Advances in Science and Technology Research Journal
Volume 13, Issue 2, June 2019, pages 168–175
https://doi.org/10.12913/22998624/108529

Received: 2019.02.26
Revised: 2019.03.21
Accepted: 2019.04.15
Available online: 2019.05.17

Analysis and Designing of a Wireless Charging System for Electric Vehicles Using the Topology of Double Sided LLC Compensator

Hamid Reza Khademi[1], Mahmoud Samiei Moghaddam[1*], Seyed Javad Mohammadi Baygi[1], Amin Hajizadeh[2]

[1] Department of Electerical Engineering, Damghan Branch, Islamic Azad University, Damghan, Iran
[2] Department of Energy Technology, Aalborg University, Esbjerg, Denmark
* Corresponding author e-mail: samiei352@yahoo.com

ABSTRACT
The purpose of the present study was to simulate the equivalent circuit in the MATLAB software in order to implement the desired relationships for both continuous-conduction mode (CCM) and discontinuous-conduction mode (DCM), and to obtain the power and efficiency values at different frequencies. Then, it was necessary to optimize the effective values on the power by Particle Swarm Optimization (PSO) algorithm. After optimization, the optimization and pre-optimization results were compared and, if post-optimization results were not desirable, effective parameters should be reviewed before the optimization stage and the tunable parameters should be changed to achieve the desired results. This process will continue to obtain the optimization results. The results show that the highest efficiency is 98% in the DCM mode and 95% in the CCM mode. In both methods, we achieved more favorable results than the with the PSO method. However, the DCM mode provides an improvement which is about 2.6% higher than CCM.

Keywords: wireless charging system, electric vehicles, continuous-conduction mode, discontinuous-conduction mode.

INTRODUCTION

Non-uniform distribution of fossil fuels and their contamination has led to a move towards replacing fossil fuels with renewable fuels such as solar energy and wind energy. Electric vehicles (EVs) are an example of this movement that can be a good alternative to current vehicles. In this field, the battery of electric vehicles is the main problem. High reliability, high lifespan, high energy density, and affordable prices are the conditions required to compete with conventional electric vehicle batteries. Lithium-ion batteries are the perfect choice. Electric vehicles with lithium-ion batteries have two major problems compared to fossil fuels. The first is their low energy density compared to fossil fuels such as gasoline. The second is their long charge time, which is longer than the normal refueling time. All of these factors increase the size of battery and hinder the advancement of electric vehicle technology [1].

Using the cable to transfer power to electric vehicles is the most common way to transfer power. These cables may be worn and can be dangerous under rainy or humid conditions. In turn, charging the battery in this way does not provide isolation between the consumer and the power supply. Most importantly, these cables are very bulky and expensive in high power transmission. All these items can be removed by using a wireless charging. The electric charge is isolated from the power supply in the case of wireless charging and does not require a physical connection to initiate the charging process, and as a result charging the battery is more comfortable for a user. With this method, power transmission can be performed under all climatic conditions and there is no risk of electric shock. Wireless charging in the static mode does not provide the main advantage of wireless charging. In other words, it is expected that this method, which does not differ much from charging via cable, will solve the main problem of electric vehicles, i.e. battery issues. The proposed solution is dynamic wireless charging. Obviously, the car can be charged without stopping with this method. It results in the reduction of battery size of an electric vehicle. Dynamic charging has particular complexity at the design stage, because the location of the receiver is not definite. Several structures were proposed to overcome these complexities [1]. Most studies are based on the changing structure of the coils. These coils are designed to provide a uniform field in a reasonable area and provide the charging process for the user in that area. The most important obstacle to dynamic charging is the high cost of implementation, which requires a large infrastructure. Wireless power transfer applications are not limited to charging electric vehicles and include medical and home applications [2]. The Samsung wireless charging pad constitutes an example of low-power wireless charging.

Short-range wireless power transfer with high power is similar to the transformer power transfer. Inductive power transfer relations are the main ones in this field. Inductive power transfer is common in the electricity industry and is performed in power transformers abundantly. The only difference in the wireless power transfer is the low coefficient of coupling, which makes it necessary to increase the switching frequency and the use of compensation capacitors [3]. Many studies have to be conducted to lead to the industrialization and prevalence of wireless charging. Fortunately, much attention has recently been drawn to this topic that led to advances in its various areas. Higher-order harmonics that is used for power transfer enables reducing the size of power transfer coils. Obviously, it is not possible to raise the frequency from a certain limit in high power applications due to the switching frequency of electronic power switches. Therefore, using a transfer method with higher-order harmonics can multiply the power transfer frequency, and produce smaller coils, especially on the charge side. This method requires investigation and development [4].

Wireless power transfer, due to the high safety and ease of use, has been widely used in medicine. In recent years, the advancement of the technology of power electronic switches has enabled wireless transfer for higher power, which has attracted the attention of many researchers. With this technology, the initial cost and size of electric vehicle batteries can be significantly reduced and the industrialization of these vehicles can be made easier. There are many obstacles to industrialization of wireless charging systems, which require suitable solutions. Permanent changes of charge, misalignment and parasitic elements are some of them [5].

LITERATURE REVIEW

The history of the electric vehicle dates back to the middle of the nineteenth century and the early twentieth century. The high cost, low speeds and short distance range reduced their use worldwide in comparison with the later fossil fuel vehicles. Since the early 20th century, the interest in electric vehicles and alternative fuels has grown, since concerns about the problems caused by hydrocarbon contaminants and vehicle fuels, such as environmental damages and the sustainability of hydrocarbon streams, have been raised. The invention of the first model of an electric vehicle has been attributed to different people. In 1828, Ányos István Jedlik invented the first model of a electric motor and designed a small electric vehicle using his new motor [6]. In 1834, Thomas Davenport who was a blacksmith from Vermont

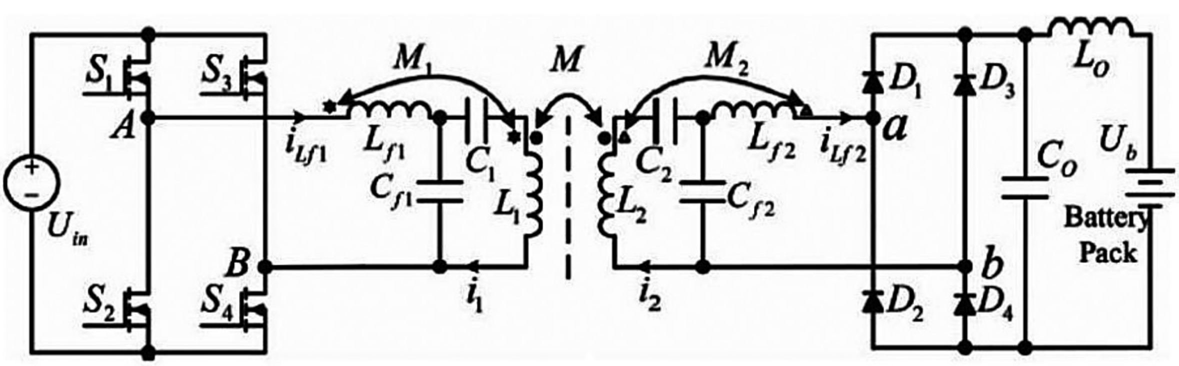

Fig. 1. Proposed LCC topology

invented a similar device that worked on a short electric route. In 1835, Professor Sibrandus Stratingh and his assistant developed a small electric machine powered by primary cells [6].

In 1837, the first known electric vehicle was built by Robert Davidson. Galvanic cells powered the vehicle. In 1841, he built a larger locomotive called Galvani and exhibited it at the Royal Scottish Society of Arts Exhibition. These locomotives dragged a load of 6 tons, which were tested on the railway in September of next year. The limited power of batteries put an obstacle in the way of general use. Between 1832 and 1839, Robert Anderson also invented a simple electric carriage. In 1840, a property right was granted for the use of rails as conductors of electric current in England, and a similar invention was issued in the United States in 1847 [7].

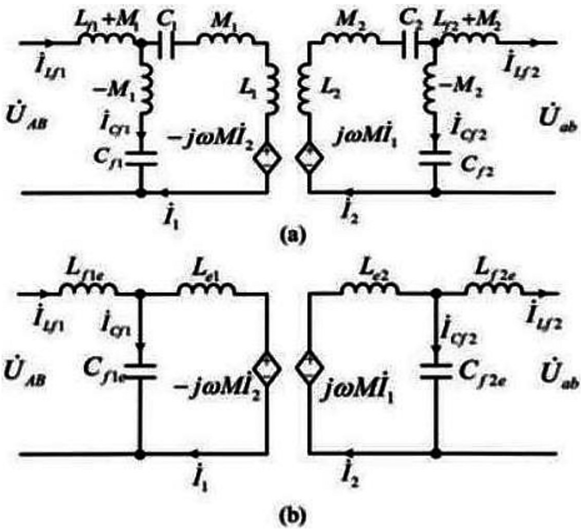

Fig. 2. The virtual circuits: (a) the discrete circuit model, (b) the simplified equivalent circuit model [12]

More recently, attention has been paid to the wireless power transfer for dynamic charging of electric vehicles while in motion, due to the lower battery requirements for greater energy storage and reliability. In a magnetic resonant coupler coupling, it is customary to use circular resonators. However, due to the various movement of the vehicle in motion, the alignment of the resonators is removed and, consequently the performance of wireless power transfer is considerably reduced. The use of dipole electric resonators was proposed to solve the problem of the study. Additionally, they compared the transmission efficiency in the non-alignment mode of the transmitter and the receiver in two types of circular resonator and dipole resonator (as shown in figure 1). Its result was the high efficiency of dipole resonator and low changes of transmission efficiency compared to the circular resonator, while the resonators of transmitter and receiver are moving in front of each other [8].

$$\dot{I}_{Lf1} = \dot{I}_1 + \dot{I}_{Cf1} \tag{1}$$

The equation above can be rewritten using the voltages and the respective impedances as follows:

$$\frac{U_{AB} - \dot{U}_{Cf1e}}{j\omega L_{f1e}} = \dot{I}_1 + j\omega C_{f1e}\dot{U}_{Cf1e} \tag{2}$$

Thus

$$U_{Cfle} = \omega_{Lf1} eI1^{\cdot}(1-\omega 2Lf1eCfle)^{\cdot} + UAB^{\cdot}\ 1-\omega 2Lf1eCf1e \tag{3}$$

The Kirchhoff Voltage Law provides the following equation:

$$\dot{U}_{Cfle} = \frac{\omega L_{f1e}\dot{I}_1}{j(1-\omega^2 L_{f1e}C_{fle})} + \frac{\dot{U}_{AB}}{1-\omega^2 L_{f1e}C_{f1e}} \tag{4}$$

Hence, replacing (3) with (4) and using $a_1 = 1 - \omega^2 L_{fle} C_{fle}$ for the current flow in the coil will result in:

$$\dot{J}_1 = \frac{\dot{U}_{AB}}{j\omega(L_{e1a_1} + L_{f1e})} + \frac{Ma_1\dot{I}_2}{L_{e1a_1} + l_{f1e}} \tag{5}$$

Similarly, the circuit equations for the receiver side can be described as follows (CMOS, 2015):

$$\dot{U}_{Cf2e} = \frac{\dot{U}_{ab}}{a_2} - \frac{\omega L_{f2e}\dot{I}_2}{ja_2} \tag{6}$$

$$\dot{I}_2 = \frac{\dot{U}_{ab}}{j\omega(L_{e2a_2} + L_{f2e})} + \frac{Ma_2\dot{I}_1}{L_{e2a_2} + L_{f2e}} \tag{7}$$

As it was mentioned, in this study we are going to use two methods of DCM and CCM signal transfer to study power and efficiency in both modes. The formulas related to 7 the power and the efficiency of each one are presented below [13].

$$P_{out_{DCM(w)}} = \frac{Uab I_{Lf2}\lambda}{2} = \frac{2\lambda U_b Q(w) cos\phi}{\pi} \tag{8}$$

$$P_{out,CCM}(\omega) = \frac{8\lambda U_b \sqrt{U_b^2 A^2(\omega) + U_a^2 B^2(\omega) - 2U_a U_b A(\omega) B(\omega) cos\alpha}}{\pi^2} \tag{9}$$

In both cases, using the following equation, the efficiency is calculated:

$$Efficiency = \frac{P_{out}}{P} \tag{10}$$

DISCONTINUOUS-CONDUCTION MODE (DCM)

In this system, there are two cases of cross-sectional conduction the relations of which are determined through the following equation:

$$\begin{cases} \dot{x} = A_1 x + B_1 u & 0 \le t \le t_1 \\ \dot{x} = A_2 x + B_2 u & t_1 \le t \le t_2 \\ \dot{x} = A_1 x + B_1 u & t_1 \le t \le T/2 \end{cases} \tag{11}$$

CONTINUOUS-CONDUCTION MODE (CCM)

The equations above can be solved using a numerical method, and the values of each state at any time can be obtained. On the basis of the above-mentioned analysis, the output power and its efficiency can be easily calculated:

$$P_{out} = \frac{2}{T}\int_0^{T/2} (u_{ab}(t).i_{L_{f2}}(t))dt \tag{12}$$

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\int_0^{T/2} (u_{ab}(t).i_{L_{f2}}(t))dt}{\int_0^{T/2} (u_{AB}(t).i_{L_{f1}}(t))dt} \tag{13}$$

In both equations presented above, the output power and the efficiency of the WPT (wireless power transfer) system are related to the system performance.

In order to explain the CCM and DCM methods, it can be said that as in CCM systems, the 7 voltage cycle may be zero; it is better to use the DCM mode to avoid this situation. In this case, the voltage cycle will vary from the positive to negative values and never becomes zero. As a result, power will not be zero at all. Furthermore, the efficiency will also be displayed in this 10 system.

SIMULATION

In a simulated system, the original coil is fed by a sine voltage source, while in the secondary circuit; the load is calculated by the battery. At this stage, we first apply the standard initial values to the simulated system. Then, the results with the intended changes are applied to the system and the effects of each series of the changes are studied, and MATLAB software is used to optimize the parameters which affect the PSO (particle swarm optimization).

Now, we use the Particle Swarm Optimization Algorithm (PSO) to determine the optimal values of Lf_1, Lf_2, Cf_1, Cf_2, C_1, C_2, L_1, and L_2 parameters as well as the frequency with the maximum power. These values lead to the optimized power. Hence,

Table 1. The initial values considered for the system

Lf_1	42.8e-6 H
Lf_2	39.4e-6 H
Cf_1	75.9e-9 F
Cf_2	75.9e-9 F
C_1	14e-9 F
C_2	15.2e-9 F
L_1	256e-6 H
L_2	256e-6 H
Lf_2	25.8e-6 H
Rf_2	1.5e3 Ohm
C_0	100e-6 F
L_0	10e-3 H

Table 2. The optimized values calculated for DCM mode

	C_1	Cf_2	Cf_1	Lf_2	Lf_1
	14e-9	72e-9	75e-9	35e-6	43.1e-6
efficiency	P_Max	f	L_2	L_1	C_2
98%	1470	97 kHz	191e-6	210e-6	15.6e-9

after optimizing the values obtained, the DCM transfer will be the same as the table 2 shows.

Considering the simulation conducted to optimize the results, we compare the optimized structure with the results obtained in the initial state. Figures 1 and 2 show the results before and after optimization, respectively. At present, due to the presence of switching elements in this circuit, the flow wave is not sinusoidal since there is current harmonics. Therefore, in these statuses, two factors can be considered for the power:

- The displacement factor is the same phase difference between the wave form of the voltage and current.
- The distortion factor which is dependent on the distortion of the waveform generated by the arrival of the harmonics.

Figure 3 shows the comparison between experimental and calculated power. Without considering power, it is possible to calculate the output using these equations in which power is set to 1. In this case, the rectifier losses are also consid-

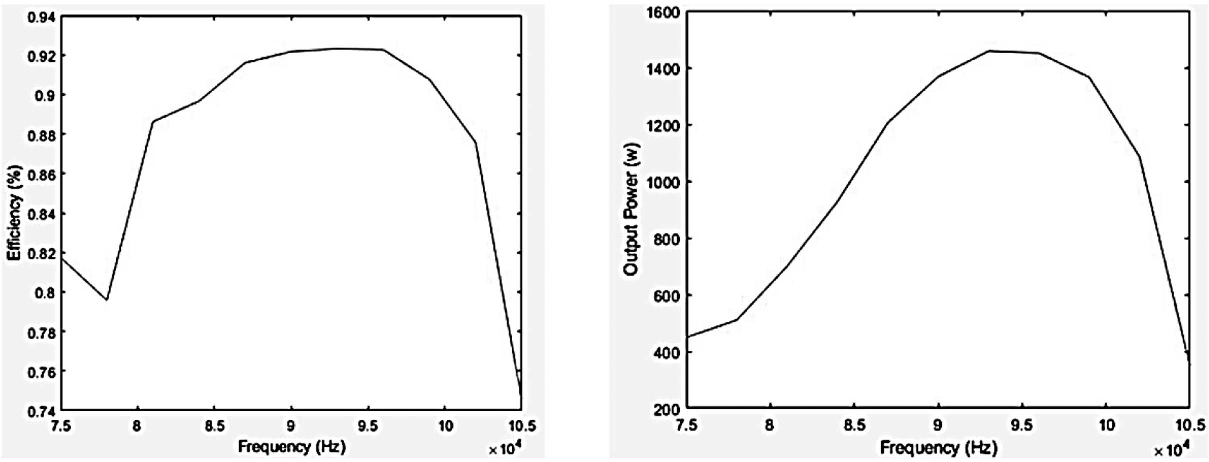

Fig. 3. Calculating the power and frequency of the initial DCM mode

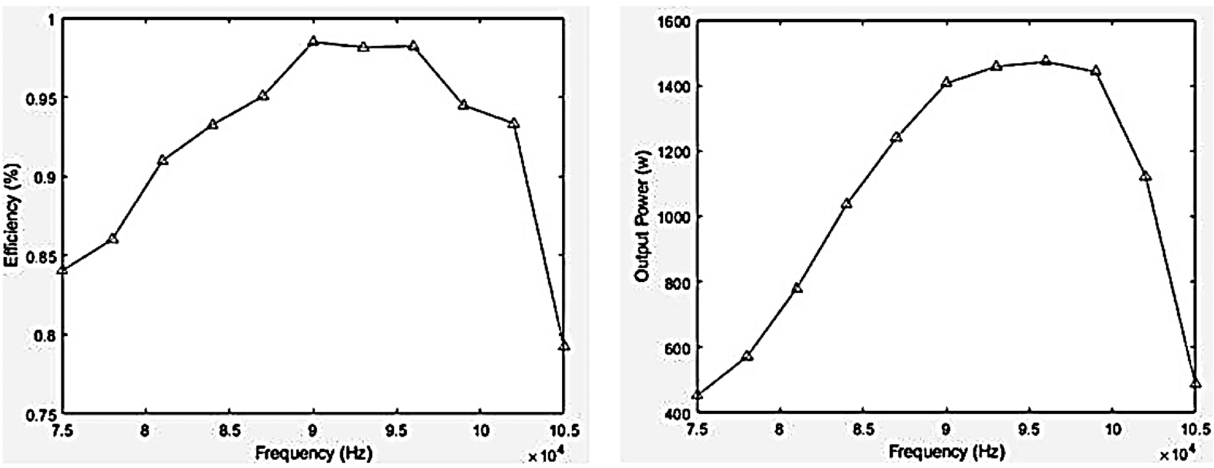

Fig. 4. Calculating the power and frequency of the DCM mode optimized using PSO algorithm

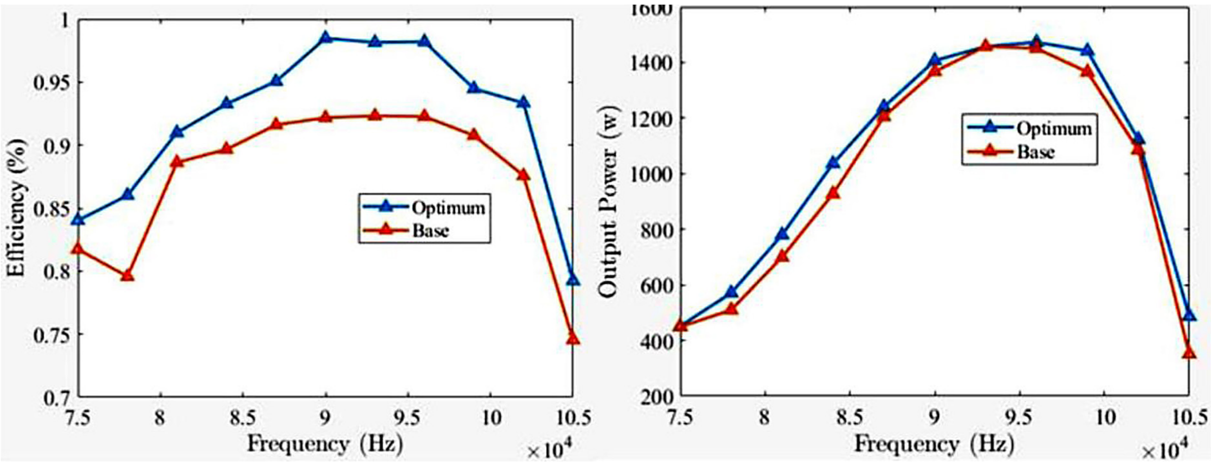

Fig. 5. Comparing the power and efficiency of DCM initial and the optimized mode

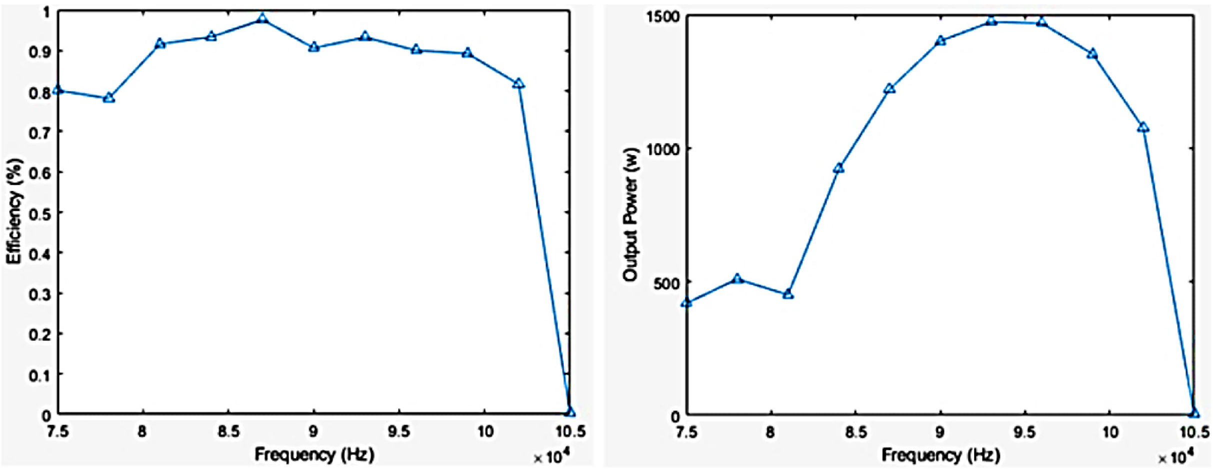

Fig. 6. Calculating the CCM power and efficiency optimized using PSO algorithm

ered. Output power, regardless of power, is much higher than the experimental and calculated power while the two sides are very close to each other.

As it can be seen from the results of this simulation, low power means low electrical efficiency which is due to the poor power switching performance in the network. The lower the power, the higher the nominal power used by the network. When the power is not modified, the system, in addition to providing efficient and effective active power supply, must provide its reactive power that is inefficient. As the result, larger and more expensive elements are used in the system. If power is modified, these elements are not needed. Lowering the power to zero, in addition to increasing the losses, causes the harmonics to flow in the neutral line and disrupts the performance of the electronic devices. Therefore, we find that the closer the power to 1 (less 10 phase difference angle and active power closer to the nominal power), the lower the value of the useless active power. In the wireless charge transformation systems, as previously stated, power is usually considered to be 1.

Finally, in order to compare the optimal result obtained using the PSO with the initial results obtained in the reference article, the following diagrams are introduced for power and efficiency.

As it is seen in this output, the efficiency obtained from the simulation and the PSO algorithm is optimized in comparison with the initial state and the result of the optimization obtained from the simulation is significant since the efficiency obtained in the initial state is almost equal to 91 percent, while in the optimal mode, it is about 98 percent.

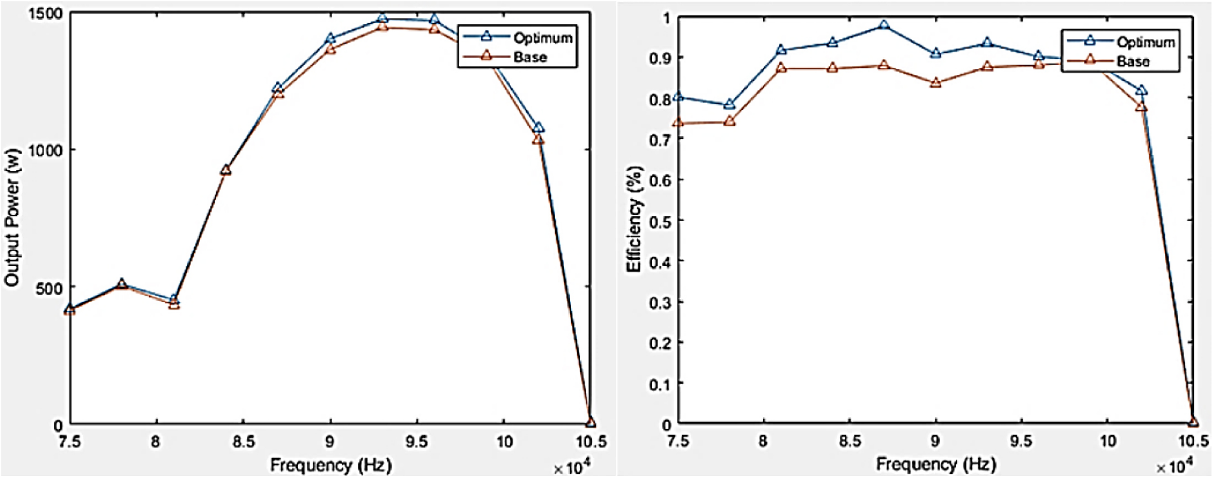

Fig. 7. Calculating the CCM power and efficiency in both initial and optimized modes using PSO algorithm

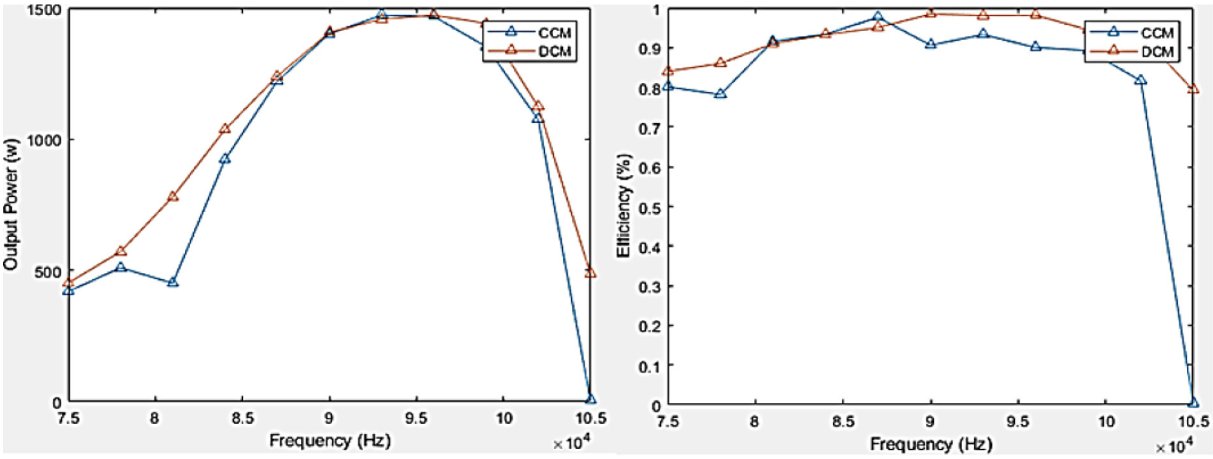

Fig. 8. Calculating the power and efficiency in both CCM and DCM modes

As it is shown, in the CCM mode, using the PSO algorithm, we were also able to optimize the results and to some extent optimize the power and efficiency. One of the challenges we faced in this paper was determining the parameters affecting the power and efficiency as well as comparing the methods of calculating power and efficiency in the CCM and DCM modes. Therefore, as shown in the following figures, after calculating and presenting the graphs related to each of them, we compared the two modes to find their differences.

As seen in the figure above, the DCM method performed better than the CCM method. One of the issues was that in the CCM method, at the frequency more than 100 kHz, a significant drop in power and, consequently, in efficiency was observed. It occurred due to the sharp decrease in 8 voltage. Therefore, the voltages and power values close to zero at a frequency of 105 kHz. This means that at the frequencies higher than 100 kHz, power calculation in the CCM mode does not yield the desired results.

CONCLUSION

According to the results, the obtained power from simulation in the initial mode is in the frequency range of 75 to 105 kHz that is approximately 1260 watts. This value is about 1464 watts in the optimized mode and in the PSO algorithm. Therefore, the optimization in the proposed simulation is very good and the results are of a higher quality than for the initial mode. Regarding 16 to the two methods of DCM and CCM, it can be noted that the highest efficiency is 98% in the DCM mode and 95% in the CCM mode. In both methods, we achieved more favorable results than with the basic mode using the PSO method. However, the DCM mode provides an improvement which is about 2.6% higher than the CCM mode.

REFERENCES

1. Hassankhani A, Sadooghipoor M, Gharepatyan G. 2016. The Effect of Scheduling of Electric Vehicle Charging in the Smart Grid on Household Demand. 24th Iranian Conference on Electrical Engineering, Shiraz, Iran.
2. Dehghanian M, Namadmalan AR. 2017. Providing an optimal design algorithm for inductive wireless charging systems of electric vehicles. 2nd National Conference on meta-heuristic algorithms and applications in science and engineering. Payame Noor 7 University, Najaf Abad, Iran.
3. Ghaffarifar S. 2017. Control of electric-vehicle charging stations in micro grids (master's thesis), (In Persian).
4. Heidari M, Bayestizehi E. 2017. Inductance Wireless Power Transfer (IPT) Based on Matrix Converter in Electric Vehicles. International Conference on Fundamental Research in Electrical Engineering, Tehran, Iran.
5. Falahati Aliabadi S. 2016. Setting the Frequency of Smart Grids Using Electric Vehicles (Unpublished doctoral dissertation). Faculty Of Electrical and Computer 16 Engineering, University of Kashan, Iran.
6. Fatahi Bandpei, Gorgani M, Firouzjah KH. 2016. Two-Stage Charging Strategy of Electric Vehicles Based on Fuzzy Control. 32nd International Power System Control, Tehran, Iran.
7. Talebi A. 2015. Application of electric vehicle in power system (Master thesis). Khorasan Institute of Higher Education, Mashhad, Iran.
8. Zhang X, KanT, You C, Mi C. 2017. Modeling and analysis of AC output power factor for wireless chargers in electric vehicles. IEEE Transactions on Power Electronics, 32(2), 1481-1492.
9. Ahmad A, Alam MS, Chabaan R. 2018. A comprehensive review of wireless charging technologies for electric vehicles. IEEE Transactions on Transportation Electrification, 4(1), 38-63.
10. Kan T, Lu F, Nguyen TD, Mercier PP, Mi C. 2018. Integrated Coil Design for EV Wireless Charging Systems Using LCC Compensation Topology. IEEE Transactions on Power Electronics.
11. Deng J, Pang B, Shi W. Wang Z. 2017. Magnetic Integration of LCC Compensation Topology with Minimized Extra Coupling Effects for Wireless EV Charger. Energy Procedia, 105, 2281-2286.
12. Wu H, Pang GKH, Choy K L, Lam HY. 2017. A scheduling and control system for electric vehicle charging at parking lot. In Control Conference 36 (ASCC), 11th Asian (pp. 13-18). IEEE.
13. Ehsani M, Gao Y, Longo S. Ebrahimi K. 2018. Modern electric, hybrid electric, and fuel cell vehic. CRC Press.