Efficient Power-Electronic Converters for Electric Vehicle Applications

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***Abstract*— This paper introduces advanced power-electronic converter topologies for Electric Vehicles (EVs) using a four-phase DC/DC interleaved boost converter (FP-IBC) and a five-level T-type DC/AC multilevel converter. A comparison between the proposed topologies and other converter topologies is performed and discussed. The simulation results are analysed to evaluate the converters based on power loss calculations and harmonic analysis. The converters are studied at different switching frequencies and various loading conditions to reflect their effects on the converter losses. The results highlight the proposed converters' higher efficiency compared to other studied converter topologies in electric vehicle applications.**

Keywords—*Electric vehicles, multilevel converter, DC/DC boost converter, T5 converter.*

I. INTRODUCTION

The growing number of human population yields increased energy consumption and depletion of finite resources such as, oil and gas. Therefore, Electrical Vehicles (EVs) are seriously considered as an alternative to fossil-fueled vehicles [1]-[2]. In EVs, the Fuel Cell (FC) stack, battery bank, and Super-capacitors (SCs) bank are usually used as clean energy sources. Combining such energy sources leads to a FC/SC/battery hybrid power system (HPS) as shown in Fig. 1 [3]-[6].

In comparison with single-sourced systems, HPS has the potential to provide high quality, more reliable, and efficient power. In HPSs, the power-electronic converters are considered as the key elements that interface their power sources to the drivetrain of the EVs. In order to design highly efficient converters for the EV's power system, advanced DC/DC and DC/AC converters are required to adapt the output voltage and current levels with high power quality.

The DC/DC converter is used to allow a desired level of dc voltage to be obtained without having to increase the stack size. It is illustrated in [7] that the Multi-Device Interleaved Boost Converter (MD-IBC) is more powerful and more efficient than other boost converter topologies such as conventional Boost Converter (BC), Two-Phase Interleaved Boost Converter (TP-IBC), and Multi-Device Boost Converter (MDBC).

In this paper, the proposed Four-Phase Interleaved Boost Converter (FP-IBC) outperforms MD-IBC with its lower ripple and current harmonics, higher reliability, higher efficiency, higher power and voltage ratings. Ripple and current harmonics are among the various phenomena that contribute to the lifespan's reduction of energy storage devices such as, FCs, SCs, and batteries [8].

On the other hand, the DC/AC converter is required to convert the dc power to a suitable ac power for the electrical machine. The most common used DC/AC converter in industry is the two-level converter [9]. This converter introduces large harmonic contents in the output voltage, which increase the machine's losses and affect its life-time. The multilevel converter is a well-known alternative to the two-level converter especially in high power and medium voltage applications. It delivers the ac power with low harmonic contents [10]. The main drawbacks of the multilevel converter are the complexity of the power circuit and the increased number of switching elements. This problem motivates researchers to develop advanced multilevel converter circuits with lower number of switches to reduce the converter complexity and cost.

In this paper, advanced and efficient power-electronic converter topologies suitable for EV applications are proposed and analyzed. A suitable battery system is selected to supply the induction machine through the converters' power circuits. A FP-IBC model is illustrated and an advanced lead-lag controller is introduced to keep the dc bus with constant dc voltage. This controller is typically designed to respond well to significant changes in operating points. Moreover, an advanced T5 converter topology is discussed. A switching function model for the T5 converter is derived and discussed as well. The proposed power converters are modeled and simulated using Matlab/Simulink. Simulation results are carried-out to evaluate the converters efficient performance based on power loss calculations and a comparison is performed against other power converters topologies.

II. PROPOSED SYSTEM

The structure of the EV's drive system is depicted in Fig. 1. It consists of a HPS, DC/DC boost converter, DC/AC converter and an induction machine. In this configuration, the FC is interfaced to the dc-bus through a unidirectional boost converter, whereas the energy storage system (ESS) such as SCs and battery is connected to the dc-bus via a bidirectional boost converter. The electrical motor is integrated with the common EV dc-link through DC/AC converter to convert the dc power to a suitable ac power. The proposed system inside the dashed lines will be discussed in details in the following sections.

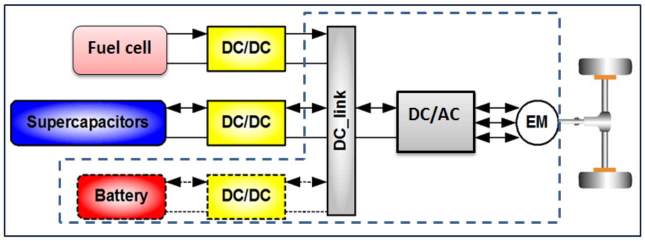

Fig. 1. Block diagram for the proposed system as a part of EVs prototype

A. Battery modeling

Lithium-Ion (Li-Ion) batteries are increasingly accepted to be an optimal choice for ESS in EV applications. In this section, the Matlab/Simulink Li-Ion battery module is designed and modelled using the equations presented in [11]-[12]. The battery module comprises a package with *Ns* cells that are connected in series and *Np* batteries that are connected in parallel.

B. FP-IBC DC/DC boost converter

1) The DC/DC Converter structure

The structure of the FP-IBC is depicted in Fig. 2a. The proposed converter consists of four DC/DC boost converter modules connected in parallel. Fig. 2b shows the switching devices gate signals at $D = 0.25$, where D is the duty cycle. The gate signals are successively phase shifted by $T_s/(n\ x\ m)$. T_s is the switching period and n is the number of phases, while m is the number of parallel switches per phase. For FP-IBC, $m = 1$ and $n = 4$. As such, the current delivered by the electric source is shared equally between each phase and has a ripple content of period $Ts/4$.

Similarly, the frequency of the output voltage and the input current is n times higher than the switching frequency f_{sw}. As results, the size of passive devices such as the capacitor and inductor will be reduced by n times compared to the conventional BC. In addition, the system's reliability and converter's power rating will be increased by using paralleling phases. Moreover, the current sharing equally between each phase will provide tight sizing of power semiconductors, distribution of losses between modules and size optimization of the converter. These advantages are behind the use of FP-IBC as a DC/DC converter for EV power systems as opposed to other converter topologies such as conventional BC, MDBC, TP-IBC, and MD-IBC.

2) Closed loop control design for FP-IBC

The FP-IBC under feedback control is a nonlinear function of the duty cycle, which makes the controller design is more challenging from the viewpoint of stability and bandwidth. The control design of FP-IBC is constructed based on two basics loops, inner and outer loop, the inner loop is considered as current control and the outer as voltage control as shown in Fig. 4.

C. The DC/AC Converter

1) The DC/AC Converter structure

The five-level T-type converter (which called T5 converter), has a reduced switching elements configuration compared to conventional five-level DCC. The circuit diagrams for the proposed T5 converter are shown in Fig. 3. The advantages of the T5 topology compared to conventional DCC are:

- Elimination of clamping diodes from the power circuit (18 diodes removed).
- Reduction of isolated dc power supplies from 22 to 14 for the driving circuits.

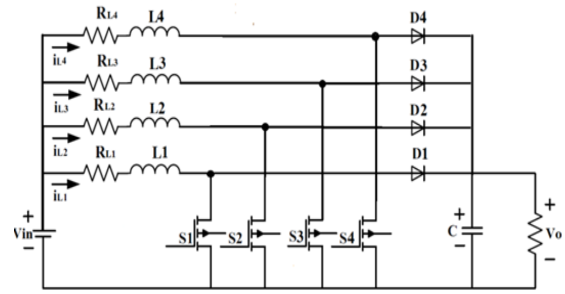

Fig. 2a. The structure conventional FP-IBC

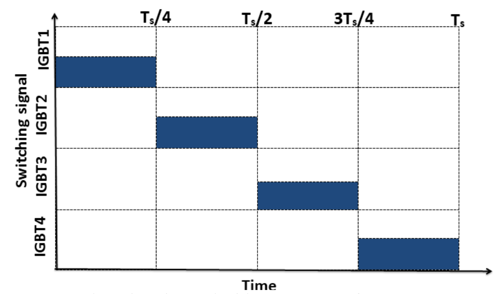

Fig. 2b. The switching pattern of FP-IBC

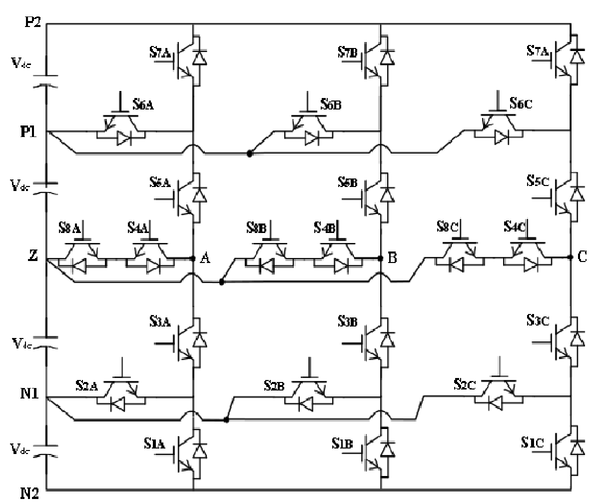

Fig. 3. Circuit diagram for one-leg of T5-type converter.

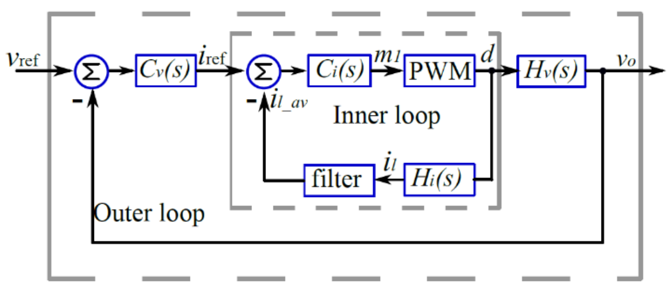

Fig. 4. Control design loop configuration

2) DC/AC Converter Modulation control technique .

The Phase-Displacement PWM (PD-PWM) technique is selected to modulate the T5 converter [13]. This technique is much simpler than space-vector pulse-width modulation (SVPWM). It also has the advantage of delivering an output voltage with low harmonic contents. It is based on a comparison between modulation waveform and four carrier waveforms. The capacitor imbalance problem is solved based on the technique which is listed in [14].

III. POWER-LOSSES CALCULATIONS MODEL

The aim of this section is to provide a mathematical tool based on the equations outlined in [15]-[17]. The losses of the power-electronic devices are calculated with different strategies. The power loss is calculated for the proposed T5 converter, Two-level, and conventional five-level DCC. In addition, the power loss is calculated for the proposed FP-IBC, conventional BC, MDBC, TP-IBC and MD-IBC.

IV. RESULTS AND DISCUSSION

Based on the block diagram shown in Fig. 5, two studies have been implemented using Matlab®/Simulink. The first study aims to evaluate the proposed converters' efficiency with regards to other converter topologies using losses calculation model presented in section III. The second study introduces the THD for the studied topologies of DC/AC converters. The parameters of the complete system used in simulations are summarized in Table 1 and Table 2.

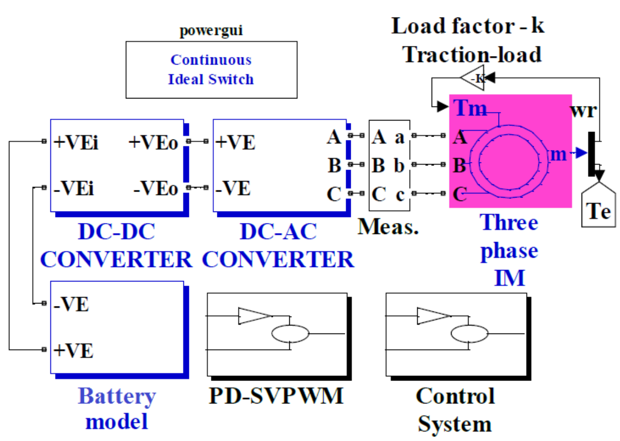

Fig. 5. A complete Simulink block-diagram for the overall system

TABLE 1. DC/DC CONVERTER PARAMETERS

Items	$R_l(m\Omega)$	$R_c(m\Omega)$	$L(\mu H)$	$C(\mu F)$	n	m
Con-BC	68	0.57	750	640	1	1
MDBC	34	1.15	380	320	1	2
TP-IBC	34	1.15	380	320	2	1
MD-IBC	17	2.13	190	160	2	2
FP- IBC	17	2.13	190	160	4	1

TABLE 2. BATTERY AND INDUCTION MACHINE PARAMETERS

Items	Parameters	
Li-ion Battery parameters	Capacity (Ah)	70
	Initial SoC	80%
	Nominal Voltage (V)	19.2
	No of modules in series	16
	No of parallel modules	3
Induction motor Parameters	Output power (hp)	50
	Stator resistance (Ω)	0.08233
	Rotor resistance (Ω)	0.0503
	Stator inductor=rotor inductance (H)	0.00072
	Magnetizing inductance (H)	0.02711
	Inertia (kg.m^2)	1.662

A. Comparative efficiency study

During the simulation, the efficiency of all studied converters is investigated at different power rating and switching frequencies. Simulation runs are carried-out using a battery whose voltage is set to 300V as the converters input voltage. The output voltage reference is set to 640V. The power loss is calculated for the proposed T5 converter, Two-level, and conventional five-level DCC. In addition, the power loss of the proposed FP-IBC, conventional BC, MDBC, TP-IBC and MD-IBC is calculated. Moreover, the passive losses for the DC/DC converter, which are the inductor and the capacitor losses, are calculated as well. The switching and conduction losses are calculated for each switch. For DC/AC converters, there are two IGBTs used in this study as listed below according to the difference of the switches voltage drop for the tested converters.

- 1st IGBT has a rated voltage of 1200 V with a number GT100DA120U.
- 2nd IGBT has a rated voltage of 600 V with a number GT100DA60U.

The different types of converters are used the IGBTs as follow:

- For two-level converter, the used switches are the first IGBT.
- For five-level DCC, the used switches are the second IGBT.
- For T5 converter, the switches S_3, S_5 are the first IGBT, while the other switches the second one.
- For all topologies of the dc-dc converters, the first IGBT is used.

For the power-loss analysis of the DC/AC converter topologies, the efficiencies for the motor operation at no-, half- and full-load are calculated. The study covers a wide range of switching frequency: 1-40 kHz. The results are summarized in Fig. 7, Fig. 8 and Fig. 9 for no-, half- and full-load cases. These figures clarify that T5 converter loss is lower than five-level DCC. This comes from the reduced switching elements of the converter power circuit. At full-load condition, the difference in the power losses between the T5 and DCC converter is about 500 watt. For the range of power of this drive system, it is assumed that the base power is 40 kW. At 10 kHz switching frequency, it is found that the T5 converter efficiency is equal to 98.25%, while the DCC efficiency is equal to 96.93%. So the proposed topology increases the five-level converter efficiency by 1.32%. Compared to the two-level converter, at the switching frequencies lower than 7 kHz, the two-level converter has lower loss.

For this frequency range, the THD factor for voltage and current is high compared to multilevel converters. The more the harmonic contents in the delivered voltage and current, the more the power loss in the machine. For the frequency range greater than 7 KHz, T5 converter has a lower loss compared to two-level.

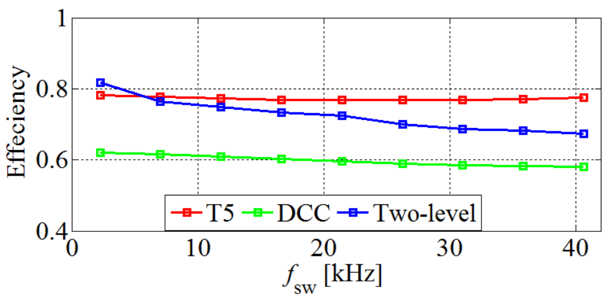

Fig. 7 Converters efficiency versus switching frequency at no-load.

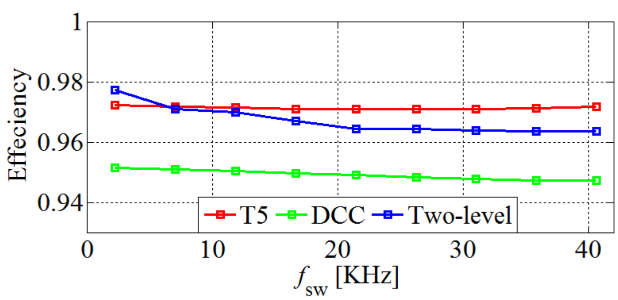

Fig. 8 Converters efficiency versus switching frequency at half-load.

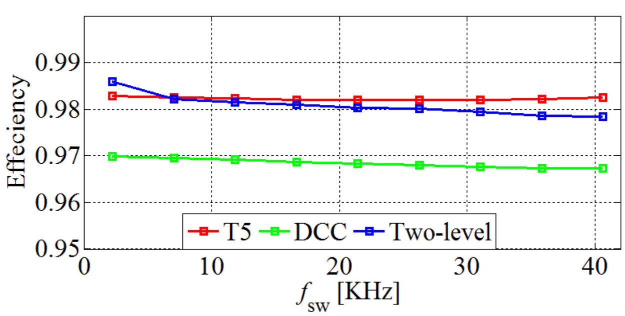

Fig. 9 Converters efficiency versus switching frequency at full-load.

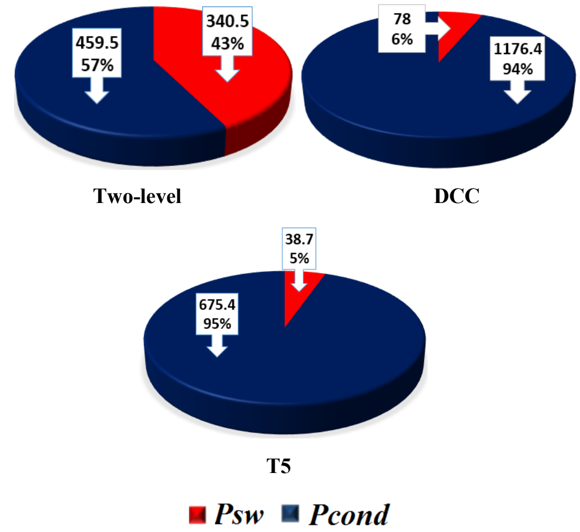

Fig. 10 Distributed power losses in (W) for each dc/ac Converters

It is well known that the main power electronics losses are conduction and switching losses. In Fig. 10, a pi-chart shows the values and percentages of switching and conduction losses for two-level, DCC, and T5 converters at 20 kHz in case of motor full-load. The results clarified that T5 converter has the lowest total loss. Moreover, T5 topology switching loss to converter total loss ratio is the lowest compared to DCC and two-level converter. This reflects the low switching stress on the converter elements.

Figs. 11, 12, and 13 show the DC/DC boost converters efficiency versus the switching frequency range from 5 to 40 kHz at power ratings of no-load, half load, and full load. It is worthy to note that for the switching frequency range [10–20 kHz] and for the case of power equal to full load, the efficiency decreases by 0.175 % for the FP-IBC and by 0.669% for the conventional BC (see Fig. 13). For the change in the operating power rating range from [half load to full load] at the same switching frequency [20 kHz], the efficiency decreases by 0.08% for the FP-IBC and 1.14% for the conventional BC (see Figs.12, 13).

As it is shown in Figs. 11, 12, and 13, the proposed FP-IBC converter has the highest efficiency and hence, the lowest total power loss compared to other boost converter topologies, in particular at high power and high switching frequencies.

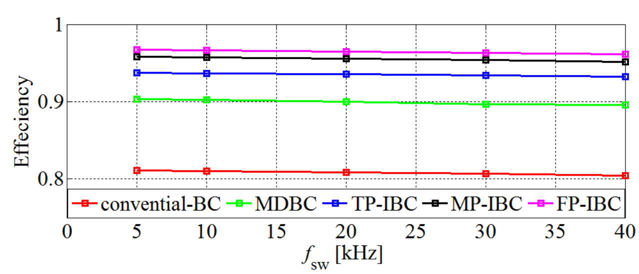

Fig. 11 DC/DC Converters efficiency versus switching frequency at full load.

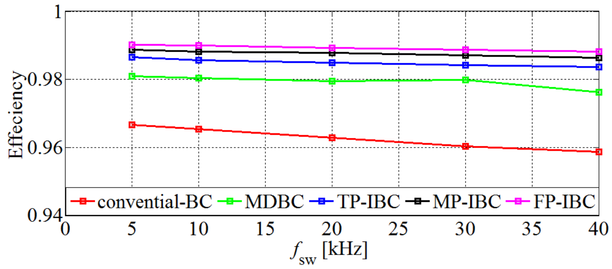

Fig. 12 DC/DC Converters efficiency versus switching frequency at half load.

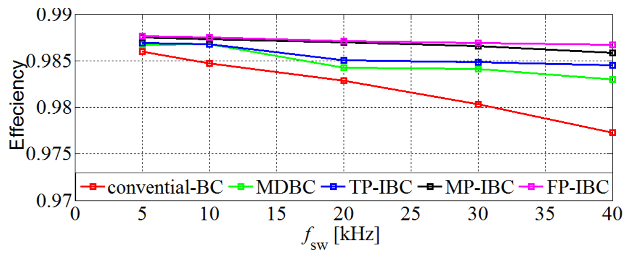

Fig. 13 Converters efficiency versus switching frequency at no-load.

Fig. 14 shows the distribution of all losses for each converter at full-load operation and 20 kHz. This case is chosen to investigate the worst case scenario in terms of power losses.

As it is illustrated in Fig. 15, the proposed converter is able to reduce the total losses and especially the passive elements losses. This comes from the reduction of its passive components size by four times compared to conventional BC and two times compared to TP-IBC and MDBC. It is noteworthy that the proposed converter (FP-IBC) efficiency characteristics make it a good candidate for EVs, particularly in high-power applications.

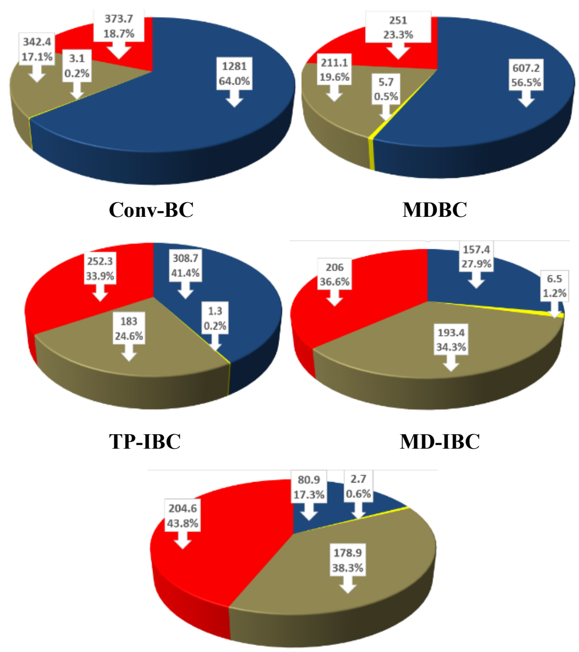

Fig. 14 Distributed power losses in (W) for each dc/dc converters

B. Harmonics analysis

For the harmonic analysis of the dc/ac converter, the total harmonic distortion (THD) factor is considered a common factor for evaluating the converter output. The THD factor is described by (1) as follows:

$$THD = \sqrt{\sum_{h=2,3,\ldots}^{\infty} \left(\frac{V_h}{V_1}\right)^2} \quad (1)$$

While V_h, V_1 are the root-mean square (RMS) values for the harmonic-order and fundamental voltage respectively. Fig. 15 shows the THD factor for a wide range of switching frequency operation at full-load case study.

The THD factor for T5 converter appears as frequency independent. This reflects the availability of operating the converter at low frequency range. However the THD factor for two-level converter is high at the low frequency range. The THD factor machine current is damped because of the machine impedance. The THD factor for T5 converter is much lower compared to two-level one.

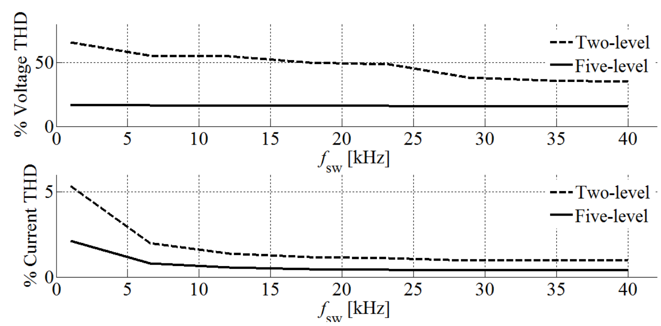

Fig. 15. THD factor for two-level and T5 converter topologies

As a result, the proposed drive system, FP-IBC connected to T5 converter (FP-IBC/T5), and efficiency characteristics can make it a good candidate for EVs (Fig. 16).

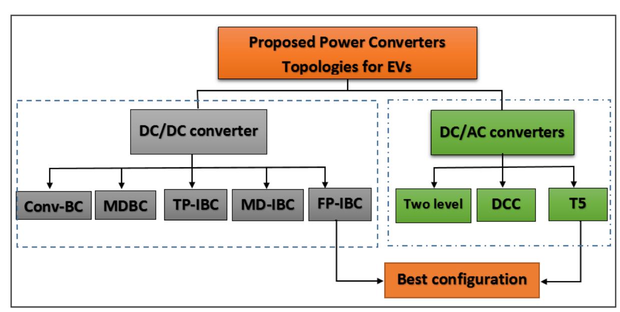

Fig. 16 Converters efficiency versus switching frequency at 10kw.

V. Conclusion

In this research, an efficient power-electronic scheme with FP-IBC connected to T5 converter has been proposed for EV applications. The proposed converters are compared against other converter topologies and evaluated numerically with power losses calculations. Simulation results show that FP-IBC and T5 converter are the most efficient converters among different DC/DC and DC/AC converter topologies which studied in the paper work. FP-IBC achieves this ranking because of the reduction of its passive components size by four times compared to conventional BC and two times compared to TP-IBC and MDBC. Moreover, the current and voltage ripples are also reduced by four times compared to conventional BC and two times compared to TP-IBC and MDBC. On the other hand, the power loss calculation of DC/AC converters indicates that T5 converter increases the efficiency of the five-level converter by 1.25 %. The T-type converter has lower losses but with more harmonic contents which affects the machine losses. Furthermore, T5 converter has the lowest THD factor for voltage and current compared to two as well as three-level converter. Simulation results along with numeric comparison for efficiency have demonstrated that the proposed converter is very promising for EVs applications.

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