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ELECTRIC VEHICLE ONBOARD CHARGING VIA HARRIS HAWKS OPTIMIZATION-BASED FRACTIONAL-ORDER SLIDING MODE CONTROLLER

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Electric vehicles (EVs) have become more popular due to their excellent efficiency and pollution-free benefits. The technology requirements for onboard chargers are increasing as the number of electric vehicles increases. This research proposes a fractional-order sliding mode controller (FOSMC) for power converters to improve the efficiency of the onboard battery charger. The Harris hawks optimization (HHO) algorithm chooses the FOSMC parameters. Independent controllers are used in a two-stage charging scheme. The grid-side ac–dc converter helps to smooth the current and voltage in the dc bus while reducing the harmonic frequency in the grid. A dc-dc converter with a constant current–constant voltage curve regulates the charging parameters of the battery on the battery side. Experiments show that HHO-based FOSMC improves the overall dynamic response of the onboard battery charger. Moreover, the proposed method performs with a current total harmonic distortion (THD) of less than 2 %. The proposed method improves 98% efficiency than existing methods such as SSA-PID and SSA-FOAFPIDF controllers.

1. INTRODUCTION

Battery electric vehicle (EV) technology has gained popularity in the modern period for its good consequences on global warming. The city is incorporating battery-electric buses into regular steps, although they must frequently recharge to be operational [1,2]. The EV battery pack comprises hundreds to thousands of cells coupled in sequence, parallel, or even more complicated ways to fulfill operating power and energy demands. Therefore, it is crucial to ensure and monitor the proper performance of the battery pack [3,4].

A battery management system (BMS) is a widely acknowledged technology for monitoring the condition of the battery pack and ensuring its security and performance enhancement. A BMS monitors and controls the battery, assessing charge estimation, health forecasting, temperature management, charge leveling, security, optimal energy, and power usage. The battery state-of-charge (SOC) is a critical BMS evaluation indicator. The SOC refers to the amount of charge left in the battery cells to its capacity. There is currently no direct technique to determine the SOC of a Li-ion battery. As a result, the SOC looks at battery metrics like current, voltage, temperature, and so on [5]. Mathematically, SOC is defined as

$$\text{State of charge}=\frac{P_{available}}{P_{rated}}. \tag{1}$$

There are two electric vehicle chargers [6]: offboard and onboard chargers. Customers choose onboard chargers since they can charge their electric vehicles anywhere. Adopting onboard chargers might enhance EV acceptance, especially among lightweight EVs designed for urban use. Galvanic separation between the grid and the vehicle is required for battery charging. At the same time, a long-life cycle and a small and light design may be used onboard are required. High charging efficiency, high power density, and adequate heat dispersion are all requirements for an onboard charger (OBC) [7].

The onboard charger (OBC) allows electric vehicles to charge from the grid. It is widely utilized in the automobile industry because of its simplicity compared to off-board charging options, which are expensive and require considerable usage [8]. Unidirectional OBCs are common because of their low battery deterioration and simple hardware requirements [9]. However, the recent evolution of electric vehicles has revealed their significance as a mobile energy source. A bidirectional onboard charger can provide the vehicle-to-grid capability to transfer electrical energy to the grid, which may be beneficial during peak power demands [10]. Furthermore, bidirectional OBCs were available for electric vehicle users to use their vehicles for other reasons, such as delivering vehicle-to-home or vehicle-to-load power while a grid failure or supplying vehicle-to-vehicle operation in a crisis [11]. Even though bidirectional OBCs have several drawbacks, including increased low power density, low system cost, reliability, weight, and complication architecture for smart grids [12], bidirectional OBCs are widely expected to become the primary charging solution.

Constant current and voltage (cc-cv) are batteries' most common charging methods [13]. The significant change in battery pack equivalent impedance is a critical problem during the charging profile. To achieve cc-cv charging, precise current and voltage management are needed on the battery side. The converters are frequently found in onboard chargers. These topologies can handle bidirectional power flow and save much equipment. The ac–dc converter is created to get unity power factor and dc bus voltage regulation. The bidirectional dc-dc converter maintains battery charging and discharging characteristics.

This research's primary objective is to develop a FOSMC that reduces the effect of grid power quality while retaining steady CC-CV charging of battery packs. An HHO

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optimization approach selects the fractional-order sliding mode controller parameters based on design equations. In MATLAB, the electro-thermal implementation of an onboard charger is employed to optimize the high-power charging system. Compared to previous systems, this proposed technique achieved high efficiency and low THD of current.

This manuscript is organized as follows: a literature survey based on an electric vehicle is discussed in section 2, detailed methodology for proposed HHO-based FOSMC is discussed in section 3, In section 4, experimental results are discussed, and the conclusion is based on performance is discussed in section 5.

2. LITERATURE SURVEY

This section explains various recent surveys related to onboard electric vehicle technologies. The present efficiency and performance of the onboard electric vehicle are discussed and provides an overview of current development in electric vehicles.

In 2020, Sharma et al. [14] presented a light electric vehicle onboard charger with an improved phase shift control to maintain the output during disturbance from the source side. Pulse width modulation control was used to regulate the dc link voltage. Double integral action of the sliding mode control resulted in no steady-state inaccuracy in charging.

In 2017, Shi et al. [15] presented a three-phase onboard charger for plug-in electric vehicles (PEV) using a Power Factor Correction (PFC) to control the voltage or current in a battery. As a result, the three-phase integrated charger provided a high-power factor and low THD with maximum efficiency. A significant disadvantage of the introduced approach is its low efficiency.

In 2020, Mohamed, A. A et al. [16] presented a salp swarm algorithm (SSA) based PV-powered electric vehicle charging station. Here, the SSA algorithm tunes the PI controller (SSA-PI). A goal is to minimize fluctuations in the dc-bus voltage and reference d and q-axis currents, represented by the signal's mean-square error. The main disadvantage is that optimal performance could be higher in obtaining volume, weight, and losses.

In 2021, Mohanty, D.et al. [17] presented an optimized. Load frequency control (LFC) method to control the frequency of a hybrid power system incorporated with numerous renewable energies, storage components, and EVs. Here, the controller is used to tune by the modified salp swarm algorithm (MSSA-PID) technique. The disadvantage is that battery regression will affect battery SOC estimation. Xu et al. [18] presented the soft switching current source rectifier (CSR) based bidirectional on-board charger system for an electric vehicle with several battery sets. The experimental findings for the suggested control and power circuit strategies for the onboard battery charging technique were provided to verify its effectiveness.

In 2019, Tran et al. [19] presented an onboard electric vehicle charger that can transfer power in both directions. The result shows that the primary current is controlled to operate at the maximum levels. Furthermore, the PFC is accomplished by controlling the grid current. The main issue with a dual active bridge converter has insufficient regulation of the electric vehicle battery.

According to the literature review, several works have some drawbacks related to low efficiency, limited charging power, and other drawbacks. To overcome these issues, this research presents a novel Harris hawks optimization algorithm-based fractional-order sliding mode controller, which effectively improves the performance of the onboard electric vehicle and efficiency.

3. PROPOSED HHO-FOSMC FOR ONBOARD ELECTRIC VEHICLE

Battery chargers can be placed within the vehicle (onboard) or outside (offboard). The dimension, weights, and volume of onboard battery chargers (OBC) are all limited [20]. In this section, FOSMC proposes to enhance the efficiency of the onboard charger, and the Harris Hawks Optimization (HHO) algorithm is used to choose the FOSMC parameters. Figure 1 shows the block diagram of the electric vehicle onboard charger using the HHO algorithm-based FOSMC.

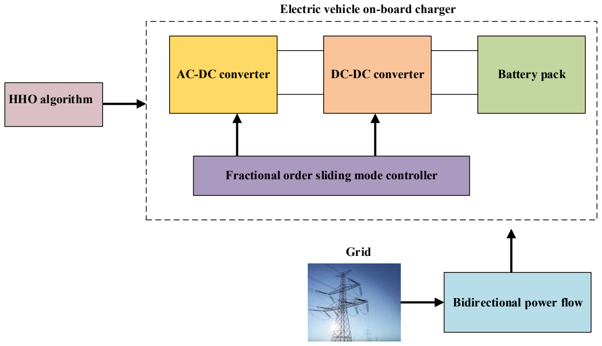


Fig. 1 – Block diagram of the proposed onboard electric charger using HHO-based FOSMC algorithm.

3.1 ELECTRO-THERMAL MODELING OF CONVERTER

An ac–dc stage and dc-dc stage are frequently found in onboard chargers. Loss estimation and thermal properties of the power converter are primary considerations in planning an onboard charger because of their impact on the efficiency and dependability of the system. A high-power DC charging system with low current ripples is designed to achieve maximum efficiency. As a result, the electro-thermal model is created in MATLAB and presented below.

3.1.1 AC-DC CONVERTER MODELING

Figure 2 depicts the proposed ac-dc converter topology, it can be performed in four quadrants of voltage and current. In this topology, the bidirectional half-bridge converter is on the primary side. The secondary side uses a full-bridge architecture to connect to the battery via a filter inductor (L_{dc}). When the fault occurs on the primary side, an extra switch with a bleeder resistor is employed to protect the primary side, and indicates the transformer leakage inductance. When the inductance is not sufficient, an external inductance is connected.

The proposed converter has four modes of operation. The converter may control both active and reactive power by controlling the power factor of the input current. When the input voltage (V_{in}) is high, and the current flows from the grid to the battery, the converter operates in mode 1. During mode 1, the gate pulses of the two pulses are 180 ° apart, and the duty cycle is kept between 0.5 and 1 to allow S_1 and S_3 to overlap, and other switches S_2 and S_3 is kept ON. The input voltage is negative during mode 2 operation, and current flows from the grid to the battery the S_1 and S_2 switches are in ON condition, S_3 and S_4 operate at high frequency with duty ratio modulation. The secondary side switches' gate pulses are phase-shifted to modify the transformer's effective voltage, thereby regulating the power flow to the grid.

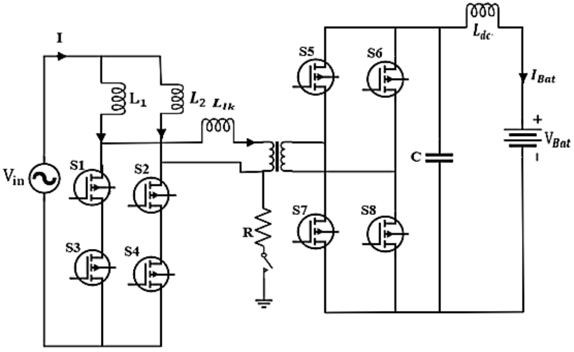


Fig. 2 – Single-stage ac-dc converter.

During mode 1 and mode 2 of operation, the relationship between input and output voltage (V_0) is described,

$$|V_0| = \frac{n\,|V_{in}|}{(1-d_1)} \tag{2}$$

where, V_0 – output voltage, V_{in} – input voltage, d – duty ratio, n - turns ratio of the transformer, which is considered 0.5.

Switching frequency and series inductance limit power transfer. During mode 3 and mode 4 of operation, the connection between the input and the output voltage is given by the relation:

$$V_{in} = \frac{(\varphi-\varphi_1)}{n} \tag{3}$$

where φ is the phase angle, varied between 0 and 0.5.

3.1.2 MODEL OF BIDIRECTIONAL DC TO DC CONVERTER

The goal of dc-to-dc power conversion is to ensure bidirectional power flow between two voltage levels in both standard and abnormal conditions. The appropriate topology of the dc-dc converter can achieve this. Fig. 3 depicts a bidirectional dc-dc converter topology that uses a half-bridge topology to mix step-up and step-down dc voltages. As a result, the primary performance is dependent on two distinct states. A bidirectional converter is installed between low-voltage and high-voltage sources to transfer energy.

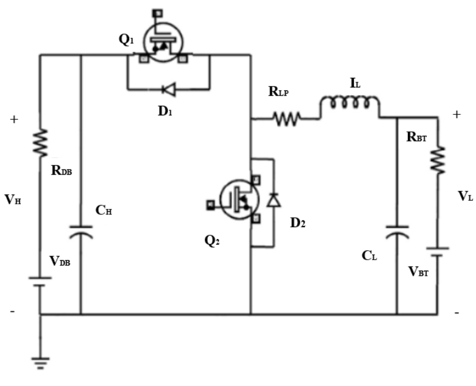


Fig. 3 – Bidirectional dc-dc converter.

The proposed converter topology is shown in Fig. 3. Energy storage elements such as inductor L, the input capacitor, C_H and output capacitor C_L. S1, S2, S3, and S4 are the MOSFET switches. These switches are also connected to anti-parallel diodes D1 or D2, which operate as a freewheeling diode during operations mode

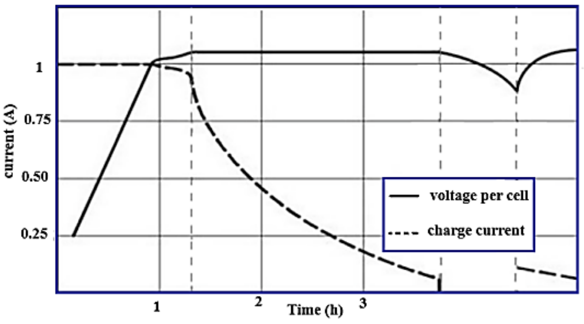


Fig. 4 – CC-CV charge stage.

Both an initial constant current and a final constant voltage are used in this method, as shown in Fig. 4. The charging procedure begins with a steady current and continues until the cut-off voltage is achieved. The battery is charged at a steady voltage just above the cut-off point. The battery is fully charged when the current decreases to between 4 and 6% of the rated current.

3.2 HHO-BASED FOSMC ALGORITHM

HHO, a programmable controller based on the Harris behavior of birds and fish, is used to evaluate the FOSMC parameters for both converters. The HHO search process begins with a hawk of Harris or a population of viable solutions, traveling through the problem space in search of the best solution. The flowchart of the proposed HHO-based FOSMC control strategy is shown in Fig. 5.

Considering that the output goal value is $S(t)$ is $S_d(t)$ then the inaccuracy in tracking is $e_x(t) = S(t) - S_d(t)$.

The fractional-order sliding mode surface is built with the system in consideration,

$$F(t) = x_1 e_x(t) - x_2 M^{\alpha} e_x(t) \tag{4}$$

where x_1 and x_2 are design parameters in the FOSMC. The order of the technique is different from $\alpha \in (0, \beta)$, and a better quality of FOSMC is applied.

$$\begin{aligned} \dot{\mathrm{f}}(t) &= x_1 \dot{e}_x + x_2 M^{\alpha} \dot{e}_x = \\ &= x_1 \dot{e}_x + x_2 M^{1+\alpha-\beta} D(E_x + F_v + A_i d) - \\ &- x_2 M^{\alpha} \dot{e}_d. \end{aligned} \tag{5}$$

Apply $\dot{\mathrm{f}}(t) = 0$ the corresponding control law calculate

$$C_{eq}(t) = (DE)^{-1}\left(M^{\beta} x_d - \frac{x_1}{x_2} M^{-\alpha+\beta e_x}\right) - F^{-1}Ex - A^{-1}A_1\widehat{d}. \tag{6}$$

The reaching law is used to meet the sliding requirement in the presence of losses

$$C_r(t) = (DE)^{-1}\left(-\frac{1}{x_2} M^{-1-\alpha+\beta}(k_1 f + K_2 sign(f)\right) \tag{7}$$

where k_1 and k_2 are constant gains.

The fractional-order sliding mode controller law is

$$\begin{aligned} \mathrm{C(t)} &= C_{eq}(t) + C_r(t) \\ &= (DE)^{-1}(M^{\beta} x_d - \left(-\frac{1}{x_2} M^{-1-\alpha+\beta}\left(k_1 f + k_2 sign(f)\right) - \frac{x_1}{x_2} M^{-\alpha+\beta e_x}\right) - F^{-1}Ex - A^{-1}A_1\hat{d} \end{aligned} \tag{8}$$

To find the best answer, the proposed HHO algorithm is used. The pursuing behavior of Harris hawks inspires the HHO algorithm. After considering local optimal solutions, misleading optima, and multimodality concerns, HHO can address search space challenges. The HHO-based FOSMC enhances system performance and finds the optimal solution. The suggested HHO algorithm has the following steps.

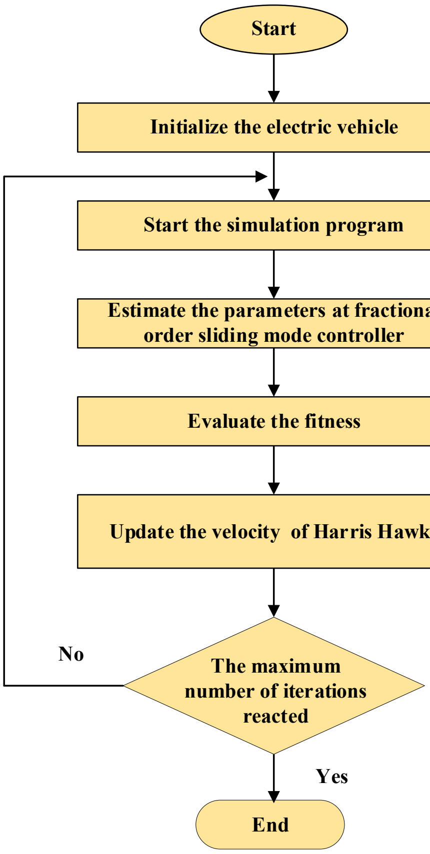


Fig. 5 –Flowchart of proposed HHO-based FOSMC control strategy.

The first step is to initialize a solution, which is written as

$$H= \{H_1, H_2, \dots, H_i, \dots, H_j\}, \tag{9}$$

where j represents the whole solution $H_i$is the i-th solution

The HHO algorithm's selection method aids in continuously updating the solution to get an ideal location. The Harris Hawks update their positions to encircle the expected prey. The current locations. The solution space is updated, and the problems are formulated as

$$H(x+1) = \Delta H(x) - E|HH_r(x) - H(x)|, \tag{10}$$

where $\Delta H(x)$ is the difference between the current position vector and its current location at iteration x, H denotes the random strength, $H_r(x)$denotes the current position at iteration x, and E denotes the escaping energy.

$$H(x+1) = H_r(x) - H(x) - E|HH_r(x) - H(x)|. \tag{11}$$

Assuming $H_r(x) > H(x)$ the equation is given as

$$H(x+1) = H_r(x) - H(x) - EDH_r(x) + EH(x), \tag{12}$$

$$H(x+1) = H_r(x) - H(x)(1-E) - EDH_r(x). \tag{13}$$

The updated equation according to HHO, is obtained by the current and previous observations and is stated as

$$H^{\mathrm{T}}(x) = \lambda H(x) + (1-\lambda)H(x-1), \tag{14}$$

where λ indicates the exponential constant and $H(x)$ represents the current solution while $H(x-1)$ indicates the previous solution.

$$H(\mathrm{x}) = \frac{H^{\mathrm{T}}(x)-(1-\lambda)H^{\mathrm{T}}(x-1)}{\lambda}. \tag{15}$$

After inserting eq. 12 into eq. 10, the resultant equation is as follows:

$$H(x+1) = \frac{H_r(\mathrm{x}) - H^{\mathrm{T}}(x) - (1-\lambda)H^{\mathrm{T}}(x-1)(1-E) - EDH_r(x)}{\lambda}. \tag{16}$$

The final equation, which is generated by combining FOSMC and HHO, is written as the proposed HHO's update equation and is written as

$$(\mathrm{x}+1)H_r(x)(1-\mathrm{ED}) - \frac{H^{\mathrm{T}}(x) - (1-\lambda)H^{\mathrm{T}}(x-1)}{\lambda}(1-E). \tag{17}$$

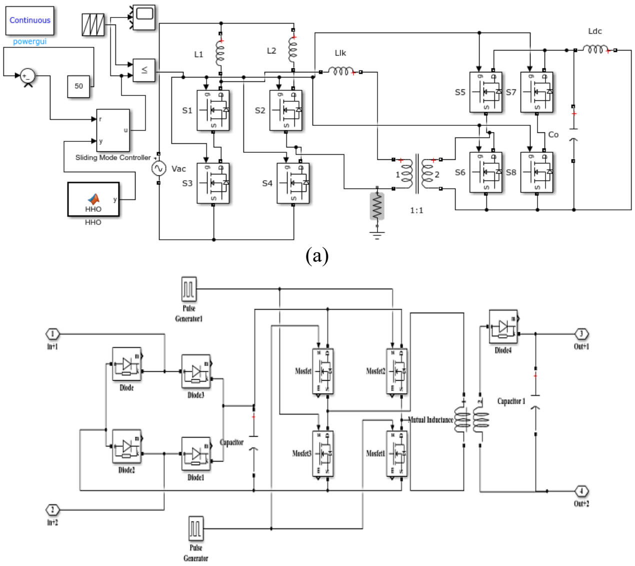
4. RESULT AND DISCUSSION

An experimental setup using MATLAB to investigate the performance of the onboard battery charger with a fractional-order sliding mode controller. This study aims to create an ideal 175 kW onboard charging system with maximum efficiency, low THD, ac ripples, and unity PF. The HHO and FOSMC design calculations are proposed to attain these objectives. The proposed HHO-FOSMC controller-based EV system is compared with the SSA-PI [16], and MSSA-PID controller [17] based EV systems. Figure 6(a) depicts the Simulink model of the proposed converter model, and Fig. 6(b) depicts the Simulink model of the EV battery charger. Figure 7 depicts the achieved THD of the line current, which is less than 2 %. An onboard charger's specifications are provided in Table 1.

Table 1

Specification of the onboard charger

Systems	Parameter
Dc load	175 kW
Ac phase voltage	400 V
Switching frequency	40 kHz
R1=R2	0.05 Ω
DC battery voltage	750 V



(a)

(b)

Fig. 6 – Simulink model of (a) proposed converter (b) EV battery charger.

The proposed system is performed with constant wind and PV power output, as shown in Fig. 8. During that time, there is a continuous 0.6 pu load demand. The system parameters are left at their default settings. While the vehicle was decelerating, the voltage drops across the battery decreased, and the battery was recharged by regenerative braking. Accordingly, the graph depicts the discharging and recharging processes as the speed changes.

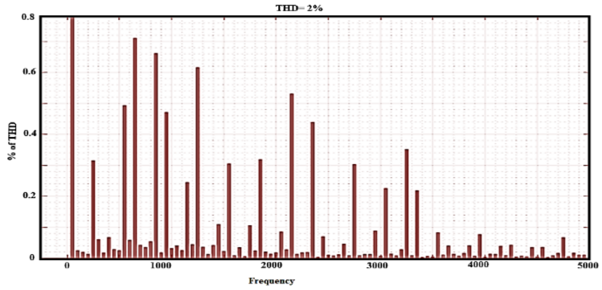
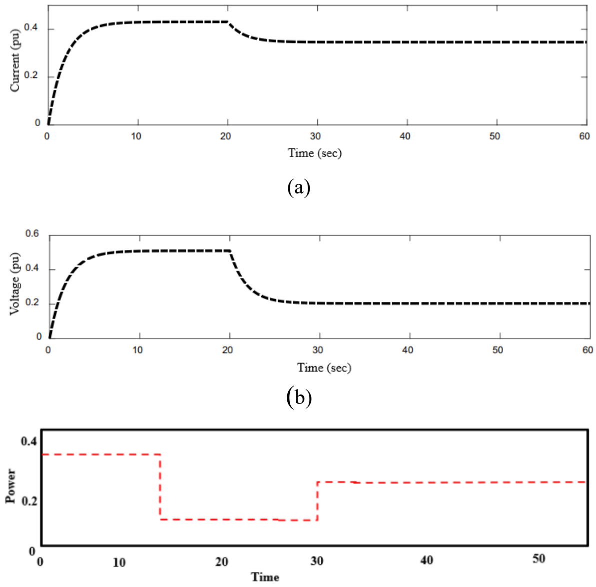


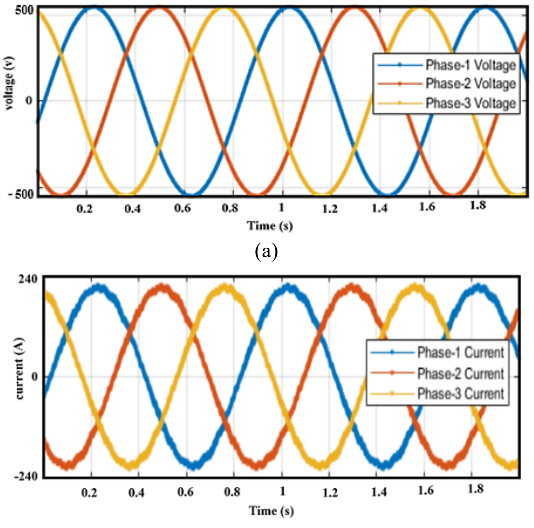
Fig. 7 – THD of input current



(a)

(b)

Fig. 8 – Simulation results of (a) Battery current; (b) Battery voltage; (c) Power demand.



(a)

(b)

Fig. 9 – 3 Φ voltage and current for ac -dc converter.

Figure 9 depicts the three-phase line current (150-300 A) and voltage (600-800 V). The suggested EV fast charger could accomplish dc fast charging by maintaining an output DC charging current of 130 A and an output dc charging voltage of 650 V. Three-phase voltage source converters can provide a constant dc bus voltage, lower harmonic distortion in utility currents, bidirectional power flow, and an adjustable power factor. They are becoming more common in high-power or high-performance drives that require rapid acceleration and deceleration because of their characteristics. In many situations, the cost of energy consumed when braking is too large, justifying the cost of a voltage source current as an integrated part of a drive or as a stand-alone device.

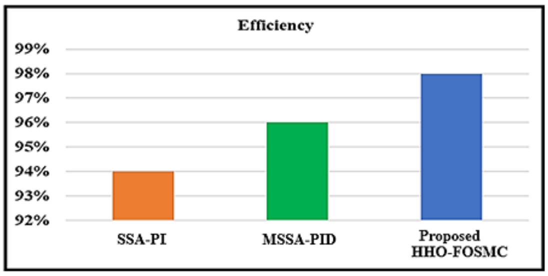


Fig. 10 – Comparison of efficiency curve with proposed onboard electric vehicle charger.

The efficiency of the HHO-based FOSMC algorithm is greater than 98%, as shown in Fig. 10. HHO-based FOSMC has the highest efficiency performance, further proving the effectiveness of the optimal design and analyses. System efficiency is critical to consider when evaluating the system's overall performance. This efficiency will be important in the design and optimization of the system.

5. CONCLUSION

A novel HHO-based FOSMC algorithm is proposed to improve the onboard battery charger's performance. Fractional-order sliding mode controller (FOSMC) for power converters to increase the performance of the onboard battery charger and the Harris hawk optimization is used to find the Fractional Order Sliding mode parameters. The grid-side ac–dc converter helps to smooth the current and voltage in the dc bus while reducing the harmonic frequency in the grid. A dc-dc converter with a constant current–constant voltage curve regulates the charging parameters of the battery on the battery side. Using electro-thermal simulation design in developing highly efficient charging systems is essential. The result shows that the THD of grid current is below 2 %, and the proposed method improves the 98 % of efficiency better than SSA-PID and MSSA-PID controllers.

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