Hybrid AC and DC Smart home resilient architecture

Transforming prosumers in UniRCons

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Abstract - Today's technological developments are drivers for new solutions towards massive renewables deployments resulting in increased network challenges. The paper presents a new approach for prosumers having such a local PV production and storage devices which allows, with adequate design, the user to change from classic prosumer to consumer-only from grid perspective, with enhanced efficiency and resilience based on a hybrid (AC and DC) architecture. Three use-cases are presented: PV behind the meter, PV and storage behind the meter and a newly proposed UniRCon (Unidirectional Resilient Consumer) architecture. This use-cases analysis considers four timeline horizons (2018, 2020, 2022, and 2025). It is shown for the selected profiles of consumption and production that PV plus storage behind the meter bring savings, as recognized and expected by today trend of business-cases, and that the complete UniRCon architecture steps in even with more savings together with higher resilience against the grid outages. The UniRCon solution gives also better ramp behaviour during the evening period, compared with the duck curve expected to challenge power systems with high PV penetration.

Keywords: UniRCon, resilience, net metering, hybrid AC and DC

I. INTRODUCTION

The efforts for ensuring environmental protection pushes the increase of renewables share in the energy mix all over the world. The main renewable sources are wind and solar; moreover, there are countries where one can rely on PV electricity production even during winter. Massive PV-based generation has been analyzed in such sunny regions, and the duck chart of California [1] is one of the well-known case study, presented in Figure 1.

Studies show that a high share of PV-based generation during daytime needs other energy production facilities to cover the gap between the aggregated PV production and the consumption which results in an equivalent duck-form load shown in Figure 1. On 31st March 2017, example shown in Figure 1, the traditional (non-PV) production needs to be increased with approximately 220% starting with 16:00 until peak hours (19-21:00), which asks for a dramatically increase of generation modelled as a ramp of 13 GW in only 3-4 hours. This situation does not cope well with most traditional power plants. This situation is a challenge even in countries with high hydro-power generation, as there is usually not so much installed capacity to support such need.

Figure 1 – Californian duck curve, specific to high solar penetration [1]

For this reason, utilities adopt as a common solution the curtailment of PV production, which can potentially reach 40% ... 50%. Other approaches consider load curve flattening by using, as an alternative, large storage facilities. A combination of these measures may be a solution from the utility perspective.

Long duration storage (LDS) opportunities [3] have great potential for return on investment based on a combination of benefits, such as renewables energy self-consumption, storing energy that would otherwise be lost due to grid constraints, and providing backup power in the event of grid failure.

Microgrids are more and more deployed, particularly in Australia, Africa, far islands but also in US, particularly California and the Northeast [7]. One option to cope with local needs relates to empowerment of the prosumer [5,6].

This paper is targeting network situations before such “duck curve” becomes effective, which correspond to the status in most European countries, where PVs are not yet so high that the network situation approaches the duck curve. Our approach is envisioning different development compared with grid-level measures, i.e. an approach based on Smart home resilient architecture, which can be applied to many consumers on the way to become prosumers by installing local PV and providing design solutions to turn them back into grid customers with load-only energy profile.

II. PROSUMER RESILIENT ARCHITECTURE

Traditional approaches for increasing renewables are based on encouraging either grid-connected RES-based plants (power range 100 kW – 50 MW) mostly connected to the HV, MV and sometime on LV network or on local electricity production from LV connected consumers becoming now prosumers, which have usually 6-10 kW roof-mounted PV. This paper focuses on such local PV installations by proposing a new resilient architecture based on a hybrid AC and DC local network.

The today over-dimensioned roof-mounted PVs can produce during sunny days of summer, with variation due to latitude and season, up to 4-5 kWh/day for each kW installed, going down e.g. to 1 kWh/day/kW during the winter period. It means that during the summer time a 6 to 10 kW PV facility can generate 24 to 40 kWh, which is much more than the 10-20 kWh average daily load of a typical house.

Figure 2. Renewables connected in three *behind the meter* architectures: PV, PV + storage and

In this context, it becomes clear that the over-production requires to be injected into the network, with all effects which have been presented in the first section, like potential need of curtailment; revenues obtained from off-grid storage as a service (SaaS) if such financial scheme is made available to keep network stability. Moreover, back-generation to the grid asks for fulfilling more demanding and expensive grid-connection requirements [2].

In this context the increase of self-consumption becomes a viable approach, supported by the condition of reaching or only approaching grid parity price in many European countries.

In this paper it is analyzed the scenario of a complete self-consumption, with a grid behaviour where there is no back-production into the network. This is labelled as an Uni-directional Resilient Consumer (UniRCon) solution [3], which means that even with local production, there is no AC network injection, thus the prosumer remaining a pure consumer on the LV network side.

Three main architectures are considered, as show in Figure 2. The UniRCon architecture is presented in more detail in Figure 3.

The following notations for quantities to be measured in AC network-side of the prosumer are used:

P_{AC_TOT} : AC active power absorbed from the DSO network;

P_{AC_LL} : AC active power to supply classic / legacy load LL;

P_{AC_IHM} : AC active power to supply UniRCon;

and the following notations are used for the Independent Hybrid Network (IHN), a DC-internal network on prosumer premises which brings resilience:

P_{DC_IN} : DC input power as output of the AC/DC rectifier;

P_{AC_RESIL} : AC active power as output of the inverter which supplies the resilient AC network-side of the IHM.

Figure 3 – The UniRCon resilient prosumer architecture

In the proposed UniRCon paradigm, PV system selection and dimensioning is based on achieving daily the operating condition: higher energy consumption E_{Cons_day} than the local generation E_{PV_day} , condition measured by a sub-unitary factor $K_{(PV_versus_cons)}$

$$E_{PV_day} < E_{Cons_day}$$

$$E_{PV_day} = K_{PV_versus_cons} * E_{Cons_day}$$

In order to analyze the economical attractiveness of the UniRCon architecture, in addition to the advantage of resilience and easiness to connect to the grid as a traditional consumer, we make simulations on typical days of PV production coupled with a typical consumption curve.

III. NUMERICAL SIMULATIONS

Typical days of various seasons are considered, where small PV modules are considered to generate power with a profile based on real measurements scaled for the purpose of the simulation, namely a PV having the peak power of 2 kW, an easy choice for roof-PV residential customers. Figure 4 shows the generation and load curves for five specific days, which are representative within acceptable modelling error the yearly variability: classic shape during a summer sunny day (August 14th); a very low production during winter time (November 29th); partially cloudy days in different seasons.

Figure 5 shows a consumption curve for a typical consumer with 15.7 kWh daily consumption (P_{Day} , in brown), superposed with the daily production curve of the 2 kW small PV during one of the days from Figure 4 (it is selected July 09, in blue).

Figure 5 shows also daily net powers exchanged with the distribution (P_{net} , P_{net1}) network in two different situations:

a) the net power P_{net} which can be measured as average 15 minute with the corresponding net meter M1; this

corresponds to classic net metering and to usual reward with feed-in tariff; the net-metering M1 indicates the energy which corresponds to consumption, including the effect of auto consumption (energy delivered by the grid to the customer);

b) net power P_{net1} measured with the same net meter, but with the condition to have only consumption from grid side, as the excess power during the day being managed by the Resilient Hybrid Microgrid, deploying control algorithm to charge the battery or demand response.

Similar curves have been derived and analysed for a number of representative days; the energy transfer has been assessed in terms of cost savings and resilience for different scenarios, which correspond to near future timelines of year 2018, 2020, 2022 and 2025.

The no-back-generation (UniRCon) during the daytime and the limited consumption during the peak hours in the evening is reducing more than 3 times the grid stress (ramp of energy demand), thus being able to address also in a convenient way the duck curve issue [1].

In order to assess the 4 scenarios, market conditions have been also modelled, by considering different variables such as cost trends for PV and storage related equipment, for communication, for curtailment.

Figure 4 – Production of a 2 kW small PV power plant in representative days during one year

Figure 5 – Consumption, production and net metered curves for one of the considered days (August 04)

Table 1 - Input conditions for calculating the economic aspects of the simulations

No.	Description	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit
1	Cost kWh_battery&Pwr.El. (install)	700	600	500	400	Euro/kWh
2	Number of total cycles for the battery	7000	7500	8000	9000	cycles
3	Cost/kWh storage service in battery	0.100	0.080	0.063	0.044	Euro/kWh
4	Tariff kWh AC network	0.120	0.130	0.140	0.150	Euro/kWh
5	Tariff cheap kWh in AC network	0.060	0.065	0.070	0.075	Euro/kWh
6	Market opportunity factor for cheap buy (classic)	20%	40%	60%	80%	[%]
7	Tariff energy back injection	0.080	0.060	0.040	0.020	Euro/kWh
8	Efficiency of the batteries	90%	91%	93%	95%	[%]
9	Curtail factor for PV excess in the grid	0.00%	10.00%	15.00%	25.00%	[%]
10	Cost of the communication (for PV curtail)	0.100	0.030	0.000	0.000	Euro/day
11	Cost/kW_PV+Pwr.El+install, UniRCon	1000	900	750	600	Euro/kW
12	Cost/kW_PV+Pwr.El+install, classic	1200	1050	900	800	Euro/kW
13	Number of PV hours/year (at PV nominal power)	1200	1200	1200	1200	hours
14	Number of years_PV&Pwr.Electr. (invest. return)	10	10	10	10	years
15	Cost kWh produced, PV with UniRCon	0.083	0.075	0.063	0.050	Euro/kWh
16	Cost kWh produced, PV classic	0.100	0.088	0.075	0.067	Euro/kWh
17	Bat.supl.installed for resilience[kWh]	0.060	0.165	0.220	0.325	kWh
18	Resilience [minutes] with UniRCon	5	15	20	30	minutes
19	Resilience, [%] per day with UniRCon	0.4%	1.0%	1.4%	2.1%	[%]
19	Energy efficiency classic (η_1)	85.0%	86.0%	87.0%	88.0%	[%]
20	Energy efficiency with UniRCon (η_2)	94.0%	95.0%	95.0%	96.0%	[%]
21	Expected year (Horison) to attend scenario	2018	2020	2022	2025	Year

In table 1 it can be seen the input conditions for calculating the economic aspects.

Numerical simulations are based on a simplified model, for which we present below main equations used in the model (1 to 14).

In these formulas, the daily consumed energy is E_{CONS} and the PV produced energy is E_{PV_PROD} . Both are calculated based on average powers on a certain interval time $T_{Interval}$, (i.e. 15 minutes), meaning 0.25 hours. The power at the level of utility net meter P_{NETM} is calculated with (3). In the UniRCon solution, the required battery capacity is the integral of power which may be injected back in the network, if no storage is present behind the meter: E_{BAT_NEC} . However, when the battery is installed behind the meter and has the capacity E_{BAT_MAX} , then the energy which may be effectively sent back to the grid is E_{PV_BCK} , shown in (5). Due to conversion efficiencies, equation (6) can be simplified considering that used PV energy as being affected by the efficiency of inverters and DC-DC converters, which is higher in hybrid networks rather than in pure AC networks (η_{TECHN_x} , with $x=1$ for hybrid inverters and 2 for our internal DC bus in the independent hybrid micro-grid). The remaining energy to be purchased from DSO grid is E_{DSO_USED} derived in (7).

With these definitions costs and savings are further computed for each considered scenario: $C_{E_DSO_CONS_100\%}$ is the cost of energy supplied from the DSO network in case of classic (consumer) behaviour, where $C_{E_Supplier}$ is the cost associated with the energy E_{DSO_USED} to be purchased. Daily costs for using PV and battery are presented in (10) and (11) and are based on

a simplified approach related to return of investment in N_{years} for PV and N_{cycles} for battery.

The simulation considers revenues (or savings) from buying cheap energy from external suppliers using DSO network, deploying a strategy of engaging unused battery capacity (12) with a market opportunity factor K_M (meaning percentage for using the market opportunity which is increasing in time based on increasing experience in accessing such opportunities) and for feed-in tariff of the PV energy sent back in the grid Sav_{SOLD_En} , which are affected by curtailment factors (13).

Finally, daily costs for a prosumer are given by (14) together with the corresponding energy losses in batteries and the cost of deploying a strategy of using the batteries during low PV availability (e.g. in the winter), by charging when market price is lower and discharging when price increases.

$$E_{CONS} = \sum_{Day} P_{CONS}(k) * T_{Interval} \quad (1)$$

$$E_{PV_PROD} = \sum_{Day} P_{PV_PROD}(k) * T_{Interval} \quad (2)$$

$$P_{NETM}(k) = -(P_{CONS}(k) - P_{PV_PROD}(k)) \quad (3)$$

$$E_{BAT_NEC} = \sum_{Day} P_{NETM}(k) * T_{Intrv}, \text{ for } P_{NETM}(k) < 0 \quad (4)$$

$$E_{PV_BCK} = \begin{cases} E_{BAT_NEC}, & \text{if } E_{BAT_NEC} < E_{BAT_MAX} \\ E_{BAT_MAX}, & \text{if } E_{BAT_NEC} > E_{BAT_MAX} \end{cases} \quad (5)$$

$$E_{PV_USED} = (E_{PV_PROD} - E_{PV_BCK}) * \eta_{TECHN_x} \quad (6)$$

$$E_{DSO_USED} = E_{CONS} - E_{PV_USED} \quad (7)$$

$$C_{E_DSO_CONS_100\%} = E_{CONS} * C_{kWh_Supplier} \quad (8)$$

$$C_{E_Supplier} = E_{DSO_USED} * C_{kWh_Supplier} \quad (9)$$

$$C_{PV_per_day} = P_{INST_PV} * \frac{C_{PV_kW_inst}}{N_{Hyear} * N_{years}} * 24 \quad (10)$$

$$C_{BAT_per_day} = (E_{INST_BAT} + E_{INST_RESIL}) * \frac{C_{BAT_kWh_inst}}{N_{Cycles}} \quad (11)$$

$$Sav_{Cheap_En} = E_{BAT_BUY_cheap} * (C_{kWh_Supplier} - C_{kWh_Supplier_cheap}) * K_M \quad (12)$$

$$Sav_{SOLD_En} = E_{PV_BCK} * (1 - K_{Curtail}) \quad (13)$$

$$C_{E_Prosumer} = C_{E_Supplier} + C_{PV_per_day} + C_{BAT_per_day} + C_{BAT_LOSSES} + C_{COMM} - Sav_{CHEAP_EN} - Sav_{SOLD_En} \quad (14)$$

The assessment shows that for each of the scenarios we considered three different use-cases:

- a first use-case, labelled as UC1-NM, is assuming net-metering applied in a classical (traditional) way, with PV on the customer premises, behind the meter, but without storage;
- a second use-case, labelled UC2-NM+Stor, is assuming net-metering applied to a customer with PV and 2 kWh storage capacity on the customer premises, behind the meter, with an algorithm deployed as to ensure as much as possible auto-consume from PV;
- a third use-case, labelled UC3-UniRCon, describes the so-called UniRCon situation where the prosumer is seen always as a load from the grid side, and uses PV production and local storage for achieving auto-consumption and self-resilience features; the use-case considers 2 kWh of storage capacity, in order to allow comparison with the second use case.

Figure 6 shows the savings from each of the use-cases for all the four timelines.

To be noted that in the UniRCon situation, additional storage is considered for supporting resilience during power outages,

which is increasing from 2018 up to 2025 timelines, with corresponding additional costs. The storage used for resilience is such that it brings in 2018 timeline an average of 5 minutes of self-resilience – sufficient to pass short duration events, up to 30 minutes of self-resilience in 2025, when storage technology is expected to be much cheaper than today.

The studied situation considered a daily average consumption of a selected residential point having $E_{CONS}(\text{day})=15.8$ kWh, and $P_{PV}=2$ kW, by treating the consumption and production versus storage in all use cases for typical days from figure 4, having typical energy production of 12.6, 7.54, 4.36 and 0.26 kWh/day (covering all seasons production expectancy), in an average combination which give 1200 h/year of production at nominal PV power, thus having a credible statistical approach.

It can be seen that in the specific case which has been studied, bigger savings have been achieved in the UniRCon situation (use case UC3-UniRCon) comparing with classic net-metering with PV with or without storage behind the meter (+7.3% compared with UC2-NM+Stor, which has also 7.7% more savings compared with classic net-metering without storage UC1-NM).

The higher savings of the use-case UC3-UniRCon comes also with self-resilience by design, which may reduce also the pressure on DSO power quality in terms of KPIs such as SAIDI or SAIFI, thus giving space for new approach of the distribution supplying resilient entities.

IV. CONCLUSIONS

The paper is introducing the UniRCon architecture, where prosumers with adequate network design of the local PV production and storage can become only consumers from the perspective of the DSO. This approach has several advantages on the utility side, as it is keeping the traditional load-only behaviour, for which the network has been designed, and also by minimizing the need of grid-reinforcing due to grid-connected RES and prosumers with much higher production than consumption, i.e. ensuring grid stability with minimum costs. Moreover, the transformation of the prosumer in entities

Figure 6 – Savings comparison for the three use cases: net metering with or without storage and the UniRCon solution

with load-only behaviour brings new optimization capabilities. The paper compares three use-cases, classic PV, PV with storage and prosumer operated as a resilient prosumer with load only behaviour, labelled as UniRCon, (uni-directional resilient consumer).

The analysis considers four scenarios, to be associated with technological and market expectations in 2018, 2020, 2022 and 2025. The input data for each scenario is given in Table 1 and the results for the three use-cases are given in Figure 6. One can observe that for all considered use cases, net metering in case of PV with storage is superior in terms of prosumer savings (8.7% savings), compared with classic PV net-metering, because storage gives more auto-consumption compared with feed-in based back injection, which in time fails to be attractively rewarded.

The UniRCon solution interface to the grid is requiring no specific conditions fulfilment, as it acts as a load-only type of customer., i.e. has lower costs when compared with consequences of application of the latest grid code requirements [2]; it also allows a DC bus on the prosumer premises, with advantages for efficient integration of PV production and storage, bringing also resilience by design for the “natural DC” and some selected AC loads. This architecture is even more attractive than the storage-based net metering, as it brings additional savings other 8% for the simulated scenarios).

UniRCon is superior to classic PV net-metering, in what concerns both savings attractiveness and resilience (the 2025 horizon is 8% better in savings and in addition allows a 60 minutes resilience, making the UniRCon more tolerant to grid outages).

Future work will consider also equivalent costs in the grid reinforcement needed to increase resilience and/or to decrease the outages (e.g. by enhanced SAIDI/SAIFI), which is expected to increase even more the attractiveness of the UniRCon solution.

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