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Operational Planning of Hybrid Power Management for Load Based on Versatile Energy Spectral Algorithm

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Abstract

In a hybrid energy system, the operational strategy is to allocate energy sources depending on their availability to match the load demand. To optimize system performance while reducing operating costs, it must compute the energy flow from the hybrid energy system sources to various loads, as well as the charging and discharging of storage devices such as batteries and super capacitors. However, energy management becomes more challenging when some Versatile Energy Spectral Algorithm (VESA) acts as central controller. The Energy Management System must be adjusted using a central controller when the topology changes. This work proposes a VESA for optimally operating a hybrid energy system with a number of sources. The VESA algorithm is designed to maximize power generation while considering load operating circumstances. The implementation of the VESA control, which consists of several rules, is used to optimize the smart grid system. The intelligent management system immediately measures the hybrid sources' power generation, and based on the computed data, the controllers take appropriate action as necessary. Its control approach improves the precision of this nonlinear system while also achieving optimization and distributed energy generation. The planned hybrid power system will be connected to a load-connected system. The suggested controller will be in charge of the power system's switching function, particularly the converter, which is employed for a specific power conversion process, and an inverter for power optimization. The performance of the model is estimated with various parameters like switching losses, EMI, Efficiency, power factor (PF), and total harmonic distortion.

Keywords: Battery Management System, Energy Storage System, Hybrid Energy Management, Smart Grid, Versatile Energy Spectral Algorithm.

Introduction

Increased worldwide power consumption, awareness of global warming, the concept of a green world, the depletion of fossil fuels, and the need for alternative energy have all fueled interest in Renewable Energy Sources (RESs). As a result, research into RESs has expanded in recent decades. Wind and solar energy are at the forefront of renewable energy sources, offering advantages such as availability at any time of the year, low costs, and environmental benefits. The Versatile Energy Spectral Algorithm is utilized in this work to design a power management control approach for a hybrid energy storage system, which improves system efficiency and battery durability while also enhancing load stability. Figure 1 shows a power management control method under development that determines the effects of load reference-based fluctuations on system performance and battery life. VESA proposes that the different frequency components of the load power demand be decomposed in order to minimize sudden fluctuations in power demand and achieve greater efficiency without lowering the system's overall efficiency. Batteries and super capacitors both have dynamic characteristics to meet the power demand requirements. Materials with high-power batteries have lower power densities. The calculations specify that the higher charge and discharge currents create significant stress on the batteries. This stress results in increased internal temperatures, which accelerate the degradation of battery materials and decrease the lifespan of the battery. Hence, controlling and limiting the higher current variations is crucial to improving the performance of the battery, ultimately reducing the life losses of the battery. As a result of the use of a bi-directional DC-DC converter, the current

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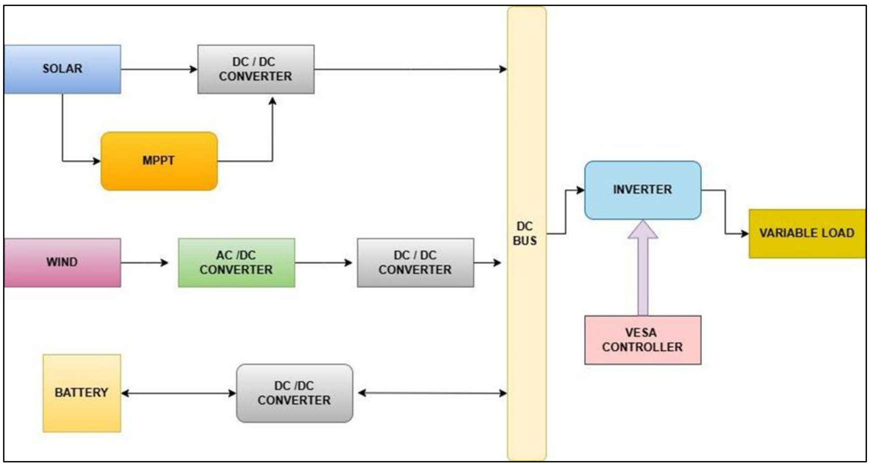

Figure 1: Hybrid Energy Load Conservation

charging capability of the batteries will be increased. Super capacitors have a high-power density with a low energy density compared to batteries. Combining these two types of ESS produces energy storage systems that are equivalent in terms of energy density, battery energy, and super capacitor peak power. The performance of HESS in the development of hybrid batteries and super capacitors has been studied extensively. The objective of this system is to improve hybrid system performance while also achieving the required load. The VESA algorithm resolves the requirements and increases efficiency due to the monitoring and controlling of both the converter and inverter, which maintain better optimization of the system. The results show that VESA can confirm that the battery can handle most of the power requirements of low-frequency components. Super capacitors can provide for all the remaining high-frequency components. This can affect battery life and improve overall system performance under heavy loads. The proposed VESA method and the output of the Simulink model provide better results. An Energy Management System (EMS) for a hybrid power system includes a wind energy conversion system along with a Battery Energy Storage System (BESS). The EMS is a Model Predictive Control (MPC) system that operates in real time. The BESS is ordered by the EMS to maximize profitability in the deregulated power market (1). The control and energy management of a grid-connected PV battery hybrid power system are examined. In this arrangement, power is transferred from the solar system in the form of the primary energy source and battery storage as a secondary source to the grid via a two-stage conversion consisting of converters and a three-phase three-level Diode Clamped Inverter (DCI, 2). Renewable energy systems that are widely designed and connected to the grid have a drawback in small, dominant orders due to control over the inverter system. Inverters used in energy systems can work on or off the grid (3, 4) for a multi-source standalone microgrid. This system regulates a variety of combined energy sources, such as renewable energy sources, diesel generators, and battery packs, efficiently equilibrating production to load (5). A Power Conditioning System (PCS) for Photovoltaics (PV), an Energy Storage System (ESS), and a Battery Management System (BMS) compensate for the hybrid system (6). An Adaptive Neuro-Fuzzy Inference System (ANFIS) is a hybrid system based on a grid that delivers different results (7). In addition to ordinary home requirements, design and assess a domestic PV system for a plug-in bus load. This system is comprised of two subsystems that are connected by a DC link (8). The efficiency curves of the fuel cells and battery systems were collected through theoretical calculations and practical testing to investigate the correlation between the overall efficiency of the hybrid system and the total energy losses (9). For a hybrid bus powertrain, various electrochemical energy storage systems, including a battery pack, a super capacitor device, and a dual buffer, were compared. Existing research compares the various ESSs in terms of all-purpose properties (10-13). The optimal power flow schedule for a grid-connected photovoltaic-battery hybrid system is offered to adequately explore solar energy and assist customers on the demand side. The proposed model for optimum power flow management in hybrid systems aims to lower energy costs while accounting for balanced power, solar, and battery outputs (14). The Genetic Algorithm (GA) is used to create an overall energy management plan for the system; as a result, the flow of energy from various renewable sources and the storage unit is controlled while also lowering the system's annual cost in order to reliably meet load needs while considering environmental concerns (15). Management and energy optimization of a grid-connected HRES were discussed. A wind turbine (WT) with a hydrogen (fuel cell) and battery-based hybrid energy storage system was used to optimize load demand. All power sources and the storage system are connected to the DC bus system using DC/DC converters. To enhance power continuity, the DC bus output is connected to the grid through a three-phase converter (16-18). A photovoltaic battery system connected to a common DC bus is introduced, with two asymmetric photovoltaic boost converters that can work separately or together, a Type T three-level DC/AC converter that operates in four quadrants, and a bidirectional DC/DC converter (BDC) that sends and receives common battery power from the DC bus, along with other peripheral equipment (19-21). PI controllers are mostly applied in the voltage and current control of energy systems. They maintain the converters and inverters and keep the system performing stably, regardless of load fluctuations. Accordingly, PI controllers also work well for hybrid energy systems (22). Meanwhile, the fuzzy logic system improves the system's flexibility and response to nonlinear and uncertain conditions. Compared to other control approaches, it is more suitable for managing the power sharing between batteries and super capacitors. Moreover, it is evident that the fuzzy systems enhance the efficiency of HESS (23). In the same way, support vector machines (SVMs) are used in decision-making for real-time energy distribution in the power system to control the power flow between the sources and loads. As observed, there is tremendous capacity for utilizing SVMs to increase the accuracy of energy consumption (24). In the case of adaptive power management systems (APMS), they optimally control energy flow with reference to the load demand in the system and the availability of energy sources, making it fit for any dynamic condition. In particular, the VESA approach is strengthened by offering strong energy control features (25). These advanced control techniques, when adopted in VESA, lead to reliable systems and battery longevity, in addition to better performance.

Methodology

The proposed model is designed to increase the energy supply for the load based on its own priority conditions. It also supports maintaining a reasonable amount of battery energy storage to match peak load requirements. Figure 2 shows the proposed architecture of PV and wind, along with a battery pack and a super capacitor for the hybrid system. Since all major energy sources are environmentally friendly, the system can be seen as a complete greenhouse power generation system. In this work, the hybrid-based optimization model was developed with a Versatile Energy Spectral Algorithm (VESA) control system.

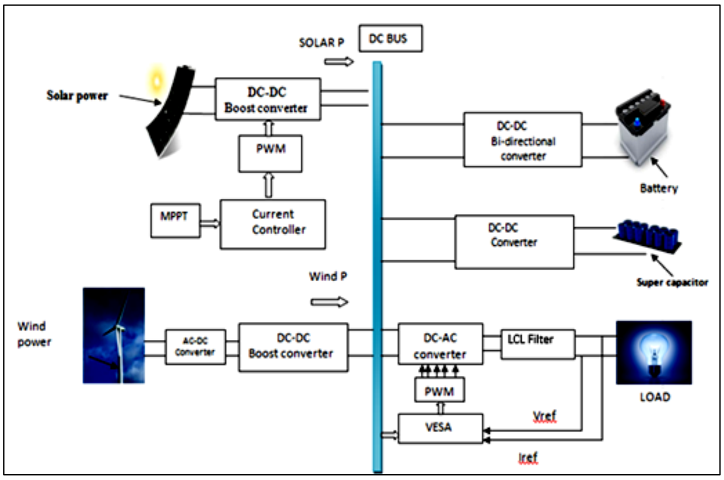

Figure 2: Proposed Hybrid Block Diagram

The VESA control system will monitor both solar and wind power generation. If there are any fluctuations in the hybrid system, VESA will provide the appropriate pulse signal to both the converter and the inverter. The battery-based energy management system is also monitored by the proposed VESA controller. During a power fluctuation, the battery power will be compensated for by the hybrid power generation system. VESA extends prior art in energy management by overcoming weaknesses in the flexibility, accuracy, and modularity of the underlying frameworks. In contrast, VESA is more flexible and adaptive in response to changes in topology and individual load requirements due to its intelligent real-time decision-making mechanism. It uses deep spectral analysis and a centralized control system that can easily coordinate distributed energy systems and storage systems such as batteries and supercapacitors, thus improving efficiency and minimizing losses. Through specified performance indicators, namely THD, power factor, and electromagnetic interference, VESA provides results superior to traditional approaches. VESA can be considered a reliable and effective method for developing hybrid power systems. The LCL filter is deployed to filter the current and voltage harmonics in the output part of the inverter. It guarantees that the AC output from the inverter side is free from harmonics and has a sinusoidal waveform, which always benefits the loads, the efficiency of the systems, and also follows the requirements of power quality standards. VESA is not only associated with the inverter; it also controls the combined inverter/converter system in the Hybrid Energy System. On the inverter side, it regulates voltage and frequency and mitigates harmonic distortion in the power line to optimize the flow of power. On the converter side, voltage stability regulation is accomplished through various control loops, including but not limited to the regulation of the DC-link voltage, which is coordinated by VESA to balance any variations in source input and load demand. This unified control guarantees the efficient use of energy while facilitating harmony in the system.

Versatile Energy Spectral Algorithm (VESA)

A microgrid energy management system using the VESA is shown in Figure 3. Recently, the use of renewable energy in microgrids has become a successful method of expanding regulatory propagation, especially in remote areas. The combination of renewable energy and non-renewable energy presents special problems for improving the grid. Hence, an effective EMS is proposed to address the needs of power generation, control, reliability, and power supply systems. The primary aim of an EMS is to improve the system's load requirements.

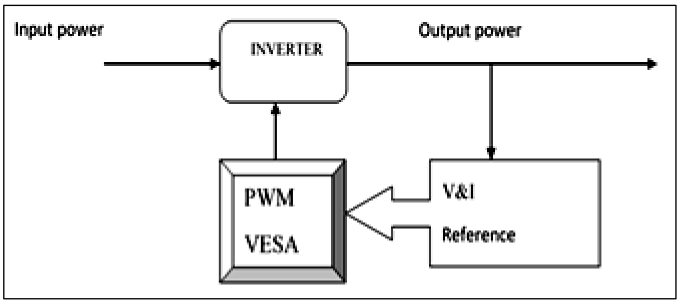

Figure 3: Block Diagram for Proposed VESA Technique

VESA Execution Procedure

The versatile energy spectrum algorithm for solving a hybrid renewable source with control devices can be summarized as follows:

Step 1: Initialization of all devices.

Step 2: Initially, both solar and wind generations are in ON condition.

Step 3: The generation of each particle (wind power, solar power, and battery power) is generated randomly. The objective function value for each particle is calculated.

Step 4: Maximize the power generation of a hybrid system using a DC-DC converter and inverter with proper pulse-width modulation.

$$V_L = \frac{1}{1 - D_t} V_S \qquad [1]$$

PWM is applied to the regulation of switching devices in DC-DC converters and inverters. In the case of a converter, the duty cycle Dt of the PWM signal is adjusted to control the output voltage VL in a manner that matches the required voltage for maximum power generation. In the case of an inverter, the input is DC, and the AC frequency and magnitude control are done by varying the duty cycle of the power device. The PWM controller provides control of the switch power, and there is control of voltage and frequency to optimize the power flow.

Step 5: The battery-based energy management operates under necessary conditions. If VL = VD, the battery is in charging mode. In this condition, power flows from the DC-DC converter or another source to charge the battery. When VL ≠ VD, the battery is connected to the inverter. In this mode, the battery supports the load by providing the necessary power, especially when other sources are insufficient. In both of these conditions, the battery Q(n) capacity and Q(t) battery charging and discharging states will be considered.

$$\mathrm{soc(t)} = \frac{\mathrm{Q(t)}}{\mathrm{Q(n)}} \quad [2]$$

Where VL is called the Load voltage supplied to the load. VD is called the battery terminal voltage

Step 6: The VESA will evaluate the grid power and generation system, which will maintain the hybrid power at the maximum level.

Step 7: An analysis of the Loss of Load Probability (LOLP), Loss of Power Supply Probability (LPSP), and the cost-effectiveness of the HRES system will be conducted.

$$\mathrm{LPSP}=\sum_{t=1}^{T} \boldsymbol{LPSP(t)} \,/\, \sum_{t=1}^{T} \boldsymbol{C1(t)} \quad [3]$$

$$\mathrm{LOLP}=\sum_{r=k}^{n} P_i \mathrm{P}\ (\mathrm{L_j}>\mathrm{C_i}) \quad [4]$$

$$Cost\ Effectiveness = \frac{Total\ Operating\ Costs}{Total\ Energy\ Delivered} \quad [5]$$

Where, L_j is the predicted peak load of hour, j and P is the loss of load probability in hour j_n C1 (t) is a constant voltage of the inverter, and LPSP (t) is the power loss variation at that time.

Step 8: The LPSP or LOLP values are analyzed based on the threshold value, and the energy prediction will increase the power quality of the HRES system. If the threshold value is varied, the PWM of the inverter should be regulated. The width of the PWM is varied; also, the falling edge PWM should be smoothed. A suitable propagation delay will reduce the switching error and steady-state error. The process can be repeated several times to obtain the average network as constrained final pulses. Also, the HRES will meet the required load power.

Step 9: Stop the process.

The VESA includes multiple methodologies to handle various conditions, such as sudden load surges and the intermittency of renewable energy sources, confirming the system's stability and reliability. The hybrid renewable energy system. VESA varies the pulse width modulation control signals of the inverter to compensate for voltage fluctuations with the load. These changes are very fast, which helps keep voltage fluctuations or drops to a bare minimum. In situations where load demand exceeds generation capability, the algorithm considers battery storage. Forcing is achieved by observing the SOC (State of Charge) and voltage thresholds, thus transferring from the 'charging state' to the 'discharging state' to meet the deficit power. In case the surge leads to the peak power of the system, VESA can apply a measure of load shedding, where important loads are supplied with power while less important loads are shed. Thus, the algorithm is representative of an adaptive type that adjusts the allocation of energy between wind, solar, and storage systems. For example, if there is a sudden fluctuation that affects wind and solar sources or battery storage, energy from the latter two is brought in to balance the situation. The LOLP approach examines the probabilities of failure in meeting the load and modifies system operation to thereafter minimize such probabilities while synchronously enhancing the performance of the hybrid system. By judging the possibility of unmet load, the algorithm adapts the system outcome and elevates the performance of the hybrid system. In transition through extreme states, PWM widths are varied, and transitions are made smoothly to minimize errors due to abrupt changes, which contribute to EMI and harmonics. The switching of the DC-DC converter and inverter is closely controlled for high-power transient handling. This coordination helps to maintain an efficient transfer of energy and avoid circumstances of system instability at the edges. If the HRES is connected to the grid, VESA has the opportunity to draw support from the grid at peak moments of either excess or deficit, selling the extra energy or buying power as required. The algorithm also keeps calculating parameters such as total harmonic distortion, efficiency, and power factor to automatically calibrate control parameters should there be changes in conditions. Otherwise, VESA adjusts the thresholds and operating parameters back to recommended levels and balances system conditions. Through the integration of these approaches, VESA establishes a reliable and dynamic method for tackling the various factors associated with the application of hybrid renewable energy systems under various and sundry conditions.

Results and Discussion

The present Hybrid Energy Management (HEM) modeling using the VESA approach is developed in MATLAB 2017b software. The performance of the proposed system is evaluated in a dynamic environment.

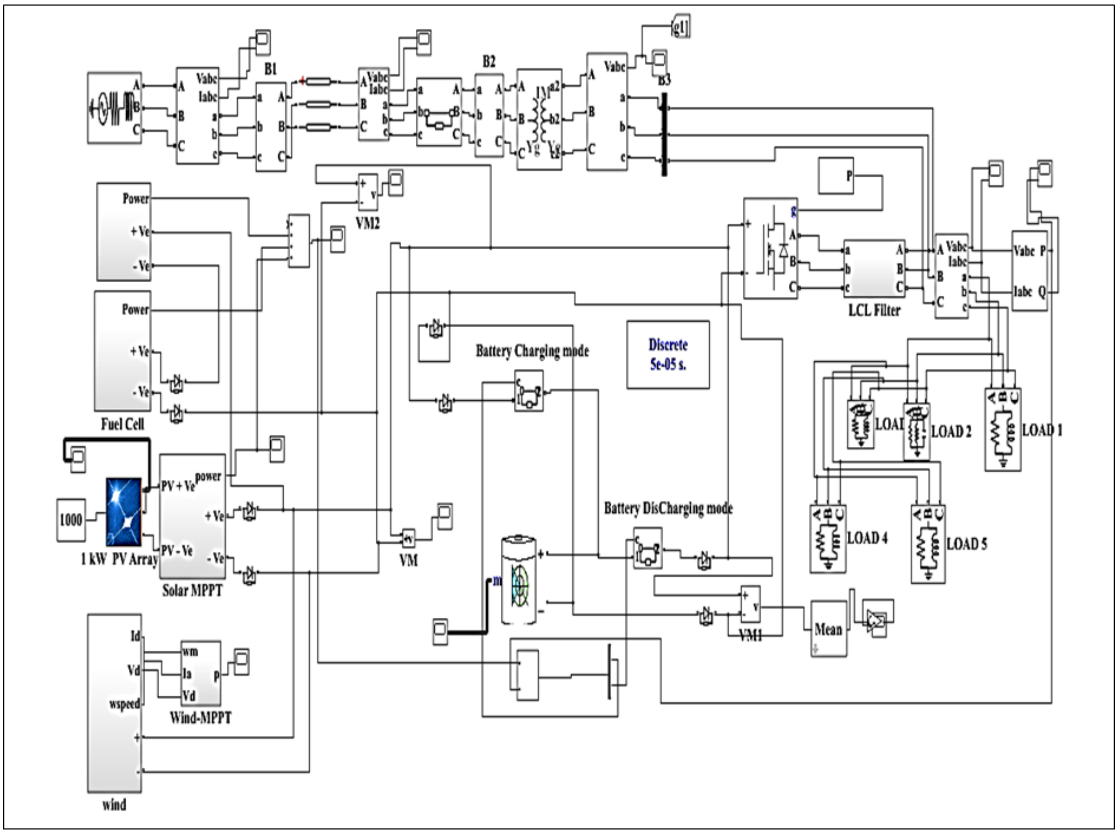

Figure 4: Simulation Model of the System

The overall formation of the hybrid management model of the grid connection system is shown in Figure 4. The Simulink model represents the hybrid renewable energy sources. The proposed idea of the model is to develop energy optimization with VESA technology. The voltage measurement point in the wind-MPPT system can be determined by following the connections around the wind-MPPT block. The Voltage Sensing Block estimates the voltage depicted by the symbol "Vd," leaving the wind-MPPT block, which is a normal output for voltage measurement in systems using the reference frame dq. The "VM" in the model means that there are voltage measurement points in different locations in the system. The efficiency of the system is measured by considering conversion efficiency, storage efficiency, and distribution losses.

$$\text{Conversion } \eta = \frac{\text{Power after conversion}}{\text{Input power to converter}} \quad [6]$$

$$\text{Storage } \eta = \frac{\text{Energy reterived from storage}}{\text{Energy Stored}} \quad [7]$$

$$\text{System } \eta = \text{ conversion } \eta * \text{ Storage } \eta \quad [8]$$

Figure 5 represents the distorted solar output voltage waveform, which produces 240 V. While employing the VESA control approach in a DC-DC converter, it produces a stable voltage of 440 V, which has a lower ripple ratio. Figure 6 represents the wind output voltage, showing more distortion in the peak amplitude of the voltage output waveform.

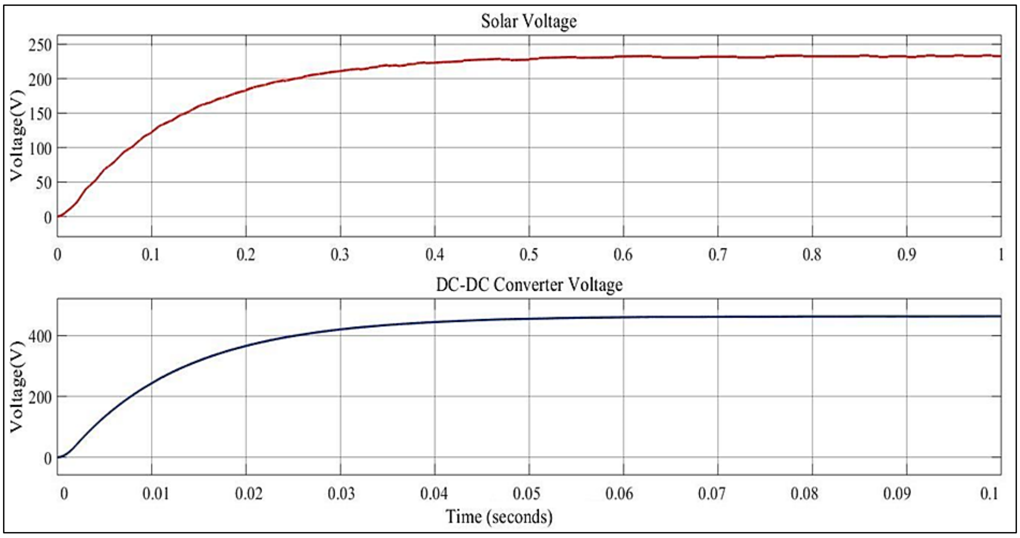

Figure 5: Solar Output Voltage

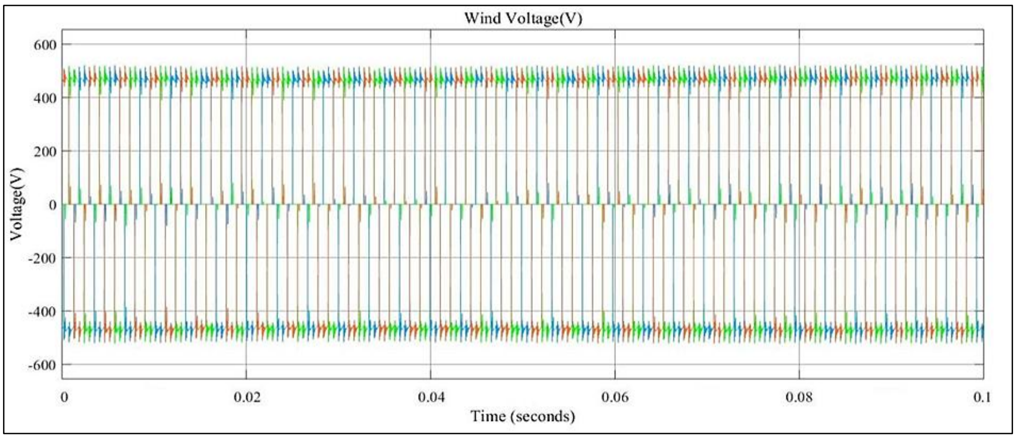

Figure 6: Wind Output Voltage

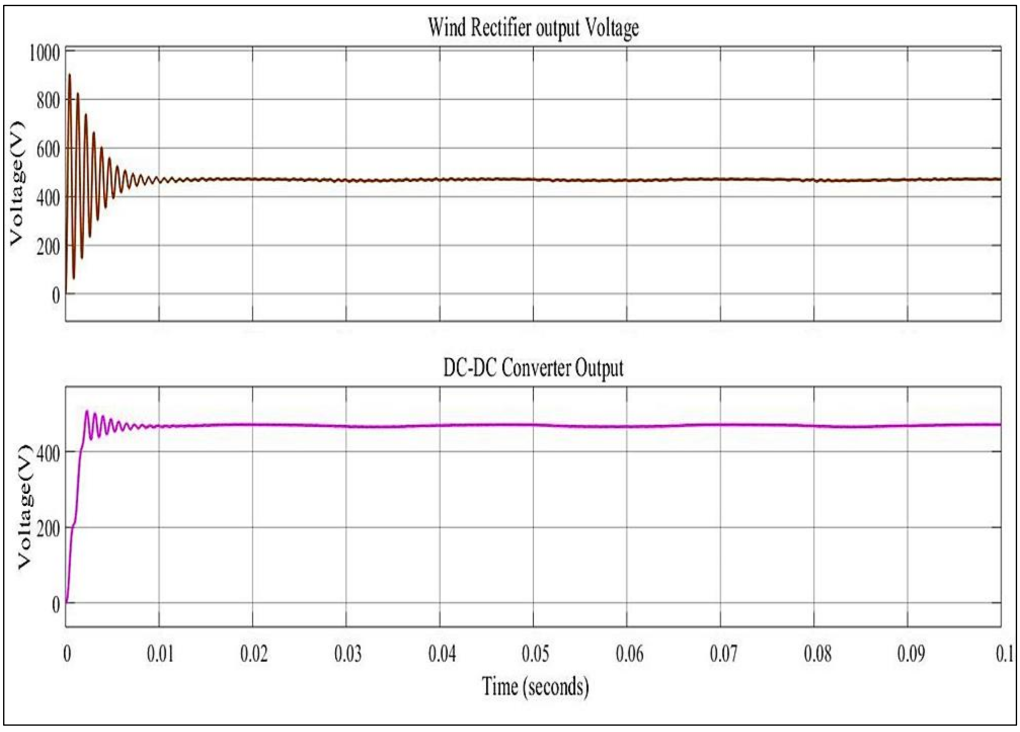

Figure 7: Wind Rectified Output Voltage

Figure 7 also shows the wind rectifier voltage and boost-converted voltage. In the waveform, it clearly shows that the proposed VESA controller will optimize the DC voltage to 400 V with respect to a time ratio of 0.1 seconds. The fluctuations or ringing effects observed in the wind rectifier output voltage are due to interactions in the wind energy conversion system. Generator speed is affected by the load, and any difference between its characteristic curve and that of the rectifier results in transient oscillations, especially during changes in wind speed or mechanical torque pulses. The DC-DC converter output voltage stabilizes over a period due to the fact that the feedback control systems alter the duty ratio of the switching devices in the converter to eliminate ripples from the output voltage. The capacitive and inductive circuit components of the DC-DC converter remove high-frequency AC components and provide feedback to set the output voltage.

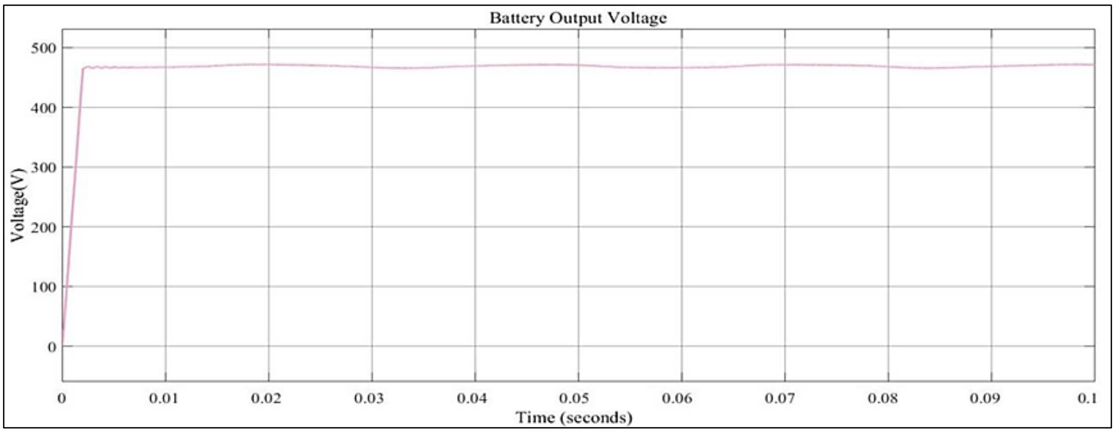

Figure 8: Battery Output Voltage

Figure 8 shows the battery output voltage V = 440 V with respect to a time of 0.01 seconds. This battery voltage will be utilized under the necessary conditions. Figure 9 shows the super capacitor voltage that will provide voltage stabilization for the grid system. During power generation, similar ripples in the output are present, and the DC-DC converter will stabilize these ripples by using the appropriate switching pulse and frequency. Figure 10 show that the three-phase voltage represents the actual power of the source inverter. This waveform represents the power stability of the hybrid system. The real power waveform shows that the maximum power of 6000 watts is reached within 0.1 seconds.

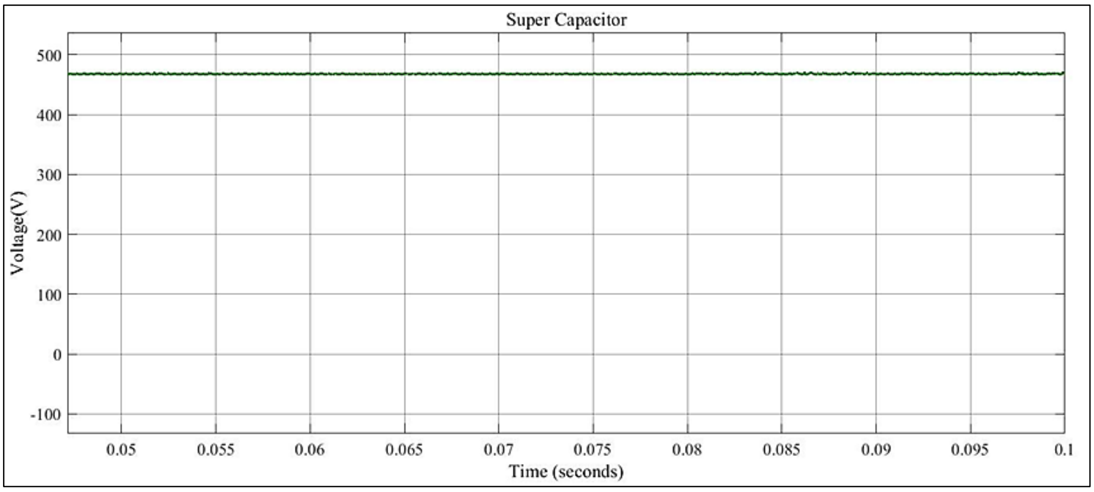

Figure 9: Super Capacitor Voltage

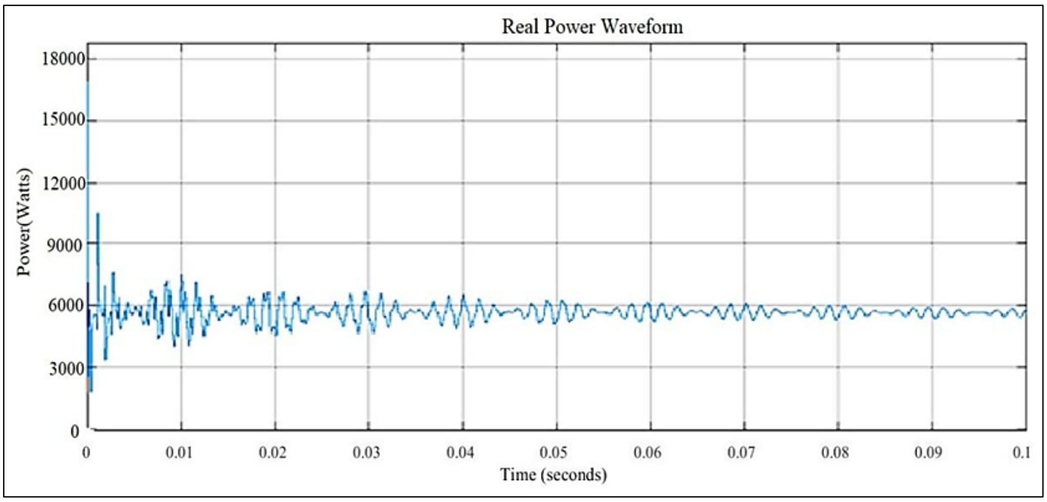

Figure 10: Real Power Output

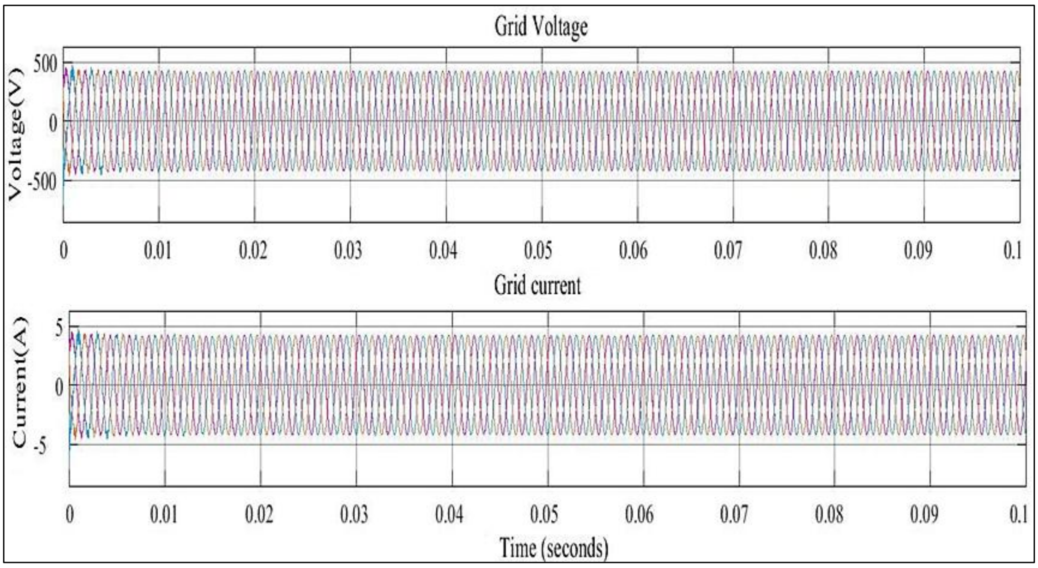

Figure 11: Grid Power

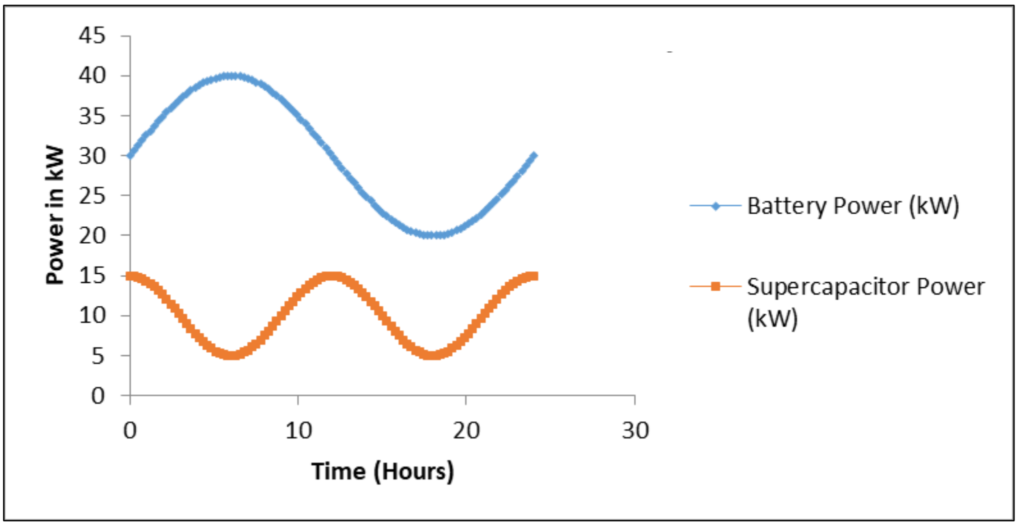

Figure 12: Power Demand Analysis for Battery and Super Capacitor

Figure 11 depicts the phase voltage and current waveforms of the load with a load voltage of 440 V and a load current of 4.85 A with respect to 0.1 seconds. Figure 12 depicts the power demand met by both the batteries and the super capacitor. The batteries provide a steady supply, and the super capacitors provide a quick response to spikes or dips. Table 1 shows the performance analysis of the proposed VESA controller for various parameters, such as switching loss evaluation, execution time, power factor, and THD. These performance parameters were obtained by averaging all the loads connected to the system.

Table 1: Performance Analysis of the VESA based Hybrid Model

Methods	Execution Time (sec)	Switching Loss (%)	Power Factor	THD (%)	Efficiency (%)
PI	0.8832	5.4	0.993	8.7	85.5
Stochastic Fuzzy Logic System	0.7845	4.8	0.994	6.43	87.4
SVM	0.6251	4.2	0.995	5.23	89.1
APMS	0.5154	3.8	0.963	4.73	96.36
VESA	0.414	3.5	0.97	4.09	97

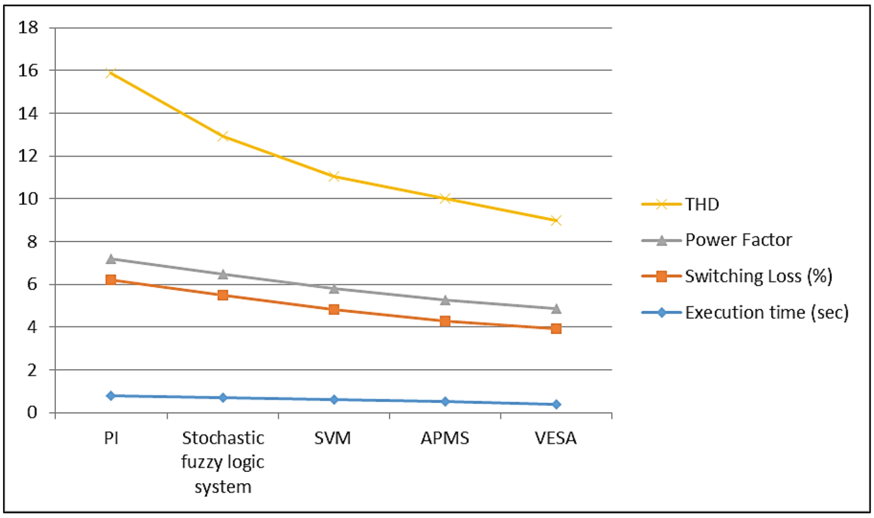

Figure 13: Performance Analysis Chart for Proposed VESA

Figure 13 shows the performance analysis of the proposed VESA controller for various parameters, such as switching loss evaluation, execution time, power factor, and THD. The x-axis represents the different energy management methods or algorithms being compared, while the y-axis represents the various performance metric values being measured.

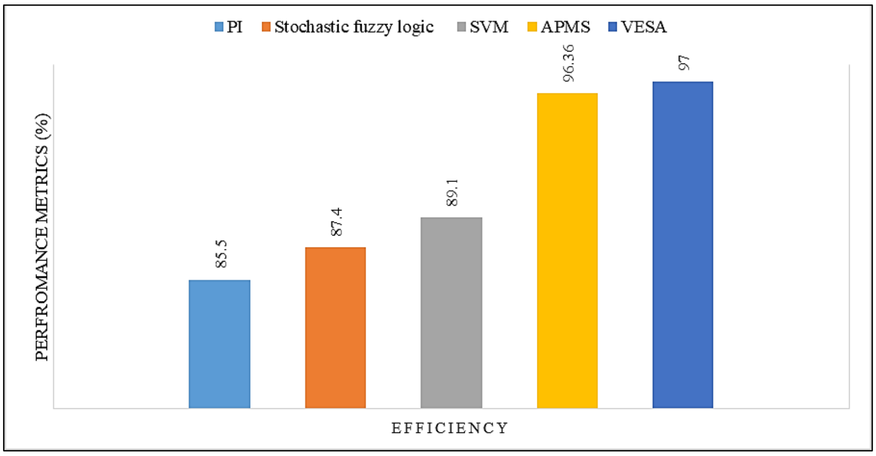

Figure 14: Performance Comparison of the Efficiency

Figure 14 shows a comparative analysis of the proposed hybrid system based on the evaluation of various techniques, such as Proportional-Integral (PI, 14), stochastic fuzzy logic system, Support Vector Machine (SVM, 15), APMS, VESA, and the proposed VESA technique, which produces better efficiency results.

Conclusion

The VESA-based optimization strategies to optimize the base load for the system elements were implemented using VESA-based techniques to ensure that the load is distributed stably. The VESA generates effective pulses that are fed to the converters to optimize the hybrid system. As a result, hybrid systems are more cost-effective, and the performance of the VESA can be evaluated with various parameters, such as switching loss evaluation (3.5%), power factor (0.997 VA), and THD (4.09%). As future work for the current study, further development of the VESA may be proposed for improved scalability and compatibility with smart technologies like IoT, smart grids, and AI. If IoT is applied for real-time monitoring and control, the system will enable some form of proactive maintenance and immediate energy adjustment. There are possibilities for integration with smart grids, which will lead to effective load balancing and demand response. In other cases, the application of AI and ML can be used to support decision-making and reinforce control to allow efficient and reliable management. Additionally, using advanced technologies such as blockchain to enable distributed decentralized generation of energy and distributed electric vehicles (V2G) can enhance energy efficiency. This advancement will establish VESA as a solid solution for future energy management needs.

Abbreviations

VESA: Versatile Energy Spectral Algorithm, EMS: Energy Management System, RESs: Renewable Energy Sources, MPC: Model Predictive Control, BESS: Battery Energy Storage System, DCI : Diode Clamped Inverter, PCS: Power Conditioning System, ANFIS : Adaptive Neuro-Fuzzy Inference System, GA: Genetic Algorithm, SVMs: Support Vector Machines, APMS: Adaptive Power Management Systems, LOLP: Loss of Load Probability, LPSP: Loss of Power Supply Probability, SOC: State of Charge, HEM : Hybrid Energy Management, ESS: Energy Storage System, HESS: Hybrid Energy Storage System.

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Author Contributions

All authors made significant contributions to this paper.

Conflict of Interest

The authors declare no conflict of interest.

Ethics Approval

Not applicable.

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