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An effective control structure of on-board battery charger for electric vehicles

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ABSTRACT

The plug-in electric vehicles (PEVs) including plug-in hybrid electric and all-electric vehicles will play a key role in the transportation future throughout the world. Consequently, a variety of works must be done to decrease the cost, improve the structure and increase the convenience of PEVs. This study proposed a single-phase, non-isolated and on-board battery charger with no use of any transformer which reduced the volume and weight of the system for PEVs. The main purpose is to provide an accurate control structure in order to achieve an acceptable charging in the wide range of voltage. The proposed structure is simulated by matrix laboratory (MATLAB) software. The results showed a high-power density, high efficiency and appropriate power factor from the structure of the non-isolated and single-phase charger.

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1. INTRODUCTION

According to vehicle technologies office (VTO) of the United States (U.S.) department of energy, improving vehicle efficiency in U.S. is essential to reducing consumers' fuel costs, supporting domestic industry, minimizing pollution, and increasing energy security through low-cost, secure, and clean energy technologies [1]. The relationship between energy and fuel efficiency, environmental pollution and focus on the clean energy is driving the transportation to develop electric vehicle (EV) industry [2], [3]. Furthermore, the pollutions, greenhouse gases and landfills are the major environmental issues in recent years [4], [5] which has attracted a lot of attention for efficiency improvement of power systems and electrical machines [6], [7]. Power electronics technology, vehicle design and batteries have provided a significant opportunity to achieve cleaner energy sources in the automotive industry that pushed the development of EVs. The general schematic of a typical EV is shown in Figure 1. Accordingly, a structure with the capability of high efficiency, high power density, low price, and appropriate control methods is required to increase the life cycle of battery and optimal use of stored energy in EVs. They should also have the ability to modify the network power factor. These chargers are designed and used in two main types such as on-board and off-board [8].

The on-board battery chargers are installed on EVs which have some advantages such as direct charge from distribution network, needless of charging station, simple system configuration, longer battery life and lower cost [9]–[14]. These chargers are common in automotive industry due to their availability and comfort [9]. However, these chargers have limited power because of their volume and weight. In some cases, the on-board battery chargers are integrated with the vehicle's electric drive to avoid extra inductors and switches that are only used to charge the battery [15]. The off-board battery chargers are some systems in the charging stations that all the devices of charging sectors installed at the center. The off-board systems have faster charging capability but their high cost and volume are the main disadvantages for many users [9], [16]. Chargers of EVs are divided into 3 categories in terms of charge levels. Level 1 charger has the slowest charging method that uses the standard with a voltage of 120 V and 11 A in the U.S.

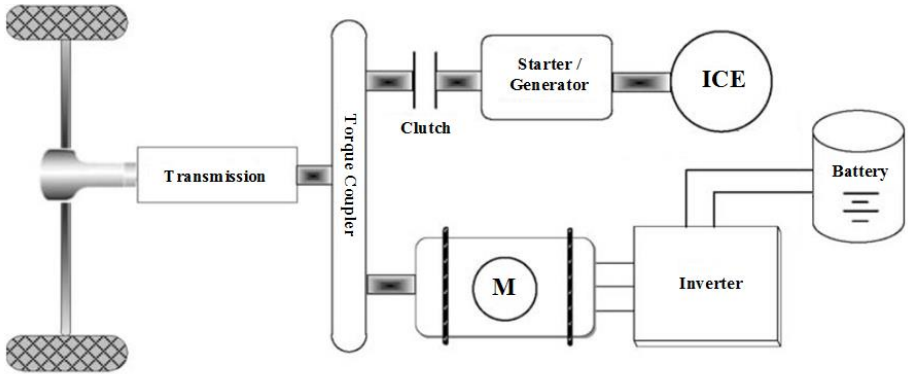


Figure 1. The schematic of an EV

Level 2 charger is suitable for public and private places and can charge with a voltage of 208-240 V and a maximum of 80 A and a maximum power of 19.2 kW. Level 3 charger can charge in less than an hour and at a three-phase voltage level of 480 V and above which is suitable for charging stations [2], [17]–[19]. Battery chargers (BCs) can also be classified into two types in method of charging including the conductive and inductive systems. The conductive charger has a physical link among the power electronic interface and power supply for charging, while the inductive charger operates wireless without any physical connection among power electronic interface and supply. Inductive chargers are mainly intended for slow charging applications [19]–[23]. The basic structure of BC system in EVs is displayed in Figure 2 [18].

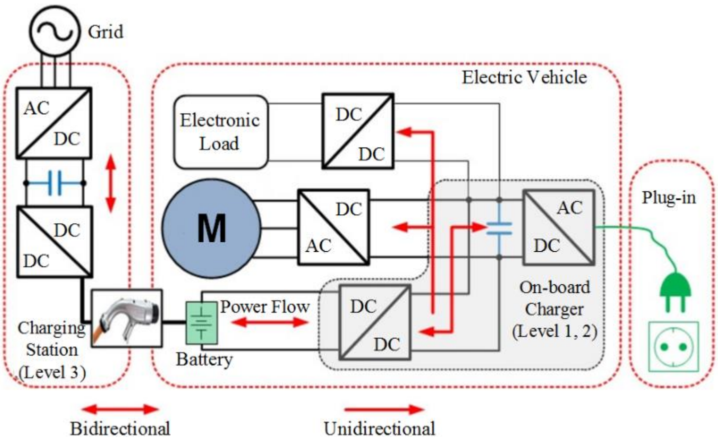


Figure 2. The structure of BC system in EVs

Another feature used to classify BCs is galvanic isolation, which is used for security reasons and at the same time makes the structure larger and heavier and requires complex controllers [22]. Finally, there are two sorts of BCs including the two-way charger that receive/inject energy from/into the grid and one-way charger which is only used to charge the battery. Two-way structures are larger and heavier than one-way types and require more components to operate in both directions. Furthermore, the structure of BCs in EVs can be divided into two kinds such as isolated and non-isolated. Isolated structures use high-frequency transformer to have the various range of voltage and an isolation layer that reduce the efficiency. Weight, volume, and parts of non-isolated types are less than the isolated ones. Few research works have been reported on non-isolated strategies for BC applications due to their output voltage and limited power capacity [24].

A non-isolated on-board BC structure was integrated with a high-power, low-voltage direct current (DC)-DC converter to charge low-voltage auxiliary batteries via [25]. The non-isolated BC is a single-stage diode bridge with a three-phase cascade interlude buck-boost converter. Due to the usage of an isolated DC/DC converter the overall efficiency of the circuit is reduced. Earlier studies [26] showed a conventional DC/DC boost converter with a rectifier as a one-way BC which provided a new phase shift control to achieve the unit power factor. An on-board single-phase BC is introduced by [27] with auxiliary charging system. A topology based on governed power factor and fixed current is used for charging the high voltage battery. The strategy is simple and reliable with the advantage of auxiliary battery charging system but switching losses are high. A high-efficiency on-board single-phase charger with a full diode bridge converter is presented by [28]. The main feature of this system is that no need of DC link capacitor. A research by [29] proposed a multifunctional converter to charge EVs based on grid and solar sources. The important feature of the circuit is to cover various modes of EVs such as charging, propulsion and regenerative braking. The outcome indicates a good performance for proposed converter. A new integrated single-phase converter for electric chargers of hybrid vehicles is presented by [30], [31] for reduction in weight and size of circuits. The introduced system is suitable for different range of voltage with longer life. This study presents a non-isolated structure for charging EV batteries with control circuits for power factor correction. Some advantages of the proposed strategy are including the high efficiency, low number of elements, low cost, volume, and weight, as well as high reliability and flexibility.

2. RESEARCH METHOD

2.1. Recommended structure of single-phase battery charge

A diode rectifier with two interlude buck-boost converters is proposed as a single-phase BC. The advantages of this structure over other non-isolated buck-boost converters are uniformity of input and output voltage polarity, low voltage stress on semiconductor elements, better performance than other topologies due to a common inductor between the buck area and the boost area, and having a common ground. Figure 3 shows the system structure considering the input source switch off and on.

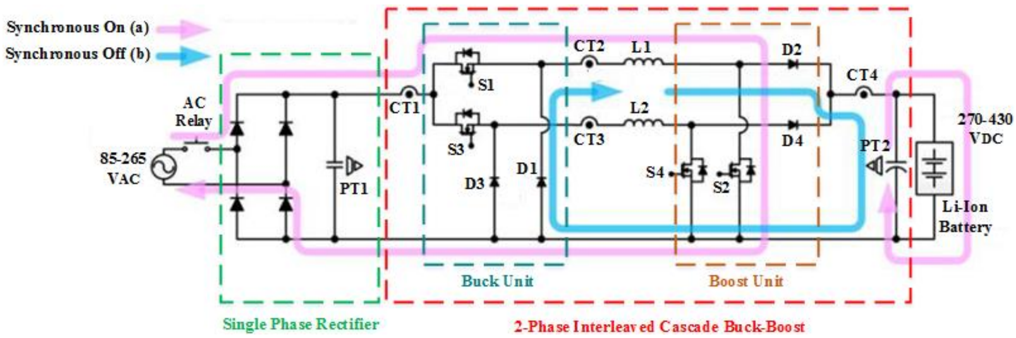


Figure 3. The proposed buck-boost converter

According to the Figure 3, when the switch is off, energy is conducted from the input source to the inductors. Energy is injected into the battery through a capacitor parallel when it is on and the charging process begin. Therefore, the performance of the above system can be considered similar to a buck-boost converter in energy transfer and the following equations can be provided to calculate the output voltage of the converter.

$$i_{L.on}(t) = \frac{1}{L}\int_0^t V_{in}dt + I_{min} \quad (1)$$

$$I_{max} - I_{min} = \frac{V_{in}}{L}DT \quad (2)$$

$$i_{L.off}(t) = \frac{1}{L}\int_{DT}^t(-V_{out})dt + I_{max} \quad (3)$$

$$I_{max} - I_{min} = \frac{V_{out}}{L}(1-D)T \quad (4)$$

$$\frac{V_{in}}{L}DT - \frac{V_{out}}{L}(1-D)T = 0 \quad (5)$$

$$V_{out} = \frac{D}{1-D}V_{in} \quad (6)$$

Where $i_{L.on}$ and $i_{L.off}$ are the inductor currents for on and off conditions, respectively, L is the inductance, I_{min} and I_{max} are the minimum and maximum currents, respectively, t is the time, V_{in} and V_{out} are the input and output voltages, respectively, T is the control period and coefficient D is the working coefficient of the buck-boost converter which determines the ratio between input and output voltages. The output voltage is controlled in a wide range of input voltage between 86 V and 265 V using a control algorithm. A switching strategy based on three functional modes as buck, boost and cascade is applied. Table 1 summarized the switching modes. The three functional modes for charging of battery are shown in Figure 4. The buck functional mode is shown in Figure 4(a), the cascade functional mode is shown in Figure 4(b), and the boost functional mode is shown in Figure 4(c).

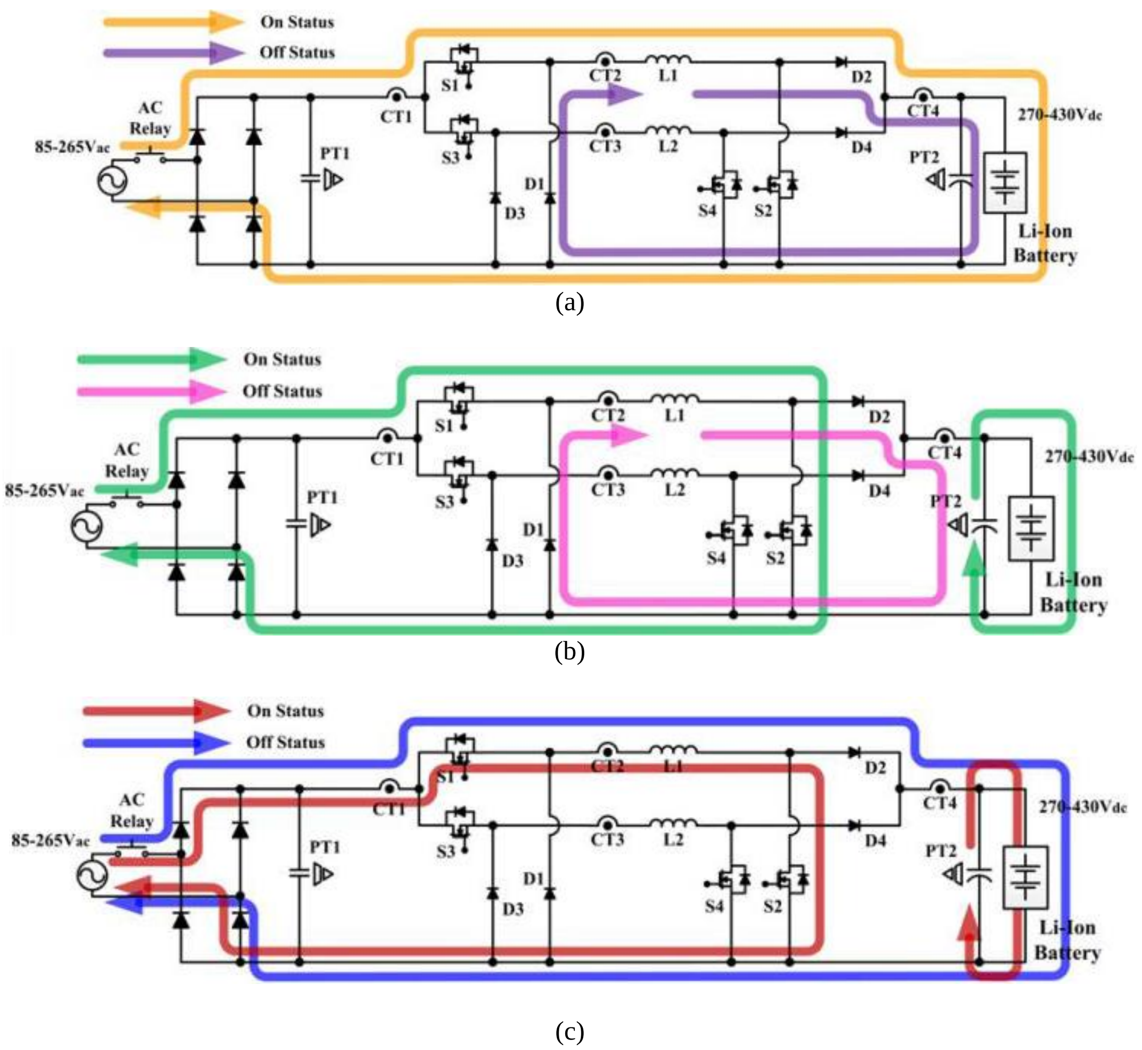


Figure 4. Circuit functioning in three switching modes: (a) buck functional mode, (b) cascade functional mode, and (c) boost functional mode

Table 1. Switching mode of converter

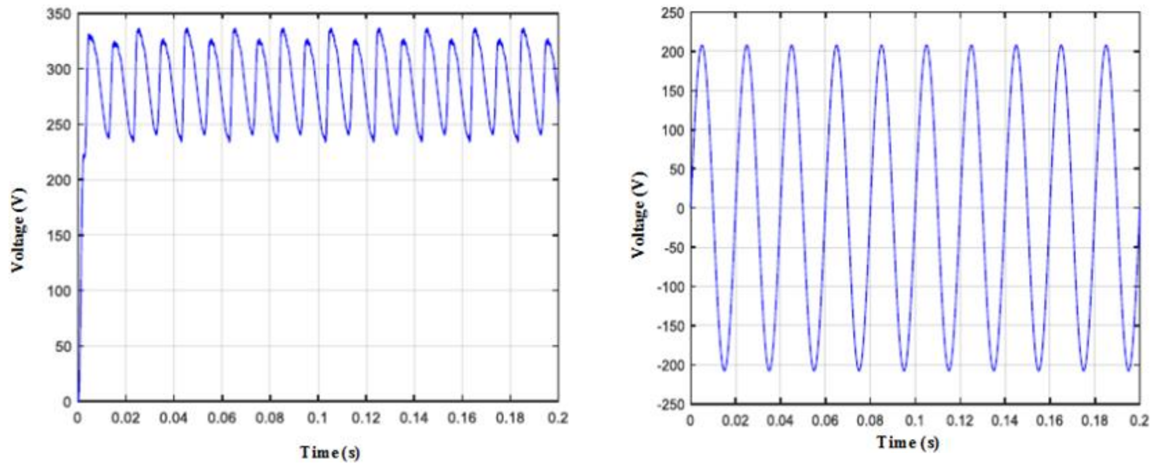
Functional mode	Buck	Boost
Buck	Off	Switching
Cascade	Switching	Switching
Boost	Switching	On

3. RESULTS AND ANALYSIS

The proposed system is analyzed using matrix laboratory (MATLAB) software. The system parameters are indicated in Table 2. Two different cases are considered. In the first case, the input voltage was 208 V and the output voltage was in the range of 280-320 V as shown in Figure 5. Figure 5(a) is the input and Figure 5(b) is the output voltages of the converter. It is clear that the values are in the desired range. The related input and output currents are displayed in Figure 6. Figure 6(a) is the input and Figure 6(b) is the output voltages of the converter. It can be observed that the DC output current is 5 A while the input current is sinusoid and has some fluctuations. One of the features of the designed circuit is to reduce of total harmonic distortion (THD) injected into the network, which is caused by the converters. According to fast fourier transform (FFT) analysis, the amount of harmonic injected into the network is about 5.84%, which is a small and acceptable value as shown in Figure 7.

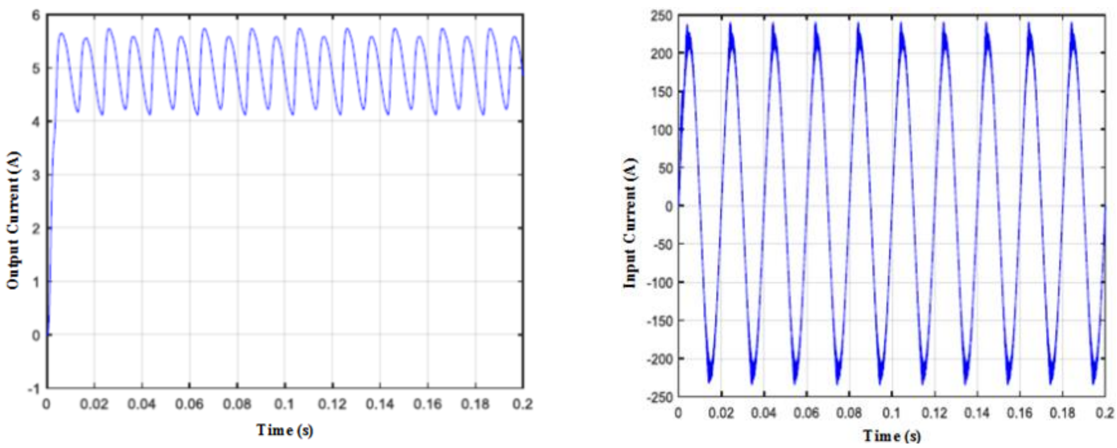
Table 2. System parameters

Parameter	Symbol	Size
Nominal power	P_{max}	3.7 kW
Nominal voltage	V_{in}	120-208-240 V
Maximum input voltage	$V_{in.max}$	265 V
Minimum input voltage	$V_{in.min}$	85 V
Output voltage range	$V_{out.DC}$	270-430 V
Output current range	$I_{out.DC}$	0-13.8 A



(a) (b)

Figure 5. Voltages of converter: (a) input and (b) output



(a) (b)

Figure 6. Currents of converter: (a) input and (b) output

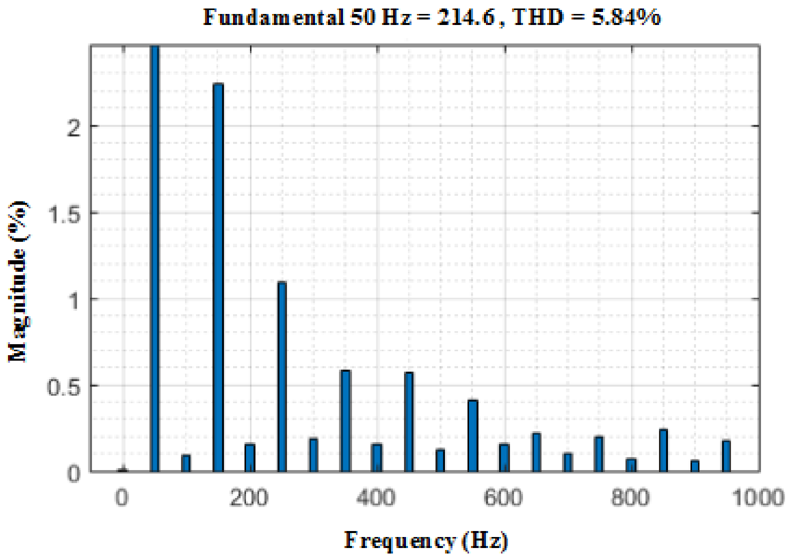


Figure 7. Harmonic analysis of current ($f = 50\ Hz$)

Another advantage of the proposed circuit is the proper operation in abnormal conditions. For instance, decrease or increase of input voltage frequency has less effect on the output and performance of the system. Accordingly, the system for network frequency of 70 Hz are examined. It can be concluded from Figure 8 that variation of frequency had little effect on the relevant curves and the battery still charged due to the proper control algorithm in the system. The THD value of the network current was also increased by only 0.14%, which is a small value as shown in Figure 9.

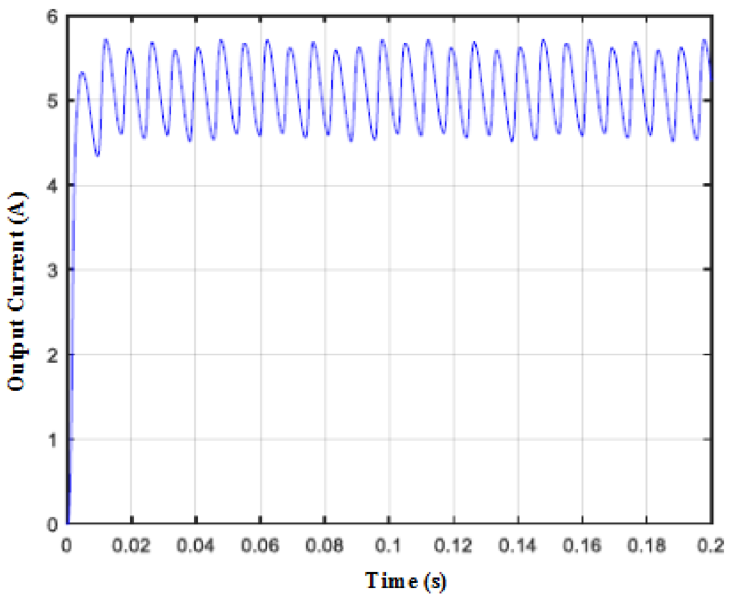


Figure 8. Output currents of converter ($f = 70\ Hz$)

The proposed converter and its control algorithm operate at high efficiency and suitable power factor in all switching modes. The efficiency and power factor of the system in the case of input voltage of 208 V are presented in Figure 10. Figure 10(a) shows the efficiency and Figure 10(b) shows the power factor of the converter for V_in = 208 V. As can be seen, the values of power factor and efficiency in all cases had an acceptable value which prove that the proposed converter operates at high efficiency.

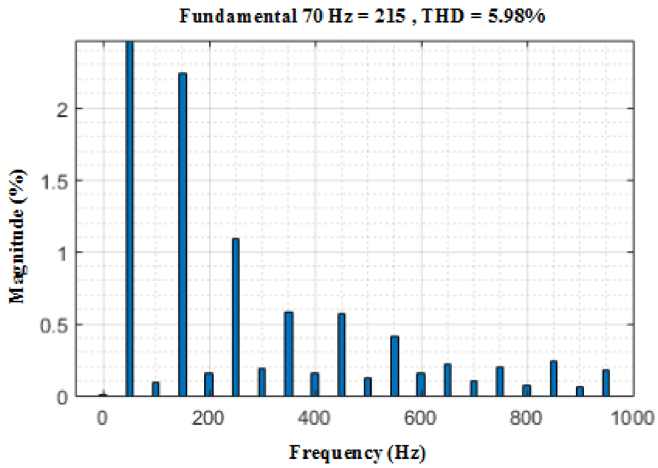


Figure 9. Harmonic analysis of current ($f = 70\ Hz$)

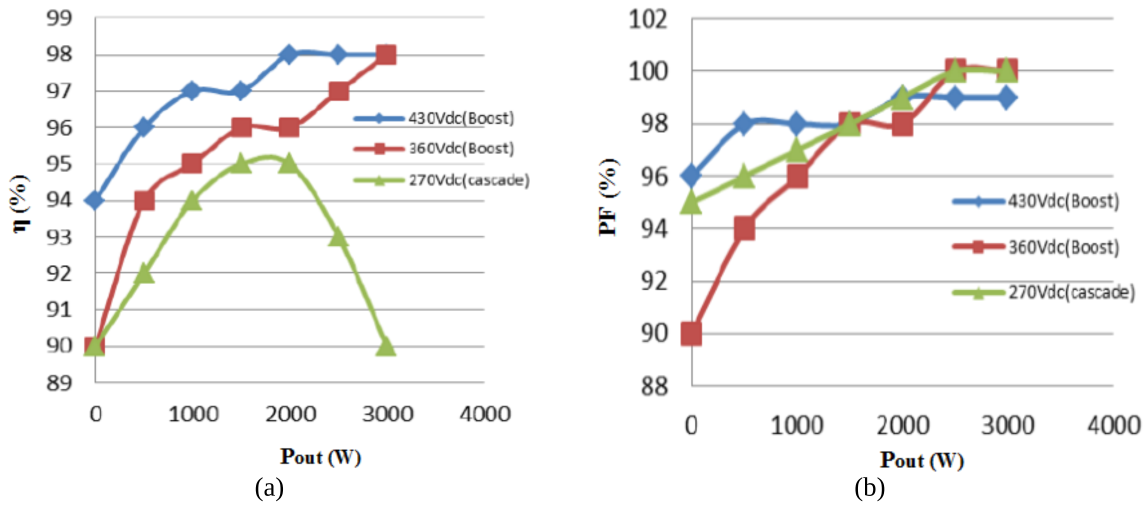


Figure 10. Case of input voltage of 208 V: (a) efficiency and (b) power factor of converter for $V_{in} = 208$ V

4. CONCLUSION

This study introduced an on-board BC for EVs with focus on reducing the size and enhancing the efficiency which is mandatory for new vehicles. A control strategy is defined for various input and output situations to achieve the high efficiency. Some of the advantages of the proposed system are including less elements are used compared to ordinary BCs, high efficiency is attained using a single stage construction without the high frequency transformer and excellent performance was achieved in battery charging.

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REFERENCES

[1] M. Sajjadi, H. Seifi, and H. Delkhosh, "A new approach for system-wide power system frequency model validation via measurement data," *Engineering Reports*, vol. 4, no. 1, pp. 1–24, Jan. 2022, doi: 10.1002/eng2.12446.

[2] A. Khaligh and M. D'Antonio, "Global trends in high-power on-board chargers for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3306–3324, Apr. 2019, doi: 10.1109/TVT.2019.2897050.

[3] J. Reimers, L. Dorn-Gomba, C. Mak, and A. Emadi, "Automotive traction inverters: Current status and future trends," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 4, pp. 3337–3350, Apr. 2019, doi: 10.1109/TVT.2019.2897899.

[4] A. Nochian, O. M. Tahir, S. Maulan, and A. R. Mikaeili, "A review of systematic approach for sustainable redevelopment of a closed landfill site," *Jurnal Teknologi*, vol. 78, no. 5, pp. 299–307, Apr. 2016, doi: 10.11113/jt.v78.8318.

[5] A. Nochian, O. M. Tahir, S. Mualan, and D. Rui, "Toward sustainable development of a landfill: Landfill to landscape or landscape along with landfill? A review," *Pertanika Journal of Social Sciences and Humanities*, vol. 27, no. 2, pp. 949–962, 2019, [Online]. Available: http://www.pertanika.upm.edu.my/pjssh/browse/regular-issue?article=JSSH(S)-0992-20

[6] M. Asadi *et al.*, "Optimal placement and sizing of capacitor banks in harmonic polluted distribution network," in *2021 IEEE Texas Power and Energy Conference (TPEC)*, Feb. 2021, pp. 1–6. doi: 10.1109/TPEC51183.2021.9384992.

[7] M. Karami, N. bin Mariun, M. Z. A. Ab-Kadir, N. Misron, and M. A. Mohd Radzi, "Motor current signature analysis-based non-invasive recognition of mixed eccentricity fault in line start permanent magnet synchronous motor," *Electric Power Components and Systems*, vol. 49, no. 1–2, pp. 133–145, Jan. 2021, doi: 10.1080/15325008.2021.1937386.

[8] M. Ehsani, Y. Gao, and A. Emadi, *Modern electric, hybrid electric, and fuel cell vehicles*, 3rd ed. Boca Raton, FL: CRC Press, 2018. doi: 10.1201/9780429504884.

[9] J. Yuan, L. Dorn-Gomba, A. D. Callegaro, J. Reimers, and A. Emadi, "A review of bidirectional on-board chargers for electric vehicles," *IEEE Access*, vol. 9, pp. 51501–51518, 2021, doi: 10.1109/ACCESS.2021.3069448.

[10] K. Uddin, M. Dubarry, and M. B. Glick, "The viability of vehicle-to-grid operations from a battery technology and policy perspective," *Energy Policy*, vol. 113, pp. 342–347, Feb. 2018, doi: 10.1016/j.enpol.2017.11.015.

[11] Y. Xiao, C. Liu, and F. Yu, "An effective charging-torque elimination method for six-phase integrated on-board EV chargers," *IEEE Transactions on Power Electronics*, vol. 35, no. 3, pp. 2776–2786, Mar. 2020, doi: 10.1109/TPEL.2019.2924538.

[12] D. C. Erb, O. C. Onar, and A. Khaligh, "Bi-directional charging topologies for plug-in hybrid electric vehicles," in *2010 Twenty-Fifth Annual IEEE Applied Power Electronics Conference and Exposition (APEC)*, Feb. 2010, pp. 2066–2072. doi: 10.1109/APEC.2010.5433520.

[13] I.-O. Lee, "Hybrid PWM-resonant converter for electric vehicle on-board battery chargers," *IEEE Transactions on Power Electronics*, vol. 31, no. 5, pp. 3639–3649, May 2016, doi: 10.1109/TPEL.2015.2456635.

[14] B.-K. Lee, J.-P. Kim, S.-G. Kim, and J.-Y. Lee, "An isolated/bidirectional PWM resonant converter for V2G (H) EV on-board charger," *IEEE Transactions on Vehicular Technology*, vol. 66, no. 9, pp. 7741–7750, Sep. 2017, doi: 10.1109/TVT.2017.2678532.

[15] F. Mandrile, D. Cittanti, V. Mallemaci, and R. Bojoi, "Electric vehicle ultra-fast battery chargers: A boost for power system stability?," *World Electric Vehicle Journal*, vol. 12, no. 1, pp. 1–21, Jan. 2021, doi: 10.3390/wevj12010016.

[16] J. Larminie and J. Lowry, *Electric vehicle technology explained*, 2nd ed. Chichester: John Wiley & Sons, 2012.

[17] M. S. Kumar and S. T. Revankar, "Development scheme and key technology of an electric vehicle: An overview," *Renewable and Sustainable Energy Reviews*, vol. 70, pp. 1266–1285, Apr. 2017, doi: 10.1016/j.rser.2016.12.027.

[18] V. T. Tran, D. Sutanto, and K. M. Muttaqi, "The state of the art of battery charging infrastructure for electrical vehicles: Topologies, power control strategies, and future trend," in *2017 Australasian Universities Power Engineering Conference (AUPEC)*, Nov. 2017, pp. 1–6. doi: 10.1109/AUPEC.2017.8282421.

[19] A. Schroeder and T. Traber, "The economics of fast charging infrastructure for electric vehicles," *Energy Policy*, vol. 43, pp. 136–144, Apr. 2012, doi: 10.1016/j.enpol.2011.12.041.

[20] S. Atanalian, K. Al-Haddad, R. Zgheib, and H. Y. Kanaan, "A review on electric vehicles battery chargers and AC/DC converters for fast charging stations," in *2021 IEEE 3rd International Multidisciplinary Conference on Engineering Technology (IMCET)*, Dec. 2021, pp. 43–48. doi: 10.1109/IMCET53404.2021.9665577.

[21] M. Yilmaz and P. T. Krein, "Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles," *IEEE Transactions on Power Electronics*, vol. 28, no. 5, pp. 2151–2169, May 2013, doi: 10.1109/TPEL.2012.2212917.

[22] A. Khaligh and S. Dusmez, "Comprehensive topological analysis of conductive and inductive charging solutions for plug-in electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 8, pp. 3475–3489, Oct. 2012, doi: 10.1109/TVT.2012.2213104.

[23] P. Sharma, A. K. Sharma, N. Priyadarshi, F. Azam, S. Padmanaban, and A. K. Bhoi, "A comprehensive study on electrical vehicle in charging infrastructure, challenges and future scope," in *Electric Vehicles*, Singapore: Springer, 2021, pp. 271–285. doi: 10.1007/978-981-15-9251-5_16.

[24] J. Liu, S. Laghrouche, and M. Wack, "Observer-based higher order sliding mode control of power factor in three-phase AC/DC converter for hybrid electric vehicle applications," *International Journal of Control*, vol. 87, no. 6, pp. 1117–1130, Jun. 2014, doi: 10.1080/00207179.2013.868609.

[25] D.-H. Kim, M.-J. Kim, and B.-K. Lee, "An integrated battery charger with high power density and efficiency for electric vehicles," *IEEE Transactions on Power Electronics*, vol. 32, no. 6, pp. 4553–4565, Jun. 2017, doi: 10.1109/TPEL.2016.2604404.

[26] C. Saber, D. Labrousse, B. Revol, and A. Gascher, "Challenges facing PFC of a single-phase on-board charger for electric vehicles based on a current source active rectifier input stage," *IEEE Transactions on Power Electronics*, vol. 31, no. 9, pp. 6192–6202, Sep. 2016, doi: 10.1109/TPEL.2015.2500958.

[27] J. G. Pinto, V. Monteiro, H. Goncalves, and J. L. Afonso, "Onboard reconfigurable battery charger for electric vehicles with traction-to-auxiliary mode," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 3, pp. 1104–1116, Mar. 2014, doi: 10.1109/TVT.2013.2283531.

[28] S.-G. Jeong, Y.-S. Jeong, J.-M. Kwon, and B.-H. Kwon, "A soft-switching single-stage converter with high efficiency for a 3.3-kW on-board charger," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 9, pp. 6959–6967, Sep. 2019, doi: 10.1109/TIE.2018.2877093.

[29] A. K. Singh, M. Badoni, and Y. N. Tatte, "A multifunctional solar PV and grid based on-board converter for electric vehicles," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 4, pp. 3717–3727, Apr. 2020, doi: 10.1109/TVT.2020.2971971.

[30] K. Verma, M. Srivastava, P. Singh Tomar, N. Sandeep, and A. K. Verma, "Single-phase integrated converter with universal battery charging capability for plug-in electric vehicles," *IET Power Electronics*, vol. 13, no. 4, pp. 821–829, Mar. 2020, doi: 10.1049/iet-pel.2019.0847.

[31] M. Karami, N. Mariun, K. Ab, R. Mohd, and N. Misron, "Analysis of rotor asymmetry fault in three-phase line start permanent magnet synchronous motor," *Facta universitatis - series: Electronics and Energetics*, vol. 34, no. 4, pp. 483–498, 2021, doi: 10.2298/FUEE2104483K.

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