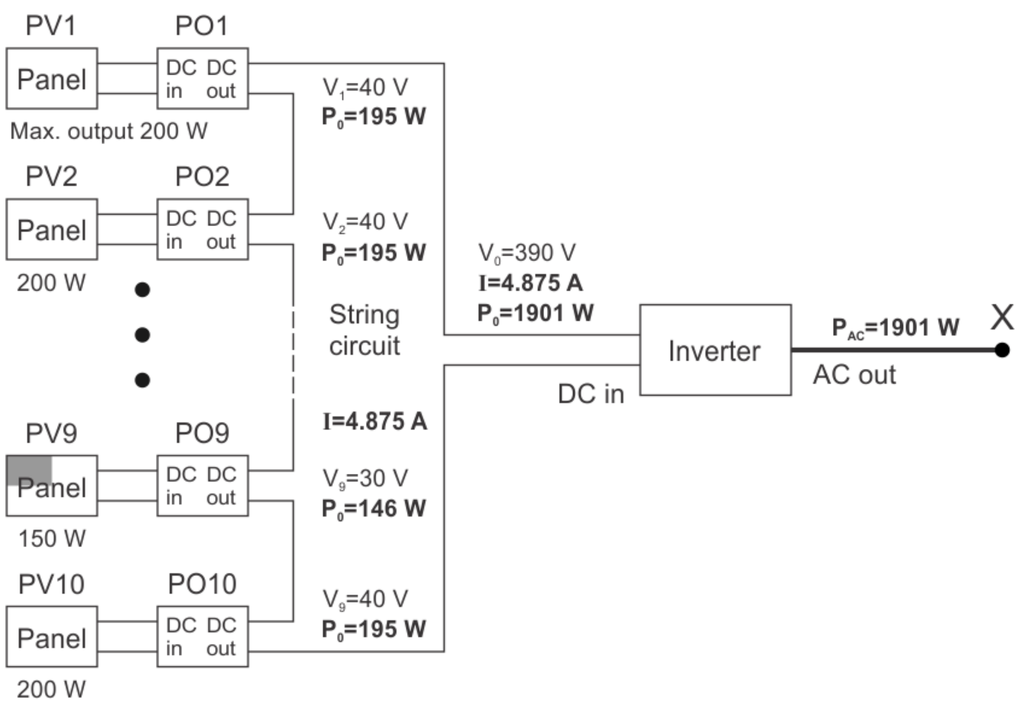

Figure 15. Inverter responds

We can follow the immediately subsequent activity on Figure 16.

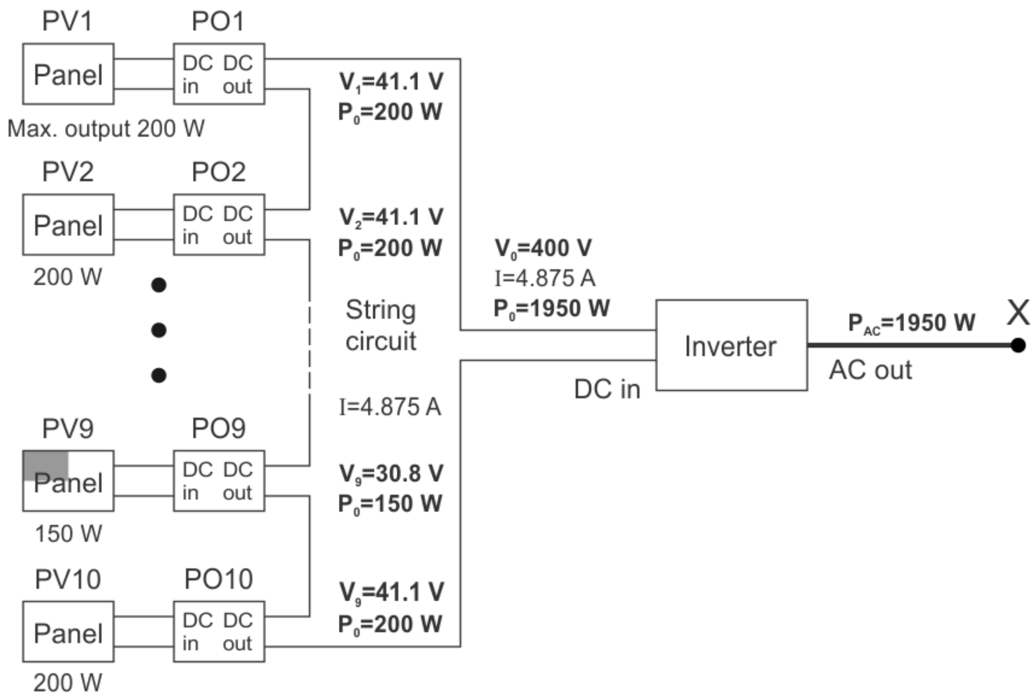

Figure 16. The final situation

At POs 1-8 and 10, which have each been enjoying a power of 200 W from their panels, they see that evidently 4.875 A is the new "string circuit current of the moment". So they each change their output voltage to about 41.1 V, so as to resume delivering that power into the circuit.

At PO9, which is has been enjoying a power of 150 W from its panel, it sees that evidently 4.875 A is the new "current of the moment". So it changes its output voltage to about 30.8 V, so as to resume delivering that power into the circuit.

The total circuit voltage (the sum of all 10 power optimizer output voltages) is now 400 V, just what the inverter wants,. (The individual voltage values I stated were rounded, but the precise values add up to 400 V exactly.)

The inverter continues to draw 4.875 A from the circuit, at 400 V, an input power of 1950 W (just as we know it has to be).

The system has attained a new steady state, each panel delivering to the process its maximum available power, and the inverter input operating at the voltage its designer wants it to. The "dance" is complete.

A.4 WITH MULTIPLE STRINGS

I noted in section 7.6.7 that in an installation of moderate size the panels may be gathered into two (or even three) strings, the string circuits all connected in parallel to the inverter DC input.

It might at first seem that this would somehow scramble the “dance” I described in this appendix. But keep in mind that, notwithstanding my fanciful description of the inverter DC input being, momentarily, a constant current sink, in the larger scheme of things it is in overall a constant voltage sink.

Thus, each of the string circuits is forced (in steady state) to operate at a constant voltage (just as for the single string in my description above), and in each string, its operation is just as described above.

A.5 WRAP-UP

Note again that this certainly does not really occur in the discrete steps of our “stop motion cartoon”. In reality, even if the output of one panel drops “suddenly” (not likely in reality), the response probably involves many iterative steps among the players. But the concepts are as I described them here.

And of course, it was though this same process that the system came to attain the steady state situation in which we found it.

Quod erat demonstrandum.

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Appendix B
The production meter

B.1 PRODUCTION METERING

Various considerations, including certain "tariff" arrangements between a homeowner with a solar energy system and his serving electric utility, and various incentives to the power utility used to promote the movement toward the greater use of renewable energy, (explanation of all of which is well beyond the scope of this article) lead to the need to accurately measure the amount of electrical energy "produced" by a residential solar energy system (the time integral of P_S in the figures above) in a utility billing period.

This quantity cannot be ascertained from the indications of the regular utility meter, since the energy usage by the home (the time integral of P_U), a term in the energy equation, is not measured.

B.2 THE PRODUCTION METER

The direct way to obtain this quantity is with a dedicated *production meter*, which might well be a watthour meter much like the utility meter. And in fact such is often used. In many cases, this meter itself actually belongs to the power utility.

Note that, unlike the main ("net") utility meter in this scenario, the production meter is only required to "run forward", and thus might be of a less elaborate type than the utility meter proper.

Modern solar energy system inverters include extensive provisions for measuring, collecting, and reporting data on their operations. These almost inevitably include provisions for totting up the total AC energy they have "produced" over some period.

But various regulations often prescribe that the determination of the energy produced be done by what is called in the industry a "revenue grade meter" (RGM). This essentially means a watthour meter whose certifiable accuracy would qualify it for use in measuring energy being sold by an electric utility company.[15] (The "utility net meter" shown on many if the figures above is perforce an RGM.)

However, the basic energy measuring mechanisms in many inverters, though doubtless quite accurate, have not been certified to the RGM standard, and so reporting based on that is not acceptable to the "agencies" involved. And in any case, the power utility may feel that

[15] This is wholly parallel to the scales used in butcher shops to weigh meat being sold, which often must be certified as "for use in trade".

this needs to be done with a meter "under their control". Thus the need for a free-standing production meter (of the RGM class) provided by the utility company.

In Figure 17 we see a system with such a production meter. In the interest of simplicity of the illustration, the entire string (PV panels and their respective power optimizers) is shown as a simple rectangle.

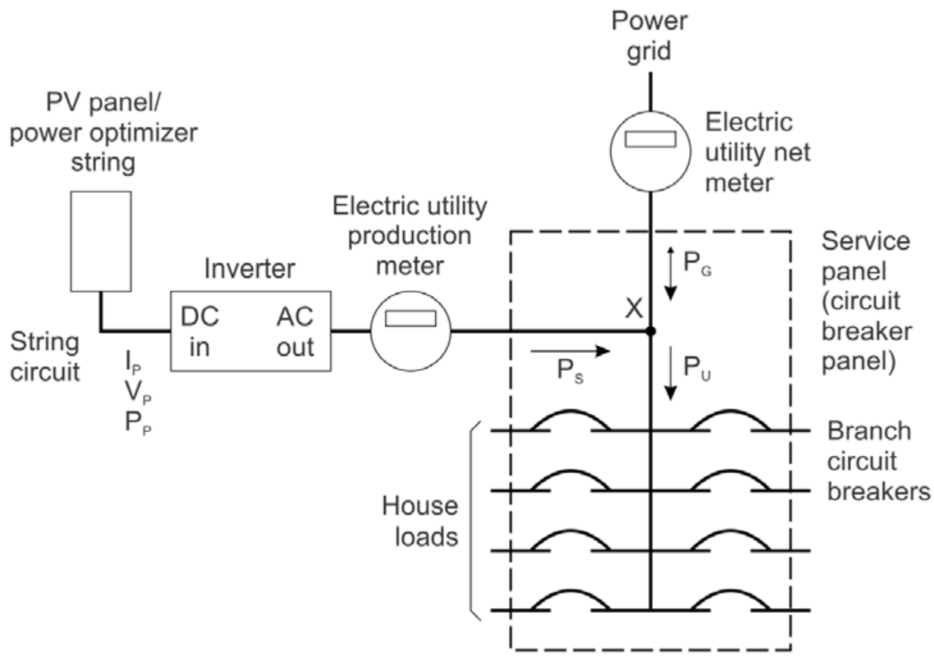

Figure 17. Production meter

I note that, especially when a production meter is present, the power utility meter I call the *net meter* may be spoken of in the literature as the *revenue meter* to distinguish it from the *production meter*. Still, when "labels" are put on the various ingredients of a solar energy system, the net meter will often be labeled "net meter".

B.3 ALSO KNOWN AS

The production meter is sometimes designated the "REC meter". "REC" stands for Renewable Energy Credit, one of the incentives given to the operator of a solar energy system, and which would be reckoned from the total energy production of the system as recorded by this meter.

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Appendix C
Consumption metering

C.1 INTRODUCTION

It is often of interest in a residential solar electrical energy system to know just how much energy is being used (consumed) by the residence.

The homeowner can possibly ascertain this, on a billing period (nominally monthly) basis from the utility bill, which will probably show the net energy import/export for the period and might show the reading of the production meter as well. The difference is of necessity the energy consumed during the billing period.

Even if the utility bill does not report the reading of the (utility-owned) production meter, the inverter will certainly, on its own, tot up that value, and if the homeowner has made provision to read data from the inverter on his computer or smartphone, he can get the **production** value that way, and make the determination.

But the homeowner may wish to know the **consumption** information on a finer-grained basis than monthly. Thus it is valuable to know the power consumption on a real-time basis. This is the role of a consumption metering capability of a solar electrical energy system.

C.2 ILLUSTRATIVE IMPLEMENTATION

The implications on system topology for an illustrative system are seen in Figure 18.

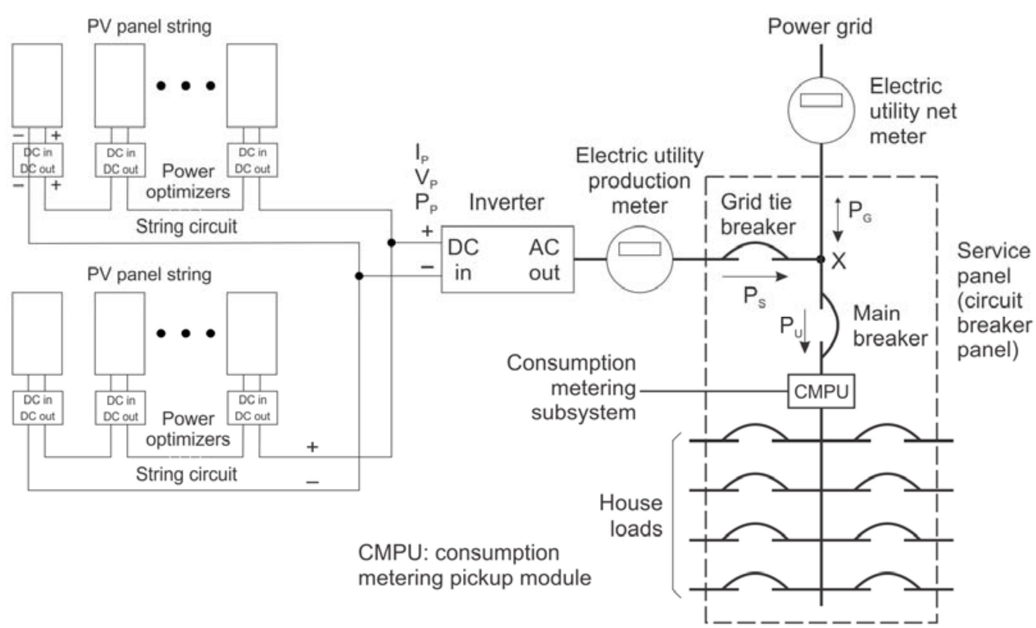

Figure 18. Consumption metering

In this figure I have elaborated many parts of the system for thoroughness of context.

The visible addition is a unit I have labeled “CMPU”, for *consumption metering pickup* (my term). It contains two *current transformers*. In these the conductors leading from the main breaker to the house load buses are themselves the primary windings (“one turn”), and there is on each transformer a wound secondary winding (“many turns”).

The result of the turns ratio implied by this configuration is that a current will be induced in the secondary winding circuit (assuming there is some low-resistance load on it) that is perhaps 1/1000 of the current in the load conductor.

In this application, the transformer secondary leads go to a precision resistor in the transformer itself [16], the voltage across which will be a direct “image” of the current in the associated load conductor. Typically the scaling is such that the output voltage for the “rated” current of the transformer is 1.000 V or 0.333 V (go figure!).

Leads from those voltage outputs, plus typically three leads picking up the voltages of the two load conductors to the neutral at this point, go to the *consumption metering circuit* (which might well actually be in the inverter itself, or in a connected auxiliary unit).

The circuitry continuously, for each current transformer, multiplies the voltage from the current transformer by the voltage (to neutral) of the associated load conductor itself to get the instantaneous power flowing through that lead, and averages that over perhaps one second.

It then adds these together for the two load conductors to get the overall short-term average power (which is the “power” that would be reported at this time by, say, a wattmeter). The system then integrates that over time to determine the cumulative energy flow into the house loads.

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[16] In the more general application of current transformers, the output of the current transformer secondary winding itself (to be seen as a current) goes to a low current range ammeter (perhaps 0-1 A or 0-5 A) that will (with the proper scaling) indicate the current being measured.

Appendix D
Reality at the circuit breaker panel

D.1 INTRODUCTION

What I have called. for most clarity, the "circuit breaker panel" is most often officially called an "electrical service panel", although manufacturers often give them clever names such as "Load Centre" (note the British spelling, an affectation in that case). But, again for clarity, I will continue to refer to it here as the "circuit breaker panel".

In much of this article I have given that item short shrift, generally portraying it in an illustrative way since its details are not the main story here.

But in fact its details can have a significant role in determining the actual hardware configuration of a residential solar electrical energy system.

In this appendix, I will discuss some of those realities.

D.2 CONFIGURATION OF THE CIRCUIT BREAKER PANEL

At one time, perhaps just after circuit breaker panels began to supersede "fuse boxes" in new residences, a typical circuit breaker panel was configured as we see in Figure 19.

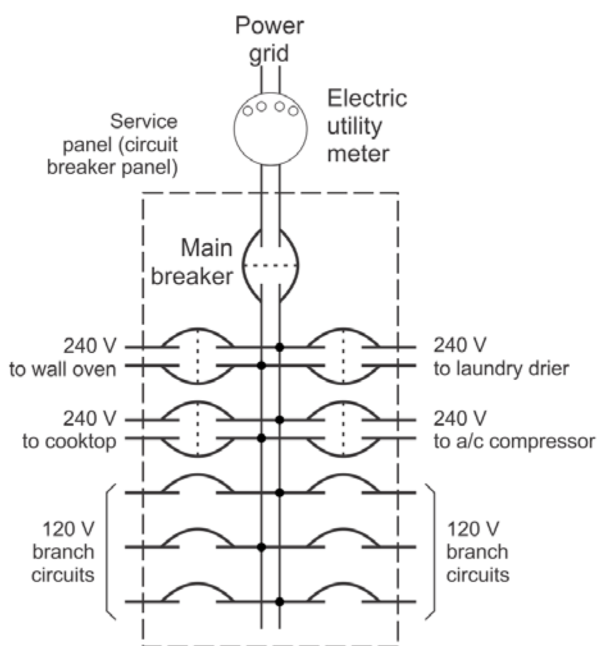

Figure 19.

I have, though, shown it in a 240 V configuration, even though when it was introduced most homes had only what would today be called 120 V service (referred to at the time as "110 V"). And have labeled it with a more modern complement of loads than was typical at the time of its emergence.

Here, and in many of the following illustrations, I have departed from the “single-line” convention for the AC part of the system, and show the two “hot” conductors separately. But to keep the drawing relatively clean, I omit the “neutral” conductor which, while important, is not interesting as to the topics discussed here.

Note that I show the connection from what we now call the “power grid” from the top. The is of course a tidy convention from a “schematic” drawing standpoint, but it also represents the traditional physical reality. At the time period to which the illustration pertains, the electrical service almost always entered a house through overhead wires, perhaps ending in insulators fastened to the “gable” of the house. Those wires typically were connected there to wires of a different type which led though metal conduit down to where the utility meter was located, where they naturally enough) connected to terminals at the top of the meter socket.

And even though today the electrical service may in fact arrive at the house underground, and go **up** through conduit to the meter, in the drawings in this article (which are, after all, “schematic”), I continue to show the utility meter at the top (and its “input” terminals are also normally actually at the top).

An important issue here is that of the main breaker, whose principal functions are to:

- Protect against a short circuit on the buses feeding the branch circuit breakers.

- Allow the homeowner, or an electrician, to “kill” all the power leading to anyplace in the home, in case of some emergency, or to facilitate work on the panel itself.

But note that in this configuration, the main breaker itself has to be of such a size and capability that it could continuously handle the totality of current drawn by all loads in the home, while being ready to (even if manually turned OFF) properly interrupt that current.

The cost of a circuit breaker goes up with its current rating (often faster than linearly). This, among other factors, caused the emergence of an alternate configuration for the typical residential circuit breaker panel, common today, which we see in Figure 20.

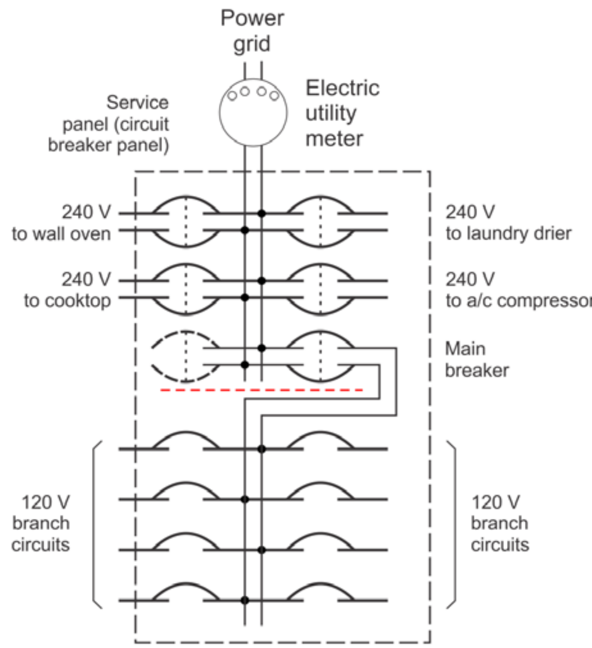

Figure 20.

The big difference here is that the "big" load circuits (mostly all 240V) are fed from circuit breakers operating from the buses directly connected to the input to the panel, not from the buses fed through the main breaker. The obvious advantage (and there are other more subtle ones) is that now the main breaker does not have to be of a size to deal with the totality of loads in the home.

A disadvantage is that, in order to "kill all the power in the house", one must turn off all of the circuit breakers above the dashed red line I show on the drawing.

The drawing suggests that there is space in the panel for one more breaker "above the red line" (it being shown fancifully with dashed lines). Hold that thought.

D.3 CONNECTING THE SOLAR ENERGY SYSTEM

The obvious way to connect a residential solar electrical energy system "to the grid" is shown, in its basic form, in Figure 21.

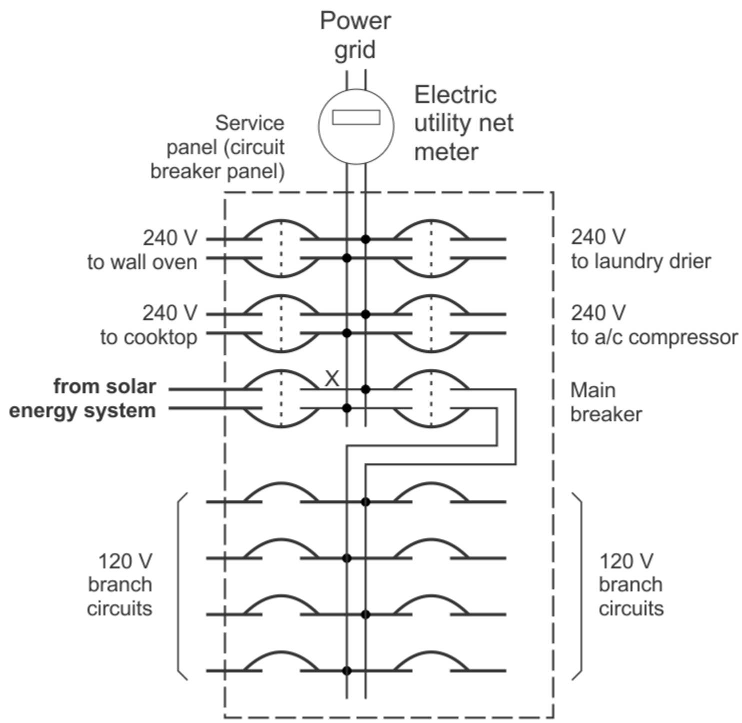

Figure 21.

We merely plug an additional two-pole circuit breaker into the available spot (yes, they just “plug in”, which can be done without much danger with the panel “live”), and connect the output of the solar energy system to its terminals.

That circuit breaker allows disconnection of the solar energy system from the house/grid, if needed, and provides protection in case of a short circuit or such in the solar system AC output circuit. It is sometimes described in this context as the “infeed” circuit breaker.

Note that the wiring from the solar energy system would usually be connected to that circuit breaker while the breaker is OFF. Thus the breaker terminals would not be “live” when the wiring is connected.

Note, as we have already seen in the body of this article, my labeling of the utility meter here as the “electric utility net meter”, the “net” reflecting the more subtle role it will have now that there is a solar energy system in the picture.

And, as we have already seen, here I use a new icon for the utility net meter, meant to suggest that rather than it being the “traditional” electromechanical type, with a “dial” register, it is an “electronic” type, as will likely be required for its new role.

D.4 THE AC DISCONNECT SWITCH

In many cases, when the basic concept of Figure 21 is followed, the utility company may nevertheless require [17] an external solar energy system disconnect switch, such as we see in Figure 22.

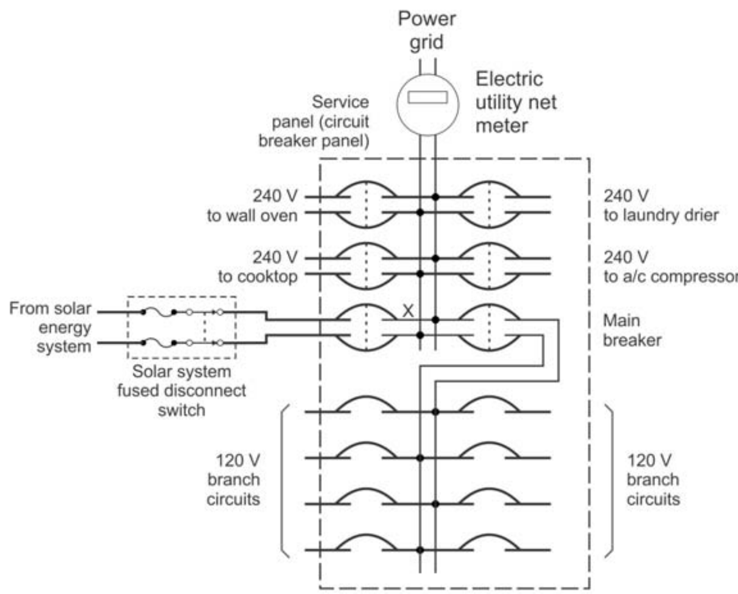

Figure 22.

Typically that switch assembly also includes fuses, which provide further protection against various mishaps.

This switch is often referred to as the Utility External Disconnect Switch (UEDS). "External" means that it is usually required that it be on the **outside** of the house, where utility and emergency personnel could easily reach it, as contrasted to the "infeed" circuit breaker in the circuit breaker panel, which is often inside the house or garage.

Another requirement that may mandate the use of such a switch so as can be the utility's requirement for a "visible break" for disconnection of the inverter AC output. The type of switch used is actually a 2-pole "knife switch", which meets that requirement. (One cannot view the "break" of the contacts of a circuit breaker.)

We can see this on figure 23, which shows a type of switch commonly used for this purpose.

[17] In some cases that requirement is imposed by state regulations. Various provisions of electrical codes or industry standards are often considered to call for, or to permit the utility to require, such a configuration.

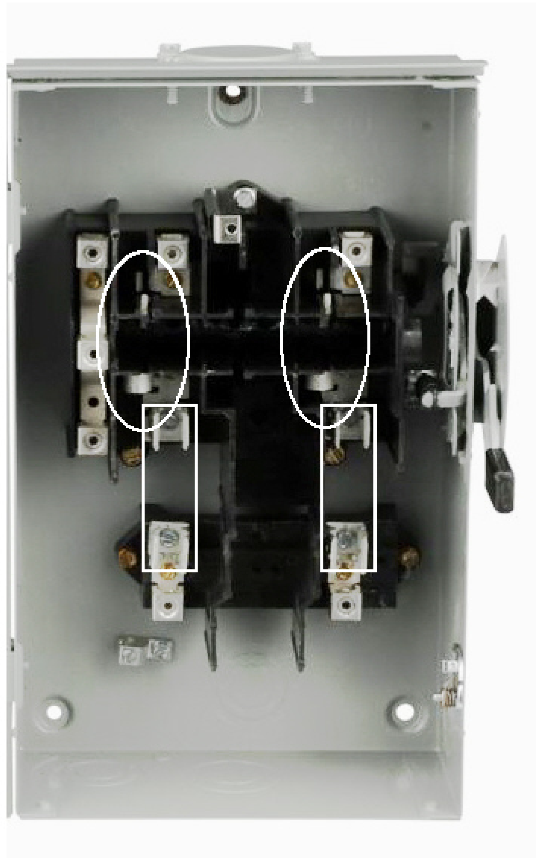

Figure 23. "Visible break" fused disconnect switch

The "knife switches" are in the white ovals.

The fuses, of the cartridge type (none in place here), go in the clips below the switch proper (in the white rectangles).

D.5 THE "LINE SIDE TAP"

But suppose the situation as the installation of the solar energy system approaches is as seen in Figure 24.

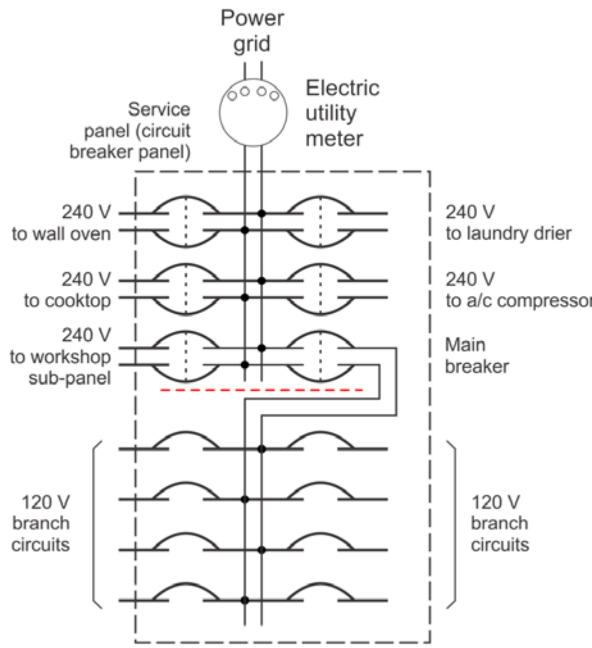

Figure 24.

There is no space available "above the red line" into which to plug in another circuit breaker The usual solution is seen in Figure 25.

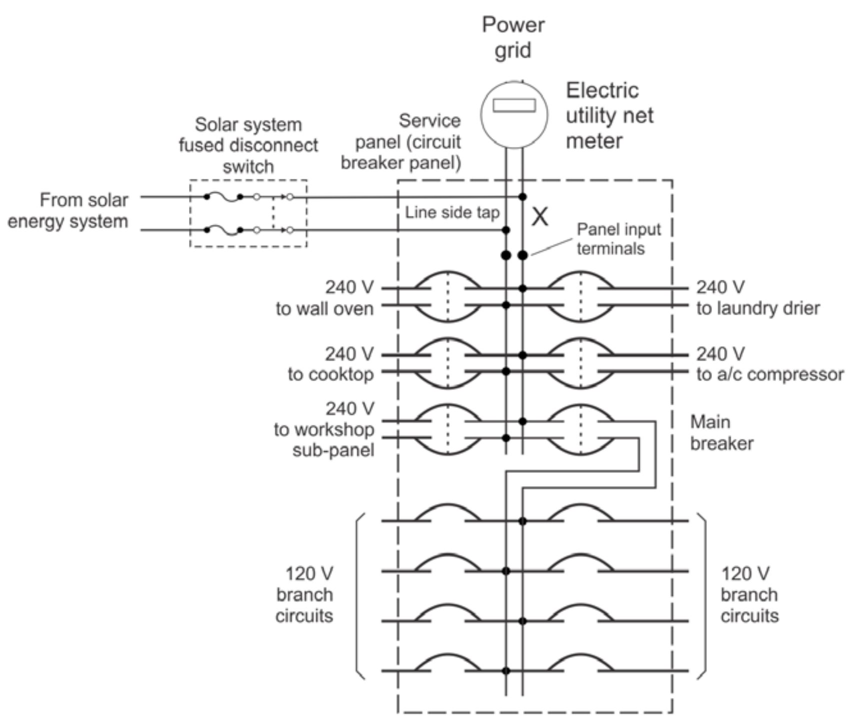

Figure 25.

Because the connection to the grid (at the infamous point "X") is now right at the incoming power line (well, after the utility meter), this arrangement is often spoken of as a "line side tap" connection.

Invariably an AC fused disconnect switch is used, and the leads from it go directly to the input leads of the circuit breaker panel.

Note that making the connection at point X in this situation will require either:

- The utility meter being temporarily removed to make the entire panel “dead” (something that usually can only legitimately be done by a technician from the power utility, and which thus requires coordination with the installing electrician).
- The connection is made with point X “live”. This can be done “safely” with the use of special connectors, tools, and techniques.

Figure 30 in Appendix E shows an actual implementation of a line side tap.

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Appendix E
The whole deal

E.1 GENERICALLY SPEAKING

Just for perspective, Figure 26 shows the overall block diagram of a perfectly-reasonable residential solar electric energy system that incorporates almost all the features described in this article.

This assumes that the panel strings use per-panel power optimizers, as seen, for example, in Figure 11. The use of a line side tap is also assumed.

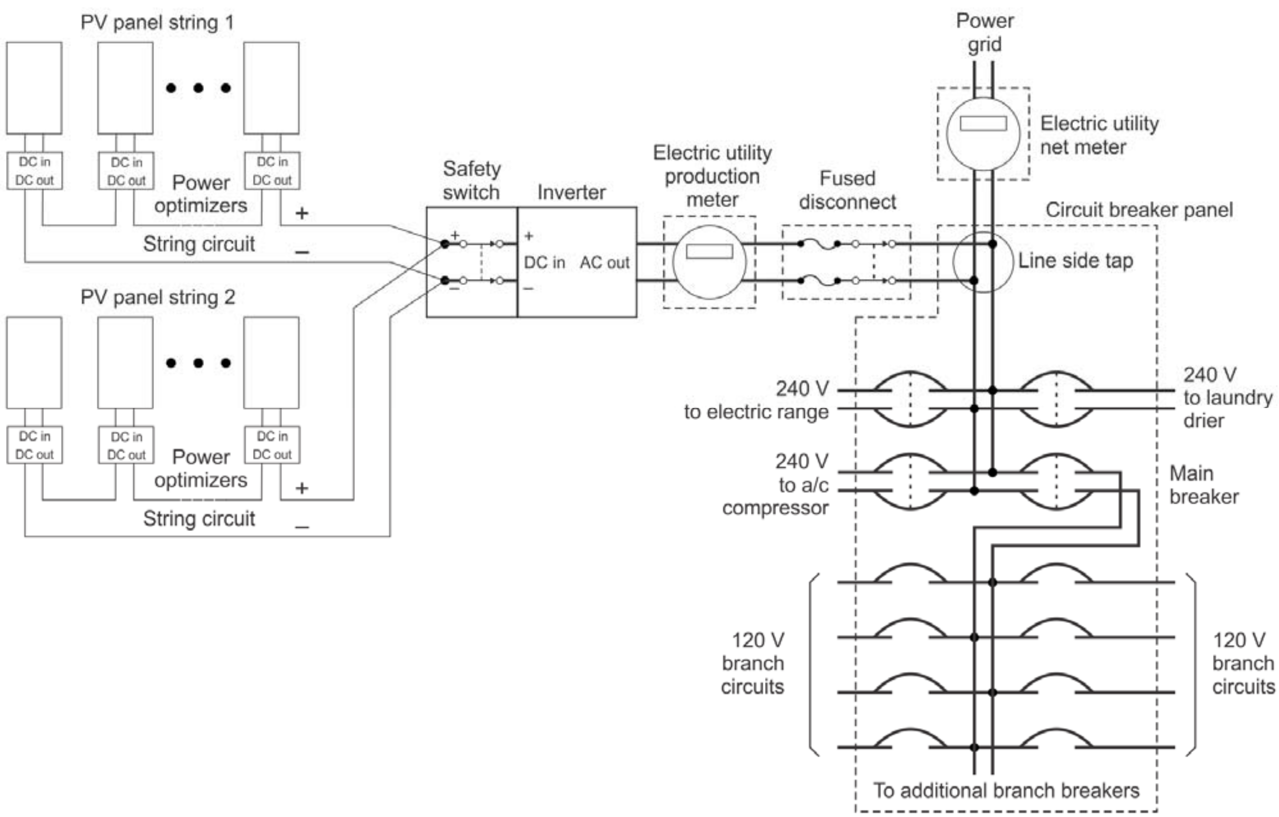

Figure 26.

E.2 A REAL THING

A substantial solar electrical energy system was recently installed at our home here in southern New Mexico (an ideal spot, incidentally, for the harvesting of solar energy). It essentially follows teh plan seen in Figure 26.

E.2.1 The Solar PV panels

Figure 27 shows the primary PV panel array (23 panels of the total of 28), located on the back roof of the house proper.

Figure 27. PV panels on the main roof

The irregular arrangement is caused by the need to avoid existing protuberances from the roof (plumbing stacks, etc.)

Figure 28 shows the secondary array (the remaining 5 panels) on the garage roof..

Figure 28. PV panels on the garage roof

The panels, made by Jinko Solar, are each rated at 385 W of output under the reference irradiation of 1000 W/m^2.

We can see that the panels are supported a few inches above the roof. This allows the natural thermally-motivated convection of air to assist in cooling the panels from the back side.

E.2.2 The "ground level" equipment

Figure 29 shows some of the "ground level" equipment items discussed in this article, as implemented in this installation, which essentially follows the arrangement shown in Figure 26.

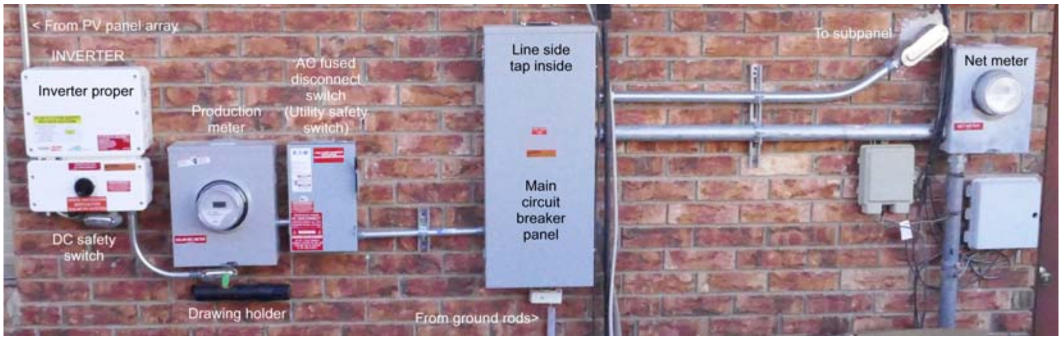

Figure 29. Ground level equipment

On the left we see the inverter assembly. The top portion is the **inverter proper**, a SolarEdge SE-7600, rated at 7.6 kVa/7.6 kW output. It is also the "brain" of the system, and all control and reporting functions are done by the microprocessor in it. It is mounted clear of the wall on brackets, as there are cooling fins on its rear face.

The lower portion is the **DC safety switch**, whose purpose is discussed in section 7.6.5. Turning it off will disconnect the panel strings from the inverter, and the individual power optimizers will then shift into their safe mode, each contributing only 1 V to the string voltage.

Just to the right is the **production meter** (as discussed in Appendix B). The meter proper belongs to, and was installed by, the power utility.[18]

To the right of that is the **AC fused disconnect switch**, as discussed in Section D.4 of Appendix D. It will disconnect the AC output of the system from both house loads and the power grid.

To the far right is what is now, for this house, the "main" **circuit breaker panel** (newly installed as part of this project). It only has a few "branch" circuit breakers in it, one of which feeds the entire "original" circuit breaker panel (just on the other side of the wall, in the garage), treated now as a "subpanel".

There is no solar system infeed breaker; connection of the solar energy system is via a *line side tap*, located inside this housing (as discussed in Section D.5 of Appendix D, and seen in this system in Figure 30, later in this Appendix). Disconnection of the solar energy system from the power grid would be done with the AC fused disconnect switch.

The small black "torpedo" just below the production meter is a weatherproof **drawing holder** in which is a copy of the overall system

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[18] It is actually labeled "REC meter" (see Section B.3 in Appendix B).

block diagram, with the detailed layout of the panels on the roof on its other side (itself laminated for further weather resistance). This is required by the power utility for reference in case of some "difficulty" with the system of concern to the utility company or emergency personnel.

To the far right we see the **power utility net meter**. It is the same one that was in place before the installation of the solar energy system, but it now sports a "net meter" sign in honor of its role as a player in this enlarged drama. It was already an appropriate type for its new role, and was configured to support that (if and when that might be needed) when it was installed, as a routine upgrade, a while ago.

In fact, I call attention to the profusion of red signs on all the system units. This is, among other things, required by the power utility involved for any "grid-connected" solar energy system. The role of each unit and, in some case, the details of its voltage and current values or limits, are given by these placards, as well as specific cautions that might be important to personnel encountering the system.

E.2.3 The line side tap in the flesh

This system uses the *line side tap* arrangement for connection to the power grid. We see its physical implementation in Figure 30, a view of the top of the interior of the main circuit breaker panel.

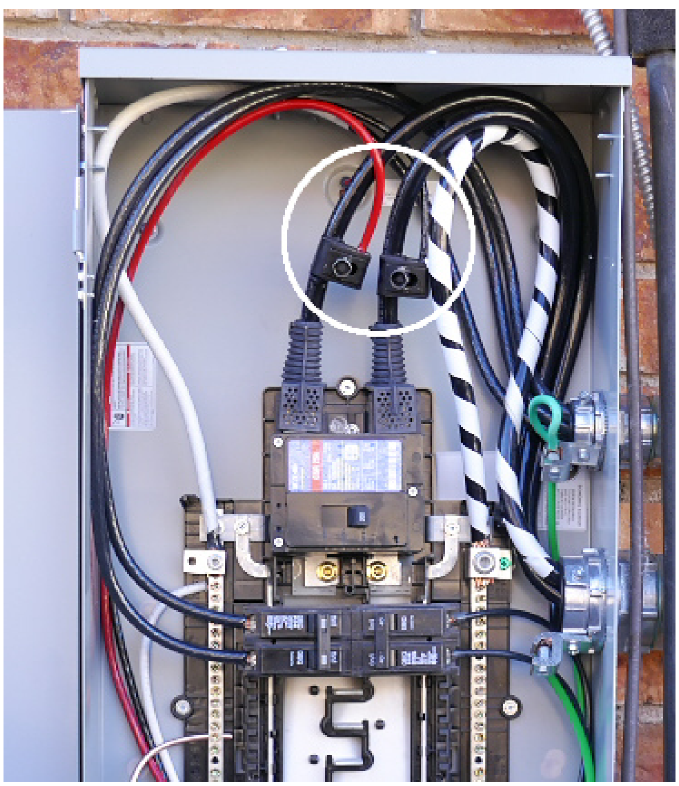

Figure 30. Line side tap

The heavy black leads are the feed to this panel from the power utility meter, going to the input terminals of the main circuit breaker. The smaller red and black leads come from the solar energy system (through the production meter and the AC fused disconnect switch. We see the insulation piercing connectors, which are arranged so that they can safely be put in place with the “host” conductors “live”. The screw heads we see on them (tightened to force the “prongs” into the host cable) are insulated from the current path, and so remain “dead”.

The reader might be curious about the heavy lead with the spiral wrapping of white tape. This is the neutral lead from the utility meter. The color of that conductor is specified as white. Usually the conductor itself has white insulation (as we see on other leads in this photo), but in this case black conductors were used for all three leads, and the neutral was given its white color code with the tape wrapping (indeed permitted by the applicable codes).

While we are here, I call attention to the gray plastic “boots” that cover the connections to the input terminals of the main circuit breaker. This way, when that main breaker if OFF, nothing in this housing that can be touched is “live”.

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