A practical project approach for teaching experimental power electronics

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Abstract- **This paper presents a design project, dc to dc converter, for a solar model car to provide hands-on engineering experience and real life educational design project. This paper focuses on the design, modelling, analysis and simulation of a dc/dc converter for a solar model car. A buck converter is designed and built to convert the output from a solar panel to a voltage level suitable for the electric motors that drive the model car. The effectiveness of the developed model is verified through simulation and corroborated using experimental results.**

Index Terms- **Renewable, Solar Model Car, Buck Converter, Simulink, Power electronics.**

I. INTRODUCTION

The topic of energy and especially renewable forms of energy is gaining attention around the world due to global warming. In the near future there will be much greater importance placed on using renewable forms of energy such as wind and solar energies. The energy from these sources will most likely be transported as electrical energy and power electronics will play a significant part in providing efficient electrical energy conversion. Therefore, it is important to introduce electrical engineering students to the concepts of power electronics and renewable energy at an earlier stage in their studies.

A buck converter performs voltage step-down function. It has been widely used in DC traction, automobile and computer power supplies. Buck converters have high conversion efficiency (usually >85%) and are particularly suitable for high output current application because they have LC filters to smoothen the current ripple. To have a regulated output voltage in the presence of varying working and circuit conditions, the output voltage has to be monitored and the duty cycle needs to be controlled to stabilize the output voltage.

At Derby University, for the Power Electronics and Applications module, a solar model car project is introduced for the first time. This project was inspired from the solar car project used at the University of Canterbury, New Zealand [1]. The solar panel and motor are purposely mismatched so that if the panel and motor are directly connected then the motor would not turn. This shows that a converter is necessary for the solar car to operate. Therefore, a buck converter is required to convert a solar panel's output to a voltage level suitable for the electric motors that drive the model car.

II. DESIGN CONSIDERATIONS

The decline in power engineering student numbers is not unique to UK but has also occurred in North America, Europe and Australia. Changes need to be made to the electrical engineering curriculum to stimulate more student interest in the hard engineering subjects with the ultimate goal of increasing the number of students selecting optional electrical power engineering courses. The Bachelor of Engineering degree structure at the University of Derby was changed significantly in the late 1990’s to give students a much wider choice of specialisations in years 2 and 3. Students tend to select the subjects that they are most interested in or the ones that they perceive will get them jobs. To provide our students with practical experience academic staff have instituted a range of strategies designed to stimulate student interest in the Electrical/Electronic Engineering. One of the projects introduced was the design and build of an autonomous guided vehicle, Derbot, which has attracted lot of interest from students from all the programmes in the Electronics and Sound Division.

As part of these changes the main author has introduced to the final year students a practical power electrical design assignment that involves a model solar car race. The students are required to design, build and demonstrate a dc-dc converter that matches the output from a solar panel to DC motors. The converter must step down the output voltage from the solar panel to an appropriate output level. This is a team-based assignment in which their mark is determined from an inspection, written report and a race. Such a project is important to stimulate the student’s interest in power electronics as well as providing them with some practical power electronic design skills. Forty eight final year students are taking part in this event. They are arranged into 12 teams of 4, each team of at least two nationalities. A “problem-based learning” approach was adopted. Teams were given a task statement, and support as they tried to resolve it.

The main objective of the project is to design a switch-mode, non-isolated, dc-dc converter with an adjustable duty cycle. The main design criteria are as specified in Appendix A. The solar car project is structured as a team-based project. The students usually work in groups of four to ensure that they all experience some aspect of design, decision-making and teamwork. A team based project means that the students also gain experience in managing a project, and communicating effectively with others.

The main advantage of using DC-DC converter it is more efficient than linear regulators. However, due to switching the output ripple voltage needs to be minimized by using appropriate filters. The output voltage ripple is a challenge in that it is a compromise between the switching frequency, efficiency, cost and size.

III. PROJECT DETAILS

Each group of the students is provided with an 18W, 400mA solar panels which are commercially available from Sunshinesolar and dc motors, MFA - 918D1001 SHROUD - MOTOR GEARBOX WITH SHROUD-100:1 with a supply voltage ranges between 1.5V and 3V and aluminium chassis which are not allowed to after any mechanical characteristics. The solar panel and the DC motor have been selected so that there is an impedance mismatch. Therefore if the solar panels are directly connected to the motor the car would not turn even under extreme sunlight conditions. The only way for the car to move is if buck converter is used.

The project is in progress and it is roughly two-thirds into its completion. It has been observed during this period that having teams of more that two is a challenge in terms of keeping up to the time schedule and motivating all the members of the group. However, there are heated debates in terms of design, simulation and application which help in solving the problem more quickly or come up with an innovative solution to a problem.

The objective is to have the fastest car on race day and the vehicle must be able to start moving under its own power as soon as sunlight falls on the panel. To achieve this objective two key design tasks have to be optimised; maximum power must be collected by the solar panel and transferred to the dc-dc converter, which in turn must transfer the power to the motor as efficiently as possible [1].

Simulation is an important process in the design of the buck converter, students have used various simulation packages, such as Simulink® and LTspice. Figs. 1 and 2 show the respective models for the buck converter.

After a series of lectures and practical laboratory sessions most of the groups got the principles of the project and what is needed to achieve the goal. At this stage students have sufficient knowledge to determine the dc-dc converter duty cycle required at start-up and also for running to produce maximum speed from maximum power. All groups have gone through the process of building a simple open loop buck converter from the initial components calculations and simulation (Appendix A and [2]) and main components such as inductors, PWM control chip, TL494 and MOSFET were provided with the associated data sheets. This exercise has proven to be a very valuable first step because it gets everyone started on some practical laboratory work and for some groups gets them over the fear of committing their ideas to hardware. Fig. 3 shows a simple buck converter build by one of groups, using a breadboard and Fig. 4 shows the PWM gating signals for the control chip TL494.

Over time, the student designs evolved to become simpler and better packaged, leading them to believe that a simple buck converter with generous functionality and expandability could be developed for a reasonable cost and could serve a wide applications. At this stage, February 2011, all students have

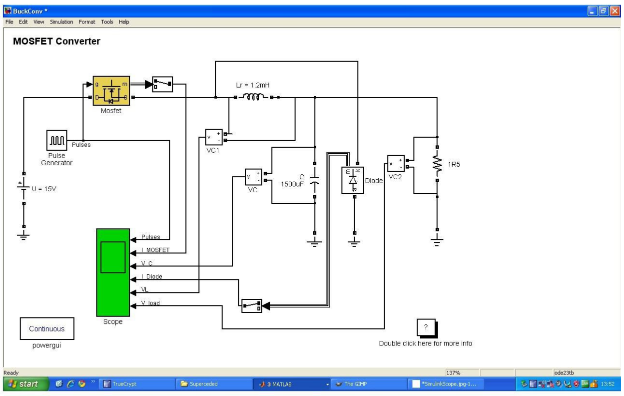

Fig. 1. Simulink model for the buck converter

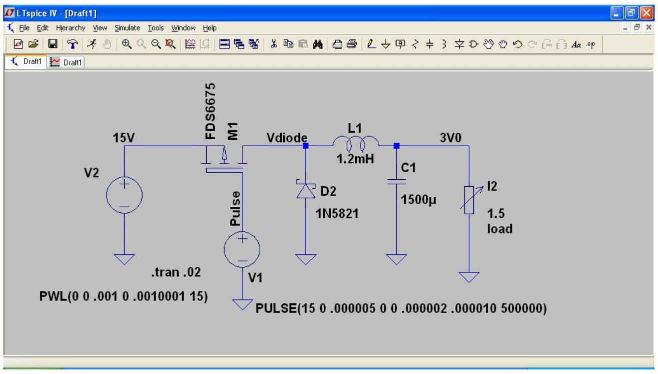

Fig. 2. LTspice model for the buck converter

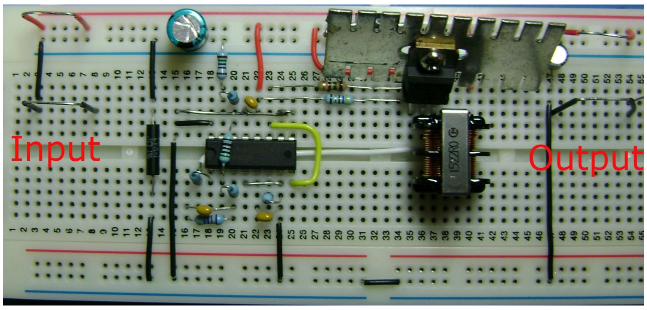

Fig. 3. Breadboard implementation of a buck converter

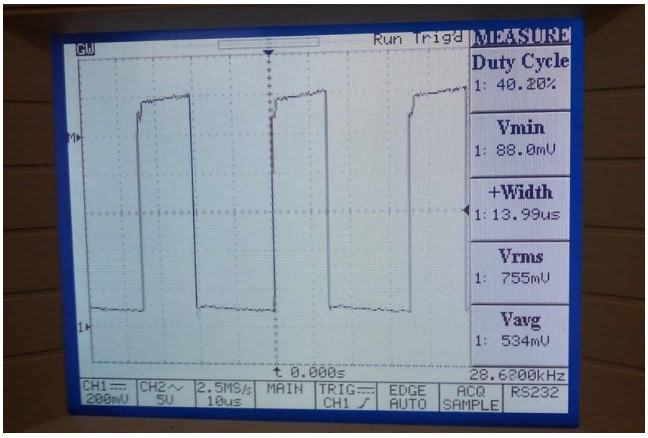

Fig. 4. The PWM control signal (Duty cycle 40%)

completed the open loop task and simulations and moving to next challenging task to design the control loop which will provides a few surprises for many students. It is not the classical feedback control loop discussed in the textbooks, where an output is measured and compared to a reference to control an output. In this case, an input is measured and compared to a reference to control an input. This subtle difference is sufficient to force the students to carefully think through the logic of their control strategy [1].

IV. RESULTS AND DISCUSSIONS

Twelve groups of 4 students each, started the project in December 2010, the progress so far is that all groups have managed to design and simulate an open loop buck converter, variable duty cycle, and interface with the solar panel. In terms of simulation, Figs. 5 and 6 show the main waveforms of the key parameter of interest such as PWM trigger signal, MOSFET current, capacitor voltage ripple, inductor voltage, and load voltage are presented for both Simulink and LTSpice. A series of experimental tests have been conducted, Fig.7 shows the PWM trigger signal for a 60% duty cycle and Fig.8 show the input/output current voltage relationship of the buck converter. This experimental and simulation results are very important for accomplishing the closed loop control systems.

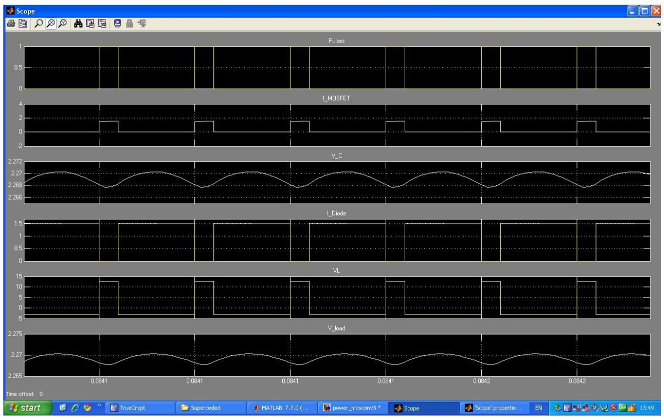

Fig. 5. Simulink Simulation Capture

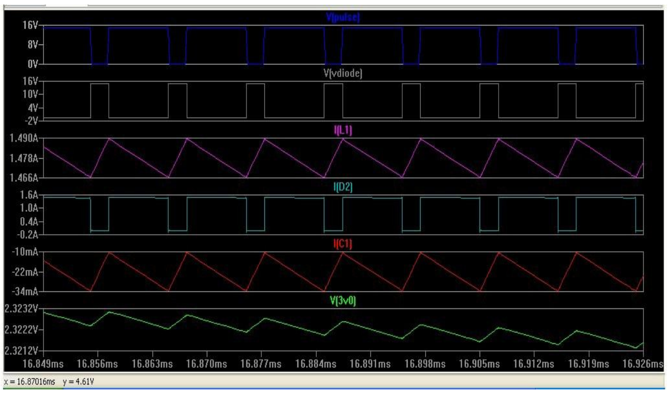

Fig. 6. LTSpice Simulation Capture

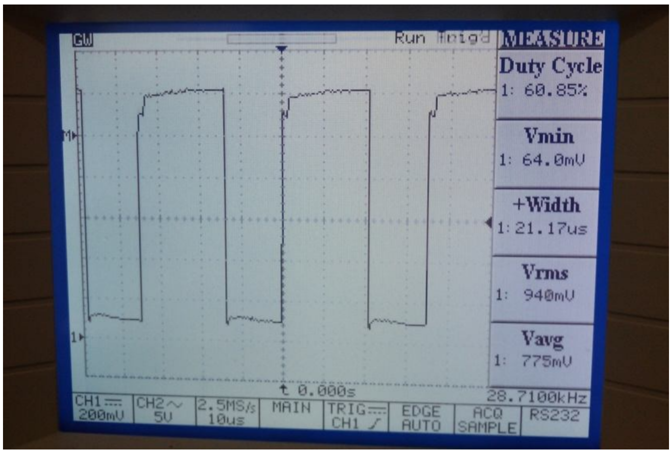

Fig. 7. The PWM control signal (duty cycle~60%)

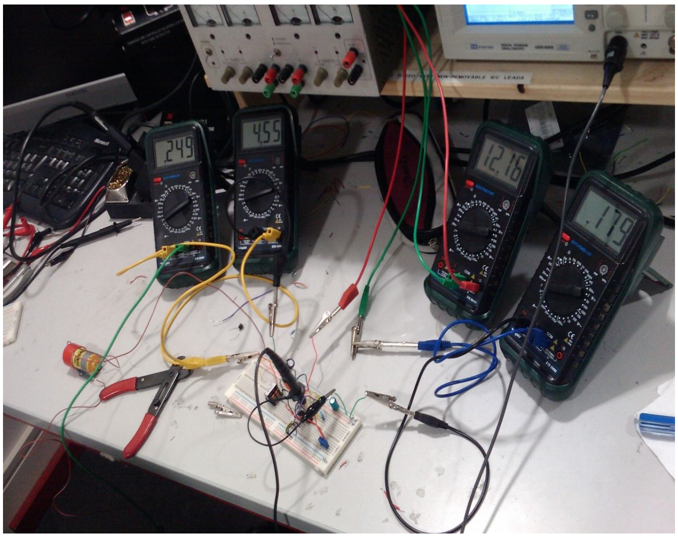

Fig.8 . Input/Output voltage/current of the DC-DC converter (D=60%)

Having completed all the preliminary testing and they are satisfied with their DC-DC converter design, students proceed to interfacing the DC-DC converter with a solar panel as shown Fig. 9 using an artificial light specially built for this application. Then the duty cycle of the converter is set up to an appropriate output voltage for the motor (1 to 3V) as shown, in Fig. 10.

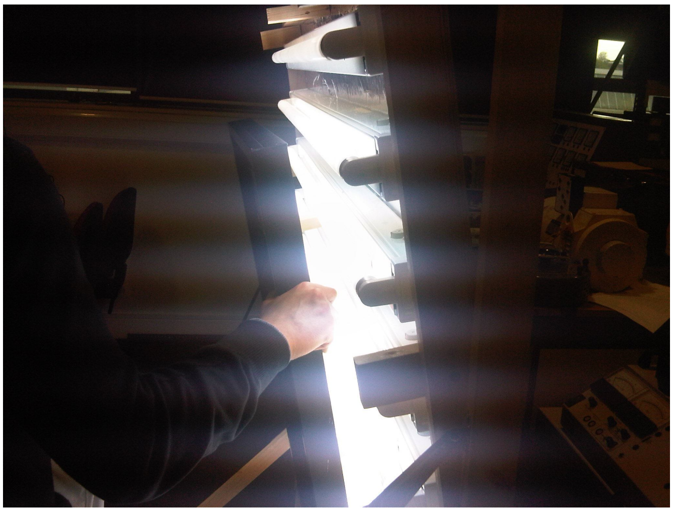

Fig.9. Arrangement of solar panel being held close to light

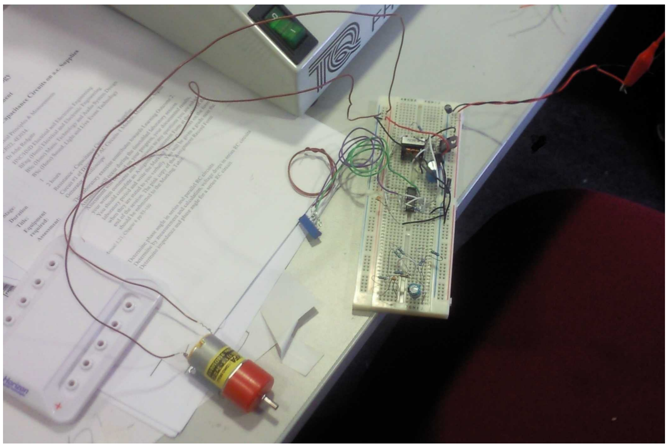

Fig. 10. Motor testing setup

Most of the students, so far, have completed this stage, interface to a solar panel, and the next stage is assemble the solar model car.

V. CONCLUSIONS

This undergraduate project work performed at the University of Derby to design, simulate and build a buck converter for a solar model has been a challenge for so many students. With the moderation process and group discussions, most of the students' feedback is positive. This paper provides a detailed analysis and design of the DC-DC converter, Appendix A. The final demonstration, race, is expected soon where the students need to demonstrate a complete closed loop controlled buck converter to drive a solar model car and hoping for sunny day. The results so far, as shown above, are very positive and students have made a good progress in both hardware and simulations. Moreover, the project is providing hands-on experience valuable for the students to better prepare them for the rapidly growing power renewable energy industry.

VI. REFERENCES

[1] Duke R.M. and Round S.D.: *Converter design for a model solar car, Proc. 10th Conf. on Power Electronics & Motion Control, CDROM T12-014 pp 1-7, 2002.*

[2] Microchip *'Buck Converter Design Example' webinar (slide and note sheet pdf) available from* *www.microchip.com*.

VII. APPENDIX A

A1.1 DESIGN CRITERIA

You will design a switch-mode, non isolated, dc-dc converter which can supply 3V at 2A nominal (6W) for powering a solar model car. The complete specifications are as follows:

- Input voltage V_d = 15V nominal, 10V min working, 20V abs max.
- Output voltage V_o = 3Vdc.
- Output current capability from 2A nominal, 3A maximum, 0.5A minimum.
- Converter Vout ripple = 100mV maximum.
- Converter output current ripple less 1%.
- Converter output voltage regulation = 0.2V (ideally 2.9-3.1V), for 0.5 - 3A load and 10-20Vdc input voltage.
- Target efficiency of > 80%.

Initially you may operate your DC-DC converter without a controller (i.e. "open loop"), but by the completion of the project you should have a control loop operating, so that you are able to meet the output voltage regulation specification above. There are a number of controller chips in the market, however, the TL494 or equivalent is recommended "generic" chip for the non-isolated design.

A1.2 PRELIMINARY CALCULATIONS

A. A1.2.1 Duty Cycle

The duty cycle is the ratio between output voltage to input voltage and given by;

$$\boldsymbol{D} = \frac{\boldsymbol{V_{out}}}{\boldsymbol{V_{in}}} = \frac{3}{15} = 0.25 \quad (A1.1)$$

B. A1.2.2 Ripple Current

From the specifications above, the ripple current is given by;

$$\Delta \boldsymbol{I} = \boldsymbol{\%ripple} * \boldsymbol{I_o} = 0.01 * 2 = 20\boldsymbol{mA} \qquad \text{(A1.2)}$$

A1.3 Component Value Calculations

With the preliminary calculation values having taken place the main component values could now be ascertained:

A1.3.1 Inductor Value

$$\frac{\Delta \mathbf{I}}{\Delta \mathbf{T}} = \frac{\mathbf{Vd - Vo}}{\mathbf{L}} \qquad \text{(A1.3)}$$

$$\boldsymbol{L} = \frac{\mathbf{(Vd - Vo)} \times \Delta \mathbf{T}}{\Delta \mathbf{I}} \qquad \text{(A1.4)}$$

$$\boldsymbol{L} = \frac{\mathbf{(12 - 3)}}{0.02} \times \frac{0.25}{10^5} = 1.2\boldsymbol{mH}$$

Where $\Delta \boldsymbol{T} = \frac{\boldsymbol{D}}{\boldsymbol{F_s}}$ and $\boldsymbol{F_s} = 100\boldsymbol{kHz}$ is the switching frequency.

Although the nominal current is 2 Amp it is best to source an inductor that is capable of the full range of expected currents, that is, 3 Amps. This value of inductor was hard to find in the current rating but finally one was sourced. A *Bourns 1140 series* 1140-122K-RC. From the data sheet specifications it is: 1.2 mH and Capable of 5.5A.

A1.3.2 Capacitor Value

Method 1 : Using the formula $\Delta V_0 = \frac{T_S V_0}{8LC}(1 - D)T_S$

Rearanging yield;

$$\boldsymbol{C} = \frac{\Delta \boldsymbol{I} \times \boldsymbol{T_s}}{8\Delta \boldsymbol{V_o}} = \frac{20 * 10^8}{0.8} = 250\boldsymbol{nF} \text{ (Minimum value)}$$

Method 2 –From Microchip notes

Using a nominal Effective Series Resistance (ESR) of 0.03Ω from the Panasonic FM series range of low ESR capacitors, which were able to withstand a 20mA ripple current the following formula is used to calculate the minimum value of the capacitor:

$$\boldsymbol{C} = \frac{\Delta \boldsymbol{I} \times \Delta \boldsymbol{T}}{\Delta \boldsymbol{V_o} - (\Delta \boldsymbol{I} * \boldsymbol{ESR})} = 402\boldsymbol{nF} \text{ (Minimum value)}$$

The capacitor would need to operate at a minimum of 3V DC , cope with 20mA ripple current and have an ESR <0.3MΩ. A suitable capacitor was chosen from the Panasonic FM series range as it had a low ESR value, this was part number EFU0J152.

From the data sheet specifications it is: 1500uF, 6.3V DC rating, 2180mA ripple current rating and an ESR value of 0.019mΩ.

A1.3.3 Diode Type

ID = (1 - D)IL
ID = (1 - 0.2)*2
ID = 1.6A

This is the value at nominal value of current draw, at 3 Amps this value would be

ID = (1 - 0.2) x 3 = 2.4A

This is the minimum current rating of diode that should be sourced. A point to bear in mind also is that the Peak Inverse Voltage (PIV) should be greater than the maximum Vd, which in this case is 20V. A Schottky diode is desirable for its low forward voltage (VF) drop and fast switching speed.

A suitable Schottky Diode is the 1N5821. From the data sheet specifications it has: PIV of 30V, Max VF of 0.5V and a forward current rating of 3A.

A1.3.4 Metal Oxide Semiconductor Field Effect Transistor (MOSFET)

A *P* channel MOSFET will be used in order to simplify the drive circuitry. It will need to cope with a maximum voltage of 20V, a maximum current of at least 3A and have a low resistance between the drain and source (RDS) when it is fully switched on. It will also need to withstand a voltage between the gate and source (VGS) of 20V. A suitable *P* channel MOSFET is the Fairchild FDS6679AZ which satisfies all these criteria and from the data sheet specifications it has :

- a maximum VDS voltage of 30V,
- a maximum current of 13A (continuous),
- an RDS of 9.3mΩ at VGS = -10V, and
- a maximum VGS of +_ 25V.

A1.4. Loss Calculations

The power loss calculations were derived by using the formulas found in the Microchip 'Buck Converter Design Example' webinar slide and note sheet.

A1.4.1 Inductor

The power dissipated due to copper losses is:

$$\boldsymbol{P_{inductor}} = \boldsymbol{ESR} * \boldsymbol{I_o^2} = 0.232 * 2^2 = 928\boldsymbol{mW}$$

From the data sheet the resistance is 0.232Ω

A1.4.2 Capacitor

The power dissipation due to the output capacitor is:

$$\boldsymbol{P_{Capacitor}} = \Delta \boldsymbol{I}^2 * \boldsymbol{ESR} = 0.02^2 0.019 = 7.6\boldsymbol{mW}$$

A1.4.3 Diode

The power dissipation due to the diode is:

$$\boldsymbol{P_{diode}} = \boldsymbol{VF} * \boldsymbol{ID} = 0.45 * 1.6 = 72\boldsymbol{mW}$$

From the data sheet 'Typical Forward Characteristics' graph, the forward voltage drop VF at 2A is approximately 0.45V.

A1.4.4 Mosfet

The drive circuit will be assumed to be ideal and that only the MOSFET characteristics will effect the turn on and turn off delay times.
The power dissipation due to the MOSFET is:

$$P_{TOTAL} = P_{CONDUCTION} + P_{SWITCHING}$$

Where

$$P_{conduction} = ID^2 * RDS(ON) * D = 1.6^2 * 9.3 * 10^{-3} * 0.2 = 4.76mW$$

$$\begin{aligned} P_{switching} &= (V_d - V_o) * \frac{ID}{2} * (T_{Rise} + T_{Fall}) + \\ &\quad C_{oss} * (V_d - V_o)^2 * F_s \\ &= (15-3) * \frac{1.6}{2} * (27+148) * 10^{-9} + \\ &\quad 665 * 10^{-12} * (15-3)^2 * 10^5 \\ &= 11.26mW \end{aligned}$$

$$P_{TOTAL} = P_{CONDUCTION} + P_{SWITCHING} = 16.02mW$$

T_{Rise} and T_{Fall} being the MOSFET switching rise and fall times, and COSS being the MOSFETs output capacitance) Using the maximum values for these specifications from MOSFET data sheet: RDS = 9.3mΩ , T_{Rise} = 27ns, T_{Fall} = 148ns
And COSS = 665pF.

A1.5 Efficiency Calculations

With the power loss calculations carried out it is now possible to calculate the efficiency of the converter.

Output Power: $P_{out} = V_o * I_o = 3 * 2 = 6W$

Total losses: $$\begin{aligned} P_{Tloss} &= P_{Inductor} + P_{Capacitor} + P_{Diode} + P_{Mosfet} \\ &= (928 + 7.6 + 72 + 16.02)10^{-3} = 1.024W \end{aligned}$$

Efficiency: $\eta = \dfrac{P_{out}}{P_{out} + P_{Tloss}} = \dfrac{6}{6 + 1.024} = 0.85 = 85\%$