ISSN: 2393-8528

Contents lists available at www.ijicse.in

International Journal of Innovative Computer Science & Engineering

Volume 11 Issue 4; 2024; Page No. 1-6

Comparative Performance Evaluation of Multi-Voltage Belt Starter Generator Mild Hybrid Electric Vehicle Systems Using Vehicle Simulation and Economic Analysis.

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ABSTRACT

The selection of an appropriate electrical voltage architecture is a critical factor in the design of Belt Starter Generator (BSG)-based mild hybrid electric vehicles (MHEVs). This study presents a comparative performance evaluation of multi-voltage BSG mild hybrid systems using vehicle simulation and economic analysis. Seven vehicle configurations, including a conventional internal combustion engine vehicle, a 12 V stop-start system, and BSG mild hybrid systems operating at 24 V, 36 V, 48 V, 84 V, and 120 V, were developed and analyzed using the Autonomie simulation platform under the Worldwide Harmonized Light Vehicle Test Cycle (WLTC). Fuel economy, battery behavior, motor performance, regenerative braking capability, and component costs were evaluated for each configuration. The results showed that fuel economy improved with increasing voltage level; however, the incremental benefits beyond the 48 V architecture were relatively small compared to the increase in system cost and complexity. The economic assessment demonstrated that the 48 V BSG system provides the most favorable balance between performance enhancement and manufacturing cost. The findings support the adoption of 48 V mild hybrid technology as an efficient and economically viable solution for future passenger vehicles.

Keywords: Belt Starter Generator; Mild Hybrid Electric Vehicle; Vehicle Simulation; Fuel Economy; Economic Analysis.

1. Introduction

Growing concerns regarding fuel consumption, greenhouse gas emissions, and increasingly stringent environmental regulations have accelerated the development of hybrid electric vehicle technologies (Ehsani et al., 2018). Among various hybrid configurations, mild hybrid electric vehicles (MHEVs) have gained significant attention because they offer improved fuel efficiency with relatively low manufacturing cost and minimal modifications to conventional internal combustion engine vehicles (Emadi, 2015).

The Belt Starter Generator (BSG) system is one of the most widely adopted mild hybrid architectures owing to its ability to provide start-stop functionality, regenerative braking, and engine torque assistance through a belt-driven electric machine (Miller, 2014). The effectiveness of a BSG system largely depends on the selected electrical system voltage. Lower voltage systems provide limited electrical assistance, whereas higher voltage architectures improve power capability but increase component cost, insulation requirements, and system complexity (Guzzella & Sciarretta, 2013).

Although several voltage architectures have been proposed for mild hybrid vehicles, a comprehensive comparison considering both vehicle performance and economic feasibility remains limited. Therefore, the present study compares the performance of BSG mild hybrid electric vehicles operating at different voltage levels using vehicle simulation. Fuel economy, battery performance, motor characteristics, and component costs were analyzed to identify the most suitable voltage architecture for future mild hybrid passenger vehicles (Onori et al., 2016).

2. Materials and Methods

2.1 Vehicle Simulation

The comparative performance analysis was carried out using the **Autonomie** vehicle simulation platform developed on the MATLAB/Simulink environment. The software enables detailed modelling of hybrid vehicle components, power flow, energy management strategies, and driving cycles for evaluating vehicle performance under realistic operating conditions (Onori et al., 2016).

2.2 Vehicle Configurations

A conventional passenger vehicle equipped with a 1.8 L spark-ignition engine served as the baseline model. Seven different vehicle configurations were investigated:

- Conventional ICE vehicle
- 12 V Stop-Start vehicle
- 24 V BSG Mild Hybrid
- 36 V BSG Mild Hybrid
- 48 V BSG Mild Hybrid
- 84 V BSG Mild Hybrid
- 120 V BSG Mild Hybrid

Each configuration was simulated under identical operating conditions to enable direct comparison of technical and economic performance.

2.3 Hybrid System Architecture

A **P0 Belt Starter Generator (BSG)** configuration was adopted, in which the electric machine was connected to the engine crankshaft through a belt drive. The system provided engine starting, regenerative braking, torque assistance, and automatic engine stop-start operation (Miller, 2014).

2.4 Battery and Electric Drive System

Lithium-ion battery models corresponding to each voltage architecture were implemented in the simulation. A permanent magnet electric motor, inverter, and DC/DC converter were integrated with the battery system to enable bidirectional energy transfer and efficient power management. The battery state of charge was maintained within the prescribed operating limits throughout the driving cycle (Ehsani et al., 2018).

2.5 Driving Cycle

Vehicle performance was evaluated using the **Worldwide Harmonized Light Vehicle Test Cycle (WLTC)**, which represents realistic urban, suburban, and highway driving conditions and is widely accepted for fuel economy assessment (UNECE, 2014).

2.6 Performance and Economic Evaluation

The simulation recorded fuel economy, battery state of charge, battery power, motor operating characteristics, and regenerative braking performance for each voltage architecture. A component-level cost analysis including battery pack, Belt Starter Generator, inverter, DC/DC converter, and electrical accessories was performed to evaluate the economic feasibility of each system. Comparative analysis was then conducted to determine the voltage architecture offering the optimum balance between vehicle performance and manufacturing cost.

3. Results and Discussion

3.1 Model Validation

The developed vehicle model was validated by comparing the simulation results with experimental data obtained from a 48 V Belt Starter Generator (BSG) demonstration vehicle. The predicted fuel economy closely matched the experimental values under the Worldwide Harmonized Light Vehicle Test Cycle (WLTC), confirming the reliability of the simulation model for comparative performance evaluation.

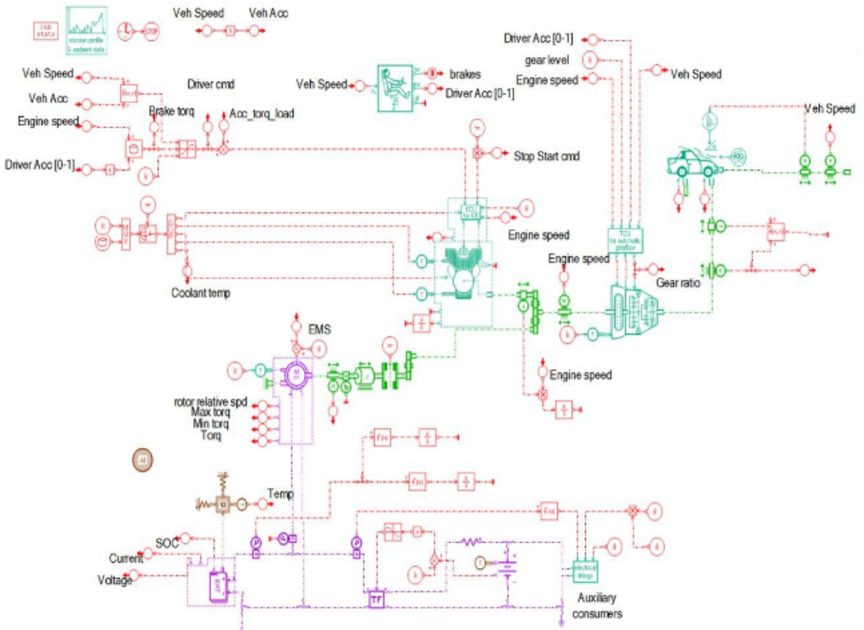

Figure 1. *48 V Mild Hybrid Vehicle Model*

3.2 Battery Performance

The battery voltage profiles confirmed stable operation for all voltage architectures throughout the driving cycle. The battery State of Charge (SOC) remained within the predefined operating range, indicating efficient charge-sustaining operation. Regenerative braking effectively recovered energy during vehicle deceleration, minimizing battery depletion and improving overall energy utilization.

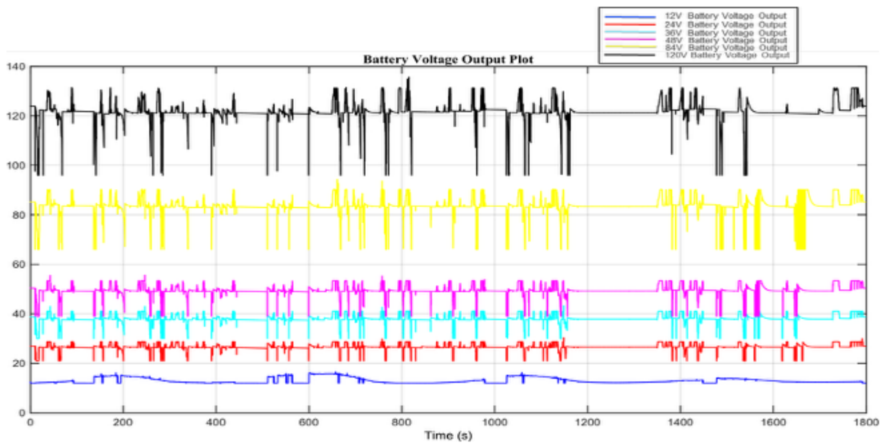

Figure 2. *Battery Voltage Output for Different Voltage Architectures*

3.3 Comparative Fuel Economy Analysis

The fuel economy results demonstrated a gradual improvement with increasing system voltage. The conventional internal combustion engine (ICE) vehicle achieved a fuel economy of **30.60 mpg**, while the 12 V stop-start system increased fuel economy to **31.80 mpg**. The 24 V, 36 V, 48 V, 84 V, and 120 V BSG mild hybrid systems achieved fuel economies of **32.75 mpg**, **33.42 mpg**, **34.02 mpg**, **34.19 mpg**, and **34.22 mpg**, respectively.

The improvements were mainly attributed to enhanced regenerative braking, engine stop-start functionality, and electric torque assistance. However, the rate of improvement gradually decreased beyond the 48 V architecture, indicating diminishing performance gains at higher voltage levels.

3.4 Battery and Motor Performance

The battery power and motor operating characteristics showed that increasing the electrical system voltage reduced current demand while improving electrical efficiency. Higher-voltage systems enabled greater regenerative braking capability and more effective torque assistance during vehicle acceleration. The 48 V architecture demonstrated efficient battery utilization with stable charging and discharging characteristics throughout the drive cycle.

Similarly, motor efficiency maps indicated that the electric machine operated over a wider high-efficiency region as system voltage increased. Although the 84 V and 120 V systems exhibited slightly improved motor efficiency, the performance advantage over the 48 V system was relatively small.

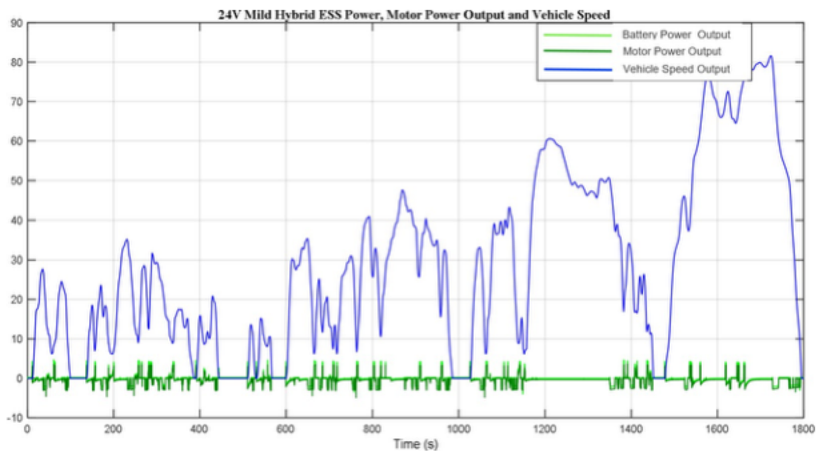

Figure 3. *Battery and Motor Electric Power Output for Various Voltage Systems*

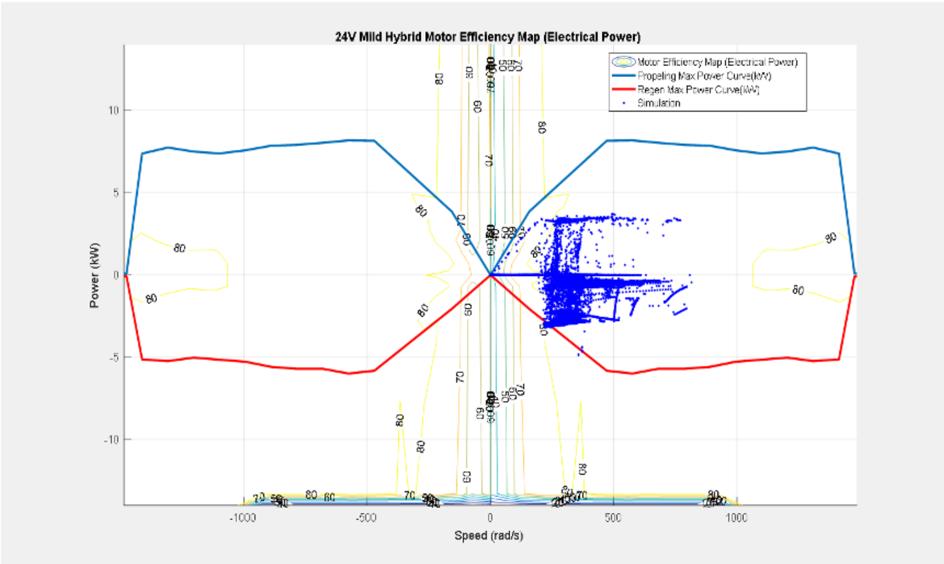

Figure 4. *Motor Efficiency Maps for Multi-Voltage BSG Systems*

3.5 Economic Analysis

The component cost analysis showed that system cost increased significantly with increasing voltage level because of larger battery packs, higher-rated Belt Starter Generators, inverters, DC/DC converters, and additional high-voltage safety components. Although the 84 V and 120 V architectures achieved the highest fuel economy, the additional improvement over the 48 V system was less than 1%, whereas the manufacturing cost increased substantially.

The 48 V BSG system demonstrated the most favorable balance between fuel economy improvement and component cost, providing the lowest cost per unit improvement in fuel economy among all investigated configurations.

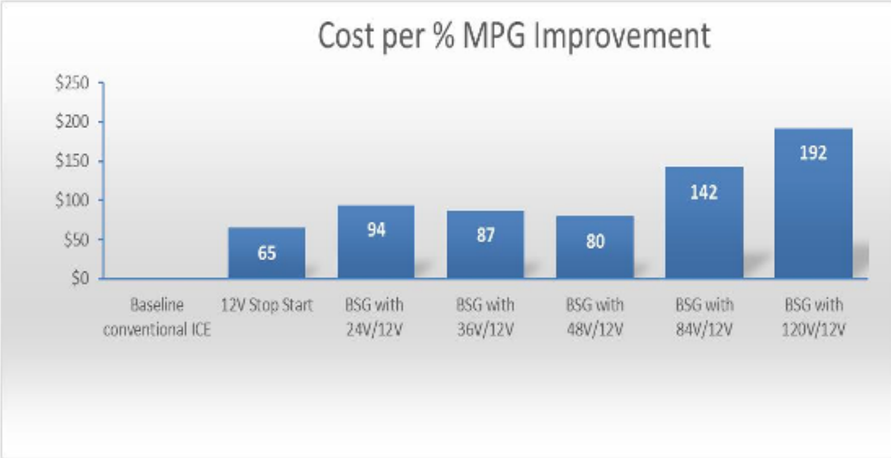

Figure 4. *Cost–Benefit Analysis of Different Voltage Architectures*

3.6 Overall Performance Comparison

A comprehensive comparison of all vehicle configurations indicates that the introduction of a BSG mild hybrid system significantly improves vehicle efficiency compared with a conventional ICE vehicle. Lower-voltage systems (24 V and 36 V) provide noticeable fuel economy improvements with relatively low implementation costs, while higher-voltage systems (84 V and 120 V) offer only marginal additional performance despite substantially higher manufacturing costs. The 48 V architecture represents the optimum compromise between electrical performance, regenerative braking capability, fuel economy, system complexity, and economic feasibility, making it the most suitable voltage architecture for next-generation mild hybrid passenger vehicles.

4. Conclusion

This study comparatively evaluated the performance of multi-voltage Belt Starter Generator (BSG) mild hybrid electric vehicle systems using vehicle simulation and economic analysis. The simulation results demonstrated that increasing the electrical system voltage improved fuel economy through enhanced regenerative braking, torque assistance, and start-stop operation. Fuel economy increased progressively from the conventional internal combustion engine vehicle to the 120 V mild hybrid configuration. However, the performance gains beyond the 48 V architecture were relatively small despite a considerable increase in component cost and system complexity. The economic analysis further revealed that the 48 V BSG system provides the most favorable balance between fuel economy improvement, electrical performance, and manufacturing cost. Therefore, the 48 V voltage architecture is identified as the optimum solution for mild hybrid passenger vehicles, offering significant energy savings while maintaining cost-effectiveness and practical implementation. The findings of this study provide useful guidance for the design and development of future mild hybrid electric vehicle systems.

References

1. Bosch. (2018). *Automotive handbook* (10th ed.). Robert Bosch GmbH.
2. Chan, C. C. (2007). The state of the art of electric, hybrid, and fuel cell vehicles. *Proceedings of the IEEE, 95*(4), 704–718. https://doi.org/10.1109/JPROC.2007.892489
3. Ehsani, M., Gao, Y., Longo, S., & Ebrahimi, K. (2018). *Modern electric, hybrid electric, and fuel cell vehicles: Fundamentals, theory, and design* (3rd ed.). CRC Press.
4. Emadi, A. (2015). *Advanced electric drive vehicles*. CRC Press.
5. Guzzella, L., & Sciarretta, A. (2013). *Vehicle propulsion systems: Introduction to modeling and optimization* (3rd ed.). Springer. https://doi.org/10.1007/978-3-642-35913-2
6. Hofman, T., & Dai, C. H. (2010). Energy efficiency analysis and comparison of

transmission technologies for hybrid electric vehicles. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 224*(5), 565–580. https://doi.org/10.1243/09544070JAUTO1408

7. Husain, I. (2011). *Electric and hybrid vehicles: Design fundamentals* (2nd ed.). CRC Press.
8. International Organization for Standardization. (2018). *ISO 23274-1: Hybrid-electric road vehicles—Exhaust emissions and fuel consumption measurements*. ISO.
9. Larminie, J., & Lowry, J. (2012). *Electric vehicle technology explained* (2nd ed.). John Wiley & Sons.
10. Miller, J. M. (2014). *Propulsion systems for hybrid vehicles* (2nd ed.). Institution of Engineering and Technology.
11. Onori, S., Serrao, L., & Rizzoni, G. (2016). *Hybrid electric vehicles: Energy management strategies*. Springer. https://doi.org/10.1007/978-1-4471-6781-5
12. Reif, K. (Ed.). (2014). *Mild hybrid systems*. Springer Vieweg. https://doi.org/10.1007/978-3-658-03975-2
13. SAE International. (2021). *SAE J1711: Recommended practice for measuring the exhaust emissions and fuel economy of hybrid-electric vehicles*. SAE International.
14. United Nations Economic Commission for Europe. (2014). *Global Technical Regulation No. 15: Worldwide Harmonized Light Vehicles Test Procedure (WLTP).* UNECE.