A Method to Calculate and Measure Losses and Efficiency in DC-DC Converters

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***Abstract*— In this paper, training on how to calculate and measure losses in power converters is presented. In the power converters all elements have losses due to circuit conditions, therefore in order to calculate the losses in the elements, all conditions are considered, so the accuracy of the calculations are high. All relationships and formulas to calculate losses are presented, so the different ways of calculating losses are clear in this paper. All basic converters in this paper are studied in term of losses, so this paper is a good reference for calculating losses in DC-DC converters. In converters with soft switching, elements are added that also have losses in the converter, which the method for obtaining losses of these elements is also taught. Finally, methods for obtaining losses in simulation and experimental prototypes are given that prove the methods and theoretical formulas.**

Keywords*— *DC-DC converter, losses, efficiency.

I. INTRODUCTION

Today, DC-DC converters have become very important in the industry [1], so that they are available in almost all sectors in the industry. These converters are used as power supply circuits [2]. Some of the important applications of these converters are in microprocessor computers [3],[4], electric vehicle system [5-8], photovoltaic systems [9-12], led drive [13-15], wind energy systems [16]-[18], office equipment [19-21] and etc. In general, these converters are either linear or switching. Linear converters or regulators are less used due to high losses and are used only in special cases [22-25]. Therefore, switching converters have received more attention, which reduces losses and increases efficiency with this technique [26]. Switching converters are divided into two general categories, isolated [27] and non-isolated [28]. The structure of non-isolated converters is simpler and has higher efficiency [29]. Transformers are used to isolate the converters [30]. The use of transformers causes losses in the converters and the efficiency of these models is lower than non-isolated. Non-isolated converters are divided into buck [31], boost [32], buck-boost [33], CUK [34], SEPIC [35] and ZETA [36]. isolated converters are divided into fly-back [37], forward [38], half-bridge [39] and full-bridge [40]. Of course, new types of converters have also been introduced [41], which all of these topologies are derived from the basic topologies mentioned.

In all switching converters the elements such as diode, switch, inductor and capacitor are used, which these elements have losses and should be considered in design. Losses in these converters are divided into conduction and switching losses. Conduction loss is related to the current and voltage on the element, but switching loss is related to switching the elements on and off with the desired frequency. To reduce conduction losses, the type of element and power of the converter is important, the use of elements with small on-state resistance reduces these losses. In the switching mode, due to the high speed of turning off and on the element, there is an overlap between the voltage and current, which creates the sum of these overlaps in the switching loss converter. In hard switching converter losses are high than soft switching converter, because in soft switching, ideally, the overlap of voltage and current is eliminated and the switching losses are zero. Today, these converters are offered completely in the form of soft switching to have high efficiency and reduce losses. However, there are losses in these elements and cause a decrease in efficiency. Therefore, calculation and measurement methods should be provided. Also, in most references, the comparison of efficiency and losses between the proposed converter with the hard switching converter has been done, which should be provided the calculation method in all converters, including basic converters. So far, no complete references have been presented on the loss and efficiency calculations, and the papers that have mentioned the losses are given briefly and only for a part of the paper structure.

In this paper, calculated of losses in the switching converters is presented. These calculations are presented completely in full detail. Section 2 describes all the elements and their specifications in switching converters. Section 3 shows how to calculate the losses of each element in full, also mentioned all the relationships. Section 4 describes how to obtain converter efficiency in an experimental prototype. In Section 5, a comparison is presented between the paper and previous papers based on loss calculations. Finally, section 6 presented the conclusion of the paper.

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II. METHODS

There are different ways to measure losses in converters, but first it is better to describe a converter and the types of losses. A basic non-isolated converter such as buck, boost or buck-boost, have one switch and one diode as semiconductor devices and have one inductor and one capacitor as passive elements. For example, Fig 1 shows a buck converter, which these elements are specified in this figure. All of these elements have losses, which described in this section.

A. Switch losses

In these converters, BJT, MOSFET or IGBT can be used for S. All of these semiconductor devices have several losses as below.

- Conduction losses
- Switching losses
- Parasitic capacitance losses

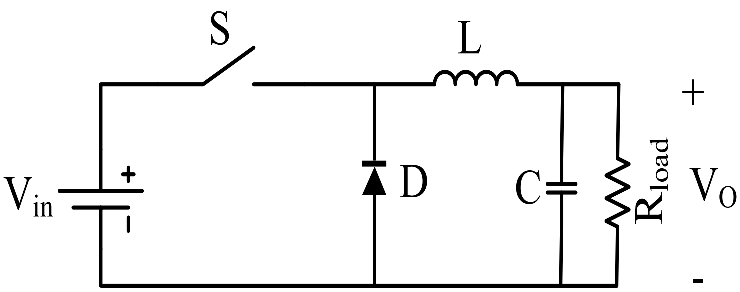

Fig. 1. A buck converter structure.

The conduction losses on the transistor are due to the connection of semiconductors in the element. These losses depend on the fabrication technology and the circuit conditions in terms of power and current passing through the element. These losses can be reduced by reducing the resistance of the junctions in the element production process. In the switching converter due to switching condition on the switch, switching losses are created, which these losses are due to the overlap of voltage and current at the moment of change of switch state. If the switch is assumed to be ideal, when it switches from on to off or vice versa, the voltage and current have no interference and the losses on this switch are zero. But a real switch has raised time and fall time during off and on times, which causes overlap.

For a better understanding of conduction and switching losses, Fig 2 is presented. As can be seen from this figure there are fixed losses that are conduction losses and the losses that exist during on and off the switch, which are switching losses. Also, the switching losses are depended on switching frequency.

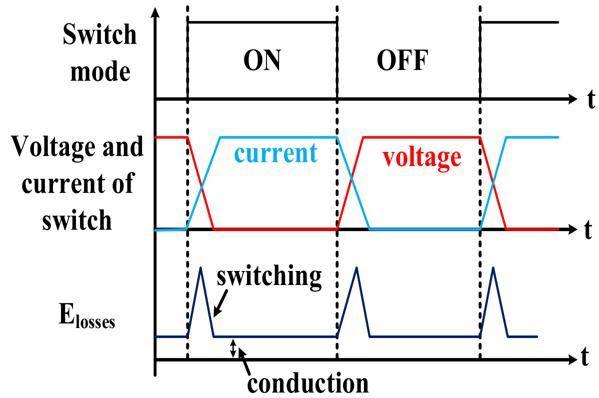

Fig. 2. Switching and conduction losses in the switch.

Parasitic capacitor is caused by connection capacitors on semiconductors. Which appears in each part of the transistor where there is a semiconductor connection. In addition to the capacitor effect at high frequencies, which causes the transistor to malfunction, this capacitor also causes losses. Fig 3 shows all parasitic capacitance in the MOSFET as sample. It is clear from this figure, each junction in the MOSFET create a parasitic capacitance. These capacitances have losses in the switching frequency, which by increasing switching frequency in the converters these losses are increased. Therefore, these losses should be considered in the converters.

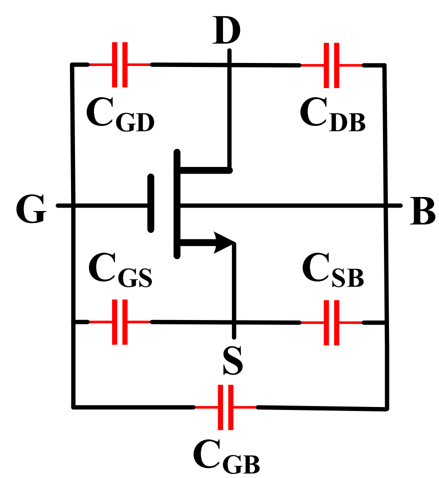

Fig 3. Parasitic capacitances on the switch

B. Diode losses

Diodes in the DC-DC converters have 3 losses as below.

- Conduction losses
- Parasitic capacitance losses
- Reverse recovery losses

When the diode is on, a current is flowed through it and a voltage is dropped on it, which cause to losses on the diode. These losses are conduction losses and, in the circuits, depend on circuit power these losses are low or high. These losses can only be reduced by the diode structure, which means that the diodes must be improved in manufacturing technology. Since the diode is a P-N junction, this connection creates a parasitic capacitor on the diode, which can obviously cause losses to the circuits in the switching converters. Therefore, to exactly design of DC-DC converters, this capacitor is also considered. In DC-DC converters, an important effect in the diode is reverse recovery time, which cause to increase losses in the converters. When the diode is off immediately, carriers must be discharged from the connection. Hence, a period of negative current is established on the diode. This reverse current does not have a good effect on the circuits, which one of the effects is the imposition of losses on the circuit. A good solution to improve this effect is to use high speed diodes. The reverse recovery time of these diodes is very low and the losses due to this effect can be ignored. But these diodes also have high prices.

C. Inductor losses

The inductor has three losses as below

- Core loss
- Dc resistance wire
- Ac resistance wire

The core loss is the manufacturing specification, which is provided by the inductor supplier. But to calculate the core losses, a formula is provided, which is given in the calculation section. This formula shows that the losses are most dependent on the frequency and material of the core. Since the inductor is made of twisted wire and the wire has resistance, passing current through this resistance causes losses. These losses are divided into two categories, DC and AC, which dc losses are due to the passage of dc current through the wire and ac losses are due to the passage of ac current through the wire.

D. Calculate of losses in all elements

In this section calculate losses in all elements in the DC-DC converters are described. The method of examining and discussing losses and efficiency in converters is to perform theoretical calculations on these values first, then obtain the values in simulation and experimental testing and compare them with each other. So this is an algorithm to discuss these values.

E. calculate of switch losses

The conduction loss in the switch, is fixing loss due to passing current in the switch. the formula to calculate of this loss in MOSFET transistor is show at below.

$$E_{loss-con}(MOSFET) = \int_0^{t_{on}} i_d^2(t).R_{ds(ON)}dt \quad (1)$$

$$P_{loss-con}(MOSFET) = E_{loss}.f_{SW} \quad (2)$$

Where E_{loss} is conduction energy on the MOSFET and i_d is drain current. Hence DC-DC converter works with switching frequency this energy can be convert to power multiplied by the frequency of the circuit. As can be seen from above equation in MOSFET, power losses are obtained from resistance on element.

Fig 4 shows the relationship between conduction loss, i_d and R_{ds} in the MOSFET. It is clear that from this figure, by increasing i_d and R_{ds}, conduction loss is increased.

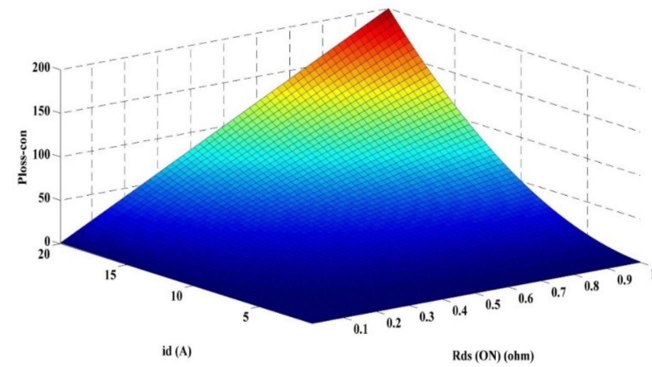

Fig 4. Conduction loss versus R_{ds} and id in the MOSFET

In IGBT, the power losses are obtained from voltage and current of element.

$$P_{loss-con}(IGBT) = \frac{1}{t_{ON}}\int_0^{t_{on}} I_F(t).V_F(t).D(t).dt \quad (3)$$

Where I_F and V_F are current and voltage of IGBT respectively. D is duty cycle of the converter.

Switching loss in MOSFET and IGBT is obtained as below. These losses are due to the overlap of voltage and current at the on and off moments, which must be calculated in both cases.

$$E_{loss-sw(on)}(MOSFET) = \int_0^{t_{d(on)+t_r}} v_{ds}(t).i_d\,(t)dt \quad (4)$$

$$E_{loss-sw(off)}(MOSFET) = \int_0^{t_{d(off)+t_f}} v_{ds}(t).i_d\,(t)dt \quad (5)$$

$$P_{SW}(MOSFET) = [E_{loss-sw(on)}(MOSFET) + E_{loss-sw(off)}(MOSFET)].f_{SW} \quad (6)$$

$$E_{loss-sw(on)}(IGBT) = \int_0^{t_{d(on)+t_r}} v_{CE}(t).i_C\,(t)dt \quad (7)$$

$$E_{loss-sw(off)}(IGBT) = \int_0^{t_{d(off)+t_f}} v_{CE}(t).i_C\,(t)dt \quad (8)$$

$$P_{SW}(IGBT) = [E_{loss-sw(on)}(IGBT) + E_{loss-sw(off)}(IGBT)].f_{SW} \quad (9)$$

t_r is raise time and t_f is fall time of the MOSFET or IGBT. Parasitic capacitor losses are not usually considered in circuits, but for more accurate calculations, it is better to consider the following equation to obtain losses on this capacitor.

$$P_{loss(cpar)} = \frac{1}{2}C_{par}V_{DS}^2 f_{SW} \quad (10)$$

For IGBT in the equation above V_{DS} change to V_{CE}. C_{par} is one of specification of transistor, which is given by supplier in datasheet.

According to (10) the curves are plotted, which is shown in Fig 5. In this Fig, the effect of V_{DS} and C_{par} on the parasitic capacitance loss is cleared as graphically.

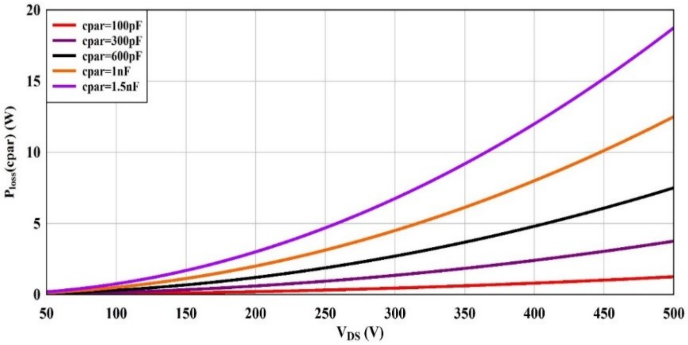

Fig 5. Parasitic capacitance loss versus V_{DS} in the MOSFET

Finally, all losses in the switch are obtained by added conduction losses, switching losses and parasitic capacitance losses.

F. calculate of diode losses

Conduction losses in the diode is calculated from below.

$$P_{con.D} = \frac{1}{T}\int_0^{t_{on}} V_F I_F(t) \cdot dt \quad (11)$$

Where T is switching period, V_F is forward voltage of diode and I_F is forward current of diode.

To calculate of parasitic capacitance on diode (12) is used.

$$P_{loss(cpar.D)} = \frac{1}{2} C_{par} V_F^2 f_{SW} \quad (12)$$

When diode turns off, reverse recovery loss is important to calculate. This loss is obtained from equation below.

$$P_{rr} = \frac{1}{T}\int_0^{trr} V_D(t) I_D(t) \cdot dt \quad (13)$$

If very fast diode is used in the DC-DC converter, this loss is usually neglected.

G. calculate of inductor losses

The core loss can be calculated from equation below.

$$P_{core}(mW) = K_1 f_{SW} B V_e \quad (14)$$

Where K_1 is constant for core material, B is peak flux density in kGauss and V_e is effective core volume in cm^3. With this equation, the core loss can be calculated by entering the K_1 co-efficient and the frequency and flux density exponents, which are unique to each core material.

According to the core loss equation, Fig 6 can be useful to obtain losses graphically.

P_{dcr} and P_{acr} are obtained from below.

$$P_{dcr} = I_{rms}^2 DCR \quad (15)$$

$$P_{dcr} = I_{rms}^2 ACR \quad (16)$$

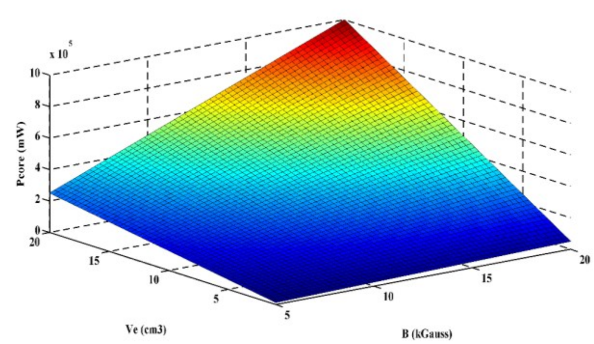

Fig 6. P_{core} in the MOSFET versus V_e and B

Where I_{rms} is the rms value of the peak current applied to the inductor, DCR is the dc resistance of the inductor and ACR is the ac resistance of the inductor

It is noted that output capacitance is also has loss, but this capacitor is part of the converters load, so it is not calculated in the converter losses and the energy reached to this capacitor is considered as the energy used in the output of the converter.

III. Results and Discussion

A. Efficiency Measurement

To obtain efficiency of the DC-DC converter, output power and input power should be obtained from simulation or experimental prototype. In the simulation, depending on the software used, these powers are obtained and by placing a wattmeter in the relevant software, the power reached to the converter load and the power drawn from the input are obtained and the result is presented. One of the most widely used software in this field is PSPICE software. In this software, power probes are for this purpose, which by placing the probe on the input source the input power is obtained, and by placing a power probe in the output load, the power reached to the load is also measured. Due to the switching conditions in these converters, the average power of each part must be measured. Therefore, in measuring when the converter has reached a steady state, the average power is measured at this time.

Fig 7 shows how to place power probes in this software. The simulated example is a base buck converter. As it is clear from this figure, the power probe is placed on the input source to measure the input power and the probe is placed on the ohmic load to measure the output power.

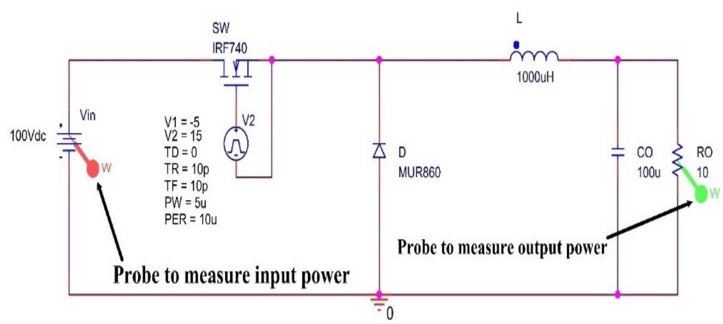

Fig 7. Probe location in simulation efficiency measurement in DC-DC converter

By simulation of circuit in Fig 7, input and output results are obtained and shows in Fig 8 and 9. Fig 8 shows the complete results and Fig 9 shows the results in more accurate values to better specify the values. As can be seen from Fig 9, the efficiency of this converter in the simulation is about 86%.

Fig 8. Input (red) and output (green) of the DC-DC converter

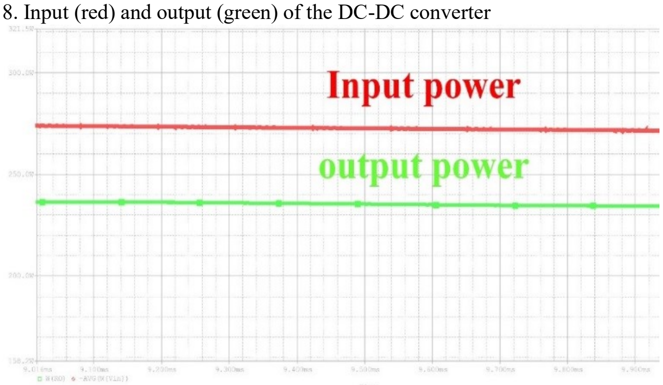

Fig 9. Exactly value of input (red) and output (green) of the DC-DC converter

When one experimental prototype is tested, similar to the simulation mode, the efficiency can be calculated, so the efficiency is calculated by measuring the input and output power. If a wattmeter is available in laboratory equipment's, the power can be easily calculated. If a wattmeter is not available, power can be obtained by measuring current and voltage on each side. Due to the high switching frequency, in experimental measurement, the values are completely averaged, which are suitable values for presentation.

B. Losses Measurement

In simulation or experimental testing, losses can be calculated based on the relationships in Section 3. According to these equations, the losses of each part are calculated by measuring the values in an experimental or simulated way, and by placing the values in the equations, the losses of each part are calculated. It is also possible to measure the amount of power on the elements by placing power meters, which usually measures conduction losses in the elements. Finally, by measuring and adding up all the losses, the efficiency can be calculated in this way.

C. Comparison Between DC-DC Converters According to Efficiency and Losses

In recent years, many converters have been presented, in which the converters have also been examined in terms of efficiency and losses. In this section, 10 of the newest of these references are reviewed and compared by simulation in PSPICE software. Table 1 shows the results of this comparison.

In this table, the theoretical results are presented according to the references. By simulating, these results in this section are also obtained and presented for comparison in the table. As can be seen from the values in this table, the theoretical results are almost identical to the simulations and differ slightly. But if it is necessary to obtain losses and efficiency with great accuracy, the results should be presented in the form of simulations with real elements or in the form of experimental test.

In all converters except [45], the efficiency presented is slightly higher than the efficiency measured in the simulation, which is due to the higher accuracy of the simulation in the loss values. In [45], the values of losses presented in the reference are by simulation, so the value measured in this paper is also very close to the reference values. In other references, the values of losses are presented theoretically and the efficiency obtained is slightly higher than this paper. Also, in order to better display the results and understand the comparison more accurately, Figure 10 presents the results graphically. From this figure, the numerical results of the table are graphically and more clearly defined.

TABLE I. COMPARISON BETWEEN TEN REFERENCES ACCORDING TO LOSSES AND EFFICIENCY (IN THE REFERENCES AND BY SIMULATION IN THIS PAPER)

parameters / converters	All losses (W)	Efficiency (%)	Nominal power rating (W)	All losses with simulation (W)	Efficiency with simulation (%)
[42]	10	95	200	11	94.5
[43]	2.2	85	15	3.5	76.6
[44]	20	96	500	23	95.4
[45]	6.8	93.2	100	6.7	93.3
[46]	16	96.1	400	17.5	95.6
[47]	6.22	87.5	50	6.34	87.32
[48]	2.5	93	36	2.9	91.9
[49]	3.2	96.8	100	3.55	96.45
[50]	24.844	93.8	400	25.2	93.7
[51]	8.6	95.7	200	9.3	95.35

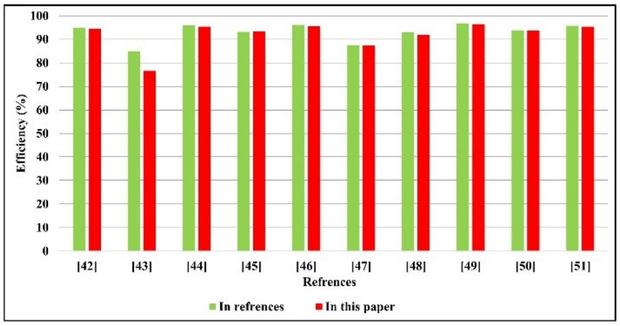

Fig 10. Comparison between ten references according to efficiency (green curves are given in references and red curves are measured by PSPICE software in this paper)

IV. CONCLUSION

How to calculate and measure losses in DC-DC converters is presented in this paper. In DC-DC converters, diode, MOSFET, inductors and capacitors must be used, which are have own losses. All the theoretical equations related to these losses were presented in this paper and how to calculate them was explained. How to measure losses and efficiencies in these converters is fully described, which is a method in simulation and a method in experimental made samples. Finally, several references presented in recent years are reviewed and simulated and the results related to losses and efficiency are presented. The results show that there is not much difference between the theoretical relationship and measurement in simulation.

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