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Preface

This project was funded by Energimyndigheten (Swedish Energy Agency), with further support from KTH's Smart Power Lab (SPL). Input from Elsäkerhetsverket (the Swedish EMC authority) is gratefully acknowledged, for information on observed problems and product enforcement. The Swedish section of IEEE EMC society provided an interested venue for discussion of radio interference issues.

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Sammanfattning

Projektet undersökte elektromagnetiska störningar orsakade av solelsanläggningar. Fokuset var på anläggningar med flera solpaneler kopplade genom växelriktare till ett växelspänningselnät, och hur dessa kan orsaka högfrekventa störningar till, exempelvis, kommunikationsystem. Denna situation är typisk för de flesta solelsanläggningar som installeras nu, till skillnad från "off-grid" anläggningar. Projektet hade ett brett omfång, för att få en översyn av: rapporterade störningar, andra arbeten som studerar relevanta frågor, lämplighet av gällande standard för att undvika störningar, exempel på uppmätta signaler i anläggningar, och studier av några utvalda aspekter av strömvägar i systemet.

Från dessa undersökningar kan följande sammanfattas. Radioamatörer har i över tio år rapporterat och undersökt störningar från solelsanläggningar, och har rapporterat hur komponenttillverkarna har försökt minska störningarna vid individuella fall; dessa rapporter har mest hittats från USA. Under senare år har även störningsrapporter kommit från andra användare av radiosignaler, exempelvis mobilnät och flygtrafik, och flera sådana fall har varit i Sverige. Det syns en korrelation mellan användning av vissa “optimerare" modeller och rapporterade och uppmätta störningar; optimerare är inte nödvändiga för en solelsanläggning, men de har betraktats som fördelaktiga i vissa fall och skulle kunna konstrueras på ett sätt som uppfyller de avsedda funktionerna utan att störa. Myndigheter ansvariga för radiostörningar har redan, vid eller innan detta projekt startades, gått in med starkare marknadskontroller och produktförbud, t.ex. i Nederländerna och i Sverige (Elsäkerhetsverket: ESV). Sådana insatser har i flera fall handlat om formaliteter såsom att det saknades korrekt produktdokumentering och bevis för utförda prov, hellre än att dessa produkter faktiskt orsakar störningar i typiska anläggningar. Det har däremot uppstått fall där produkter som har varit ifrågasatta gällande uppmätta radiostörningar har saknat bevis för prövning enligt lämpliga sätt för att undvika sådana störningar. En väsentlig del av problemet är att komponenter liksom växelriktare eller optimerare, vilka båda kan bidra till störningar genom snabbswitchande elektroniska komponenter, kommer att sättas ihop med paneler och kablar i olika utformningar för att skapa diversa system, vilka komponenttillverkarna inte känner till i detalj. En tillverkare behöver se till att en sådan komponent inte skapar störningar även när den används som en del av ett system där andra komponenter kan bete sig som antenn för att sprida störningar. Inom EU har det inte funnits harmoniserade standard som specifikt, explicit, handlar om begränsning av störning från solelomriktare, optimerare eller system. Detta har lämnat en otydlighet angående vilka standard och metoder som borde betraktas som tillräckliga. Situationen har delvis förbättrats av nya standard och ökad medvetenhet, t.ex. efter produktförbud.

När det gäller hela anläggningar, så har det också varit flera undersökningar de senaste åren, även inom Sverige. Störningsmätningar hos solelsanläggningar har utförts i Sverige av flera organisationer, vilken ger material att utgå från för en

översiktsbild av nivåer och frekvenser. Ett annat projekt undersökte installationskvalitet, men hänsyn till flera parametrar inklusive störningsrelevanta konstruktionsdetaljer.

Mot denna bakgrund har det här projektet gjort en review över befintliga rapporter och studier av störningar, samt av kunskap angående hur sådana störningar skapas och överförs. Tekniska studier har sedan utförts med simulering, laboratoriearbete och mätningar på strömmar i en anläggning. Laboratoriearbetet handlade om överföring av 'common-mode' strömmar genom solpaneler, då sådana strömmar har en hög potential för störningar. Dessa studier har publicerats i konferenser och tidskrifter. En projekthemsida har skapats med information, publikationerna (open access) och data. Efter projektets formella slut är det förväntad att hemsidan kommer att uppdateras med flera resultat från studier med mikroväxelriktare och optimerare som inte var kompletta under projektets gång.

Summary

The project investigated electromagnetic disturbances caused by solar photovoltaic (PV) installations. The focus was on grid-connected installations with several solar panels connected through inverters to an AC power grid, and how these can cause high-frequency disturbances to, for example, communication systems. This type of installation is typical of most solar generation being installed now (at least in Sweden), as opposed to off-grid systems. The project had a wide scope, to get an overview of: reported disturbances, other works studying relevant issues, suitability of the current standard for avoiding disturbances, examples of measured signals in components and complete installations, and studies of some selected aspects of current-paths in the system.

From these investigations the following can be summarized. Radio amateurs have been reporting and investigating interference from solar installations for over ten years, and have reported how component manufacturers have attempted to reduce interference in individual cases; these reports have mostly been found from the United States. In recent years, interference reports have also come from other users of radio signals, for example mobile networks and air traffic; several such cases have been in Sweden. There is a correlation between the use of certain “optimizer” models, and reported and measured disturbances; optimizers are not necessary for a solar plant, but they have been considered beneficial in some cases and could be designed in a way that fulfills the intended functions without interfering. Authorities responsible for radio interference have already, at or before the start of this project, stepped in with stronger market controls and product bans, e.g. in the Netherlands and in Sweden (Electricity Safety Agency: ESV). In several cases, such efforts have been about formalities such as the lack of proper product documentation and proof of tests performed, rather than the fact that these products actually cause interference in typical facilities. However, there have been cases where a product that has been called into question due to measured radio interference has lacked evidence that it has been tested in accordance with appropriate methods to avoid such interference. A significant part

of the problem is that components such as inverters or optimizers, both of which can produce disturbance through their fast-switching electronic components, will be assembled with panels and cables of different designs to create diverse systems, which the component manufacturers do not know in detail. A manufacturer needs to ensure that its component does not create interference even when used as part of a system where other components can act as antennas to spread interference. But there has not been a harmonised standard in Europe that specifically, explicitly, deals with the limitation of interference from solar inverters and optimizers. This has left an ambiguity as to what standards should be considered sufficient tests. The situation has been somewhat improved by new standards and increased awareness and enforcement, e.g. through the above-mentioned product bans.

As far as entire installations (PV systems) are concerned, there have also been several investigations in recent years, also within Sweden. Disturbance measurements at solar installations have been carried out in Sweden by FOI and Elsäkerhetsverket, providing material to start from for an overview of levels and frequencies. Another project from Sweden investigated installation quality, but considering several parameters including disturbance-relevant design details.

Against this background, this project has made a review of existing reports and studies of disturbances, as well as of knowledge regarding how such disturbances are created and transmitted. Technical studies have then been carried out with simulation, laboratory work and measurements of currents in a facility. The laboratory work was about the transmission of common-mode currents through solar panels, as such currents have a high potential for interference. These studies have been published in conferences and journals. A project website has been created with information, the publications (open access) and data. After the formal end of the project, it is expected that the website will be updated with several results from studies with microinverters and optimizers that were not complete during the course of the project.

Background

Interference

In modern homes, offices, factories, vehicles, etc, there are technical “systems” such as telephones, motors, power networks, or cars, whose operation depends on electromagnetism – for example radio waves or electric currents in wires. Correct operation of such a system can be disrupted by electromagnetic signals coupling to it from other systems or from natural sources, by various possible paths. (Here, “signal” is used in the broad sense, including e.g. currents fields or waves, regardless of whether they are intended to convey information. A signal that isn’t intended to couple to a system is a disturbance.) “Electromagnetic Compatibility” (EMC) describes the state where systems can operate correctly. This state is possible by a combination of: systems tolerating a sufficient level of externally imposed signal; systems producing a sufficiently low level of signal; and systems being sufficiently separated from each other.

Some types of system inevitably send out strong signals that could disturb others. Radar is an obvious example, but the principle is true for anything that needs to transmit radio signals, such as a mobile telephone. In contrast, a solar PV system with PV panels, wiring and inverter, has no such need. It needs only to allow DC currents to flow through panels and their wiring, and an AC current at the electric-grid frequency to flow into the grid. If this were all that happened, these systems would have a very limited potential for disturbance to other systems: just a slow-changing magnetic field near the DC wiring, and an increased AC grid voltage when power is injected into the grid.

However, in practice, disturbances have been reported from some PV systems, interfering with other systems. Signals even in the megahertz range have been measured in the DC wiring and in the air; there are also typically frequencies in the tens and/or hundreds of kilohertz in the AC connection wires. The origin of these signals is power conversion equipment using “switch-mode” electronics, as is usual in practically all modern power-electronic conversion, from computer-boards up to to transnational DC power links. Power conversion is necessary in a PV system, to maximize power output of solar panels at different illumination levels, and to perform conversion if connecting to an AC grid.

It is possible to filter these unwanted higher-frequency signals coming out from a converter, to reduce them to whatever extent is chosen based on many factors including cost and imposed requirements. In some products for PV systems, this has not been done sufficiently to obtain compatibility with surrounding systems when the converter is used with particular constructions of PV panels and wiring. It should not be assumed here that “converter” must mean an *inverter* (DC-AC converter) – the DC-DC optimizers that are used in some system configurations also have switch-mode conversion. Indeed, the severe reported disturbances have tended to be associated with systems using particular models of optimizers.

PV System configurations

Solar PV systems of the type considered here have power-electronic converters in either or both of two main places: attached to the individual PV panels, or connected to a group of multiple panels through DC wiring. Another description with diagrams can be seen in reference [RI19].

A *microinverter system* has converters only at the panels, with their outputs going directly into an AC collection system: these are therefore *inverters* i.e. DC-AC conversion. This has some advantages over a string-inverter system, but the converters currently have a higher cost per kilowatt for bigger systems, and a lower efficiency. Potential advantages for the user include: no single point of failure in a single expensive converter; individual handling of each panel's output to give maximum-power-point tracking at the panel level; no series-connected panels and thus no multi-hundred-volt DC system; and individual monitoring of panels (if the microinverters support communication). The microinverter system is *not* the typical choice for a multi-kilowatt solar PV installation in Sweden. We have not found reports of substantiated radio interference (i.e. reduction of function in other systems) from PV systems with microinverters, but the less widespread use of this system may be part of the reason.

The opposite extreme is to use a DC collection system leading from all panels to one converter. For rooftops with up to a few tens of panels, the panels can be series-connected into a single “string”, with a pair of wires connecting it to a *string inverter*. If this would result in too high voltage or power for the chosen components or safety regulations, then multiple strings can be used, connecting to one or more inverters. For larger systems, particularly ground-mounted panels in solar farms, a set of strings may be parallelled and the output taken to a central inverter.

The growth of domestic rooftop solar in Sweden and many other countries is primarily by string inverters. Since about 2010 these have moved to a “transformerless” design that avoids galvanic isolation between the AC and DC sides, to reduce cost and losses. They have reached impressive stated efficiencies such as 99%.

The main weaknesses of a simple string of panels connecting to one inverter are the lack of control or awareness about individual panels, and the presence of a DC collection system at hundreds of volts that cannot be de-energised as long as the sun is shining. The significance of not being able to control individual panels is that the power available from the panels may increased by individual control if the panels in a string are not all behaving in the same way. Differences between panels can arise from their being mounted at different angles to the sun, being shaded at certain times by trees, chimneys or other panels, or having varied soiling by dust, pollen, etc. There also could be difference at manufacture or due to different degradation by aging. The inverter sees only the series connected string of all the panels together, so it can at best find the optimal (power-maximising) current for the whole string. Obtaining the maximum possible power for each individual panel (when these are not in identical states) would require the ability to set a different current for each panel. Individual handling of panels is potentially useful not just for control but also for monitoring to see whether degradation or soiling is significant on specific panels that should therefore be cleaned or replaced.

The combination of a string inverter and *DC optimizers* is one way to try to obtain some advantages of the central and the distributed types of converter. This typically uses an optimizer on each panel, sometimes known as module-level optimizers. The optimizers are essentially DC-DC converters that allow the panel's current to differ from the string's current, so that each panel can be made to provide its maximum power. Some models have a monitoring function: this may be performed by signals sent to the string inverter along the string conductors, i.e. “power-line carrier”, which gives further potential for disturbance; in other cases a wifi-type communication is used.

Requirements and Standards

In the EU, the "EMC directive", assimilated into national laws, gives the essential EMC requirements for products to be put on the market. Essential requirements are broad, along the lines that equipment shall not disturb other equipment and communications. Enforcement authorities have strong powers to prevent the sale or use of products that actually do interfere, e.g. with other legitimate users of the radio spectrum. It is observed in [Key14] that in practice the powers are often used mildly, which is borne out in the case leading up to a PV product ban in Sweden [ESV21s], where further sale was stopped only after a long communication process, without an extensive recall or further penalty.

To help manufacturers, users and enforcement authorities to establish what tests can reasonably be made to show that a product is acceptable, European *harmonised standards* considered relevant for the directive are listed and updated in the EU's Official Journal. Products fulfilling the relevant harmonised standards have a presumption of conformance to the Directive, in those regards that the standards consider. However, it is not always clear which one or more of these standards a product should be tested to, nor whether this/these would satisfy all aspects of the Directive. As of end-2023, the latest list for the EMC Directive is from 2022 [EU22], listing nearly 200 harmonised standards. There are items specific to lifts and escalators, or doors and gates, or resistance-welding etc, but no title includes any obvious search-word about solar, PV, inverter, converter, etc., to suggest a standard actually aimed at PV systems or any component thereof. This is surprising, in view of how widespread PV equipment is, and of the potential for problems when switch-mode converters are coupled to large areas of solar panels arrays through wiring systems.

According to [Key14] one manufacturer tested its PV inverter according to criteria specific to computer equipment, given that the inverter had an onboard computer and ethernet port; this standard had no requirement for measurements on the DC side since typical computer equipment doesn't handle a high-power connection to an array of solar panels. However, given the lack of relevant harmonised standards (rather than EMC directive's essential requirements for the likely use-scenario) this doesn't seem totally unreasonable. From the enforcement side, the Swiss regulator OFCOM decided [Hae17] to treat a PV installation that had communication between optimizers and a string inverter as being a "telecommunication system" for the purposes of enforcing demands on the system's performance.

A seemingly reasonable default choice of harmonised standard for household-type PV equipment is EN 61000-6-3, which is a generic standard for residential environments. This has been widely used, but it does not map clearly onto PV system components: its definition and requirements for "ports" mainly consider a power input and communication ports, although the case of battery connections is also explicitly considered. The 2007 version (superseded in 2021) doesn't clearly put requirements on the emission at the PV-array side of an inverter. The 2021 version is more adapted to DC ports and cable lengths, but the tests are generic, i.e. not specifically declared for PV conversion equipment.

The CISPR 11 standard for “Industrial, Scientific and Medical” equipment, in the form of harmonised standard EN 55011, has been seen as a more suitable standard. This was suggested in the investigation of SolarEdge optimizers in [ESV21s], for products that had been tested to the generic EN 61000-6-3. The scope of CISPR 11 includes semiconductor inverters and rectifiers, although the standard’s name doesn’t make clear the connection to components for PV systems. It remains the main standard relevant to EMC testing of PV converters.

Even if individual products have been shown to conform to the relevant harmonised standards, a complete installation that puts converters, panels and wiring together may still cause interference. For example, the configuration may happen to be well tuned to radiate at a particular frequency, that a converter makes within the allowed limits. Or the sheer number of weaker sources (e.g. optimizers on panels) may combine to have a stronger effect than considered in the standards. It can then be that the owner of the installation is required to stop the interference. The path back to the manufacturer may need to go through an installer, and may not be easy [PVE20]. This points to the importance of using reputable installers, and also to installers choosing equipment carefully and following manufacturer instructions.

Execution

At the start of the project a broad review was made, considering practical and academic literature, news items, complaints, standards etc. This was initially mainly oriented to: reported disturbances, actions by authorities and companies, and studies performed to measure disturbance levels (conducted or radiated) from components or systems. At this time, the Swedish EMC regulatory authority Elsäkerhetsverket was finalising some product investigations that led to bans on sale (late 2021), so the documents involved in those cases were included in the study. There were also useful reports by FOI, e.g. [Lin21] with results from measurements. Some attention was then given to the complicated situation of standards.

Based on these inputs it was considered that the particularly severe cases of disturbing equipment were identified and being acted on by authorities, so more subtle problems were a better subject for continued study.

For example, the extent of conducted disturbance on the DC side of an inverter is affected by the array of panels that it is connected to, and the wiring between them. The array and wiring also determine the relation of this conducted current to the radiated disturbance. This means that actual disturbance levels may vary significantly for different choices of installation or even for wet versus dry panels. Requirements for converter equipment should be developed to avoid exceeding disturbance limits for plausible worst-case conditions.

An important role is played by the common-mode circuit on the DC side of a string inverter. This is the path taken by currents from the inverter, to the array by either conductor, and back via typically capacitive coupling to other structures or through any earthing conductor from the panels if such is included (in Europe it is common to have no earthing of a residential-size array). This forms a larger current-loop than the “differential mode” of the currents passing around the string (like the intended DC current-flow), and therefore has potential to cause more radiated disturbance for a given current. The distance from the panel array to a string inverter may plausibly be a significant part of a wavelength for the megahertz range. This can make the common-mode circuit particularly able to spread disturbance. It also can result in small differences in installation lengths and configurations making significant differences to disturbance levels.

A further literature study was therefore made on impedance measurement, simulation and modelling, with particular attention to the common-mode currents. This led to a study based on finite-element simulations and laboratory tests. Several panel types were obtained, along with metal mounting frames. The impedance spectrum was modelled even for the higher (>1 MHz) frequencies that can arise from conversion equipment. The case with a single panel has relevance even to the local loop of an optimizer and panel, but also to the panel’s contribution to the inverter/array circuit. Measurements were made on the panels in different situations, to compare to modelled results. A sensitivity study was made to consider the effect of different conditions such as mounting angle (change of capacitance to surroundings) and water coating (high-permittivity substance).

Measurements of conducted disturbance, in the common and differential mode, were also made on a 10 kW rooftop system with string inverters and long runs of cable to the rooftop. Common-mode and differential-mode currents were recorded simultaneously to show a spectrum from below 50 Hz, up to 1 MHz, in order to give a further example of the levels of switching noise and the variation with power loading.

The large, scattered literature relevant to this work comes from disciplines of EMC, power engineering, amateur radio, standards, etc, and has changed significantly in the past few years. No general review was found, so having collected material from many sources it was decided to make a review paper in order to collect many references that could be useful for someone coming newly into the subject. Writing this was the final main part of the project.

A further thread of the project concerns related side-issues: items imported without any attempt at following EU directives, and the potential of “plug-in” or “balcony” PV. These studies have been continued beyond the main project, and will be reported further on the webpage in 2024.

Results and Discussion

The studies of the common-mode circuit, based on simulation and laboratory work with solar panels, are reported in publications [P1] and [P2]. The capacitance between a panel's two DC conductors due to the path through the cells was seen to be large compared to the capacitances from the whole set of cells and conductors to the panel's frame and surroundings, so it makes sense to approximate a single capacitance between the panel's active parts (wires and cells) and its frame at lower frequencies. At frequencies in the megahertz range the inductances in the common-mode circuit of the array and wiring are not negligible, so the simple capacitive common-mode model that has been popular at lower frequencies is inadequate. The presence of water on panels significantly changes the capacitance between active parts and the frame.

The measurements performed on a PV installation have been reported in [P3]. They supplement studies such as [Lin21], giving an example of a system whose currents to the array or mains show negligible spectrum beyond a few times its modest (16 kHz) switching frequency. They also show the variations of these quantities with different levels of power transfer as the sunlight varies.

The review article [P4] brings together references from several disciplines to give a view of the problems that have been encountered with EMC in PV systems, some of the studies that have been performed, and aspects of converters and panel arrays that contribute.

The following subsections discuss further points that are not taken up in detail in the project's publications to-date.

Future

Careful market surveillance and strong consequences are important for avoiding the spread of EMC problems in installations. It is converter equipment manufacturers who can best control emission problems, by ensuring that all radio-frequency signals from their devices are tightly controlled so as not to cause interference in plausible situations of the PV installation and surrounding equipment. Existing reports show a wide variation of EMC behaviour between manufacturers.

If outright bans or further penalties are expected for transgressions, manufacturers with significant market share will assuredly adapt. As long as the most economic course is to make cheap, high efficiency equipment and leave the EMC issues to installers or to after-installation fixes when interference is reported and well substantiated, there are likely to be manufacturers that give too little attention to EMC. Note that minimising filtering has the potential for more competitive cost, size and efficiency figures.

Standards

The earlier description of harmonised standards made clear that there has been a lack of a standard that is clearly *the* correct one to use for PV system components, and that has limits set with careful attention to PV systems. Although standards have been adjusted to be more suitable for PV system components, it is still true that a newcomer to the landscape of EU harmonised standards could easily miss one that a national EMC authority might consider necessary for a presumption of conformance with the essential requirements of the EMC directive. It is tempting to suggest, in hindsight, that a PV-specific standard should have been made a decade or more ago, to avoid a lot of guesswork and interference with other systems. PV systems are, after all, remarkably widespread, large and high powered, compared to most other switch-mode electronic apparatus in residential or commercial areas. As a substitute, guidance and market checks from EMC authorities can help make clear what is expected.

Optimizers ("MPE")

The advantage of using optimizers should not be assumed, even if some shading is expected. It is desirable to avoid putting further electronic components on a rooftop, unless there's a strong justification. Labour costs arise if faulted components need replacing, or indeed if EMC problems require fitting ferrite cores or changing optimizers. The severe disturbance cases of recent years have strong correlation to particular types of optimizers [PVE20][ESV21s] rather than to plain string inverters or microinverters.

Based on recent reports, e.g. [Fra19][Bau23], it appears that the actual benefit of optimizers for "yield", i.e. energy production over some period such as a year, is not as obvious as is widely assumed, even with some degree of shading. Optimizers consume some power, by losses and control circuits. They are connected to whole panels, so they cannot fully recover the potential output of all the non-shaded cells in a panel, when one or more series-connected cells are shaded. The bypass diodes within panels (three per panel is currently typical) anyway provide a simple way to avoid that a shaded panel strongly affects other panels in a string. Modern panel designs with "split cells" have (at least) two parallel paths, in different parts of the panel, which also helps to reduce the effect of partial shading.

A financial benefit of optimizers is even less clear than the yield benefit, since the cost of purchasing an optimizer is not a trivial part of the cost of a solar panel. A substantial yield increase would be necessary in order to give a reasonable payback rate for cost of adding optimizers. However, considerations other than yield could motivate the use of optimizers for particular cases.

Appendix A continues this subject, with an estimate of breakeven time for including optimizers in a PV array, relative to the breakeven for the array with a plain string inverter. It also lists some non-yield benefits of optimizers.

Private Import and Online Marketplaces

The problem of products coming into the EU from external sources without proper attention to directives and standards has been noted over the past decade for many products by many parties. A regular example is USB chargers, which are potentially dangerous for shock and fire risk, besides EMC issues, if not constructed following good practices. Online marketplaces facilitate ordering products of impressive specification, at low prices. There is often low or zero shipping cost from outside the EU. Being based outside the EU, the actual sellers have little legal risk for how their products behave. Meanwhile, the marketplaces point out that their own role is just to facilitate the buyer/seller interaction, not to import products themselves. If they remove one listing for being reported as a bad product, another can go up soon after. Sometimes products from a seller based outside the EU are even offered with shipment from within the EU, through a local collaborator, as has been the case for some products that we have tested. Further, small businesses in the EU may innocently see an opportunity for selling cheap chargers or other small equipment, unaware of the EU Directives and product declaration that a party putting an electrical product on the EU market ought to follow. These issues have been raised repeatedly in the past decade, as different authorities observe problematic products. However, the situation has not appreciably changed: a great range of equipment can be ordered by private people, and thereby imported, via the likes of Amazon, Ebay, Alibaba etc. Recent discussions can be seen for Sweden [ESV21a] and the UK [ESF23].

Equipment for PV systems is not an exception: one can buy a range of microinverters, optimizers and inverters, from sellers typically in Asia, sometimes with free international postage, or postage from within Europe. It is unlikely that a major professional supplier or installer would directly buy from a source that doesn't have a credible EU representative and product declaration. However, a home user with interest in putting up a few PV panels might be interested in cheap microinverters.

It was therefore of interest to try a few microinverters from sources seen as unlikely to have any genuine EU declaration of conformity, and to compare also with an example from a reputable source and manufacturer. Full results from the EMC and safety aspects of this testing will be published on the project webpage. The disturbance current into the megahertz range on the DC and AC sides has been seen to be tens of times as much in some cheap imports compared to a properly sourced product.

Plug-in Solar, or Balcony PV

Existing concerns about plug-in PV are mainly related to safety rather than EMC. However, the use of PV panels and inverters together as a plug-in “appliance” may increase the chance of products being obtained by private people from sources without attention to EU directives, or in general to good EMC behaviour.

Sweden has for the moment the official view (Elsäkerhetsverket) that products interfacing a solar inverter to the AC network via a normal "schuko" plug are not permitted to be sold. The obvious worry is about how one can be assured that the exposed pins will not have a hazardous voltage, when the object connected to them is a form of generator. Other classic worries include less protection of wiring from overload when both the normal supply-source and the local source (PV) can both supply loads within the same final-circuit, or if multiple sources are connected mainly to one phase and loads mainly to another, leading to high currents in neutral-conductors. The only type of "plug-in" solar suggested (in Sweden, currently) as acceptable would use a specialised connector for just this purpose, with no exposed conductors on the plug or socket, and with a socket specially installed for the purpose, on its own final-circuit.

However, several other countries in Europe have a very different approach. In Germany there is genuine "plug-in PV" (or "Balkonkraftwerk"), with official consent. PV sources up to 600 W (in the initial framework), and recently up to 800 W (revised level), can be connected by the householder to the existing installation through a normal household plug and socket, i.e. the "schuko plug" that is used in Germany, Sweden and many other countries. The obvious advantage of a plug-in approach using normal socket outlets is that many residents can use existing sockets on balconies, facades etc, avoiding the cost of installation work and avoiding seeking permission from building owners. As of end-2023 the cost in Germany for a 800 W system of two panels and a microinverter can be around 6000 SEK/kW, whereas installed multi-kW rooftop systems in Sweden are typically two or more times this level.

Plug-in PV was pushed by Deutsche Gesellschaft für Sonnenenergie (DGS) [DGS] around 2013 to 2016, with formulation of a standard, DGS-0001 for inverters and user-instructions. The German electrical standards organization VDE held out for some years, not liking the use of the schuko plug, but by 2023 [VDE23] it acknowledged that to promote the energy transition a schuko-connected solar generation even up to 800 W should be accepted. For some five or more years before that, products had anyway been sold and used according to DGS-0001, with acceptance that users could themselves report the equipment to their network company. The rules in Germany are progressively made simpler, to facilitate low-bureaucracy plug-in PV.

The plug-in operation of solar power is not unique to Germany but is seen in similar form in several countries, such as the Netherlands as mentioned in [Key14]. There are claimed to be around 250 000 such PV sources running in Germany [PVM24]. There is no compelling reason to suppose that the same equipment would become significantly more dangerous if used in Sweden. Further issues around user-installed plug-in PV are the mechanical security of the large panels, e.g. for windy times, and issues of permission from building owners if used in multi-occupancy buildings with attachment to a wall or railing.

If plug-in PV becomes popular in Sweden, it can be hoped that the size of panels will make it less practical than with smaller equipment to have mail-order from unreputable sources that ignore EU product standards, and that reputable local vendors will offer competitive products. Microinverters have not been found reported as a reported source of interference from installations (see even [PVE20] regarding the clearer standards requirements for microinverters than for optimizers), but microinverters made without attention to EMC compliance could be a different matter, as noted in the previous subsection.

Publications

The following publications in journals and conferences have been made within the project.

[P1] M. Kane, N. Taylor, D. Månsson (2022). "*Characterization of Parasitic Impedances of PV Panels from Common Mode Perspective*". 2022 International Symposium on Electromagnetic Compatibility – EMC Europe, 2022. Presented at the 2022 International Symposium on Electromagnetic Compatibility – EMC Europe, September 5-8, 2022.
https://doi.org/10.1109/EMCEurope51680.2022.9901119

[P2] M. Kane, N. Taylor, D. Månsson (2023). "*Experimental Investigations into Common Mode Impedance of PV Panels*". Presented at the IET Renewable Power Generation and Future Power Systems Conference 2023, 15 - 16 November 2023, Glasgow, UK. https://doi.org/10.1049/icp.2023.3243 (open)

[P3] M. Kane, N. Taylor, D. Månsson (2024). "*Investigations Into Conducted Emissions of A 10 kW Photovoltaic Plant*". IEEE Letters on Electromagnetic Compatibility Practice and Applications.
https://doi.org/10.1109/lemcpa.2024.3359485

[P4] M. Kane, N. Taylor, D. Månsson (2024). "*Modeling and Analysis of Electromagnetic Compatibility Aspects of Solar Photovoltaics: A Review*". Submitted to IEEE Access in February 2024. This will be linked from the project page https://smp.eecs.kth.se/proj/sols/ when published.

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The above links can also be found archived at https://web.archive.org

For a review of a large number of sources, see the review publication [P4].

Appendix A.

Simple pro and con of optimizers, with breakeven time relative to string.

Accurate estimates of PV-system profit or payback cannot reasonably be claimed, given the uncertainty over future energy prices, credits for green export, and network charges. However, we can give a good order-of-magnitude estimate of optimizer profitability *in relation to* a string-inverter system without optimizers.

Based on prices quoted in 2023 in Sweden (Solsam.se), a 6 kW domestic rooftop system with 14 panels and a string inverter (no optimizers) could be fitted for a total price of about 125k SEK, including VAT and before any tax rebates for solar or home-improvement work. This can be expected to produce about 6 MWh annually, most of which would be in the summer months. The payback depends of course on many factors over future years, including household consumption patterns, electricity price contracts, and the already mentioned external details of market prices, network charges, green credits etc. However, even optimistic views have trouble in seeing a payback much better than 10 years.

If all produced electricity could be directly consumed (own-consumption) then with a currently available (end of 2023) fixed energy cost of 1 SEK (exc.VAT), energy tax, network charge and VAT, the total cost for import can be around 2 SEK/kWh; in this case the payback would be around 10 years if the price persisted *and* interest rates were 0. The income per kWh for exporting is unlikely to be as high as the above avoided-cost by own-consumption, even with the various green credits, although the exceptionally high summer-prices for energy in 2022 came into this range. Thus, 10-year payback seems optimistic. The potential for further costs such as inverter replacement should not be neglected from a longer-term analysis.

Optimizers have prices starting around 500 SEK. If applied to all the panels in the above system, even without any further labour cost, this would add 7k SEK, i.e. around 6% of the cost of the system without optimizers. If every generated kWh is equally profitable, the optimizers would need to increase the system's yield by 6% in order to have the same rather long and uncertain payback time as was already discussed for the system. If own-consumption is more profitable than export, and some of the extra power from optimizers comes at times when it will be exported, then even more yield-increase would be needed. In fact, the suggested improvements in yield due to optimizers, that have been reported in recent studies rather than sales brochures, are not this optimistic. The study in [Bau21] reports an advantage of around 2% in yield due to optimizers, for examples of chimney or dormer-window shading. In [Fra19] the presence of optimizers was claimed to worsen the yield in some studied cases, or to add a few percent in others. The profitability is in this case far less favourable for optimizers than for the basic system, and consideration of interest rates accentuates the difference.

The above can be adjusted to consider that optimizers could be applied to just a subset of the panels if there are special conditions of orientation and shading. This potentially improves the case for optimizers. However, an alternative is a string inverter with two or three separately optimized string inputs instead of a single one, or even the use of more, smaller, string inverters, which helps avoid the single-point-of-failure.

Besides the optimization of panels' power outputs, some optimizers offer other types of advantage when compared to a direct connection of panels to a string. Some technical ones are listed below.

One advantage is monitoring of individual panel outputs, to show the owner if some panel or group has a fault or strong degradation.

Another potential advantage of optimizers is a safety feature found on some models, whereby the optimizer's output to the string is disabled unless a enabling-signal is present (typically from the string inverter). In this way, one avoids having a string with hundreds of volts of open-circuit voltage that cannot be turned off as long as the sun is shining; as soon as the inverter or its AC connection is shut down, the enable-signal stops and the optimizers block their panels from the string.

A side-effect advantage of the optimizer’s primary function (optimizing) is potentially a reduction of localised heating of cells by power supplied to a shaded cell from other cells. Bypass diodes prevent this happening to an extreme extent, but typical panels now and in the past decade have only three bypass diodes for the whole panel, i.e. 20 or more series cells per bypass diode. When the diode bypasses a group of cells, it holds their total voltage close to zero, but this still allows the non-shaded cells in the group (e.g. 19 of 20 in the extreme case) to transfer some power to shaded ones (i.e. the remaining 1 of the 20 in this same case). With weak shading, an optimizer that chooses the true maximum power point will prefer to drop the panel's current to the slightly lower shaded value rather than losing ~1/3 of the voltage by causing a bypass diode to activate. This behaviour avoids the local heating of the shaded cell, by preventing the entire voltage of the others in its group being applied to it. With stronger shading the bypass state can start to be the higher-power choice, which the optimizer may therefore choose anyway. However, the transfer of power within the bypassed group is less with the low current that comes from strong shading, so less heating would be expected in this condition than in the moderate-shading condition in which the optimizer helps avoid the bypassed state. This is mentioned for completeness, but one should have clear evidence of the need and actual advantage of an optimizer before basing a design decision on this point. Part-shaded installations successfully exist without optimizers and without damage.

In summary: the use of optimizers should not be a default, even for particular circumstances such as known shading, unless justified by analysis for the particular case with consideration of studies of actual optimizer performance. This is a general point for profitability. From the EMC perspective, optimizers have been a particular problem [PVE20][ESV21s] and are also harder to access than a string inverter in the event that changes become required due to interference.