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To enhance efficiency in photovoltaic systems using optimization methods in battery management system

Penumala Poornima, Kannan Boopathy
Department of Electrical and Electronics Engineering, Aarupadai Veedu Institute of Technology, Vinayaka Mission's Research Foundation, Deemed to be University, Chennai, India

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ABSTRACT

Battery management systems (BMS) have undergone significant advancements over the years, transitioning from basic control strategies to sophisticated optimization algorithms. Historically, established BMS approaches were limited in their ability to handle energy efficiently, often leading to suboptimal power utilization and higher total harmonic distortion (THD). Integration of in a BMS application in modern days. advanced algorithms, such as flying squirrel search optimization (FSSO), have been optimized using grey wolf optimizer (GWO), and artificial neural network (ANN) significantly enhanced the performance of the system. These algorithms are efficient in terms of optimizing the duty cycle, whereby there is even a healthy energy flow between renewable load requirements and power requirements. These algorithms are analyzed, and their effectiveness in comparing their effectiveness is different operational scenarios. GWO algorithm is indicated as having the best reduction of THD and consequently improving the quality of power in a minimized way reliability. The ANN shows great expertise in voltage. regulating, low level of THD. Meanwhile, the FSSO algorithm shows significant potential in improving energy efficiency and reducing operational costs, despite its higher THD levels in current phases. GWO has a minimal current THD of 4.65% in Phase 1, exceeding ANN and FSSO. ANN has a voltage THD of 10.61%. FSSO has greater current THD values over 15% and good voltage control, highlighting decisions.

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Corresponding Author:

Penumala Poornima
Department of Electrical and Electronics Engineering, Aarupadai Veedu Institute of Technology
Vinayaka Mission's Research Foundation, Deemed to be University
Chennai, Tamil Nadu, India
Email: poorni07p@gmail.com

1. INTRODUCTION

State-of-health (SOH) estimate of lithium-ion batteries, energy storage optimization in microgrids, and power conversion control in grid-connected applications are the main topics of this literature review, which looks at recent developments in energy management and storage systems. Increasing the efficiency of wind power, electric vehicles (EVs), and industrial systems using deep learning, sophisticated algorithms, and real-time data analytics are important topics. Deep learning and differential thermal voltammetry (DTV) are recent developments in the estimation of lithium-ion battery SOH. Peaks, valleys, and integral values are used as health indicators (HIs) in a study [1] that extracts DTV curves to examine battery degeneration. These HIs are linked to capacity via Pearson correlation, and an LSTM network increases the accuracy of SOH estimation by 11.6% MAE and 10.01% root mean square error (RMSE).

Energy distribution is optimized for EV charging stations with a shared energy storage system (ESS) via a unique distributed coordination technique. It balances load, lowers peak demand, and boosts efficiency by utilizing real-time data, which results in significant cost savings [2]. Quadratic programming is used to optimize ESS in DC microgrids, minimizing degradation and guaranteeing peak performance. This model improves microgrid performance, increases ESS lifespan, and forecasts lifecycle costs [3]. In grid-connected applications, a control strategy for DC-DC converters based on supercapacitors improves stability [4]. The ideal BESS size for wind power dispatchability is found via an iterative heuristic optimization technique. It improves economic feasibility and reduces intermittency [5].

Even with advancements in battery management systems (BMS), minimizing total harmonic distortion (THD) while maximising system efficiency is still difficult. For renewable energy storage technologies to be dependable and effective, BMS are essential. The conventional approaches of BMS cope with simple charge and discharge management and tend to result in high THD. Serious THD reduces the efficiency and power quality of the system. In order to improve BMS performance, ANN, grey wolf optimizer (GWO), and flying squirrel search optimization (FSSO) are advanced methods of optimization that are examined in recent research. However, the voltage and current THD between various optimization methods is better compared with a careful methodology. Non-existent, and most of the contemporary studies focus on either one methodology or limited conditions. Compared to ANN, GWO, and FSSO in reducing THD in BMS, providing numerical information about the algorithm performance, and finding out which strategy would be the most reliable and effective in terms of energy management, this paper satisfies this research gap. The present study is a novel method as it tests numerous optimization methods simultaneously. quantitative measures of performance and bode suggestions on how the BMS is to work and be designed.

2. MICROGRID PV AND ENERGY STORAGE DEVICE

The microgrid system is a combination of a photovoltaic (PV) system and a BMS that manages and distributes electrical power efficiently [6]. Some of the elements that are incorporated in the diagram are voltage source converters (VSC), load management units, and control systems, which emphasize an extensive configuration of the dependable energy management [7]. The PV system is the most important energy source that taps sun energy and transforms it into electricity. The system uses maximum power point tracking (MPPT) methods to guarantee the maximum power output under varying solar conditions [8]. Direct current (DC) generated is then changed to alternating current (AC) power by the inverters to be used in the microgrid [9]. BMS is paramount in storing surplus energy that is produced by the PV system and to power it when the solar generation is low [10]. The BMS looks after the fact that the batteries are working within safe parameters. It entertains the prevention of overcharging and deep discharging, which prolongs the battery life and ensures system dependability. It also controls the charge and discharge cycle to maintain the demand and supply of the load [11]. VSC control is usual with things, unit ensures that there are stability and quality of the power distributed into the grid [12]. It regulates the voltage and current by operating the inverters with the adjustment and synchronization of them with the grid parameters [13]. The control unit is also useful in controlling the flow of power between the PV system, battery storage, and the grid [14]. The system has several loads (Load1, Load2, Load3) which are linked to the microgrid, representing the various power consumers [15]. Managing every load is done in order to maintain a balance and efficient management distribution of power. The loads may be ranked according to importance and power outage, which will improve the dependability of the power supply [16]. The increasing use of EVs points out the fundamentals of a planned efficiently charging network [17]. End usage load shapes describe a process of generating correct electricity data of load profile of specific city [18]. The hybrid system of the microgrid combining PV and BMS provides a strong one solution to effective energy management. The PV system is integrated as demonstrated in the simulation model whereby an ESS controlled and BMS was in Figure 1.

The system allows by means of advanced control methods and efficient management of loads stable, efficient, and dependable power supply, which would be suitable in the home and business use. Further enhancement of control algorithms and addition of more can be made in order to improve it in the future. renewable energy resources in case of more sustainability [19]. Before using the system, it consists of a PV array and a bi-directional battery converter, and a distributed grid having multi-loads [20]. Figure 2 demonstrates that the PV output power is maximum varies with the different levels of irradiance with the BMS varying the duty cycle dynamically have the best energy saving.

BMS is a very efficient tool that will be able to control the incorporation between the PV systems and the storage of energy [21], [22]. It manages energy balanced allocation, is able to hold constant load current and voltage, and is able to adjust to variable conditions of irradiance and load [23]. This brings in the prospects of improved optimization algorithms in not only improving the performance [24] and reliability of renewable energy systems [25] but also making sure to design an efficient one stable grid integration [26].

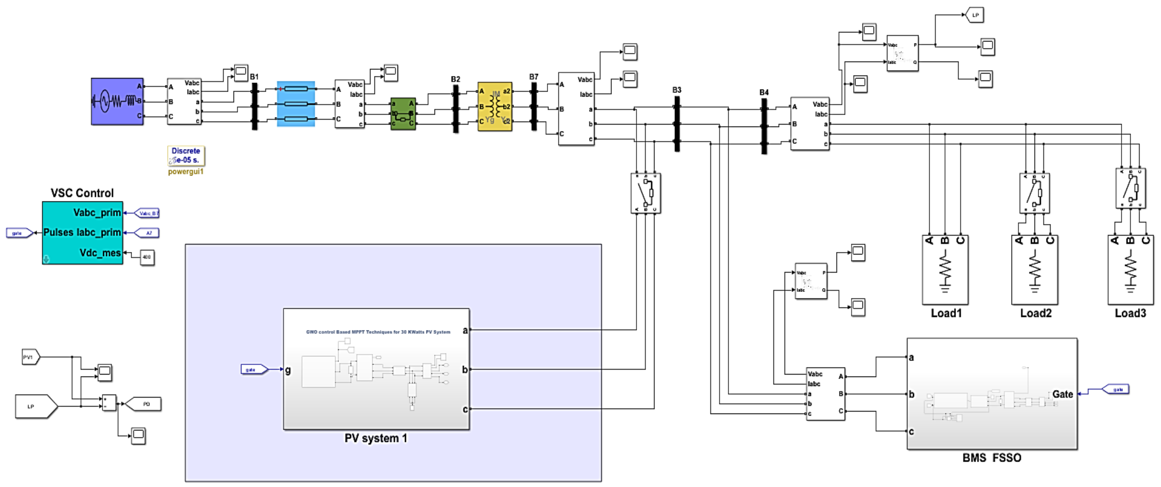


Figure 1. Simulation model of grid integration of PV system with ESS

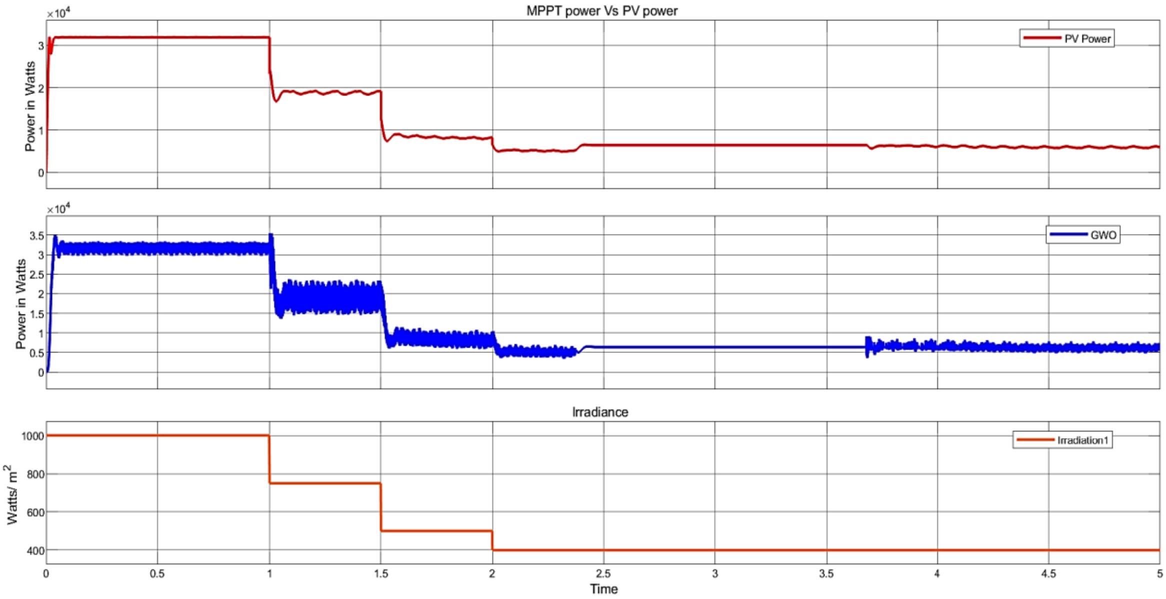


Figure 2. PV output power waveform under various irradiance

3. FSSO ENERGY MANAGEMENT SYSTEMS

The grid stability is crucial in terms of combining PV systems with battery energy storage and a good supply of power. In this report, the use of the FSSO algorithm is examined with regards to optimization of the adaptation of PV systems and BMS to the grid. The FSSO algorithm was based on the gliding flight as well as the foraging behavior of flying squirrels. It is a blend of exploration and exploitation with the aim of solving effectively. Difficult optimization tasks, and thus it is especially applicable in energy management. In the purpose of PV and BMS integration, the first optimization goals will be energy maximization efficiency, improving reliability, and minimizing costs. The approach will entail the collection of real-time information. PV panels, batteries, grid interactions with the FSSO algorithm, controlling the conversion of control parameters, and testing and validating the optimized system with different operating conditions with simulation models. The main characteristics of FSSO are that it always has an adaptive exploration phase, where this algorithm tries to explore a broad solution space, as well as its exploitation stage, which narrows the search to obtain the most superior solutions.

Assessment of an FSSO-founded BMS is concerned with its performance and THD analysis in different operating conditions. The FSSO algorithm also maximizes the duty cycle to equalize renewable power inputs and load demands effectively. Figure 3 represents the structure of the system in which renewable power (RP) and load are fed into the system varies power (LP) as inputs to get the optimal duty cycle by use of the FSSO algorithm. The most important elements of the BMS constitute a battery, LC filter, and inverter that make it stable and effective in terms of energy consumption. management. Figure 4 indicates that the FSSO-based BMS and release voltage phase chart in the form of THD are presented in Figure 5, and the THD current stage of the FSSO-based system is presented in Figure 6.

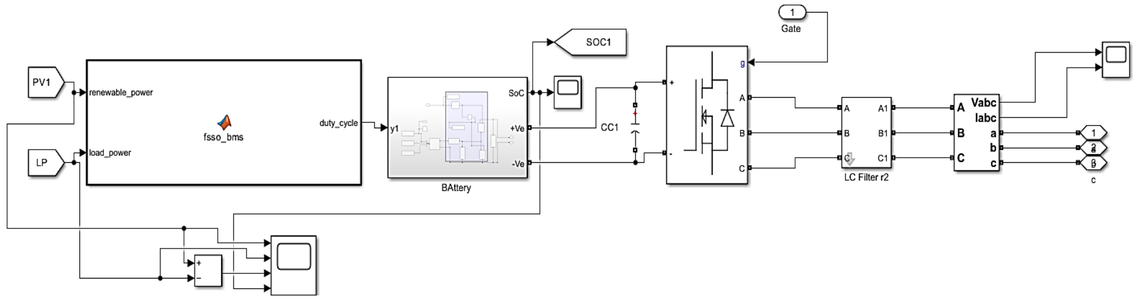


Figure 3. FSSO-based battery management system

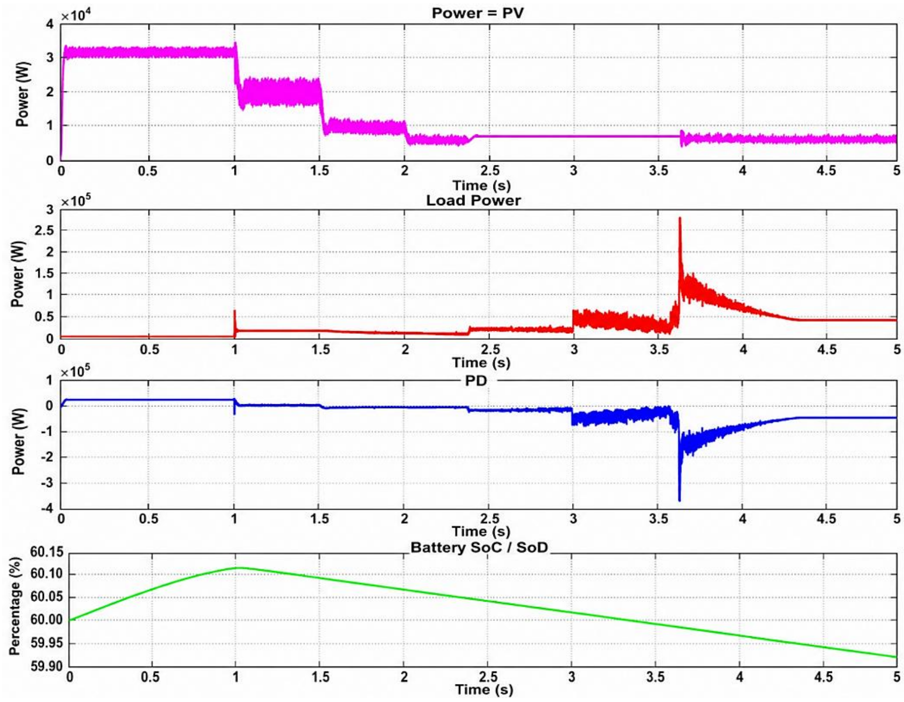


Figure 4. FSSO-based battery management under various operating conditions

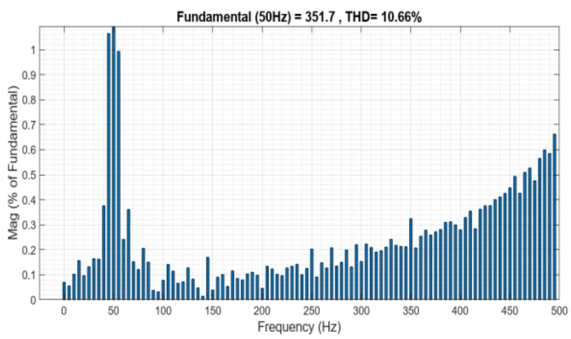


Figure 5. FSSO – THD voltage Phase

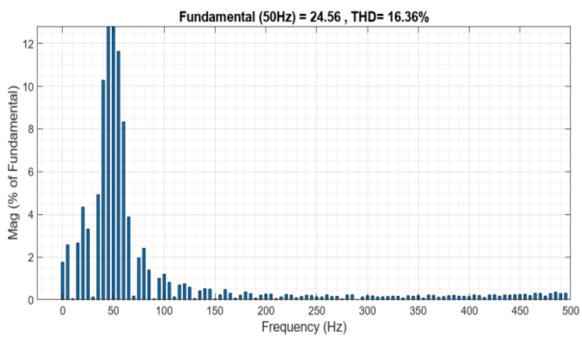


Figure 6. FSSO – THD current Phase 1

4. GWO-BASED ENERGY MANAGEMENT SYSTEM

The combination of PV systems and BMS is essential to improve the stability of the grids and guarantee a stable power supply. In this report, the GWO algorithm is considered when it comes to grid integration optimization of PV systems and BMS. The GWO algorithm fulfils these goals by maximizing power conversion, storage, and distribution control parameters. It includes the real-time data gathering of PV panels, batteries, and grid interactions, the use of the GWO algorithm to identify optimal settings, and the simulation to verify the optimized system. The GWO algorithm has two key steps in the main loop, where every iteration consists of two steps:

i) Fitness evaluation: Fitness of individual wolves is computed using the calculated fitness. The function assesses the suitability of the individual potential duty cycles to the optimization objective. In case the fitness of current wolf is more than that of the alpha wolf, the alpha wolf is corrected to the current wolf position, and the alpha score is updated to the current wolf fitness score.

ii) Position update: The wolves update their position depending on their relative position to the alpha wolf. The parameter is reduced in a linear fashion between 2 to 0 as a progression of the iterations, and this is used to regulate the convergence of the algorithm. The social hierarchy and influence of the alpha wolf is modeled using the parameters of A and C. The new location of the wolves is then computed and kept within the range [0, 1]. The general layout of the GWO-based BMS presented in Figure 7 is the system that combines inputs of RP and LP to provide the optimal duty cycle to manage the battery. The parts of the system, such as the battery, LC filter, and the output voltage, are made such that there is constant operation of the system, with the duty cycle being changed depending on the GWO algorithm. Figure 8 shows the performance of GWO-based BMS in varying operating conditions. The plots show the power of PV, load power, power difference (PD), and battery state of charge (SoC) power. The GWO is also efficient in controlling the flow of energy and keeping the battery within the optimum SoC range as well as balancing the power produced and consumed. For a measured waveform with harmonic amplitude Vn and fundamental amplitude V1 is described in (1). Here, V1 is the RMS value of the voltage's fundamental component, Vn is the RMS value of the voltage's nth fundamental component, and N is the highest order of harmonic. THD analysis is critical for assessing the power quality in the BMS.

$$THD = \frac{\sqrt{\sum_{n=2}^{N} V_n^2}}{V_1} \times 100\% \tag{1}$$

The evaluation of a GWO-based BMS is presented with an emphasis on system performance and THD analysis. The GWO algorithm optimizes the duty cycle to ensure efficient energy management between renewable power sources and load demands.

In Figure 9, Phase 1 voltage shows a fundamental frequency of 50 Hz with a magnitude of 353.8 and a THD of 10.61%. For current phases, Figure 10 shows Phase 1 with a fundamental frequency of 50 Hz and a THD of 4.65%. Finally, the BMS based on GWO proves to have good energy management and maximization in different circumstances. The THD analysis shows the ability of the system to retain power quality, having different degrees of harmonic distortion in different phases.

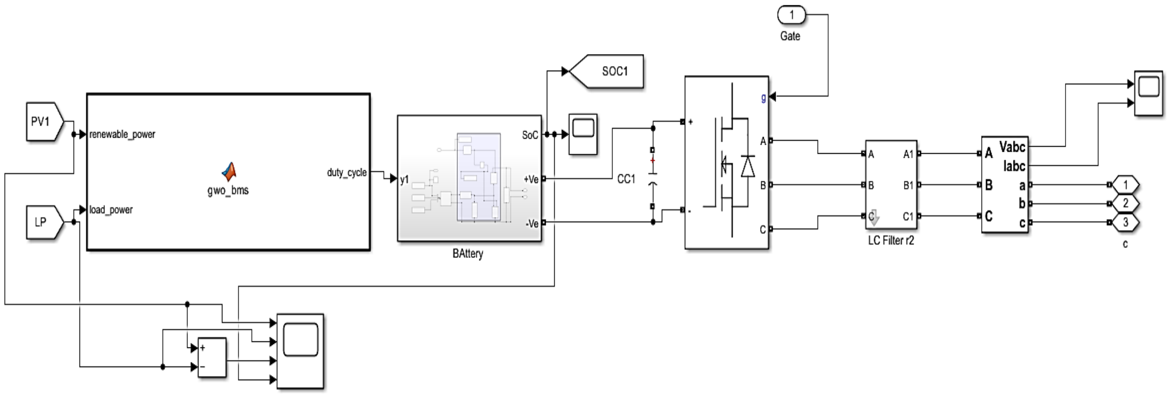


Figure 7. GWO-based battery management system

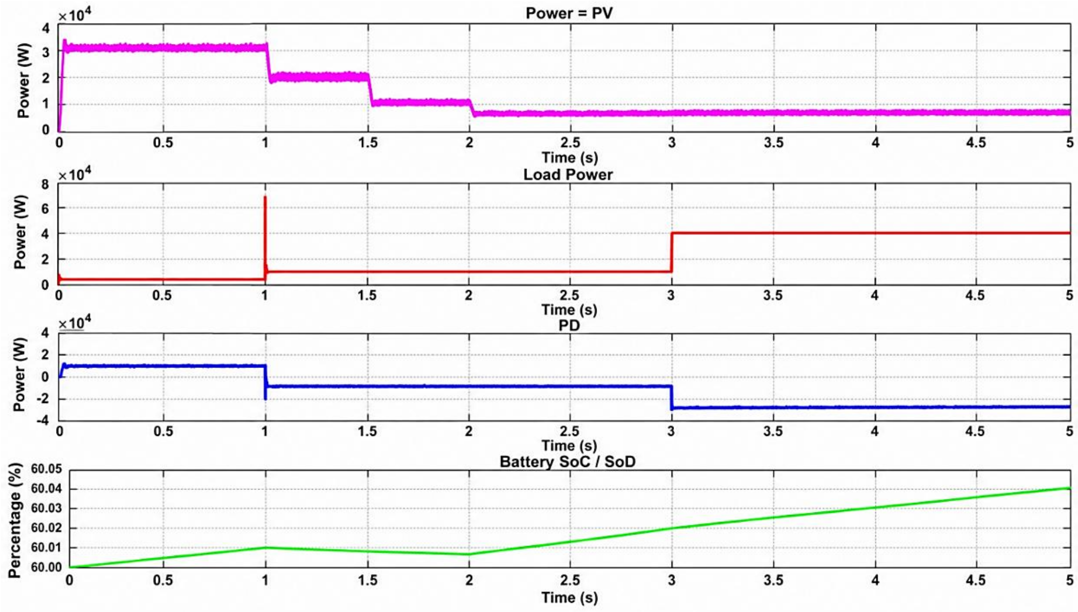


Figure 8. GWO based battery management under various operating conditions

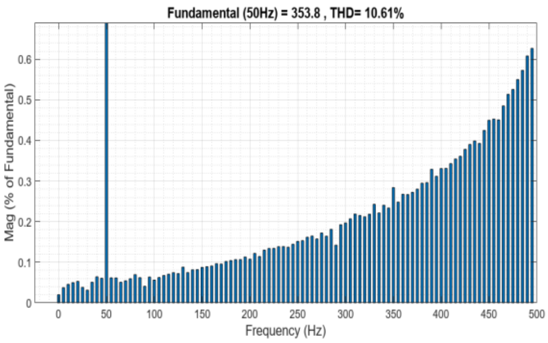


Figure 9. GWO – THD voltage Phase 1

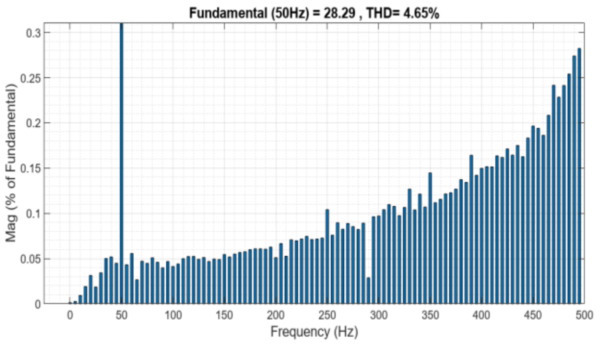


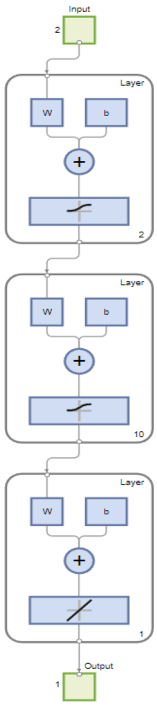
Figure 10. GWO – THD current Phase 1

5. ANN BASED ENERGY MANAGEMENT SYSTEM

The combination of PV systems and BMS is crucial to enhance the stability of the grid and provide a reliable power supply. This report discusses the use of ANN using a feed forward network structure, maximizing the grid assimilation of PV systems and BMS. The feed forward network of ANN is a potent one. Machine learning model that can process nonlinear relationships in data which is complex and therefore best suited to energy management applications. In the PV and BMS integration, the major objectives are optimizing energy consumption, improving system reliability, and lowering the costs of operation. The ANN feedforward network attains these aims through learning past and real-time data to forecast optimal control parameters of power conversion, storage, and power distribution. This implementation and ANN performance of a BMS and GWO performance. The BMS is essential in the effective management of energy, especially in the systems that use renewable sources. They are used to compute ANN-based and GWO maximize the duty cycle and the general performance of the BMS. The architecture is shown in Figure 11.

The network is made up of various layers whereby there are input, hidden, and output layers. The input layer is fed by two parameters, and the hidden layers process the information using weights and biases to produce one output which is the duty cycle. The regression results are presented in Figures 12 and 13, illustrating the performance of the ANN model on the training, validation, testing, and overall datasets. The correlation coefficients (R-values) are large approaching 1 suggest a great deal of correspondence between the actual and the predicted values. This is confirmation of the ability of ANN to behave on the BMS itself with a high degree of accuracy on different conditions.

The GWO-based BMS performance to various conditions of operation is presented in Figure 14. Analysis of THD in ANN based BMS indicates that significant information on the quality of power in the system can be observed. The THD analysis is imperative because it shows the amount of distortion that is brought about by the harmonics within the system. For voltage phases, Figure 15 shows that Phase 1 has a fundamental frequency of 50 Hz with a magnitude of 355.1 and a THD of 10.61%. The plot indicates significant harmonic components around the fundamental frequency and at higher frequencies. For current phases, Figure 16 shows Phase 1 with a fundamental frequency of 50 Hz, a magnitude of 25.95, and a THD of 19.39%.



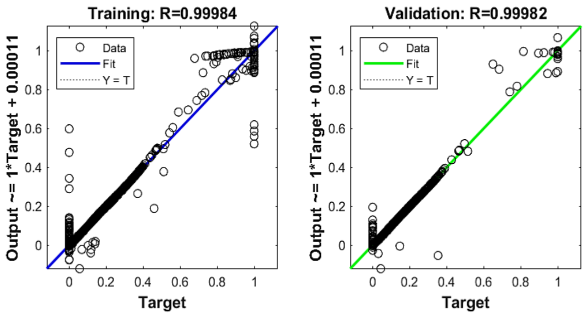


Figure 12. ANN training and validation results

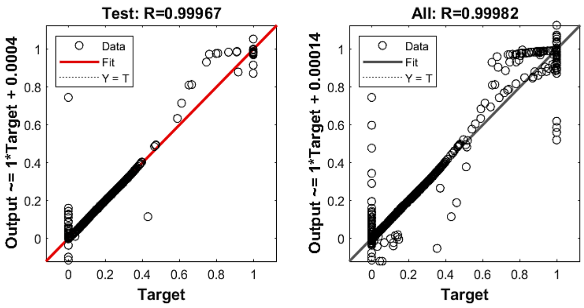


Figure 11. ANN algorithm for battery management system

Figure 13. ANN algorithm test and overall regression results

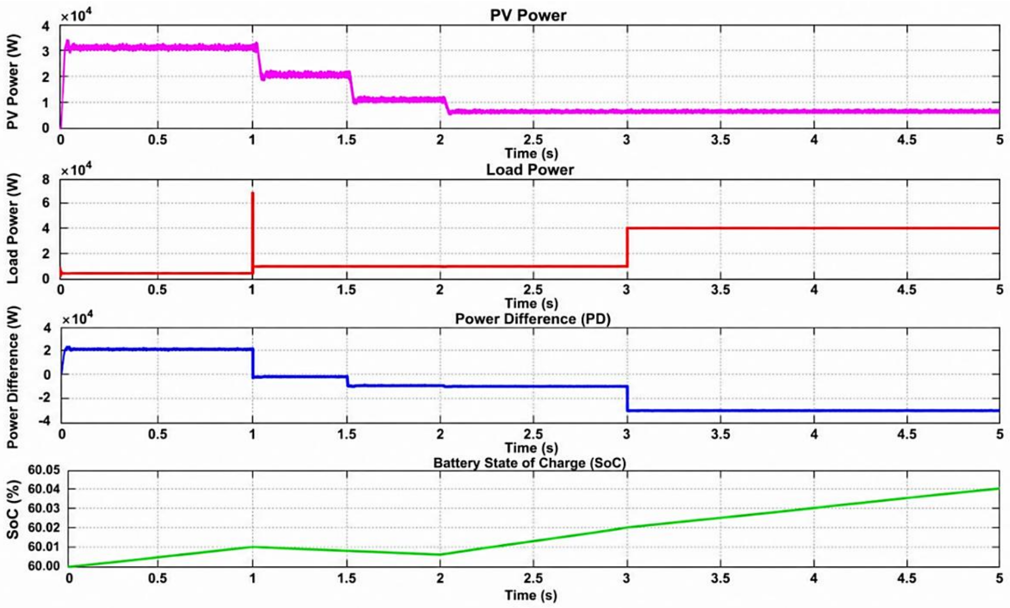


Figure 14. GWO based battery management under various operating conditions

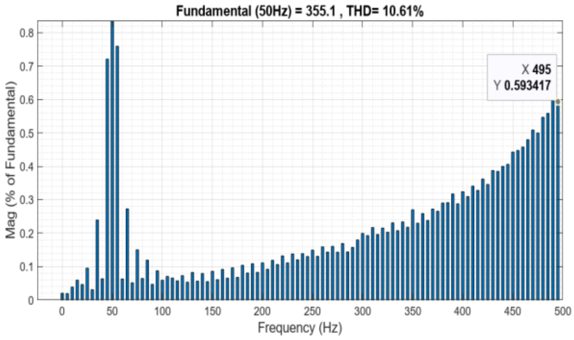


Figure 15. ANN – THD voltage Phase 1

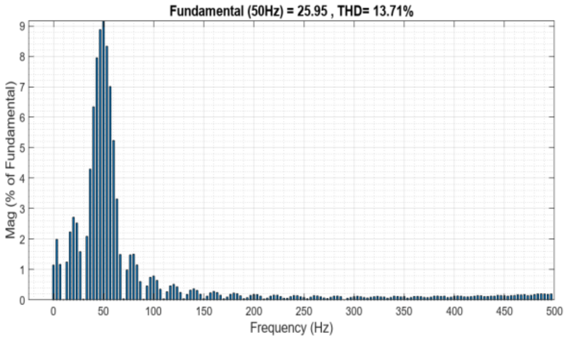


Figure 16. ANN – THD current Phase 1

This phase exhibits significant harmonic distortion, resulting in a higher THD compared to the voltage phases. In conclusion, the THD analysis of the ANN-based BMS highlights significant harmonic distortions across different phases of voltage and current, and the comparison of the THD voltage Phase 1 obtained using the FSSO, GWO, and ANN methods was 10.66%, 10.61%, and 10.61%, respectively. Both quantitative performance evaluation and comparison with previous research were used to validate the applicable approaches. The capacity of the ANN-based BMS to keep voltage THD around 10% in Phase 1 was confirmed, which is in line with ANN-based control techniques that have been documented in the literature.

As previously shown by optimization-based research, the GWO method's capacity to suppress harmonics was validated when it showed the lowest current THD (4.65% in Phase 1). The FSSO approach proved to have shown good energy balancing, although it was recording higher values of current THD (>15%), which validated its suitability to energy-centered optimization. The correspondence of the findings to the already published information ratifies the accuracy and reliability of the applied methods, which ensures that the results compared in this study is a true representation of the system functionality in real life. A high level of worldwide search and a low level of convergence are the features of FSSO. Computationally, it is more complicated with transition rules. It is suitable for offline optimization. While GWO can be used for real-time BMS duty cycle optimization since it can converge faster and with less computational cost, its effective balance between exploration and exploitation makes it suitable for ANN-based real-time applications. In real time applications, ANNs give fast results and converge very fast, although they are highly trained. Comparison of THD of voltage and current in three optimization algorithms FSSO, GWO, and ANN indicate that they have different characteristics. performance variations. In the case of voltage THD ANN is always a good performer in Phase 1 low THD 10.61, and FSSO and GWO also have similar results in Phase 1, albeit slightly outperforming GWO. In the case of current THD, GWO is always the best in comparison with FSSO and ANN phase, and a rather low THD of Phase 1 (4.65%) ANN, competitive voltage performance THD, is lagging behind GWO in current THD, especially in Phase 1. In terms of THD, FSSO is the best current in all stages, which means that it is less effective in reducing the distortions of currents than GWO and ANN.

Comparative analysis of THD voltage and current shows that the GWO technique tends to give a better result as compared to the voltage and current is even better than FSSO and ANN. GWO has a better performance in reduction of current THD in all the phases, especially the best Phase 1 with the lowest THD values. Although ANN shows competitive performance in voltage THD, and it is consistently low in Phases 1, it competes with GWO's current THD performance. Even though FSSO exhibits fair performance in the voltage THD, especially in Phase 1, it is not as effective in the reduction of current THD. These findings suggest that GWO is the most effective method for minimizing THD in both voltage and current, making it a preferable choice for applications requiring low harmonic distortion. The research shows that ANN, GWO, and FSSO reduce THD, certain areas need additional investigation. Simulation findings give significant insights, but hardware justification in real-life BMS systems may expand this work. The research concentrates on harmonic distortion efficiency, but future studies might include temperature, condition, and fault-tolerance.

6. CONCLUSION

This research measured the functionality of BMS in relation to THD by applying three complicated optimization methods: FSSO, GWO, and ANN. The research demonstrates that GWO keeps current THD below 5%, assuring enhanced power quality, while ANN handles voltage THD up to 10% across phases. Despite reasonable voltage performance, FSSO has a current THD of 15%, limiting its practicality. While

FSSO achieves respectable voltage THD findings, it shows the highest current THD over all phases, suggesting that it is not very successful in minimizing harmonics. In renewable energy applications, the GWO approach enhances power quality and system dependability by minimizing THD in both voltage and current. In terms of voltage control, ANN is still a strong option, while FSSO shows potential for efficiency gains but needs work on harmonic reduction to be fully realised. To further enhance cost, reliability, and power quality, future studies will examine hybrid optimization techniques that syndicate the capabilities of multiple methodologies, validate these algorithms in the real world, and estimate their efficacy in large-scale BMS installations.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Penumala Poornima	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓		✓
Kannan Boopathy	✓	✓		✓	✓	✓				✓			✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article [and/or its supplementary materials].

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BIOGRAPHIES OF AUTHORS

Penumala Poornima was awarded an M.E. in power system engineering in 2013 from Vinayaka Mission's Research Foundation in Salem, India. In 2009, she graduated with a B.E. from Anna University in Chennai, India. She is currently working on her Ph.D. at Vinayaka Mission's Research Foundation in Salem, India, in the Department of Electrical Engineering. In reputable international journals and conference proceedings, she has published over ten publications. His areas of interest in research are energy management systems, PV power forecasts, optimization methods, and the integration of renewable energy. She can be contacted at email: poorni07p@gmail.com.

Kannan Boopathy is a professor at Aarupadai Veedu Institute of Technology, VMRF, Chennai, in the Electrical and Electronics Engineering Department. He graduated from Madras University in 1999 with a B.E., Anna University (MIT Campus) in 2003 with an M.E. in electronic engineering, and Anna University, Chennai, in 2012 with a Ph.D. in power electronics. He has more than 24 years of teaching and research-consulting experience, and he has been actively involved in educational administration for over 10 years. For leading the top UG project, he was given the "Best Project Award" in the All-India Radio project competition. In addition to conference proceedings, he has authored a large number of publications for both domestic and foreign journals. He now has five patents that have been awarded, and four more that have been posted on the Indian IP portal are pending hearings. He also wrote two textbooks in 2020 and 2021, titled "Electronics Circuit-II" and "Power Electronics for RES," respectively. He can be contacted at email: boopathyk@avit.ac.in.