UNIVERSITY OF MISKOLC
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DEVELOPMENT AND TESTING OF AN INTELLIGENT HYBRID SOLAR UNINTERRUPTIBLE POWER SYSTEM

THESIS BOOKLET

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1. INTRODUCTION

1.1. Actuality of the topic and the state of the art

Smart solar hybrid uninterruptible power systems and their optimized dynamic power management are a relatively new and interdisciplinary research area. It requires a high level of continuous economic and technological research. The integration of uninterruptible energy-storage PV systems has been considered and researched since the 2000s, but progress has only been made in the last decade. This is when the need for optimization and energy management increased due to increased consumption and the use of renewable energy sources. Hybrid uninterruptible power systems are designed to supply consumers for a short time in the event of a power outage. The name "hybrid" comes from the fact that the system combines several types of energy storage, making the supply more reliable and diverse. The energy management system decides from which energy storage or electronic converter the inverter supplies the consumers. The basic task of the energy management system is to deliver energy to the consumers in an economical way with maximum efficiency. This requires managing energy storage, optimizing generators, developing economic models and selecting modes of operation.

The dynamic energy management of hybrid, uninterruptible systems has thus become an increasingly prominent area of research due to the increasing use of renewable energy sources and the growing energy demands. This has led to the need for the development of advanced control and optimization methods to ensure economical and reliable operation of systems under different operating conditions. Similarly, the development of DC nano- and microgrids requires continuous innovation, as they contribute to sustainable energy management not only by diversifying energy sources, but also by efficiently interacting with the central grid.

The current development of micro- and nanogrids has been the result of a long process. Previously, research by Nassef et al. introduced bidirectional power control between the grid and the microgrid [1]. Chen and colleagues have also made progress in the field of DC voltage control. They described how two generators simultaneously supply the consumer, how this can be balanced and demonstrated this by measurements [2]. Research has also been done on energy management strategy, Zhang and his colleagues have researched the continuous maintenance of power balance between generators (solar panel, battery, supercapacitor) [3]. In addition, different operating states are presented, which relate to energy flows. Unfortunately, a system stability problem is caused by the fact that the DC voltage varies by about 10 V for the different operating states, while large oscillations occur.

DC micro- and nanogrids will continue to be very popular research topics in the future. This is due to the increasing number of energy storage devices currently being integrated into electrical circuits. In previous research, system stability was not satisfactory. Furthermore, load balancing between parallel producers integrated into the system needed to be improved, especially when the consumption varies or the environment has an impact on the producers. For this purpose, adaptive or dual-loop load-dependent droop control has been explored [4], [5].

Droop control plays a critical role in maintaining the stability of the system and helps to dynamically distribute the load.

Droop control is still a relevant research topic in 2024, as the response of previous algorithms to transients is rather slow, a question that Yang and colleagues have addressed [6]. An important line of future research is droop control, complemented by energy management. In all these research, the problem is tuning the system with conventional PID controllers combined with a difficult to tune fuzzy controller or with complex modelling procedures based on calculations. Kanwal and colleagues have implemented sliding mode droop control combined with neural networks for autonomous microgrids [7]. In this research, artificial neural networks are already emerging, but they only make predictions about solar panel production. Overall, current research focuses on optimizing the DC voltage quality metrics as environmental parameters change. They do not consider the economics of buying electricity from storage and generation.

Consumers who buy electricity on a 15-minute settlement are considering installing solar panels, or energy management, and are forced to use different strategies to reduce costs. Energy management is a higher level and slower control compared to droop control. Energy management is planning, for example, taking into account the expected weather or based on energy demand. In 2015, Bhavsar and colleagues published research in which a DC microgrid can be disconnected from the grid by a static switch, the switch is controlled by the energy management algorithm [8]. The problem with this kind of regulation is that it does not aim to be optimal, but it is possible that buying all electricity would reduce energy costs. In 2020, Santos Neto and colleagues presented a technical approach to linking the DC microgrid to the AC grid. They showed that it is optimal to use the energy bought from the AC grid and the energy produced by DC generators in different proportions [9]. This solution indirectly reduces the lifetime of batteries and individual system components, while reducing grid dependency, but the authors did not consider the economic aspects. It is expected that soon time-series (quarter-hourly) billing will be replaced by minute-by-minute billing, thus requiring research into management procedures and algorithms that dynamically intervene in DC micro- and nano-grids. However, the challenge is not only the management arising from time series accounting, but also the additional cost arising from peak load. This creates incentives for consumers to reduce system load. Optimized energy management is not only necessary for consumers, but also for the grid. It will undoubtedly contribute to increasing the reliability of the grid. Shahid described in his paper how to connect a grid-interactive microgrid system to the grid [10]. His system can operate in stand-alone and grid-connected mode, while supplying consumers connected to the microgrid without interruption. The results show that the efficiency of the system and the quality of electricity supply are excellent, while the system also improves the power factor. On the other hand, the research did not address the economic aspects.

Although current research has made significant progress in the field of stability and performance optimization of DC micro- and nanogrids, many challenges remain. Future research must not only address existing technological problems, such as transients caused by droop control, but also consider the economics of power distribution, where power sharing must be dynamically controlled. The integration of energy storage systems is expected to increase in the coming years, as well as the introduction of time-series billing systems, even for residential customers, which will put further pressure on the development of energy management systems. Thus, researchers are looking for new algorithms and management strategies that can ensure the stability and economic operation of systems in the face of dynamically changing environmental and market conditions.

1.2. The objective of the dissertation

My objective in this PhD thesis is to develop an intelligent hybrid solar uninterruptible power system within the framework of the topic group of measurement and control information systems, which integrates separate systems such as solar cells, uninterruptible power supplies and uninterruptible asynchronous motor drives. Furthermore, for this combined system, I will develop the algorithm and block scheme of the central control unit, which implements power sharing without droop control, combined with voltage control. I develop two control strategies for the central controller. One strategy involves conventional PID controllers, and the other strategy implements intelligent artificial neural networks for power sharing and voltage regulation in the system. My goal is to develop a new algorithm for the neural network that facilitates training. By simulations, I investigate the sensitivity of a hybrid solar uninterruptible system with PID controllers and a neural network, including the resulting harmful transients and harmonics. For validation purposes, I will also implement a manually controlled hybrid uninterruptible PV system and measure it, also for sensitivity testing. For the measurements, I will implement electronic converters of my own design, so that I can change parameters that are not possible to modify when using factory equipment. The aim of the measurements is to prove that the developed system can be implemented in practice.

For the developed centralized control strategies, I create an energy management system that sets the power sharing based on a new economic model, i.e., generates the power sharing setpoint for the centralized controller. The economic model and computational methods I develop allow the power management to always ensure the lowest possible unit cost of electricity in the system, while helping to maximize battery lifetime.

2. NEW RESULTS

In the following chapter, methodological problems, new scientific results and theses are presented.

2.1. Hybrid solar uninterruptible power system

2.1.1. Methodological problem statement

The main challenge in developing hybrid uninterruptible systems is to integrate different energy sources (grid, battery and solar) and to ensure proper power sharing. Conventional uninterruptible power supplies typically consist of a rectifier, battery and inverter, while PV systems offer a separate power supply solution. In current industrial practice, these systems operate independently of each other, even though a more efficient and cost-effective integration could be achieved by using a common DC grid.

Solutions in the literature mainly use droop control to provide power sharing in micro- and nano-grids. However, this method can cause voltage fluctuations and instability problems, especially for nonlinear generators and variable loads. For smaller, non-autonomous hybrid systems, droop control could be omitted, but there is no clear methodology on how to achieve stable power sharing without droop for two distributed electronic converters.

The research raised several methodological problems. Currently, there is no scientifically sound methodology for power sharing without droop control for two distributed generators in uninterruptible systems combined with PV, which poses a significant regulatory challenge. Abandoning droop control requires a new control strategy to ensure stable operation under varying load conditions and different energy sources. A further methodological problem is the compatibility of older uninterruptible systems with thyristor rectifiers with modern PV systems, as rectifiers can cause grid distortions that need to be taken into account in the new control approach.

To solve these problems, I have developed a centralized control strategy that uses a central controller to dynamically adjust the operation of the rectifier and LLC converter, ensuring stable voltage regulation and desired power sharing. The developed control strategy was validated in MATLAB/Simulink environment and laboratory experiments were conducted for sensitivity testing. The results demonstrated that centralized control provides a more efficient and stable solution than conventional droop-based approaches and allows for cost-effective integration of uninterruptible and PV systems.

2.1.2. Results

In this subsection the developed central control method is presented, which is shown in *Figure 1.* The parameters shown in the figure are described in time by *Equations 1 to 4,* which are satisfied only if *Equation 5* is true and the three-phase voltage system is symmetric, i.e. the three line voltages (U_{RS}, U_{ST}, U_{TR}) are equivalent.

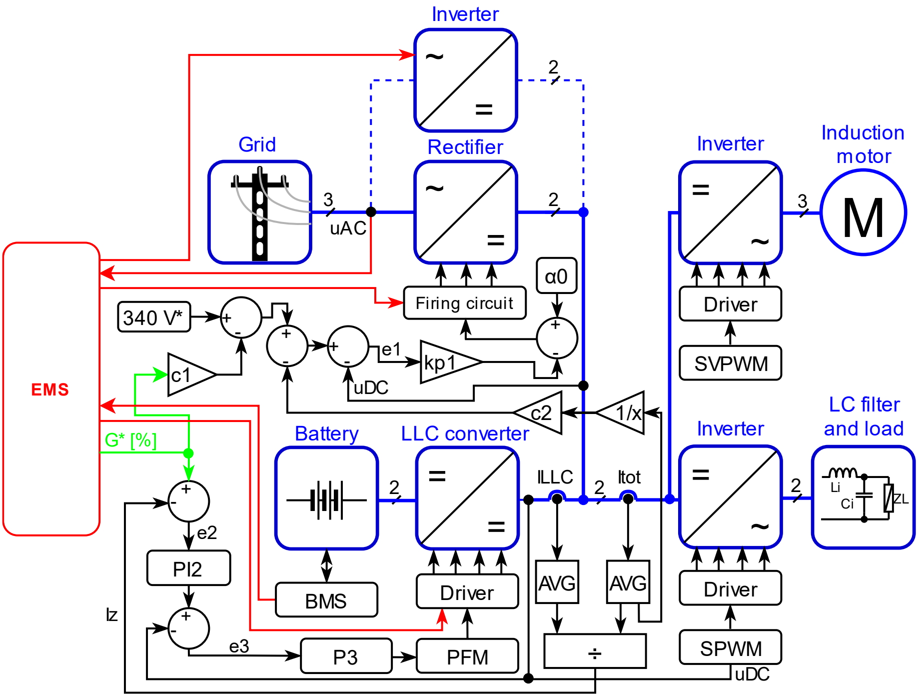

Fig. 1: *Central control strategy for hybrid PV uninterruptible system with thyristor rectifier*

$$e_2(t) = G^*(t) - \frac{\frac{1}{T}\int_0^T i_{LLC}(t)dt}{\frac{1}{T}\int_0^T i_{össz}(t)dt} \tag{1}$$

$$e_3(t) = \left(K_{p2}e_2(t) + K_{i2}\int_0^T e_2(t)\,dt\right) - u_{DC}(t) \tag{2}$$

$$f_{sw}(t) = \left(K_{p3} e_3(t) + K_{i3} \int_0^T e_3(t)\, dt \right) \quad (3)$$

$$\alpha(t) = a_0 - K_{p1} \left(\left(\left(U_{DC}{}^{*} - c_1 \cdot G^{*}(t) \right) - \frac{c_2}{\frac{1}{T} \int_0^T i_{\ddot{o}ssz}(t) dt} \right) - u_{DC}(t) \right) \quad (4)$$

$$\mathrm{U_{0DC}} < \sqrt{2} \cdot U_{RS} \cdot \sin \frac{2\pi}{3}, \quad (5)$$

where: U_{0DC} is the average value of the DC voltage.

2.1.3. Formation of Thesis 1.

I have developed a new centralized control strategy for hybrid uninterruptible photovoltaic systems that allow power sharing without droop control. It can be applied to a DC circuit fed by a thyristor rectifier and an LLC converter, while implementing both primary and secondary control levels in the controller.

Related publications: [S1], [S2], [S3], [S4], [S5], [S7], [S8], [S9], [S10], [S11], [S12]

2.2. Intelligent dynamic power sharing

2.2.1. Methodological problem statement

A fundamental requirement for stable and efficient operation of hybrid uninterruptible systems is the stability of the DC bus voltage, which has a direct impact on both power sharing and energy efficiency. The centralized control strategy without droop control presented in the previous chapter provides a reliable solution for system control, in which the P and PI controllers ensure an appropriate dynamic behavior. However, the efficiency and stability of the control is significantly affected by the tuning of the controllers, which is a complex and time-consuming process, especially under varying load conditions and renewable energy sources.

The research has identified several methodological challenges that directly affect the stability and efficiency of the system. Ensuring the voltage stability of the DC bus voltage is of paramount importance for system operation, especially under dynamically varying load and generation conditions. The key element of the control strategy is the proper tuning of the P and PI controllers, which is a significant challenge as a balance between fast dynamic response and low steady-state error has to be achieved.

Fine tuning of conventional PID controllers, both manually and automatically, is a time-consuming task and not always able to adapt well to changing operating conditions. Therefore, modern control engineering approaches, such as neural network-based control, are gaining more and more attention, offering the possibility to implement adaptive control.

This can reduce voltage fluctuations, improve the quality of supply to consumers and ensure dynamic power sharing, which is essential for efficient system operation. To solve these problems, research has developed an intelligent control strategy that uses adaptive, intelligent control solutions to stabilize the DC bus voltage instead of conventional P and PI controllers. The method reduces the need for manual parameter tuning while increasing the responsiveness and stability of the control system. The effectiveness of the new control strategy is demonstrated using MATLAB/Simulink simulations. The results show that intelligent control provides more stable and adaptive operation than using only conventional PID controllers.

2.2.2. Results

The hybrid uninterruptible system and the corresponding smart control strategy are shown in *Figure 2.* The main circuit consists of the grid, rectifier, battery, LLC converter, and inverters. In the main circuit, the rectifier and the LLC converter need to be controlled in order to share the power and to stabilize the DC bus voltage. These converters are regulated by an artificial neural network-based unit with inputs of green current base signal (G*), load resistance (R_t) and battery voltage (u_{bat}). An active rectifier is used in the figure, but a thyristor rectifier can also be used.

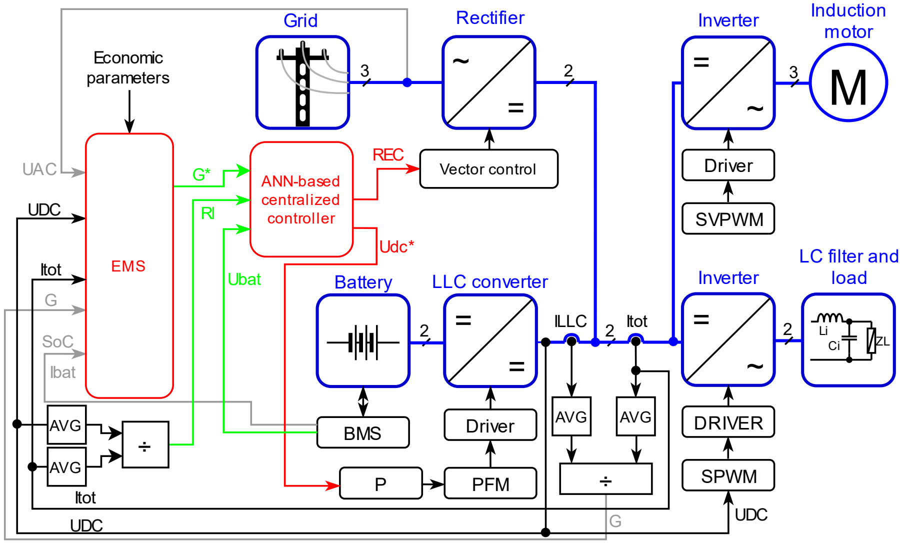

Fig. 2: Intelligent central control strategy with active rectifier

The G* green current setpoint (power sharing rate) is generated by an intelligent energy management system considering operational (technical) parameters and economic aspects. The operating parameters are: the grid voltage (u_{AC}), the DC bus voltage (u_{DC}), the total inverter current (i_{tot}), the actual green current ratio (G), the battery state of charge (SoC), and the battery current (i_{bat}). Economic parameters such as the current tariff (weighted average price) of grid electricity, LCOE of energy extracted from battery, LCOE of energy extracted from solar panel.

The data set for neural network training is generated by the algorithm shown in *Figure 3.*

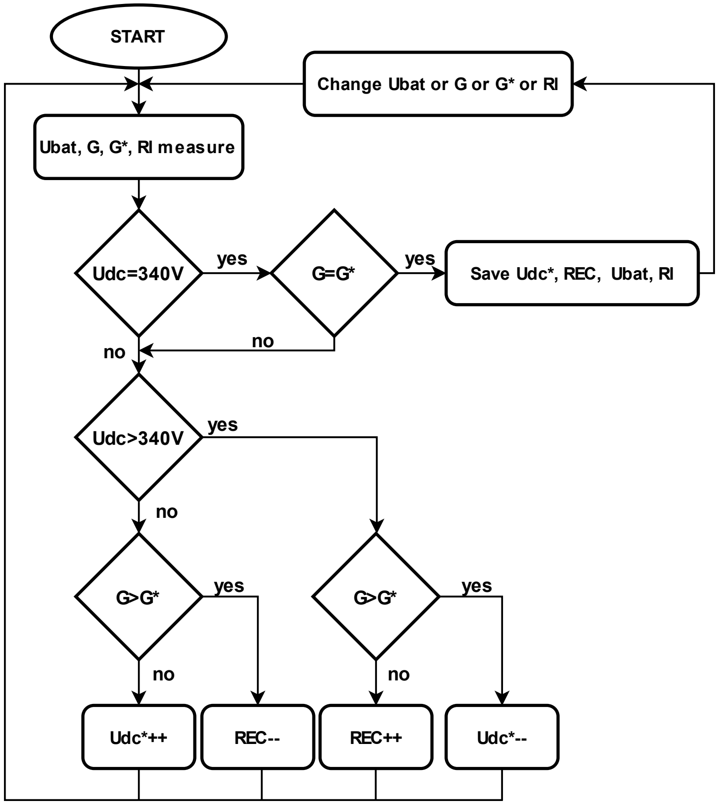

Fig. 3: *Identifier algorithm for hybrid PV uninterruptible power system with thyristor rectifier*

When the algorithm starts, it gets the desired green current ratio setpoint signal and measures the battery voltage, the magnitude of the green current ratio, the magnitude of the load. It then compares the voltage of the DC bus with the desired value (e.g. 340 V). If not equal, it also tests for equality. If the U_{dc} voltage is greater than 340 V and the green current ratio is greater than the desired value, then increase the firing angle for a thyristor rectifier. If G is greater than the desired value

(G*), then the base signal of the LLC converter is reduced, and so on. The process runs until the DC bus voltage and the green current ratio reach the desired value. When this happens, the algorithm saves the base signals of the converters, the battery voltage and the load magnitude. The algorithm shall be run for multiple battery voltage, load and green current ratio setpoint signals to cover all possible values in the system and to include values for extreme values in the data set.

For active (Park-vector controlled) rectifiers, minimal modification to the algorithm is required. If $U_{dc} < 340$ V and $G > G^*$, then REC parameter increase is required. Furthermore, if $U_{dc} > 340$ V and $G < G^*$, then REC parameter reduction is required

The incrementing and decrementing rates can be set by a ramping method.

2.2.3. Formation of Thesis 2.

I developed a new central control method for hybrid PV uninterruptible systems that use an artificial neural network to control the DC bus voltage and power sharing between the grid rectifier and LLC converter without using droop control. I developed a new identifier algorithm that allows the neural network to be easily trained. The developed control method implements primary and secondary control levels.

Related publications: [S6]

2.3. Optimized intelligent energy management

2.3.1. Methodological problem statement

Optimizing the operation of hybrid PV uninterruptible systems requires a dynamic energy management strategy that can determine the power allocation from each energy source in real time. The aim of the control is to continuously adjust the green current ratio, considering not only operational parameters but also economic factors.

Based on current research, the energy management of hybrid solar uninterruptible systems does not consider the life cycle specific energy cost (LCOE) of each generator, electronic converter and energy storage. However, the calculation of the LCOE indicator is essential for the design of systems that can be operated economically in the long term. One of the biggest challenges in energy management is to reconcile the investment and operating costs of different installations with actual energy production and consumption data.

The research has identified several methodological challenges that directly affect the effectiveness of energy management. Currently, energy management systems do not apply LCOE-based decision making, so the optimization of power sharing does not consider the true economic efficiency of each energy source. Consequently, system operation does not always ensure the best economics and energy efficiency in the long term.

To solve these problems, it is necessary to develop a dynamic energy management model that can determine the optimal green electricity yield by considering both operational and economic parameters. This will ensure that the system is not only technically stable but also economically sustainable, considering the investment and operating costs of each energy source.

2.3.2. Results

In the following subsection, the equations for the developed economic model are presented, based on which the economically optimal control of the uninterruptible system at the working point is achieved.

$$C_{\Delta bat} = \frac{20}{Cycle_x} [\%]$$

$$t_{dis} = \frac{C_{bat}}{{I_{bat}}^k} \ [h]$$

$$C_{real} = t_{dis} \cdot I_{bat} = \frac{C_{bat}}{{I_{bat}}^k} \cdot I_{bat} \ [\text{Ah}]$$

$$E_{real} = \frac{U_{batnom} \cdot C_{real}}{1000} \ [kWh]$$

$$C_{\frac{real}{kWh}} = \frac{E_{real} \cdot DoD}{100} \ [kWh]$$

$$C_{\Delta real} = \frac{C_{\Delta bat}}{C_{\frac{real}{kWh}}} \left[\frac{\%}{kWh}\right]$$

$$LCOE_{bat} = \frac{C_{\Delta real}}{20} \cdot C_{inbat} \left[\frac{EUR}{kWh}\right]$$

$$LCOE_{bat} = \frac{\frac{10^5}{Cycle_x}}{U_{batnom} \cdot \frac{C_{bat}}{{I_{bat}}^k} \cdot I_{bat} \cdot DoD} \cdot C_{inbat} \left[\frac{EUR}{kWh}\right]$$

$$LCOE_{batreg}(I_{bat}, DoD) = c_0 + c_1 \cdot I_{bat} + c_2 \cdot DoD + c_3 \cdot {I_{bat}}^2 +$$
$$+c_4 \cdot DoD^2 + c_5 \cdot I_{bat} \cdot DoD + c_6 \cdot {I_{bat}}^3 + c_7 \cdot DoD^3 + c_8 \cdot {I_{bat}}^2 \cdot DoD +$$
$$+c_9 \cdot I_{bat} \cdot DoD^2 + c_{10} \cdot {I_{bat}}^4 + c_{11} \cdot DoD^4 +$$
$$+c_{12} \cdot {I_{bat}}^3 \cdot DoD + c_{13} \cdot I_{bat} \cdot DoD^3 + c_{14} \cdot {I_{bat}}^2 \cdot DoD^2 \left[\frac{Ft}{kWh}\right]$$

$$LCOE_{batPV0} = \frac{G_{PV0}}{100} \cdot LCOE_{batregrealPV0}(I_{batrealPV0}, DoD) +$$
$$+\left(1 - \frac{G_{PV0}}{100} \cdot C_{grid}\right) \left[\frac{EUR}{kWh}\right]$$

$$I_{batrealPV0} = \frac{P_{tot} \cdot 1000}{U_{bat}} \cdot \frac{G_{PV0}}{100} \cdot \frac{100}{\eta_{LLC}} =$$
$$= \frac{P_{tot} \cdot 1000}{U_{bat}} \cdot \frac{G_{PV0}}{\eta_{LLC}} \; [A]$$

$$\eta_{LLC} = f \cdot \left(1 - e^{-g \cdot \frac{P_{tot}}{P_L} \cdot 100}\right) \; [\%]$$

$$LCOE_{PV} = \frac{C_{inPV}}{E_{25year} \cdot \eta_{charge}} \left[\frac{EUR}{kWh}\right]$$

$$LCOE_{LLC} = \frac{C_{inLLC}}{365 \cdot 24 \cdot T_{LLC} \cdot P_{LLC}} \approx \frac{C_{inLLC}}{E_{25year}} \left[\frac{EUR}{kWh}\right]$$

$$LCOE_{totPV0} = \frac{G_{PV0}}{100} \cdot \left(LCOE_{PV} + LCOE_{LLC} + LCOE_{batregrealPV0}\right) + \\ + \left(1 - \frac{G_{PV0}}{100} \cdot C_{grid}\right) \left[\frac{EUR}{kWh}\right]$$

$$G_{OPTPV0} = e_1 P_{tot}{}^6 + e_2 P_{tot}{}^5 + e_3 P_{tot}{}^4 + e_4 P_{tot}{}^3 + \\ + e_5 P_{tot}{}^2 + e_6 P_{tot} + e_7$$

$$G_{PV} = \begin{cases} \dfrac{100 \cdot (P_{PV} + P_{batPV0})}{P_{tot}}, if\ G_{PV} \leq 100 \\ 100, \quad if\ G_{PV} > 100 \end{cases} [\%]$$

$$P_{batPV0} = P_{tot} - P_{gridPV0}\ [kW]$$

$$P_{gridPV0} = P_{tot} - \left(\frac{G_{PV0}}{100} \cdot P_{tot}\right) [kW]$$

$$P_{batPV0} = P_{tot} \cdot \frac{G_{PV0}}{100}\ [kW]$$

$$I_{batrealPV} = \begin{cases} \dfrac{100 \cdot I_{required}}{\eta_{LLC}}, if\ I_{realPV} \geq 0 \\ I_{required}, \quad if\ I_{realPV} < 0 \end{cases} [A]$$

$$\eta_{LLC} = f \cdot \left(1 - e^{-g \cdot \left(\frac{P_{tot}}{P_L} \cdot G_{PV}\right)}\right) [\%]$$

$$I_{required} = \frac{1000 \cdot P_{batPV}}{U_{bat}}\ [A]$$

$$P_{batPV} = P_{tot} - P_{grid} - P_{PV}\ [kW]$$

$$P_{grid} = \begin{cases} 0, & if\ P_{PV} \geq P_{gridPV0} \\ P_{tot} - P_{PV} - P_{batPV0}, & if\ P_{PV} < P_{gridPV0} \end{cases} [kW]$$

$$LCOE_{totPV} = \frac{G_{PV}}{100} \cdot \left(LCOE_{PV} + LCOE_{LLC} + LCOE_{batregrealPV}\right) + \\ + \left(\frac{100 - G_{PV}}{100} \cdot C_{grid}\right) \left[\frac{EUR}{kWh}\right] \\ \text{if } I_{batrealPV} \geq 0$$

$$LCOE_{totPV} = LCOE_{PV} + LCOE_{LLC} \left[\frac{EUR}{kWh}\right], \qquad if\ I_{batrealPV} < 0$$

$$LCOE_{totPV} = 0 \left[\frac{EUR}{kWh}\right], \qquad if\ P_{tot} = 0$$

$$G_{PV} = \begin{cases} 0, & if\ C_{grid} \leq 0 \\ \dfrac{100 \cdot (P_{PV} + P_{batPV0})}{P_{tot}}, & if\ C_{grid} > 0 \end{cases} [\%]$$

For example, *Figures 4* and *5* illustrate how the total LCOE and power sharing (green current share) vary as a function of load, grid cost and solar panel output when DoD is 70%.

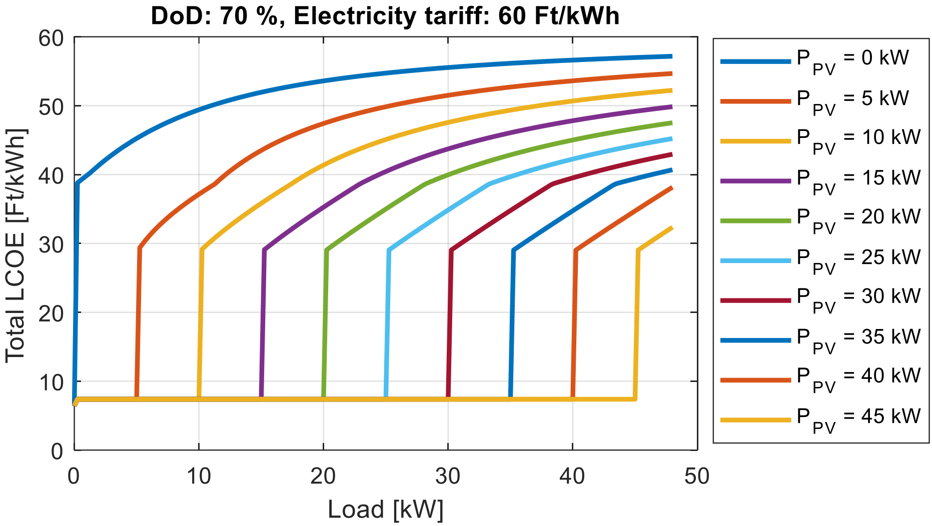

Fig. 4: *Total LCOE as a function of load for different PV production*

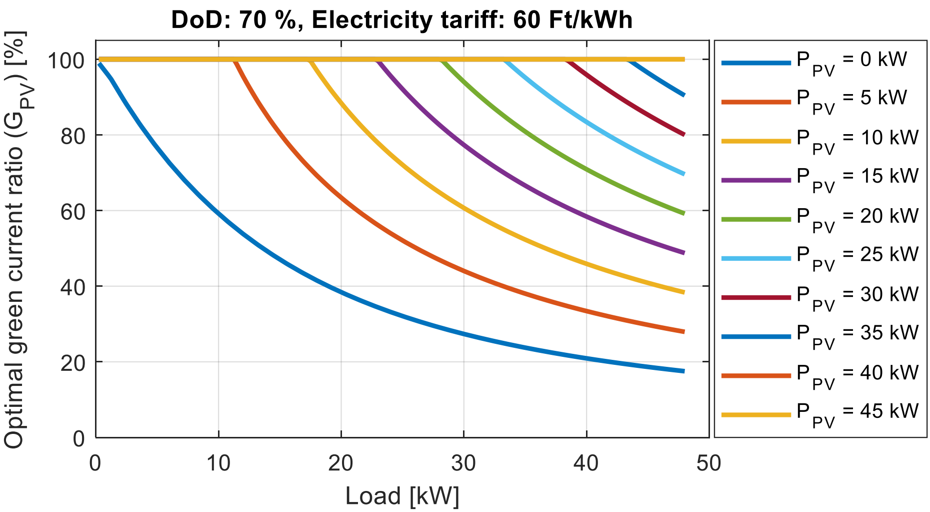

Fig. 5: *Optimal green current ratio as a function of load for different PV production*

2.3.3. Formation of Thesis 3.

I have developed a new economic model and a calculation method for the economically optimal operation of hybrid uninterruptible PV systems, based on which the power management determines the power sharing of two parallel generators. The model can be used to control the distributed generators in real time, while considering the grid energy tariff and the specific energy cost of the system components over their entire life cycle. It also considers the actual electrical parameters (load, PV generation, battery voltage). All these are considered for the economically optimal control of the working point.

Related publications: [S6], [S13]

3. SUMMARY

In the early stages of my research, I discovered that integrating PV systems, uninterruptible power supplies and uninterruptible motor drives into a grid can substantially reduce system investment costs. This finding was further reinforced by the observation that the legal environment for PV systems in Hungary had recently undergone substantial and rapid changes, which had a considerable impact on both residential and industrial investments. Initially, the focus was on small-scale residential systems; however, as time progressed, the potential in industrial systems became increasingly evident. These systems, with their established time-series accounting, offer a higher potential for cost savings. A comprehensive literature review revealed that microgrid and nanogrid systems integrate the aforementioned systems, function as independent controllable units, and possess the capability to supply electricity in a diversified manner. However, given my research objective of reducing investment and operating costs, the further development of microgrid and nanogrid systems was not a viable option, as they are known to have significant initial costs. Consequently, my research shifted to hybrid uninterruptible power systems, which are more cost-effective to install in practice.

A comprehensive review of the extant literature indicates that in hybrid UPS systems, incorporating microgrid and nanogrid systems, the interaction of individual electronic converters, consumers and producers is a critical issue. When multiple system components are supplying consumers concurrently, effective control of power distribution and the provision of reliable electricity become paramount. Power distribution is facilitated by droop controllers, the stability of which is also a crucial consideration. The findings of this study suggest that, for smaller systems, the implementation of power sharing without droop controllers is a viable option. To this end, the development of control strategies that facilitate the implementation of power sharing while stabilizing the vol has been undertaken. In the future, there is still a lot of research to be done on smart, solar, hybrid combined systems. The optimization algorithm for an intelligent central control unit could be created by a team of engineers and economists. The resulting algorithm can work according to a predefined equation or even rely on artificial intelligence. The parameters of an intelligent combined system must be defined individually, system-specific, making it difficult to formulate a general equation or algorithm. It is also a challenge to express the operation of the combined system in mathematical form, since there are many parameters in the system whose values can only be estimated in order of magnitude.

My objective was to develop energy management for control methods and system topology that would allow to achieve an economically optimal operating point. I have developed a new economic and optimization model to determine the LCOE of the electricity consumed for each system element. I have also demonstrated by demonstrations that it is worthwhile controlling the power sharing in solar hybrid uninterruptible systems in real time, as a function of several parameters. In the literature search, I did not come across any publications in which power sharing was adjusted based on the LCOE of each system element, loads, generation and grid energy price, so this is also a new area of research. Optimization also results in an increase in battery lifetime, so in summary, not only more cost-effective but also more sustainable uninterruptible systems can be implemented in practice. I would venture to say that in the future, quarter-hourly billing will be replaced by much more dynamic time intervals, making the use of energy management systems even more important.

In the future, there is still a lot of research to be done on smart, solar, hybrid uninterruptible power systems. Further studies are needed to fine-tune the energy management algorithm, especially in the areas of real-time decision making and predictive control. Energy management could consider the expected weather, expected electricity tariffs, consumption patterns, planned outages, etc. The identification algorithm for smart control could be further developed for three or more distributed generators. In this case, it would be worth comparing it with the efficiency of droop control. In the years to come, the increasing penetration of renewable energy sources is expected to make similar systems smarter and more efficient, making practical applications of these developments even more important.

4. AUTHOR’S PUBLICATIONS

4.1. Quality publications related to the dissertation:

[S1] R. R. Boros and I. Bodnár, „LLC Resonant Converter Design and Simulation for PV Motor Drives”, in *22nd International Carpathian Control Conference (ICCC 2021)*, 2021, o. 1–5. (**Scopus**, **WoS**, number of citations: **2**)

[S2] R. R. Boros and I. Bodnár, „Grid and PV Fed Uninterruptible Induction Motor Drive Implementation and Measurements,” *ENERGIES*, vol. 15, no. 3, 2022.
(**Scopus**, **WoS**, **Q1**, **IF: 3.2**, number of citations: **4**)

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