Protection, Automation and Control in Electrical Energy Systems

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***Abstract*—The emergence of prosumers supported by advances in distributed energy technologies have enabled operation of flexible micro-grids. Demand Side Management (DSM) strategies coupled with dynamic tariff structures offer effective means to optimise energy usage and reduce operational costs. Battery Energy Storage Systems (BESS) are integral to these strategies. However, high ownership costs and lack of long-term empirical studies pose significant challenges towards widespread adoption. This paper presents a MATLAB Simulink model of a residential micro-grid comprising 6 grid-connected photovoltaic (PV) households and a centralised BESS system at Point of Common Coupling (PCC). The model evaluates the micro-grid's self-sufficiency, BESS sizing for one-day autonomy and economic impacts of DSM under dynamic tariff regimes. Additionally, the effects of full and surplus PV feed-in strategies are analysed from perspective of a Distribution System Operator (DSO). Simulation results support the deployment of BESS for energy autonomy while dynamic tariffs and full feed-in strategies yield higher economic benefits. The study supports the viability of integrating DSM and BESS for cost-effective, self-sustaining residential micro-grids.**

***Index Terms*—Micro-grids, Battery Energy Storage Systems, dynamic tariffs, feed-in tariffs, Demand Side Management, Photovoltaic Systems, Energy Autonomy**

I. Introduction

In this study, a small micro-grid consists of 6 households is modeled in MATLAB Simulink. Each of them has grid connected PV system, and three-phase load. The Battery Energy Storage System is also conncted at the Point of Common Coupling. The objective of this study is to check the self-reliance of the micro-grid. It also discusses how to enhance the self-reliance of the micro-grid. Moreover, this study analyses the impacts of the Demand-side Management strategies in the micro-grid from Distribution System Operator (DSO) perspective.

To meet the excessive electricity demand, the traditional technique increases the generating facilities. However, this approach is not environmental-friendly. The renewable energy sources and energy management techniques, collectively improves the low reliability of the energy supply that eventually turns into electricity crisis and environmental issues. As a result, Demand-side Management stratagies are important from system reliability, economical and environmental perspective. Demand-side management stratagies enable consumers to alter their load consumption pattern in such a way that energy prices are economical for all [1].

II. Methodology

A. Global Tilted Irradiance Data Retrieving

The Global Tilted Irradiance (GTI) is the total irradiance (direct + diffuse + reflected) on a solar panel with a specified tilt and azimuth angle. The GTI data is retrieved from the open-meteo website via API. This website offers the additional parameters such as geographical coordinates, solar panel tilt angle and azimuth angle. These parameters are configured for Gummersbach, North Rhine-Westphalia, Germany shown in Table I. The 43° South tilt angle is the optimal tilt angle for Gummersbach [2].

TABLE I
Parameter configuration for GTI data

Location	*Latitude*	*Longitude*	*Tilt Angle*
Gummersbach, Germany	51.02	7.56	43° South

The forecasted GTI data is retrieved with 15 minutes temporal resolution for a single day. This data is further interpolated and scaled into 4 seconds time duration then fed into the PV-array block of the SIMSCAPE Electrical library in MATLAB Simulink.

B. Photovoltaic System Modeling

Each household has different electricity generating capacity of PV system. The detailed configuration of the PV system in each household is shown in Table II.

TABLE II
PV rating for each household

Household	*Ns*	*Np*	*PV Output (kW)*
1	5	8	16.5
2	5	5	10.4
3	5	3	6.2
4	5	6	12.4
5	5	4	8.3
6	6	4	10

The PV-array block is connected to the 2-level converter block through DC-DC boost converter. This converter is controlled by Maximum Power Point Tracking (MPPT) utilizing incremental conductance algorithm. It controls the power output of PV array by regulating DC link voltage. Then 2-level converter block converts it into stable three-phase AC voltage output.

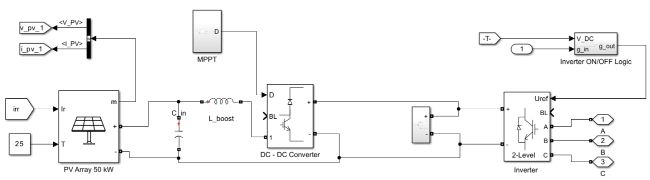

Fig. 1. PV System Modeling in MATLAB Simulink

C. Household Load Modeling

In this study, three-phase household loads are modeled in MATLAB Simulink. Each household has different load consumption pattern throughout a day. The load consumption data has been taken from the zenodo website [3]. The website offers the load consumption data for 38 households measured in a small village in Lower Saxony, Germany with different temporal resolutions. The data has extensive list of features such as per phase active power, reactive power, apparent power, voltage, and current. Out of 38 households, 6 households' active and reactive power consumption data has been taken with 15 minutes temporal resolution for this study. The data is further interpolated and scaled into 4 seconds time duration then fed into the three-phase dynamic load block.

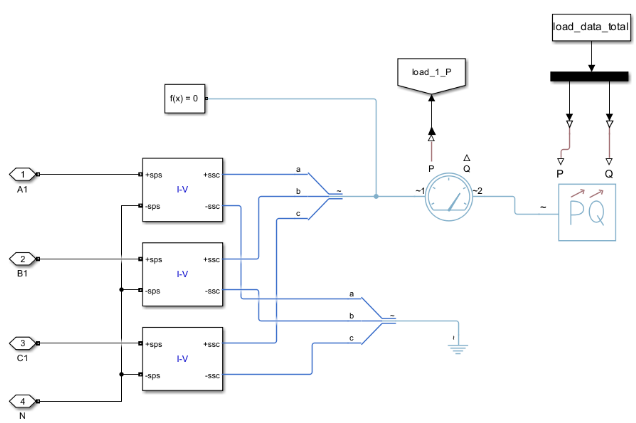

Fig. 2. Load Modeling in MATLAB Simulink

D. Battery Energy Storage System Modeling

Battery Energy Storage System (BESS) is modelled using a Battery connected with a DC link through a bidirectional DC-DC converter. This DC link is connected to the AC grid with a 2-level converter. The inverter blocks for both the PV and BESS are operated in grid-following mode controlled using a Phase Locked-Loop (PLL) controller to synchronise with the grid.

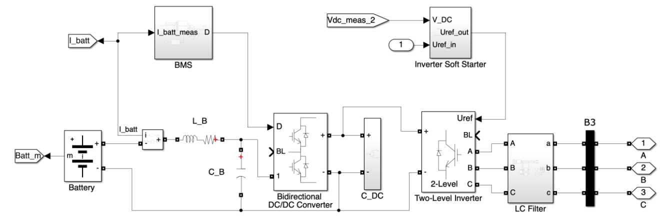

Fig. 3. BESS Modeling in MATLAB Simulink

E. Utility Grid Modeling

The Grid is modelled as a 3-phase symmetric voltage source. It is simulated as a strong grid with S_{sc} of 10 MVA and X/R ratio of 6 [4] and provides voltage and current signals for PLL synchronization of PV and BESS inverter. A grounding transformer is connected with the bus to allow a ground connection for the 3-phase wye connected bus without a neutral. To mitigate reactive power imbalance due to inverter based sources connected with the grid, a 500 VAr capacitor bank is connected with the grid.

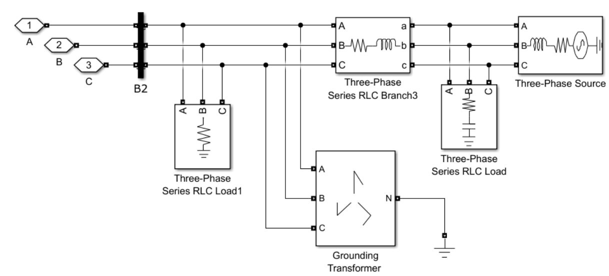

Fig. 4. Grid Modeling in MATLAB Simulink

F. Dynamic Tariff Data

The day-ahead dynamic tariff data has been taken from the SMRAD website [5]. This data has been taken for the Amprion's control area in Germany and the available prices are the exchange prices (Euro/MWh). To convert these exchange prices into consumer-facing prices, first it has been converted into cent/kWh by dividing them by 10. Then aditionally taxes and grid fees (collectively approx. 18 cent) are added to the base price [6]. This data is available for the 1 hour resolution only, and between each timestamp the prices remain constant. This data is further scaled into the 4 seconds time duration as shown in figure 5 and fed into the demand-side control logic block.

The model setup in the MATLAB Simulink environment is shown in Figure 6.

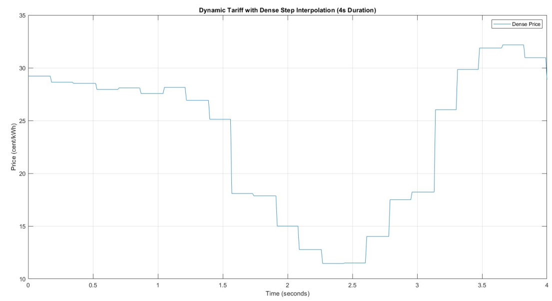

Fig. 5. Dynamic Tariff

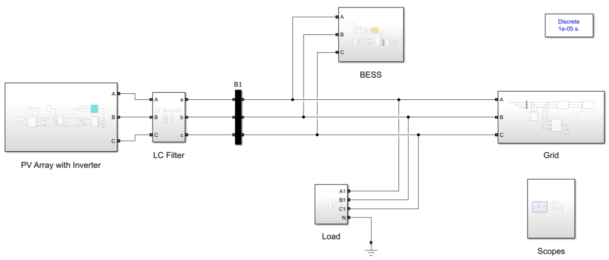

Fig. 6. MATLAB Simulink Setup

III. Results and Discussion

Question 1: Check the self-reliance of the micro-grid. Whether the battery energy storage system is sufficient during less PV generation period or not.

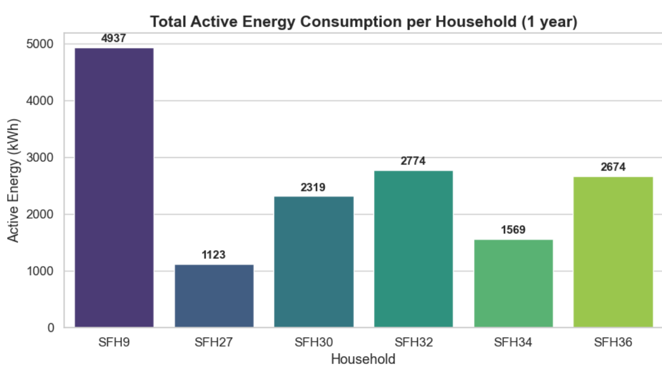

Fig. 7. Active Energy Consumption

Initially, to estimate the size of the battery energy storage system, the following approach has been followed:

Figure 7 shows the active energy consumption(in kWh) of each household over a year in the micro-grid. These 6 households collectively consumes approximately 15,500 kWh of active energy in a year. So, in a day, the micro-grid consumes approximately 42.5 kWh of active energy. The value is further divided by the battery efficiency (98%), followed by inverter efficiency (97.2%) to get the required battery capacity [7]. This gives the required battery capacity of 45 kWh.

Depth of Discharge (DoD) is the percentage of the battery's total capacity that can be safely used without significantly damaging it. The minimum battery size is determined by the following formula [8]:

$$E_{\text{BESS}} \geq \frac{\Delta E}{\text{DoD}} \tag{1}$$

For the lithium-ion battery, the DoD is 80% [9]. This gives the minimum battery size of 56.25 kWh. So, in this study, the BESS is modeled with 60 kWh capacity.

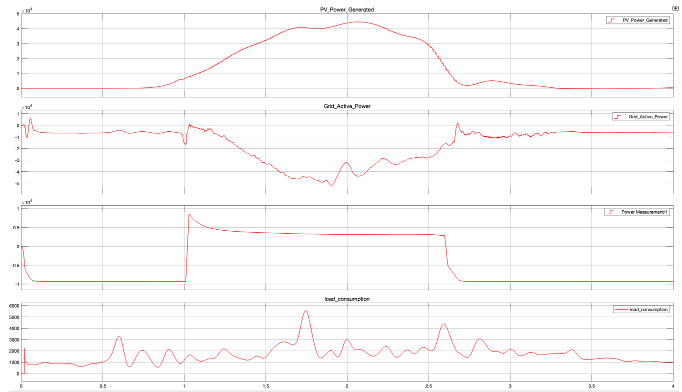

Fig. 8. Simulation Results of Self-reliance

The figure 8 shows the simulation result of the micro-grid with 60 kWh BESS. Initially, for six hours, there is no or minimal PV power generation compared to load demand. During this hours, the BESS is discharging to meet the load demand. However, the BESS power output is nearly 10 kW and the maximum load demand during that period is approximately 3.3 kW. The surplus power is being exported to the grid. That is clearly noticed in the figure.

For next 10-11 hours duration, the collective power generation of the PV systems of six households is more than the load demand. During this hours, PV system itselt is sufficient to meet the load demand and charging the BESS. The suplus power is being exported to the grid.

Similarly, for the rest hours, the BESS is again discharging to meet the load demand and the suplus power is being exported to the grid.

By this observation, it is concluded that the designed micro-grid is self-reliant.

Question 2: Determine the size of the Battery Energy Storage System for the micro-grid for one day autonomy.

The analytical formula for the battery capacity is given by the following equation [10]:

$$C_{\text{Bat}} = \frac{P_L \times D_{AD}}{\eta_{in} \times \eta_{Bat} \times DoD}$$

where, $\mathrm{P_L}$ is the load demand energy in kWh, $\mathrm{D_{AD}}$ is the days of autonomy, η_{in} is the inverter efficiency, η_{Bat} is the battery efficiency, and DoD is the depth of discharge.

For this study, the load demand energy is 42.5 kWh, the days of autonomy is 1 day, the inverter efficiency is 97.2%, the battery efficiency is 98%, and the DoD for the lithium-ion battery is 80% [9].

$$
\begin{aligned}
C_{\text{Bat}} &= \frac{42.5 \times 1}{0.972 \times 0.98 \times 0.8} \\
&= \frac{42.5}{0.762} \\
&= 55.8\,\text{kWh}
\end{aligned}
$$

For this microgrid, the required size of the Battery Energy Storage System is 55.8 kWh for one day of autonomy. This is consistent with previous findings and thus the battery capacity selected in previous question is correct. Furthermore, the analytical formula is validated by previous findings.

Question 3: What is the impact of dynamic tariff implementation in the micro-grid compared to fixed tariff?

To answer this question, PV system and Battery Energy Storage System have not been taken into consideration. The load consumption is fed by the utility grid only. Initially, the simulation has been conducted with fixed tariff of the 34 cent/kWh [11].

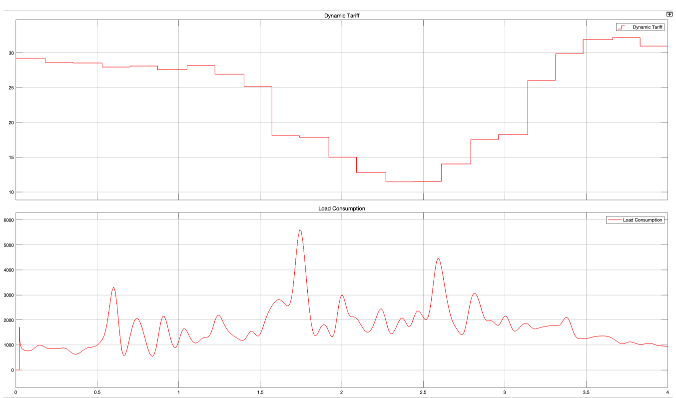

Fig. 9. Simulation Results of Dynamic Tariff

After that, the dynamic tariffs are implemented in the micro-grid as shown in figure 9. It is noticed that during the first 9 hours, the dynamic tariffs are higher than 25 cent/kWh. During next 9 hours, the dynamic tariffs remain lower than 20 cent/kWh. During last 6 hours, tariffs are again higher. Cost calculation for the both simulations is shown in the figure 10.

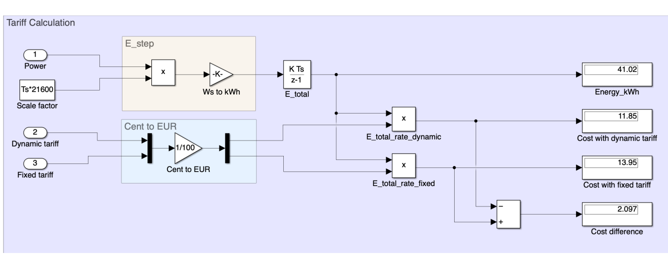

Fig. 10. Tariff Calculation

The energy consumption of the micro-grid is 41.02 kWh for one day. The cost calculation for the fixed tariff is 13.95 Euro, and for the dynamic tariff is 11.85 Euro.

The cost savings is 2.10 Euro for specific one day. It is not significant for the one day simulation data. As dynamic tariff data is available 1-day before (Day-Ahead), the simulation is not possible for more than one day with real data. However, dynamic tariffs are definitely beneficial for the long term like for the weeks or months.

Question 4: What are the impacts of full feed-in and surplus feed-in of PV power generation to the micro-grid?

Feed-in is the energy fed in the utility grid from the PV system, and in exchange to that one receives feed-in tariff. Full feed-in means all energy generated by the PV system is fed in the utility grid, whereas surplus feed-in means the energy which is not consumed and stored in Battery Energy Storage System fed in the utility grid, and in exchange one receives surplus feed-in tariff. In Germany, full feed-in tariff is 12.60 cent/kWh, and surplus feed-in tariff is 7.94 cent/kWh [12].

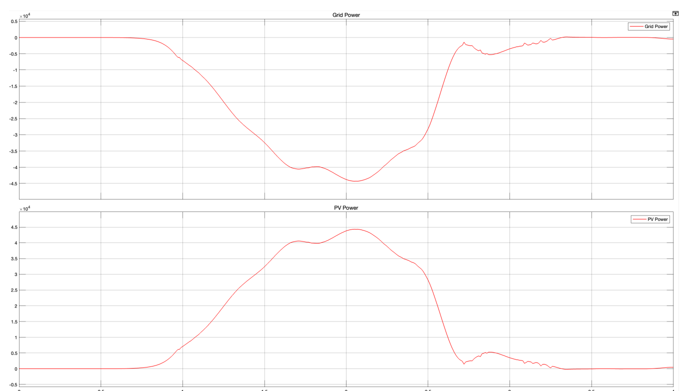

Fig. 11. Full Feed-In

The installed PV system in each household of the micro-grid, collectively generates approximately 325 kWh of energy in a day. For the full feed-in, all of this energy is exported to the utility grid. The simulation result of the full feed-in is shown in figure 11.

Based on the full feed-in tariff, the total revenue from full feed-in is 40.95 Euro for one day. However, the load demand and Battery Energy Storage System is supplied by the utility grid, assumed that the micro-grid has implemented the dynamic tariff. So, the net amount which micro-grid receives for the full feed-in is calculated as follows:

$$
\begin{aligned}
\text{Net Amount} &= \text{Revenue generated} - \text{Import from Grid} \\
&= 40.95 - 11.85 \\
&= 29.10\,\text{Euro}
\end{aligned}
$$

Figure 12 shows the simulation result of the surplus feed-in. During the day time, the PV system feeds the load demand and the Battery Energy Storage System. The excess energy is exported to the utility grid, known as surplus feed-in. The micro-grid exports approximately 281 kWh surplus energy. Based on the surplus feed-in tariff, the total revenue from surplus feed-in is 22.31 Euro for one day.

Thus, in this case, the full feed-in energy is more economically beneficial than the surplus feed-in energy.

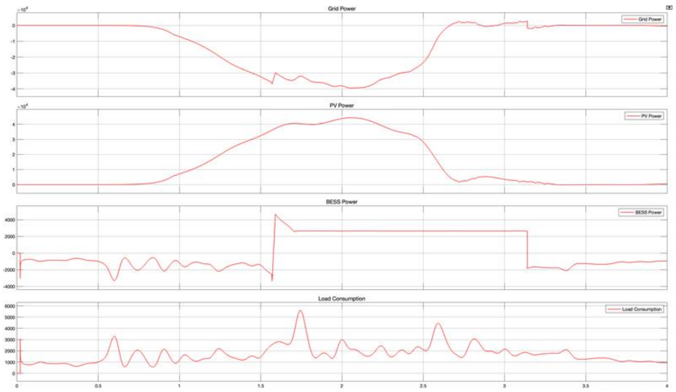

Fig. 12. Surplus Feed-In

IV. Conclusion

In this study, only one day of simulation has been done as dynamic tariff data only available for day ahead prices. To see the significant impact of the dynamic tariffs, based on the historical data (of one year to cover all seasons), using sequential data modeling techniques such as Recurrent Neural Networks (RNN), one week or one month of dynamic tariff data can be forecasted.

This similar approach is applicable for the Global Tilted Irradiance (GTI) and load consumption data forecasting based on the historical data.

V. Micro-grid Model

The detailed micro-grid model is available on the Github repository: https://github.com/warlock1102/PACEES_Project

References

[1] A. H. Nebey, "Recent advancement in demand side energy management system for optimal energy utilization," *Energy Reports*, vol. 11, pp. 5422–5435, 06 2024.

[2] A. Robinson, "Solar pv analysis of gummersbach, germany," Profilesolar.com, 01 2025. [Online]. Available: https://profilesolar.com/locations/Germany/Gummersbach/

[3] M. Schlemminger, T. Ohrdes, E. Schneider, and M. Knoop, "Wpuq," *Zenodo (CERN European Organization for Nuclear Research)*, 11 2021. [Online]. Available: https://zenodo.org/records/5642902

[4] Z. Xu, N. Zhang, Z. Zhang, and Y. Huang, "The definition of power grid strength and its calculation methods for power systems with high proportion nonsynchronous-machine sources," *Energies*, vol. 16, p. 1842, 01 2023. [Online]. Available: https://www.mdpi.com/1996-1073/16/4/1842

[5] "Smard — smard - market data," Smard.de, 03 2025. [Online]. Available: https://www.smard.de/en

[6] "Net electricity prices for end customers fall below zero for first time in germany," pv magazine International, 05 2025. [Online]. Available: https://www.pv-magazine.com/2025/05/14/net-electricity-prices-for-end-customers-fall-below-zero/

[7] C. D. GmbH, "Tps hv 80 e industrial energy storage — tesvolt ag," TESVOLT AG, 2022. [Online]. Available: https://www.tesvolt.com/en/products/e-series/tps-hv-80-e.html

[8] A. Ashabi, M. M. Peiravi, P. Nikpendar, S. S. Nasab, and F. Jaryani, "Optimal sizing of battery energy storage system in commercial buildings utilizing techno-economic analysis," *International journal of engineering. Transactions B: Applications*, vol. 35, pp. 1662–1673, 01 2022.

[9] S. Secure, "The importance of depth of discharge (dod) in battery performance," Solar-secure.com.au, 2025. [Online]. Available: https://www.solar-secure.com.au/blog/the-importance-of-depth-of-discharge-in-battery-performance/

[10] M. Gupta and A. Bhargava, "Optimal design of hybrid renewable-energy microgrid system: a techno–economic–environment–social–reliability perspective," *Clean energy*, vol. 8, pp. 66–83, 01 2024. [Online]. Available: https://academic.oup.com/ce/article/8/1/66/7513378

[11] Statista, "Electricity prices around the world 2018 — statista," Statista, 2018. [Online]. Available: https://www.statista.com/statistics/263492/electricity-prices-in-selected-countries/

[12] "Welcome to zscaler directory authentication," Enpal.de, 2025. [Online]. Available: https://www.enpal.de/photovoltaik/einspeiseverguetung