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Power Losses Analysis of Multiphase Interleaved DC-DC Boost Converter using OrCAD PSpice Software

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***Abstract*—DC-DC converters with multiphase structures are widely used in electrical and electronic devices because of their advantages over conventional boost converters, such as reduction in input current ripple and low conduction loss. As technology advances, more delicate needs have to be fulfilled for better load performance. Traditional boost converters are still feasible but with certain drawbacks, such as high current ripples, significant switching losses, and high switch voltage stresses. This paper presents a novel multiphase DC-DC boost converter, with an output power range between 50 Watts to 200 Watts. The number of phases for this multiphase boost converter is limited to 5-phase. This paper focuses on power losses in the converter, namely conduction losses in diodes and MOSFET, switching losses in MOSFETs, as well as losses in inductors and capacitors. The discussion includes an analysis of the relationships between multiphase boost converters in terms of the number of phases and power loss. Simulation results show that the 3-phase DC-DC boost converter contributed to the least losses (at P=200 Watts) with the efficiency of 94.09 %, in addition to the smaller number of components used; by comparison between 3-phase and 4-phase. The performance analysis was done using OrCAD PSpice software.**

Keywords—boost converter, interleaved, PSpice, multiphase, power losses

I. INTRODUCTION

DC-DC boost converter is a device that has a high gain level and low input current ripple which steps up unregulated input voltage to be regulated output voltage [1]– [3]. The DC-DC boost converter is among the devices that have the ability to increase the DC output voltage[4]. In a non-isolated configuration, the boost converter has a simple circuit arrangement; containing at least two semiconductor devices, and one inductor. However, conventional DC-DC boost converter configuration has several drawbacks, such as high current and high voltage ripple. In high-power applications such as renewable energy as well as automotive and communication, the conventional boost converter is unable to cope with high input current, especially when the input voltage is low [5]. Thus, the converter suffers high current stress and high power losses in the load. The development of power converters has introduced a new way of increasing the system's overall performance, which is by multiphase configuration.

Nowadays, DC-DC converters with multiphase structures are common in telecommunication devices, renewable energy applications, drives, and electronic devices. The multiphase configuration has several advantages: reduction in cost, size, and weight, high efficiency at high output power, improved thermal performance, and excellent transient response [6]–[9]. Furthermore, for systems that require low EMI and low output voltage ripple, multiphase is the most selective configuration. Multiphase converters operate in parallel with typical pulse-width modulation (PWM) controllers, by relative phase shift using an interleaved technique based on N-identical [1], [6]-[8]. Multiphase interleaved converters are mainly used to reduce current ripple; subsequently lessening the current stress at the input side [13]–[15]. Thus, the current flowing through the components (inductor, diode, and switch) is significantly reduced. Therefore, the components' weight and size can be reduced, in addition to power losses in the converter [16].

Recently, multiphase structures with coupled inductors have been intensively studied, to reduce the size of hardware [17]–[19]. This configuration, however, has a disadvantage; it requires a complicated design of switching signals, thus increasing the system's complexity. In this case, sensing current with a sampling frequency well above the switching frequency is required. Therefore, a high-speed microprocessor is required to monitor the inductor current, which can cause high input current ripples, increasing the complexity of the system [20], [21]. Besides, the coupled inductor may cause leakage inductance, which reduces the efficiency of the converter. Leakage inductance in the multiphase converter can be alleviated using a soft- switching technique with the appearance of a resonant tank circuit [22]–[24]. Therefore, the arrangement of the converter circuit will be more complex due to the additional components [25].

The focus of the discussion in this paper is regarding the relationships between multiphase boost converters in terms of the number of phases and power loss as the number of phases increases, the power losses in the converter decrease. Thus, this paper aims to address the drawbacks of high current stress and high-power losses in traditional DC-DC boost converters and presents an analysis of the power losses of multiphase DC-DC boost converters including inductor loss, capacitor loss, switching loss, and conduction loss. Analysis was performed on 1 up to 5 phases with output power from 50 Watts, 100 Watts, 150 Watts, and 200 Watts. The number of phases discussed in this paper was limited to five phases because of the design consideration while the power range of the multiphase DC-DC boost converter ranged between 50

Watts to 200 Watts due to the selection of critical components such as inductor which limits the current that follow through it. This paper focuses on power losses in the converter, namely conduction losses in diodes and MOSFET, switching losses in MOSFETs, as well as losses in inductors and capacitors and it is crucial to analyze in the context of DC-DC converters to optimize the efficiency of the converter. Thus, power losses were compared and analyzed in terms of the duty cycle and the number of phases, followed by a comparison of the efficiency and performance of multiphase boost converters.

II. Multiphase DC-DC

The circuit configuration of the 5-phase DC-DC boost converter is shown in Fig. 1. It consists of three key elements: the inductor, diode, and MOSFET, which are also recognized as power stage components. Each power stage is increased along with the increment of the number of phases. The PWM switching signals for each phase are phased shifted by 360/N, where N is the number of phases. However, the duty cycle and switching frequency for all configurations (1 to 5 phases) remain. Fundamentally, the multiphase DC-DC boost converter operation is similar to that of the conventional boost converter. The primary function of a multiphase DC-DC boost converter is to eliminate the drawbacks of a conventional boost converter, such as high current stress, high output current ripple, high conduction losses, bulky components, and low efficiency. The multiphase boost converter can be designed to operate either in Discontinuous Conduction Mode (DCM) or Continuous Conduction Mode (CCM). For this study, CCM was selected due to its advantages of high output power and low input current ripple.

The boost converter generally has two-mode operation in one full complete cycle. The first mode is when the switch is turned on while the diode is turned off. Meanwhile, in the second mode, the diode is turned on while the switch is turned off. The multiphase with interleaving switching operation principle is similar to a conventional boost converter whereby the operating mode is increased by two times (N × 2) when each N phase is increased.

Theoretically, a conventional DC-DC boost converter (single-phase) generates higher power losses than the multiphase when increased output power. This is because the fixed losses corresponding to conduction losses are directly dependent on the current through the inductor and the on-state resistance [26], [27]. To reduce the current flowing through the inductor, the number of phases increases, which also affects the reduction of current ripples [28]. Therefore, an optimum duty cycle is required to reduce the current ripple in the multiphase boost converter. Fig. 2 shows the concept of current ripple reduction by increasing the number of phases. It can be seen that when the number of phases increases, the magnitude of the current ripple decreases. Also, the optimum number of duty cycles differs depending on the increment of the number of phases.

III. Power Losses Formulas

The general power loss of a DC-DC boost converter is given by ($P = I^2 \times R$), where the increase of several phases can reduce the power losses by simply increasing the number of current branches. The diminishing value of current going through each phase causes the power losses to be reduced. DC-DC converter has two types of semiconductor losses: switching loss and conduction losses.

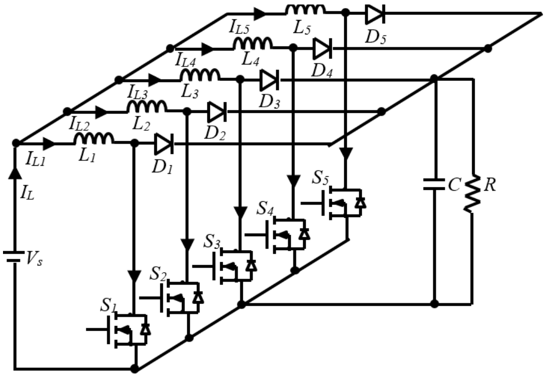

Fig. 1. Multiphase DC-DC boost converter circuit configurations.

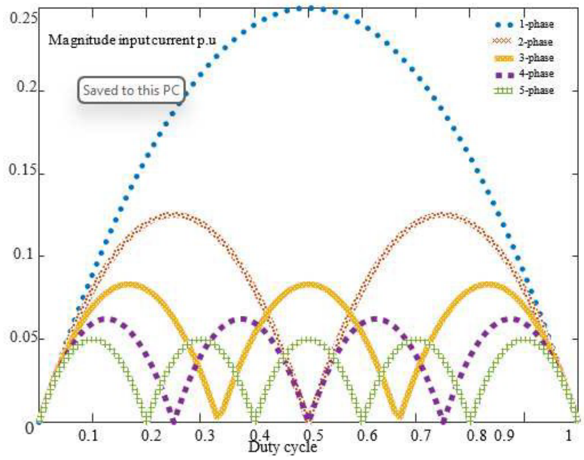

Fig. 2. Concept of input current ripple with the variation of the number of phases.

A. Switching Loss

Switching losses in MOSFETs are losses that occur in the switch due to its turned-on state and turned-off state of transition and it is a critical factor to consider when designing converters because switching losses contribute to high-frequency system losses. Thus, minimizing the switching loss will improve the efficiency of the designed power converters. Semiconductor losses are a consequence of energy losses during the transition and switching frequencies. Switching losses occur in the switch due to its turned-on state and turned-off state of transition. The equations used to determine switching losses are expressed by (1) to (3).

The switching loss during turn-on:

$$P_{sw,on} = \frac{V_{DS,\max} \times I_{DS,\max}}{6} t_r f_s \tag{1}$$

The switching loss during turn-off:

$$P_{sw,off} = \frac{V_{DS,\max} \times I_{DS,\max}}{6} t_f f_s \tag{2}$$

Thus, the total semiconductor loss is given by:

$$P_{sw,total} = P_{sw,on} + P_{sw,off} \tag{3}$$

B. Conduction loss

Conduction losses generally occur in power semiconductor devices, where DC-DC converters are diodes and active switches; BJT, MOSFET and IGBT. In diodes and MOSFETs, conduction loss impacts the overall efficiency and performance of the multiphase boost converter by increasing the power dissipation and reducing the efficiency of the system. The conduction loss for an active switch occurs when it is in a turned-on condition, while the conduction loss of a diode occurs during its forward-biased condition. The conduction loss equation for the active switch is expressed as:

$$P_{cond,MOSFET} = I_{DS}{}^{2} R_{on} D \quad (4)$$

The conduction loss equation for the diode is expressed as:

$$P_{cond,diode} = I_{diode,mean} V_{(F)} (1-D) \quad (5)$$

C. Inductor Loss

Inductor losses consist of resistance losses and core losses that cause increased power dissipation and potential temperature rise thus affecting the efficiency and performance of the DC-DC boost converter. The demand for improvement in the efficiency of the multiphase boost converter and thus, the efficiency of the inductor is rising at a fast pace, due to the ever-increasing demand of the output current of the power supply at the same time. An alternative effort is to dissipate the amount of heat from the power supply. This directly affects the overall efficiency of the power supply. The study on the reduction of heat is particularly significant since the production of heat and the inductor losses are directly related to it, it is essential to reduce the inductor losses. The fundamental parameter to define the power loss of inductor losses is given by (6) or (7).

$$P_{L(DCR)} = \left[I^{2}{}_{out} + \frac{(I_p - I_v)^2}{12} \right] xDCR \quad (6)$$

$$P_{L(DCR)} = I^{2}{}_{out} DCR \quad (7)$$

The losses occur simply because of the DC resistance (DCR) of the coil and the current flowing in the inductor.

D. Capacitor Loss

Although multiple losses are generated in the capacitor, including series resistance, leakage and dielectric losses, these losses are simplified in an overall loss model as equivalent series resistance (ESR) that affects the efficiency of the converter. The capacitor losses can be calculated by using (8).

$$P_{cap(ESR)} = (I_{cap})^2 \times ESR \quad (8)$$

IV. ORCAD PSPICE SOFTWARE

The software used for the performance analysis was OrCAD PSpice software and it is suitable for this type of research because the software includes an extensive library of components that facilitate realistic circuit representation for accurate performance assessment. This section discusses the simulation that had been done using OrCAD PSpice software, as in Fig. 3. The simulation was conducted according to the parameters shown in Table I. The parameters specifications for conventional boost converter, 2-phase, 3-phase, 4-phase, and 5-phase multiphase were similar, to compare the results in terms of efficiency and power loss of the converter. The inductors' value was chosen to be much higher than the calculated value to make sure that the converter would operate in CCM, even with a smaller range of duty cycles.

V. RESULTS AND DISCUSSIONS

In this section, power loss analysis for dynamic (switching) and fixed losses (conduction), capacitor, and inductor losses are reviewed in detail. Therefore, an optimized number of phases can be chosen based on the calculated value of the conduction loss and switching losses during steady-state. Table II compares power losses between 1-phase to 5-phase converters, ranging from 50 Watts to 200 Watts. The switching losses showed a constant increase along with an additional number of phases (reduction of losses along with a greater number of phases). Fig. 4 shows the simulation results, executed using OrCAD PSpice, which had been further validated with the calculation.

Using a conventional boost converter (1-phase), the conduction loss was the highest. The conduction losses were reduced when the number of phases was increased. Since the duty cycle affects the value of line losses of the diode and the MOSFET, it is crucial to select an optimum duty cycle for the converter. The value of the duty cycle is directly proportional to conduction loss. Similarly, switching losses and inductor losses increase when the number of phases is increased. This is due to the additional number of inductors and switches required when the number of phases is increased. The high

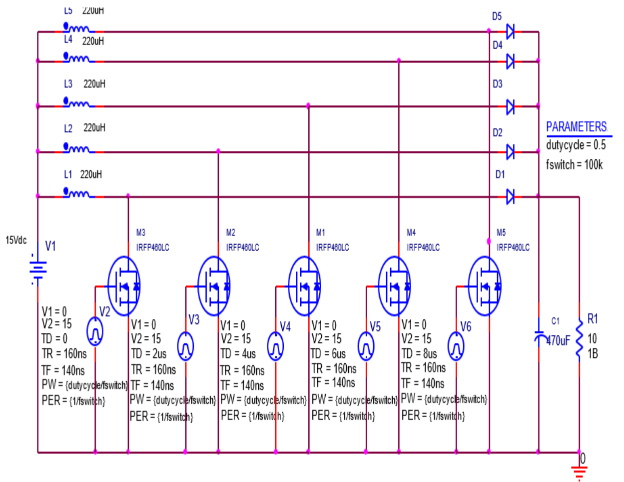

Fig. 3. Simulation circuit of a 5-phase boost converter in OrCAD PSpice software.

TABLE I. PARAMETER VALUES

Parameters	Value
The input voltage, V_{in}	20 Volts
Inductance, L_n	220 µH
Resistance, R	150 Ω
Capacitance, C_n	470 µF
Switching frequency, f_s	100 kHz
Rise time, t_r and Fall time, t_f	160 ns and 140 ns

TABLE II. COMPARISON OF POWER LOSSES BETWEEN 50 WATTS, 100 WATTS, 150 WATTS AND 200 WATTS

N-phase	1-phase	2-phase	3-phase	4-phase	5-phase
50 Watts					
Conduction	2.664	2.090	1.280	0.928	0.722
Switching	0.220	0.460	0.510	0.600	0.700
Inductor	0.016	0.034	0.089	0.147	0.208
Capacitor	0.204	0.131	0.049	0.020	0.013
Total	3.104	2.715	1.928	1.695	1.643
100 Watts					
Conduction	7.014	5.338	3.121	2.216	1.718
Switching	0.410	0.880	0.960	1.160	1.350
Inductor	0.062	0.131	0.345	0.575	0.819
Capacitor	0.062	0.823	0.369	0.169	0.045
Total	7.546	7.172	4.795	4.120	3.932
150 Watts					
Conduction	12.592	9.332	5.306	3.776	2.838
Switching	0.580	1.260	1.410	1.680	2.600
Inductor	0.131	0.283	0.763	1.280	1.803
Capacitor	0.082	0.022	0.987	0.782	0.316
Total	13.385	10.90	8.466	7.518	5.557
200 Watts					
Conduction	19.252	14.028	7.835	5.478	4.072
Switching	0.740	1.640	1.860	2.280	3.150
Inductor	0.221	0.490	1.335	2.245	3.162
Capacitor	0.103	0.037	0.019	0.888	0.489
Total	20.316	16.195	11.049	10.891	10.873

current through the MOSFET and diode contributes to high conduction losses by the converter. In- circuit driver rise time t_r and fall time, t_f also contribute to the significant impact of switching losses in an active switch.

The capacitor contributed to the smallest amount of losses compared to the other components. Fig. 5 shows the total power losses in a multiphase DC-DC boost converter. Fig. 5 shows that the total power losses in the 3-phase boost converter (for P=200 Watts) were less significant compared to those of the 4-phase (1.43 %) and 5-phases (1.59 %). It seems that by the increase of output power (P=200 Watts) and number of phases, the conduction losses decreased, while inductor and switching losses increased. It can be concluded that the 3-phase DC-DC boost converter (with a specification in Table I) had a small difference in losses (at P=200 Watts) with a lesser number of components (compared to 4-phase and 5-phase).

Fig. 5 shows the comparison of power losses from 100 Watts of 1-phase to 5-phase boost converters. In 1-phase, all power losses, except conduction loss, were approximately the same. The switching loss and conduction loss were approximately similar when the number of phases was increased to 5. This clearly shows that the multiphase boost converter is indeed capable of reducing conduction loss.

The efficiency of the multiphase boost converter is shown in Fig. 6. The efficiency of the multiphase boost converter increased when the number of phases was increased. By 50 Watts, the conventional boost converter or 1-phase had the lowest efficiency, at 94.08 %. In comparison, the 4-phase and 5-phase had the highest efficiency, at 96.55 % and 96.69 %, respectively. The efficiency decreased when the output power increased. The efficiencies of 3-phase, 4-phase and 5-phase were almost similar when the output power was 200 Watts, achieving 94.05 %, 94.31 % and 94.38 %, with the smallest losses respectively. Overall, the optimum number of phases for a multiphase DC-DC boost converter to achieve the most efficiency is 3, considering power losses, efficiency, and number of components. Also, the advantage is that the 3-phase DC-DC boost converter configuration uses a smaller

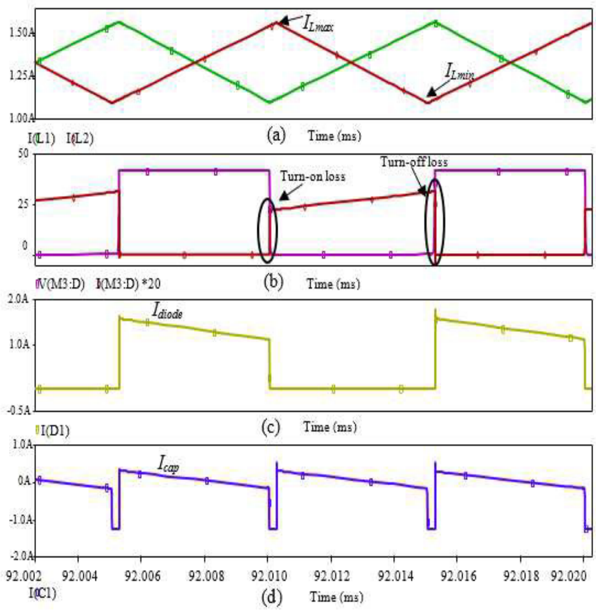

Fig. 4. Simulation results of 2-phase DC-DC converter (a) inductor current, (b) drain-to-source voltage and current, (c) diode current, and (d) capacitor current.

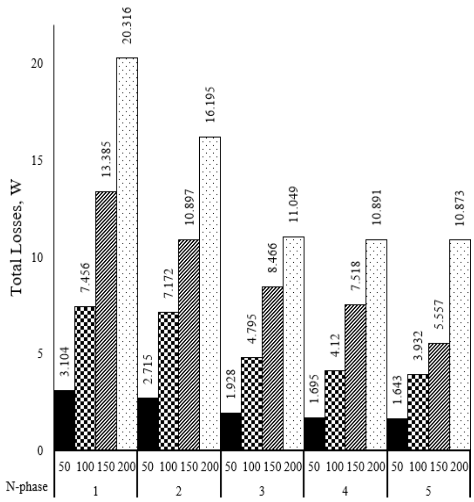

Fig. 5. Total power losses by 1-phase to 5-phase.

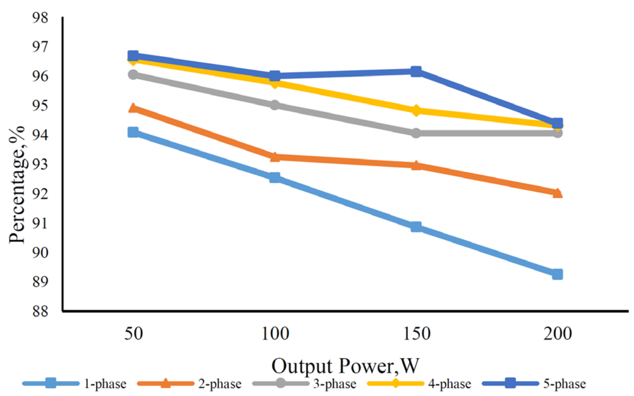

Fig. 6. Efficiency versus output power.

number of components compared to 4-phase DC-DC boost converter configuration.

VI. CONCLUSION

Simulation for a multiphase DC-DC boost converter with a range from 50 Watts to 200 Watts has been reviewed. Analysis and comparison between 1-phase and 5-phase have been presented in detail, by consideration of power losses such as switching loss, conduction loss, inductor loss and capacitor loss. Increasing the number of phases can significantly reduce diode and MOSFET conduction loss. Efficiency at specific points of the converter load can also be increased by increasing the number of phases. Although switching loss increases when the number of phases increases, it is not as significant as the conduction loss. Switching loss can also be reduced by using the soft- switching technique, as proposed by previous researchers. For the inductor and capacitor, the losses totally depend on the current flow and the value of DCR and ESR, respectively.

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