Analysis of Low Temperature Effects on the Performance of SEPIC in a Fuel Cell System

M. Noh[*], S. Kim[**] and Y.-W. Park[***]

[*]Department of Mechatronics Engineering, Chungnam National University
Daehak-ro 99, Yuseong-gu, Dajeon, Korea, mnoh@cnu.ac.kr
[**]Chungnam National University, Daejeon, Korea, sunzero86@nate.com
[***]Chungnam National University, Daejeon, Korea, ywpark@cnu.ac.kr

ABSTRACT

A DC/DC converter is an electronic circuit which converters a source of direct current (DC) from one voltage level to another. Military applications require electronic equipment to withstand low temperature and impact. This paper presents an analysis on how the performance of a DC/DC converter is affected in terms of the losses due to a power MOSFET, the most dominant component in the converter. The converter is to be used in a fuel cell system for military applications. A simple temperature-dependent loss model for a MOSFET is set up and validated against the results from PSPICE simulations. In addition, this paper presents a survey on passive components that are robust in low-temperature operation required by MIL-STD-810F.

Keywords: dc/dc converter, SEPIC, Temperature effect, MOSFET, Power losses

1 INTRODUCTION

A DC/DC converter is a conversion circuit that adjusts one level of voltage to another. DC/DC converters are widely used in many applications ranging from consumer products to specialized military equipment. Most of the research on DC/DC converters focuses on maximizing the conversion efficiencty, maintaining the output stability in spite load variations, or minimizing the output ripples when the input voltage swings. However, a literature survey has found little on whether the operating temperature has any effect on the performance of converter. MIL-STD-810F stipulates that any military equipment must be operable in the temperature between -51℃ and 71℃. It is then important to estimate the effect of the temperature on the performance of a converter, when the converter is to be used in a military device.

In this paper, we presents an analysis on how the performance of a DC/DC converter is affected in terms of losses by a MOSFET, the most power-consuming component in the converter. The converter is to be used in a fuel cell system for military applications. In addition, this paper summarizes a survey on passive components that are robust in low-temperature operation required by MIL-STD-810F.

2 FUEL CELL STACK

The fuel cell stack where the DC/DC converter is to be used is a direct-methanol type with the output capacity of 24 W and 2 A. It is intended for powering up personal electronic equipment of a soldier such as communication devices, global positioning systems, or computers. Fig. 1 shows the typical output of such fuel cell stacks. It can be seen that there is a large variation in the stack voltage depending on the stack current. Therefore, a DC/DC converter is necessary to maintain a constant output voltage in spite of the changes in the load current.

Fig. 2 shows the output of fuel cell stacks according to its temperature. The fuel cell output displays a transient behaviour up to about 3 minutes, because it requires preheating to reach 45℃ (optimal stack operation

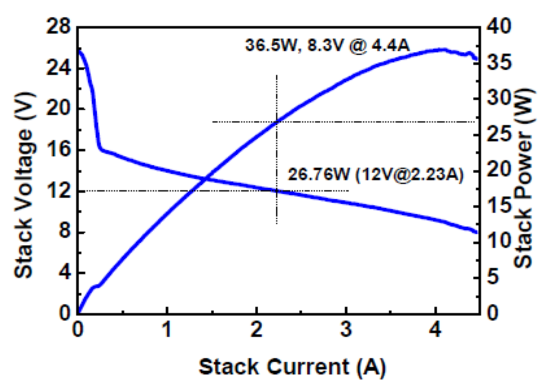

Figure 1: Output of a 24-W fuel cell stack [1]

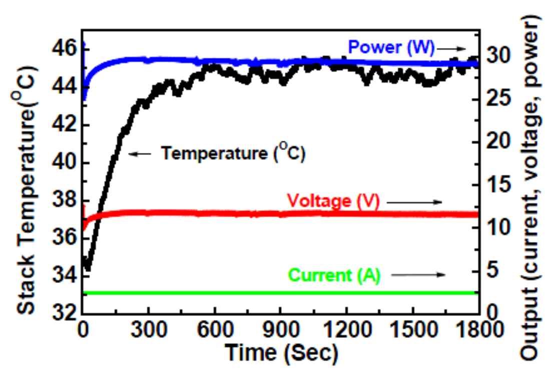

Figure 2: Output of Fuel Cell Stacks with Temperature [1]

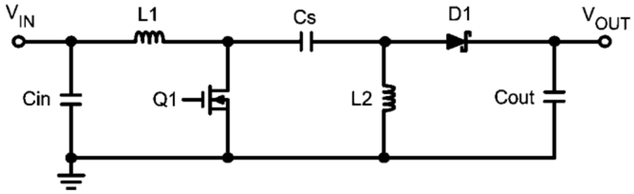

Figure 3: Topology of SEPIC

temperature). Therefore it needs to confine the output by the end of preheating. Because of the parameters of the operating condition, the stack would behave non-linearly. Thus a DC/DC converter is needed at the next stage of the stack [1].

3 SEPIC

Shown in Fig. 3 is the DC/DC converter the topology of which is the single-ended primary inductor converter (SEPIC). It is a type of DC/DC converter that utilizes inductors for storing energy to maintain a constant output with a wide range of input voltages. It is a buck-boost converter where the input voltages can be either lower or higher than the output voltage. This feature is particularly useful for a fuel cell, as the output of the fuel cell can vary drastically depending on the operating parameters. A coupling capacitor between first and second inductors allows energy transition and isolate the output from the input, thus protecting the stack from an inverse voltage. This fearture is also useful for a fuel cell.

The converter consists of capacitors, inductors, diode and switching elements such as MOSFETs. Therefore, it is important to analyze the temperature characteristics of each component to predict temperature-dependent performance of a SEPIC [2].

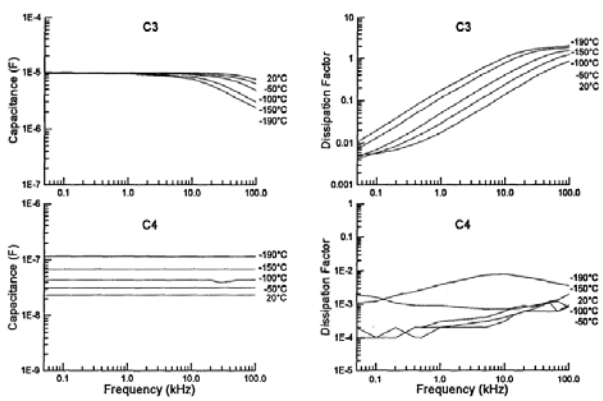

Figure 4: Capacitance and disspation factors of solid tantalum capacitors (C3) and ceramic capacitors (C4) with respect to frquency [3]

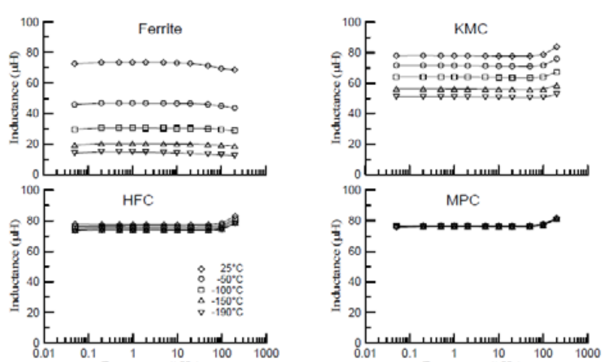

Figure 5: Inductance variations with respect to temperature and frequency [4]

4 PASSIVE COMPONENTS

1) Capacitor

The effect of frequency on the dielectric properties of the solid tantalum and ceramic capacitors is depicted in Fig. 4. The solid tantalum capacitors exhibit a decrease in their capacitance and an increase in their dissipation factor as the temperature is decreased. The ceramic capacitors exhibit an increase in their capacitance with decreasing temperature. It is clearly evident that while the capacitance of the ceramic capacitors, at any given temperature, remains very stable with frequency. However, the dissipation factor of the ceramic capacitors, exhibits a slight decrease, increase and sometimes showing a peak characteristic, which indicates strong dependency on temperature, although the changes in the actual values of the dissipation factor of the ceramic capacitors are not as signficant as they appear to be. Therefore, ceramic capacitors are usable at low temperature [3].

2) Inductor

Ferrite and three types of powder-cores such as Moly Permalloy Core (MPC), High Flux Core (HFC), and Kool Mu Core (KMC) were considered for a potential use in a low temperature setting. All cores were wound with the same wire type and gauge to give equal values of inductance at room temperature. Fig. 5 shows the variation of the inductance as a function of temperature and frequency. While the MPC and HFC exhibited insignificant change in their inductance with temperature, the other two cores; the ferrite, in particular, displayed a great variation in this property. It is found that MPC inductors changes least with respect to temperature and frequency, and thus are

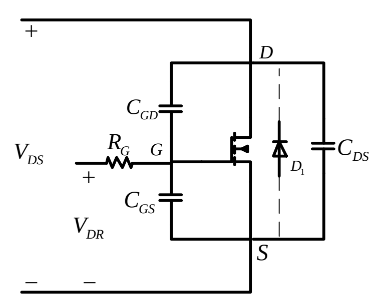

Figure 6: Conventional piecewise equivalent model of a MOSFET

most appropriate to be used at low temperature [4].

5 MOSFET

Fig. 6 shows the conventional piecewise equivalent model of a MOSFET. We can be obtain each parameter from the datasheet provided by the manufacturer. Generally speaking, we can classify losses of a MOSFET in a DC/DC converter as switching power dissipation, conduction power dissipation, driving power dissipation and output capacitor dissipation. Each loss model can be obtained in terms of the parameters available in the datasheet [5].

1) Switching power dissipation

$$P_{loss\_sw} = \frac{V_{DS} \cdot I_D}{2} \cdot \left(\frac{Q_{G(SW)} \cdot R_G}{V_{DR} - V_{GS(th)}} + \frac{Q_{G(SW)} \cdot R_G}{V_{GS(th)}} \right) \cdot f_s \quad (1)$$

If $Q_{G(SW)}$ is not provided in the datasheet, it can be approximated by $Q_{G(SW)} = Q_{GD} + Q_{GS} / 2$.

2) Conduction power dissipation

$$P_{loss\_on} = I_D^2 \cdot R_{ds\_on} \cdot d_{on} \quad (2)$$

These power losses are due to the R_{ds_on} when MOSFET is on-state.

3) Driving power dissipation

$$P_{loss\_drive} = Q_G \cdot V_{dr} \cdot f_s \quad (3)$$

These power losses are due to the gate charging of the MOSFET.

4) Output capacitor dissipation

$$P_{loss\_co} = C_{DS}(V_{ds}) V_{ds}^2 f_s \quad (4)$$

C_{DS} is junction capacitor, which are non-linear and dependent of V_{ds}. Combining (1), (2), (3), and (4). We can get overall MOSFET power loss

$$P_{loss} = I_D^2 R_{ds\_on} d_{on} + f_s \left(\frac{V_{DS} I_D}{2} \left(\frac{Q_{G(SW)} R_{G\_on}}{V_{DR} - V_{GS(th)}} + \frac{Q_{G(SW)} R_{G\_off}}{V_{GS(th)}} \right) + Q_G V_{DR} + C_{DS}(V_{DS}) V_{DS}^2 \right) \quad (5)$$

Based on (5), temperature-related parameters require establishing thermal model. Generally R_{ds_on} and $V_{GS(th)}$ are temperature dependent and approximate models are as follows.

5) $V_{GS(th)}$ (Threshold voltage)

$V_{GS(th)}$ can be approximated as

$$V_{GS(th)} = V_{GS(th)0} \cdot (1 - k_1(T - 25)) \quad (6)$$

An approximate ratio, k_1 can be made by using transfer chracteristics from the datasheet. $V_{GS(th)0}$ is $V_{GS(th)}$ at 25℃

6) R_{ds_on} (On-state resistance)

When MOSFET is turned on, MOSFET operates like a resistor, controlled by the gate voltage relative to both the source and drain voltages. The current from drain to source is modeled as:

$$I_D = u_n c_{ox} \frac{W}{L} \left[(V_{GS} - V_{GS(th)}) V_{DS} - \frac{1}{2} V_{DS} \right] \quad (7)$$

If V_{DS} is small enough

$$I_D = u_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{GS(th)}) V_{DS} \right] \quad (8)$$

Eq. (8) means that it is operated as linear resistance R_{ds_on}. R_{ds_on} can be approximated as

$$R_{ds\_on} \cong \frac{1}{u_n \cdot C_{ox} \cdot (\frac{W}{L}) \cdot (V_{DR} - V_{GS(TH)})} \quad (9)$$

u_n and $V_{GS(TH)}$ are temperature dependent. Therefore R_{ds_on} is varying when temperature is changed. Thus, the on-state resistance can be approximated

$$R_{ds\_on} = R_{ds\_on0} \cdot (1 + k_2(T - 25)) \quad (10)$$

where R_{ds_on0} is R_{ds_on} at 25℃. The approximate ratio, k_2 can be obtained from the on-resistance vs. junction temperature curve available in the datasheet.

6 SIMULATION RESULTS

The MOSFET used for testing was BSC340N08NS3 Power MOSFET (Infineon; Germany). Based on the datasheet, $V_{GS(th)0}$ =2.8V, R_G =1Ω, $Q_{G(SW)}$ =2.6nC, $C_{DS}(V_{DS})$ =200pF. Assume that I_D =12A, V_{DS} =20V, d_{on} =61%, f_S =300k Hz, V_{DR} =10V.

Then the gate threshold voltage $V_{GS(th)}$ can be approximated by (6) as

$$V_{GS(th)} = 2.8(1 - 1.59 \times 10^{-3}(T - 25)) \quad (11)$$

Fig. 7 shows the $V_{GS(th)}$ variance with temperature. Using the datasheet, the nominal on-state resistance R_{ds_on0} can be approximated by (9) as

$$R_{ds\_on0} = \frac{0.198}{V_{DR} - 2.8} \quad (12)$$

Therfore R_{ds_on} can be calculated from (10) as

$$R_{ds\_on} = \frac{0.198}{V_{DR} - 2.8} \times (1 + 0.00364(T - 25)) \quad (13)$$

To validate the thermal model of the on-state resistance, we implemented the PSPICE library model of the MOSFET provided by the manufacturer. Fig. 8 shows the comparison results of R_{ds_on} between PSPICE simulation results and results from the numerical model of (9) at different temperatures. As shown Fig. 8, the numerical model matches fairly well with PSPICE simulation model well.

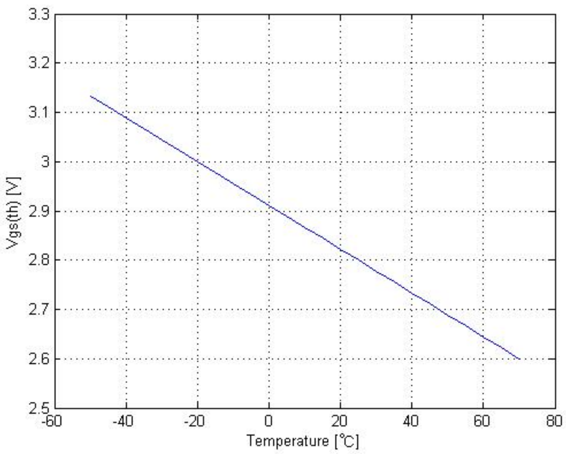

Figure 7: Vgs(th) variance with temperature

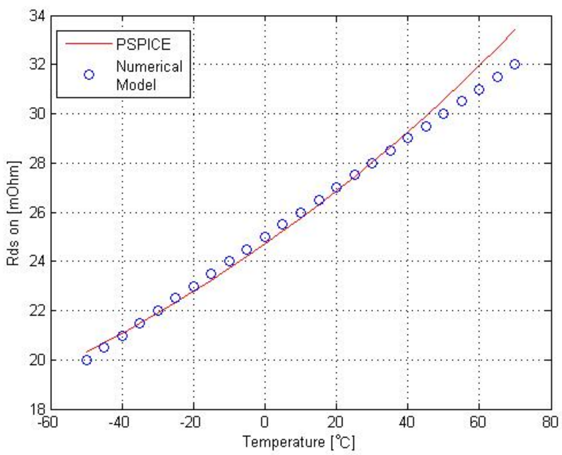

Figure 8: Rds_O variance with temperature

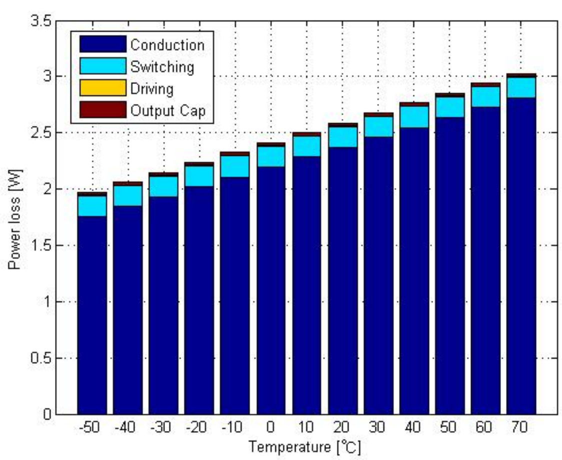

Figure 9: Power loss with temperature change

Fig. 9 shows the power losses of the MOSFET based on (5). Most of losses are due to the conduction power dissipation. Therefore the conduction losses are the most dominant factor in the power losses of the MOSFET, and thus, the temperature-dependent model of R_{ds_on} can be quite useful for predicting the effect of temperature on the overall losses of the converter.

7 CONCLUSION

In this paper, we presented an analysis of temperature-dependent model for the on-state resistance of a power MOSFET which take up the most of the overal power losses of a DC/DC converter. This thermal model must be validated experimentally in the future.

REFERENCES

[1] Su-Hwan Baek, Seongyop Lim, Young-Chul Park, Doo-Hwan Jung, Sang-Kyung Kim, Mignon Park, Dong-Hyun Peck, "Performance and Operating Characteristics of a 20W Class DMFC Stack", 44th Power Sources Conference, Las Vegas, Nevada, June, 2010, pp. 223-226

[2] M. Noh, O. Oh, S. Kim and Y.-W. Park, "A Controller Design for SEPIC in a Fuel Cell System," CleanTech2013, Washington DC, May 2013

[3] Patterson R.; MacDonald, T.; Hammoud, A.; Gerber, S., "Performance of surface-mount ceramic and solid tantalum capacitors for cryogenic applications," NASA Center for Aerospace Information (CASI) NASA/TM-1998-208489; NAS 1.15:208489; E-11268; Electrical Insulation and Dielectric Phenomena, Atlanta, GA, United states, 25-28 Oct. 1998 , 19980801; Aug. 1998

[4] Elbuluk, M., Hammoud, A., Patterson, R., "Power electronic components, circuits and systems for deep space missions". Proc. IEEE Power Electronics Specialists Conf. – PESC, 2005, pp. 1156–1162

[5] Xiaoyan Yu, Paul Yeaman, "Temperature-related MOSFET Power LOSS Modeling and Optimization for DC-DC Converter", Applied Power Electronics Conference and Exposition(APEC), 2013 Twenty-Eighth Annual IEEE, 2013, pp. 2788-2792.