Design of Adaptive Hysteresis Current Control Based on Artificial Neural Network for a Single-Phase Bidirectional Voltage Source Inverter

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***Abstract*— The rapid growth of electric vehicles and energy storage systems requires an efficient bidirectional power conversion system that operates in Grid-to-Vehicle (G2V) and Vehicle-to-Grid (V2G) modes, such as a bidirectional inverter. However, conventional Hysteresis Current Control (HCC) produces unstable switching frequencies that degrade power quality and system performance. To address this limitation, this study proposes a single-phase bidirectional Voltage Source Inverter (VSI) with a full-bridge topology controlled by an Artificial Neural Network (ANN)-based Adaptive Hysteresis Current Control (AHCC) scheme. In the proposed method, an ANN is used to determine adaptively the hysteresis band to maintain stable switching behavior. The system consists of a grid-connected bidirectional VSI and a bidirectional DC–DC converter interfacing the battery through a DC-link. Simulation results indicate that the proposed method maintains the inverter current within the hysteresis band while stabilizing the switching frequency near 15 kHz, with average values of 15.16 kHz during charging and 14.27 kHz during discharging. On the other hand, the DC-link voltage can also be maintained at 400 V during charging and discharging. So that, in the charging condition, the system can supply 2,107 kW from the grid, and the battery receives 2,048 kW. Meanwhile, in the discharging condition, the system can supply a load of 6 kW by distributing power between the battery (3.1 kW) and the grid (2.9 kW). hese results demonstrate that the ANN-based AHCC effectively stabilizes switching frequency and DC-link voltage while enabling reliable bidirectional power flow.**

Keywords—Bidirectional Voltage Source Inverter, Adaptive Hysteresis Current Control, Artificial Neural Network, V2G, G2V.

I. INTRODUCTION (*HEADING 1*)

Increasing electricity demand, decarbonization policies, and rapid advances in the transportation sector are driving the advancement of electric power conversion. Significant advancements have occurred in the transportation sector, particularly regarding electric vehicles that produce energy for distribution. [1][2]. The principles of V2G and G2V relate to bidirectional inverters/converters capable of transferring electricity between the battery and the grid in both directions. To enhance efficiency and ensure the stability of grid power flow and storage systems, employ bidirectional AC-DC converter topologies, such as dual-active bridges. Furthermore, the advancement of inverter topologies in electric cars, including Split-Source and Z-Source inverters, facilitates the application of Sinusoidal Pulse Width Modulation (SPWM) controls for bidirectional power delivery; however, dynamic switching frequency control has yet to be realized [4][5]. Consequently, the HCC is implemented; fixed band-HCC control applied to a single-phase inverter connected to the grid exhibits a dynamic response but also a variable switching frequency. Therefore, AHCC is utilized for a three-phase inverter to connected to the grid, ensuring superior dynamic response during transient conditions compared to SPWM [6][7].

The hysteresis band in AHCC is defined by input parameters such as frequency modulation, grid voltage, DC voltage, and reference current slope, which can vary the power flow with frequency switching close to constancy, thereby improving the current quality on the grid relative to the fixed band-HCC [8]. The AHCC-based iterative learning control (ILC) method achieved frequency stability by compensating for non-ideal effects and stabilizing the VSI switching frequency; however, it functioned unidirectionally, and the ILC learning mechanism did not facilitate mapping for determining the hysteresis band width [9]. As the complexity of bidirectional power systems increases, various advanced control strategies have been developed. One approach is the implementation of AHCC with digital control techniques, such as fuzzy logic-based bidirectional converters, which can dynamically adjust the hysteresis band according to load variations and operating conditions, enabling operation in both V2G and G2V modes [2].

Furthermore, V2G and G2V processes have been implemented in grid-connected bidirectional AC–DC and DC–DC converters for battery energy storage system applications. These systems commonly employ PID controllers or control strategies based on the dq domain, this method has a slower transient response than HCC. Therefore, ANN has been introduced to enhance power quality by reducing DC-link voltage ripple and minimizing the total harmonic distortion (THD) of grid current and voltage [10]. The application of ANN to inverters in a predictive current control scheme is able to improve the system's ability to handle non-linearity and parameter variations [11]. Although the method performs well under steady-state conditions, the control structure is relatively complex and requires a high computational load. In addition, the switching frequency is not explicitly controlled and the transient response tends to be slower than HCC. On the other hand, AHCC provides a very fast current response and a simple control structure, so in determining the band hysteresis bees still depends on analytical calculations that are sensitive to changes in operating.

Based on this explanation, this study proposes a single-phase bidirectional VSI with a full-bridge topology, equipped with a current control strategy that combines the advantages of AHCC with the nonlinear mapping capability of ANN for adaptive hysteresis band determination. As a result, the switching frequency can be maintained more stably while preserving the system’s fast dynamic response. This method maintains a constant switching frequency without affecting the system's dynamic response.

II. CONFIGURATION SYSTEM

V2G and G2V systems include a single-phase bidirectional VSI connected to the grid, a bidirectional buck-boost converter connected via a DC link, and and a battery supply as the source DC. The configuration system is shown in Fig. 1.

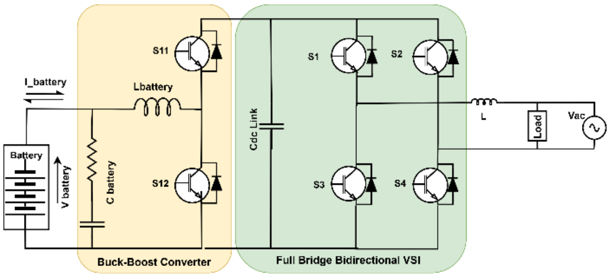


Fig. 1. Configuration System.

A. Buck-Boost Converter

A buck–boost converter interfaces the battery, DC-link, and inverter, enabling bidirectional power flow during charging and discharging modes. In the G2V condition, the converter operates in buck converter to step down the DC-link voltage to the battery voltage level. In this mode, switch S1 is controlled using PWM, allowing energy from the DC-link to be temporarily stored in the inductor (L_{bat}), while S2 remains off. When S1 is turned off, the energy stored in the inductor is transferred to the battery. The circuit of buck bost converters can be seen in Fig. 2.

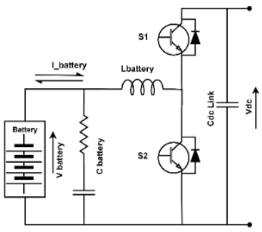


Fig. 2. Buck-Boost Converter Circuit.

Conversely, in the V2G condition, the converter operates in boost converter to raise the battery voltage to the DC-link level before delivering the energy to the grid through the inverter [14]. In this mode, switch S2 is modulated using PWM, while S1 remains off and conducts through its antiparallel diode. When S2 is active "ON", energy from the battery is temporarily stored in the inductor. When S2 is turned "OFF", the stored energy is released to the DC-link capacitor (C_{DC}) and subsequently delivered to the grid through the inverter. The switching of S1 and S2 is controlled by PWM, with the duty cycle determined by the voltage conversion ratio between the battery voltage and the DC-link voltage.

The design of the inductor and capacitors follows the Continuous Conduction Mode principle. The values of the inductor (L_{bat}) and capacitor (C_{bat}) are calculated for both buck and boost operating modes based on (2) until (5), and the maximum value is selected to ensure stable bidirectional power flow [14]. The capacitor (C bat) is used to limit voltage ripple during the switching process, while the DC-link capacitor (C_{DC}) functions as an energy buffer and reduces power fluctuations during the transition between charging and discharging, as determined in (1).

$$C_{DC} = \frac{P}{2\pi . f_g . V_{DC} . \Delta V} \tag{1}$$

$$L_{buck} = \frac{(V_{DC} - V_b)\, D_{buck}}{f_{sw}\Delta I}, D_{buck} = \frac{V_b}{V_{DC}} \tag{2}$$

$$L_{boost} = \frac{V_b\,(V_{DC} - V_b)}{V_{DC} f_{sw}\Delta I} \tag{3}$$

$$C_{boost} = \frac{V_{DC} D_{boost}}{R_0 \Delta V}, D_{boost} = 1 - \frac{V_b}{V_{DC}} \tag{4}$$

$$C_{buck} = \frac{\Delta I}{8 f_{sw} \Delta V} \tag{5}$$

B. Bidirectional Voltage Source Inverter (VSI)

A bidirectional VSI serves as a link between the DC side, such as the DC link or battery, and the AC power grid in grid-connected applications, with a full-bridge topology as shown in Fig. 3. A two-way VSI consists of four IGBT semiconductor switches with diodes. In inverter mode, the system transmits power from the DC side to the grid by alternately turning on the S1-S4 or S2-S3 switches, thus generating AC waves with the desired frequency and voltage. In discharging mode, the system supplies an AC load because the grid power is limited. So the grid and the battery meet the load's power needs. Furthermore, in the rectifier mode, the current direction reverses, from the grid to the DC side, causing the inverter current to be out of phase with the grid voltage, and the power flow direction reverses from the Grid side to the DC side. From this explanation, power can flow in two directions between the AC and DC sides [3][4][13].

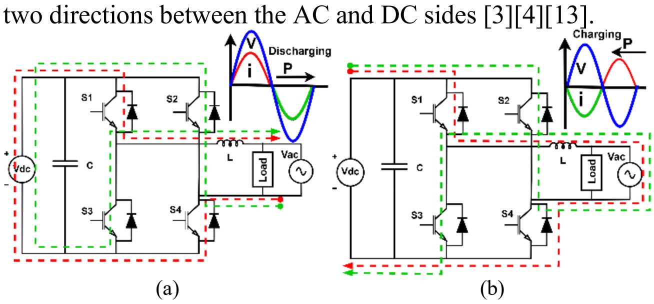


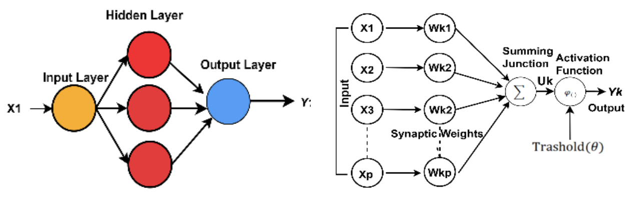
Fig. 3. Single-Phase Voltage Source Inverter Connected to Grid Circuit (a) Discharging Mode. (b) Charging Mode

Furthermore the filter inductor functions as a current limiter and harmonic switching damper, and maintains the quality of the current supplied to the grid in both operational modes. Therefore, the quality of current control is an important factor in maintaining power quality in systems connected to the power grid. [5][12][13].

C. Artificial Neural Network (ANN)

The ANN applied to the bidirectional three-phase full-bridge system is a feedforward neural network including an input layer, a hidden layer, and an output layer [15]. Each neuron in the hidden layer has a summing process like a summing junction, which adds the result of multiplication between the weight and the input, expressed in (6). The summation results are processed through a nonlinear activation function by considering the threshold value to produce the neuronal output signal, thus forming a nonlinear mapping between the input and output variables of the system [15].

$$Y_k = F(U_k - \theta_k)\,, U_k = \sum W_{kj} X_j \tag{6}$$



(a) (b)

Fig. 4 (a) Layer ANN Structure, (b) Mathematical Model for ANN [15].

ANN training uses the Levenberg–Marquardt algorithm to minimize errors and optimize weights and biases, in addition to having the speed of convergence and stability in studying the nonlinear characteristics of the system [15]

III. METHODOLOGY

The system configuration consists of a battery linked to a DC-link using a buck-boost converter. Then the DC-link is connected to a full-bridge bidirectional VSI. The control system is divided into two: buck-boost converter control to regulate battery charging and discharging, and ANN-based AHCC current control on the bidirectional VSI to regulate power flow between the battery and the grid, enabling V2G and G2V operation. The required parameter values are shown in Table 1.

TABLE I. SYSTEM PARAMETERS USED FOR SIMULATION

Notation	***Parameter***	***Value***
Ah	Battery capacity	120 Ah
$\Delta I, \Delta V$	Current ripple, Voltage ripple	10%, 1%
P_{bat}	Battery rated power	3,13kW
V_{BN}	Battery nominal voltage	60 V
L_{bat}	Battery side filter inductance	654μH
C_{bat}	Battery side filter capacitance	7,24μF
C_{DC}	DC-Link capacitance	6230 μF
V_{DC}	DC-link voltage	400 V
F_{sw}	Switching frequency inverter & converter	15 kHz
L_{inv}	Inverter side inductance	6,87mH
V_g	Grid Voltage	220 V

A. Buck Boost Converter Control

In battery charging operation or buck mode, the charging reference current is determined from the difference between the battery's actual voltage and its reference voltage, processed through PI control with a limiter, it shown in Fig. 5. When discharging the battery or in boost mode, the discharge reference current is determined from the difference between the DC-Link reference voltage and the actual DC-link voltage, processed by the PI controller and limiter. The charging reference current is marked negative, which means the current is flowing into the battery. On the other hand, the discharging reference current is positive, indicating the current flows from the battery. Then both reference currents enter the selector mode to activate buck or boost operation depending on the operating mode in progress, so that energy from the battery can be channeled to the DC-link or vice versa. Furthermore, the PI control and limiter outputs are converted to a PWM signal to control the power switch.

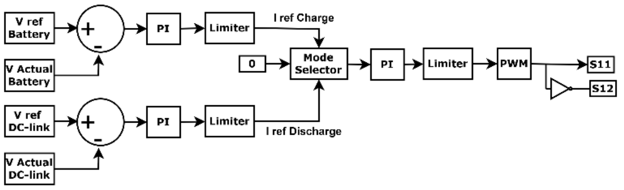


Fig. 5. Buck Boost Coverter Controler.

B. Adaptif Hysteresis Current control based ANN for Bidirectional VSI.

An ANN generates the optimal band hysteresis value to study the nonlinear relationship between the input of the system's operating condition and the output, i.e., adaptive band hysteresis. AHCC's current control ensures that the current flowing to the grid follows the reference current from the PLL configuration. The adaptive value of the hysteresis band is determined by the rates of change of the inverter's reference current $\left(m = \frac{i_{ref}}{dt}\right)$, DC-link voltage ($V_{DC}$), and instantaneous grid voltage (V_s), all of which are ANN inputs. Furthermore, the hysteresis band generated by the ANN is used to form the upper and lower limits of the inverter current, which is a reference in the hysteresis control logic to generate the PWM signal of the power switch controller, as shown in (7) and (8), and Fig. 6 for the full bidirectional bridge control of the VSI.

$$H^+ = i_{ref} + HB \; (Upper\ Band) \quad (7)$$

$$H^- = i_{ref} - HB (Lower\ Band) \quad (8)$$

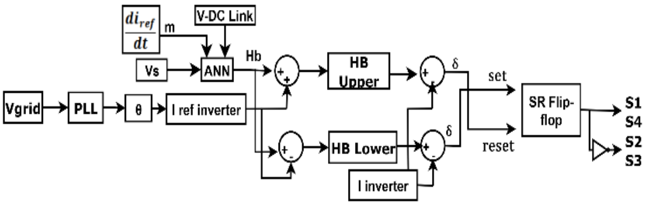


Fig. 6. Full Bridge Bidirectional VSI.

C. Training ANN

The ANN learning process is carried out offline using the MATLAB Neural Network Toolbox with the Feed-forward Neural Network (FNN) architecture. The ANN learning process can be seen in Fig. 7.

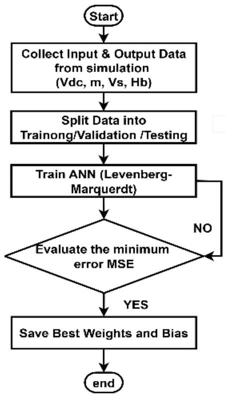


Fig. 7. Flowchart training ANN

The training dataset was obtained from simulation results of the conventional AHCC system under operating conditions for charging and discharging modes. The architecture consists of three ANN inputs, one hidden layer with 10 neurons, and one neuron on the output layer, which is the hysteresis value of the band, as shown in Fig. 8.

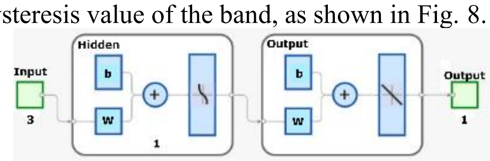


Fig. 8. Feed Forward ANN Architecture.

ANN training uses the supervised learning method with the Levenberg–Marquardt (LM) algorithm because it has a high convergence speed and good stability in minimizing training errors. The training data is randomly split into 75% for training, 13% for validation, and 12% for testing to ensure generalization and minimize the risk of overfitting. The maximum number of iterations (epochs) is set at 1000 epochs, with a validation check limit of six times. The training results in Fig. 9 show that the mean squared error (MSE) for the training, validation, and testing data is relatively small and consistent at the value "1", and the training process is stable until it achieves the best performance without any indication of over fitting.

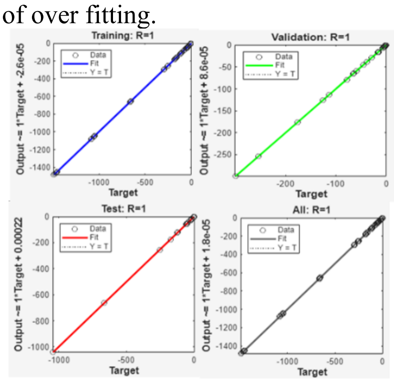


Fig. 9. Regression diagram

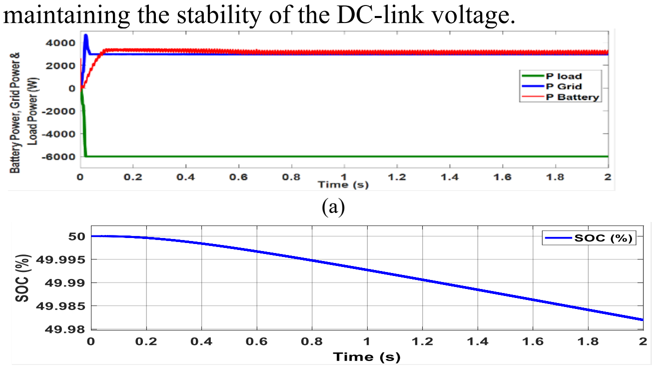
IV. Result

The bidirectional battery charging and discharging system is made in MATLAB / Simulink. The circuit consists of a lithium-ion battery connected to a bidirectional buck-boost converter and a bidirectional VSI connected to the grid and equipped with the parameters already summarized in Table 1.

A. Mode V2G

In V2G mode, the electric vehicle battery delivers energy to the AC Load. The results in Fig. 10 (a) show that the AC load is 6 kW, which is filled jointly by the battery and the grid, which is 3,1 kW and 2,9 kW. During the 2-second simulation, in Fig. 10 (b) the battery's SOC value decreased slightly from 50% to 49,998%, indicating the energy from the battery was channeled to the AC Load. In the Fig 10. (c) and Fig. 10 (d) the battery current reaches a stable condition at about 48,92 A and is able to follow a reference current of 48,84 A, which indicates good current tracking capability. Meanwhile, the battery voltage remains stable at around 63,99 V, which indicates that the converter system is able to maintain the stability of battery operation during the discharging process.

In Fig. 10 (e) the DC-Link voltage is stable at 0.616s with a value of 400 V and a deviation of ±4,4V (1.1%). This shows that the buck-boost converter control is effective in maintaining the stability of the DC-link voltage.



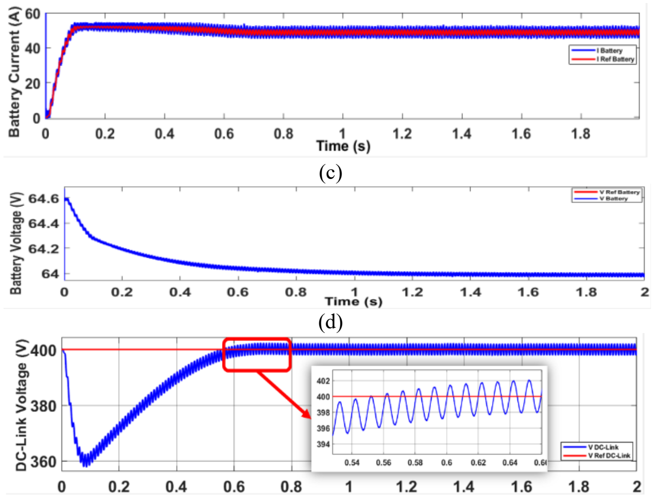
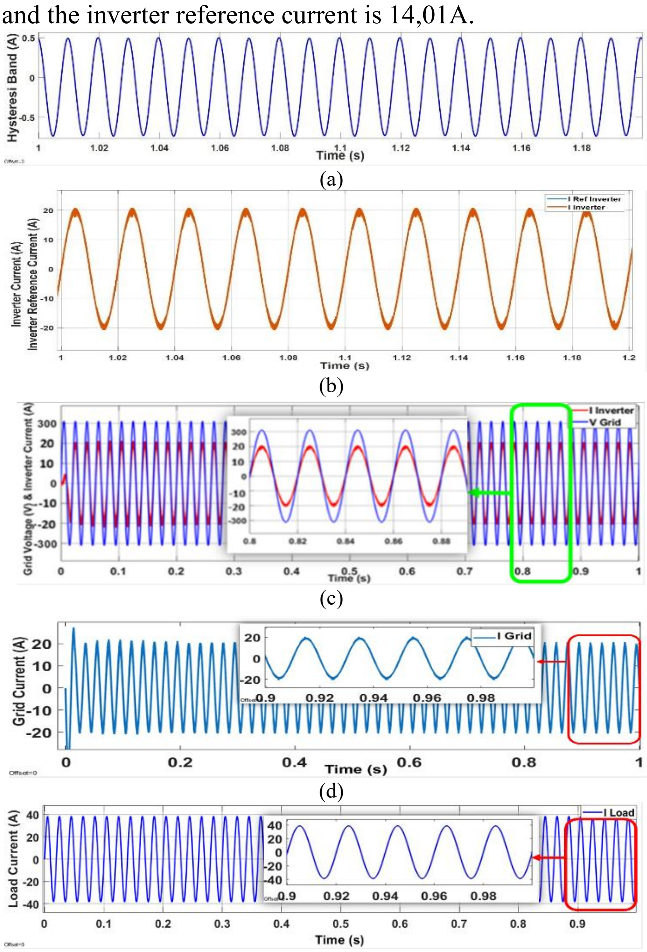
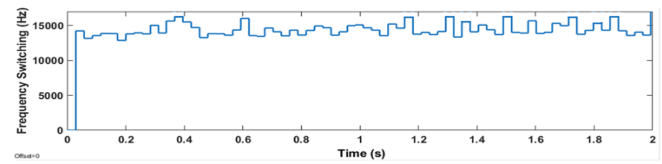


Fig. 10. Simulation results of the V2G mode operation. (a) Battery power and grid power. (b) Battery state of charge (SOC). (c) Battery current and reference current. (d) Battery voltage. (e) DC-link voltage and reference voltage.

The performance of the inverter current control is further analyzed by applying the Adaptive Hysteresis Band (HB) shown in Fig. 11(a). The results of the simulation showed that the band hysteresis value was adaptive, ranging from about −0,73 to 0,49. The HB value keeps the inverter current within the upper and lower band limits, so that the inverter current can closely follow the reference current, as shown in Fig. 11(b), The RMS inverter current value is obtained at 13,80A, and the inverter reference current is 14,01A.





(f)

Fig. 11. (a) Adaptif Hysteresis band. (b) Inverter Current and Inverter references Current. (c) Inverter current and grid voltage. (d) Grid Current. (e) Load Current. (f) Switching frequency of the inverter.

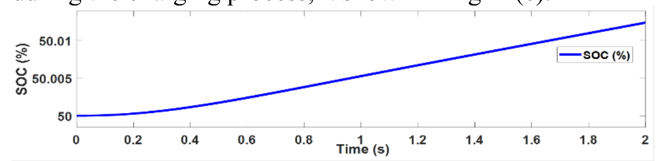
Furthermore, the correlation between the inverter current and the grid voltage is shown in Fig. 11(c), where the inverter current is in phase with the grid voltage, resulting in active power being supplied. its shows that the active current control is working well. Meanwhile, the grid current and load current are 13,33 A and 27,11 A, respectively, with the grid RMS voltage value and load RMS voltage of 219 V, as shown in Fig. 11(d) and Fig. 11(e).

In addition, the adaptive mechanism generated by the ANN also helps maintain the stability of the inverter switching frequency, as shown in Fig. 13(f), with an average inverter switching frequency of 15,16 kHz. It can be concluded that the ANN-based AHCC control is functioning effectively and maintaining the stability of the Vdc link and the switching frequency during V2G mode.

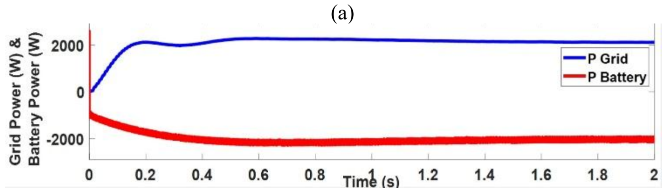
B. Mode G2V

In the charging (G2V) condition, energy from the grid flows to the battery through a bidirectional inverter and buck–boost converter. This is shown by the increase in the State of Charge (SOC) from 50% to 50.02% during the 2s simulation, indicating that the battery receives energy from the grid, as shown in Figure 12. (a). The power absorbed by the battery is 2.048 W, while the power supplied by the grid is 2.107 W, as shown in Fig. 12(b).

As seen in Fig. 12(c) and Fig. 12(d). The charging condition can be seen from the direction of the battery current which has a negative value of −48 A, which indicates a current flowing towards the battery with a stable battery voltage of about 64,5 V DC-link voltage reaches a stable condition at t = 0,605 s with a value of about 400 V and a deviation of ±4,095 V (1%), which indicates that the buck converter can maintain the stability of the DC-link voltage during the charging process, it shown in Fig 12(e).



(a)



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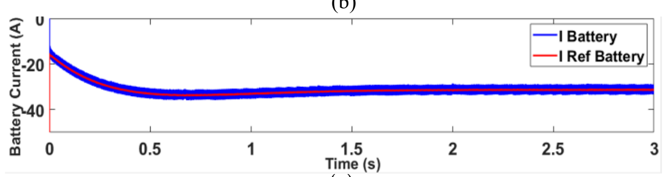
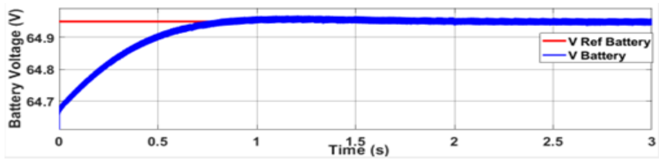
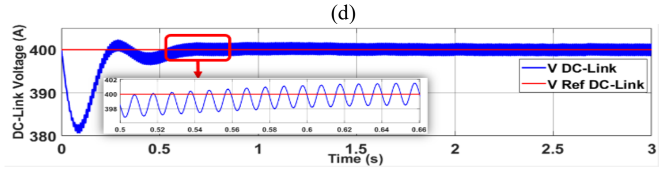


(c).



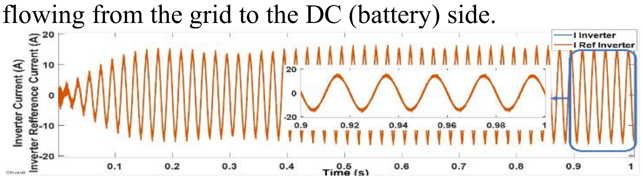
(d)



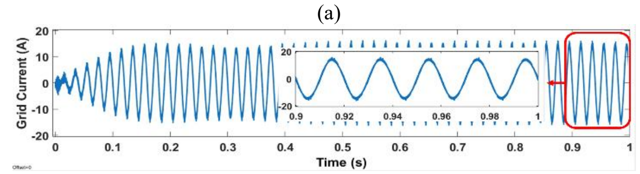
(e).

Fig. 12. Simulation results of the G2V mode operation. (a) Battery state of charge (SOC). (b) Battery power and grid power. (c) Battery current and reference current. (d) Battery voltage. (e) DC-link voltage and reference voltage.

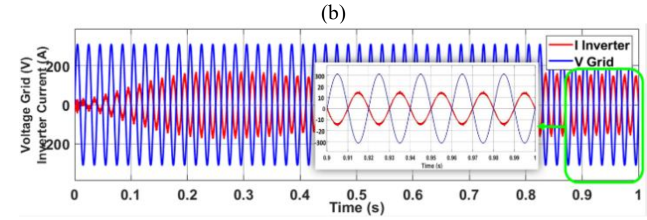
Furthermore, the performance of the Adaptive Hysteresis Band (HB) shows that the inverter current remains within the upper and lower band limits, so that the inverter current can closely follow the reference current. The RMS value of the inverter is 9,59A, with a reference current of 9,36 A, as shown in Fig. 13(a). In addition, the grid current remain stable during the charging process, with the grid current being 13,33A, as shown in Fig. 13(b). Furthermore, the correlation between the inverter current and the grid voltage in Fig. 13(c) shows opposite-phase conditions, indicating that power is flowing from the grid to the DC (battery) side.



(a)



(b)



(c)

Fig. 13(a) Inverter current and Inverter References Current. (b) Switching frequency of the inverter. (c) Inverter Current and Grid Voltage.

On the other hand, the adaptive Hysteresis band produced by the ANN also maintains the inverter's switching frequency at an average of about 14,27 kHz, without significant frequency spikes during battery charging, as seen in Fig. 14. It can be concluded that the ANN-based AHCC control is functioning effectively and maintaining the stability of the Vdc link and the switching frequency during V2G mode.

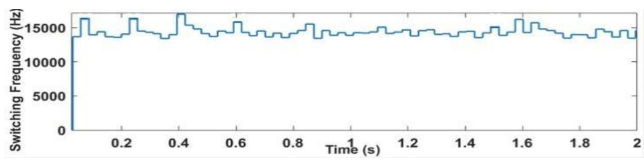


Fig. 14. Simulation results of the Switching frequency of the inverter.

V. Conclusion

Based on the simulation results, the proposed ANN-based AHCC method improves the performance of the VSI bidirectional system under V2G and G2V operating conditions. ANN is used to adaptively determine the hysteresis band, so that the inverter current remains within the hysteresis band and can follow the reference current. This mechanism also allows the inverter switching frequency to remain stable near the desired value of around 15 kHz, with average values of 15,16 kHz in charging mode and 14,27 kHz in discharging mode, without significant frequency spikes. In addition, the proposed control method maintains the DC-link voltage at approximately 400 V during charging and discharging. In the charging condition, the grid-supplied power is 2.107W, and the battery receives 2.048W. Meanwhile, in the discharging condition, the system can supply a load of 6 kW by distributing power between the battery (3,1 kW) and the grid (2,9 kW). The overall simulation showed that the system could operate stably in bidirectional power flow between the battery and the power grid.

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To Author:

Artikel ini membahas tentang sistem kendali arus histerisis secara adaptif berbasis Artificial Neural Network pada sistem VSI bidirectional dan telah disajikan dengan baik. Namun demikian masih diperlukan peningkatan penyajian artikel dengan menanggapi komentar-komentar berikut ini. 1. Penggunaan simbol parameter dalam persamaan perlu ditambahakan keterangan dan satuan yang digunakan. 2. Arsitektur ANN yang digunakan dalam simulasi perlu diberikan penjelasan yang lebih rinci dan detail agar mempermudah pemahaman pembaca tentang penerapan ANN pada sistem kendali arus histerisis adaptif. 3. Pada bagian kesimpulan disebutkan bahwa ANN mampu memperbaiki kinerja sistem VSI bidirectional untuk kedua kondisi V2G dan G2V. Namun demikian, pada hasil dan pembahasan belum ada analisa yang mendukung hal tersebut. Disarankan untuk disajikan data dan pembahasan dengan menggunakan data pembanding lainnya sehingga perbaikan kinerja jelas terlihat. 4. Masih terdapat beberapa kesalahan ketik pada naskah, sebaiknya diperiksa dan diperbaiki secara cermat. Sepertinya terdapat kesalahan urutan penulisan citasi, perlu di cek dan diperbaiki. Sebagai contoh pada bagian pendahuluan terdapat nomor citasi [1][2] lalu dilanjutkan dengan [4][5]. Kenapa nomor citasi [3] tidak ada? 5. Resolusi gambar perlu ditingkatkan sehingga meningkatkan keterbacaan dan mudah dipahami pembaca.	This article discusses an adaptive hysteresis current control system based on an Artificial Neural Network for a bidirectional VSI system, and is well presented. However, the article still requires improvement by addressing the following comments. 1. The use of parameter symbols in the equations needs to be accompanied by explanations and the units used. 2. The ANN architecture used in the simulation needs a more detailed explanation to facilitate the reader's understanding of the application of ANN in the adaptive hysteresis current control system. 3. The conclusion states that ANN is capable of improving the performance of the bidirectional VSI system for both V2G and G2V conditions. However, the results and discussion section lacks an analysis to support this claim. It is recommended to present data and discussion using other comparative data so that the performance improvement is clearly visible. 4. There are still several typos in the manuscript; these should be carefully checked and corrected. It appears there is an error in the citation order; this needs to be checked and corrected. For example, in the introduction section, there are citation numbers [1][2] followed by [4][5]. Why is citation number [3] missing? 5. Image resolution needs to be improved to enhance readability and make it easier for readers to understand.

To General Chair:

Artikel ini membahas tentang sistem kendali arus histerisis secara adaptif berbasis Artificial Neural Network pada sistem VSI bidirectional dan telah disajikan dengan baik. Paper ini sebaiknya dimasukkan ke dalam kelompok AI for Power and Energy System.	This article discusses an adaptive hysteresis current control system based on an Artificial Neural Network for a bidirectional VSI system and is well-presented. This paper is more appropriately categorized under “AI for Power and Energy Systems.”