IOP Conference Series: Earth and Environmental Science

Air-cooled Design of 4 kW DC Bus Converter on Airplane

To cite this article: Kaichang Xue and Zongxin Luo 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **252** 032086

Air-cooled Design of 4 kW DC Bus Converter on Airplane

Kaichang Xue [1, 2, a] **and Zongxin Luo** [1, 2, b]

[1] The 0616-research institution of Guizhou Aerospace Linquan Motor Co., Ltd., Guizhou 550081, China
[2] National Engineering Research Center for Small and Special Precision Motors, Guizhou 550081, China

[a] xuekc@nercsspm.cn., [b] luozx@nercsspm.cn.

Abstract. To meet the application requirements of 4 kW DC 270 to DC 28 V converter on airplane, an air-cooled design method is proposed. According to converter's circuit structure, the losses of main components and the air-cooled design structure are determined. The thermal resistance model of the air-cooled is built, and the process of the air-cooled design is illustrated. Then the air pressure and air volume of fan are determined. The results demonstrate that the temperature rise of the heat sink is less than 35°C when the output is 4 kW and the converter can work reliably when ambient temperature is 70°C.

Keywords: converter; aircraft DC bus; air-cooled; high temperature experiment.

Nomenclature

A_i-- Area of baseplate outside, m^2
A_o--Total surface area of fins, m^2
A_v--Cross-sectional area of a fin, m^2
c_a--Specific heat capacity of air, J/(kg·°C)
c_1--Stripe coefficient
f_{app}--Apparent friction factor
h--Heat transfer coefficient, W/(m^2·°C)
H--Height of fin, m
k_a--Thermal conductivity of air,W/(m·°C)
k_f--Thermal conductivity of heat sink, W/(m·°C)
L--Heat sink length, m
L_f--Air circulation length in heat sink, m
L_s--Heat source length, m
n_f-- Fin number of heat sink
Nu--Nusselt number, hs/k_a
p--Static pressure of fan, Pa
p_m--Rate value of the static pressure of fan, Pa

$\triangle P_a$--Total pressure drop, Pa
$\triangle P_l$--Total pressure drop of inlet and outlet, Pa
$\triangle P_c$--Core pressure drop, Pa
P-- Power, W
Q--Volumetric flow rate, m^3/min
Q_m--Rate value of the volumetric flow rate of fan, m^3/min
R_{ba}--Thermal resistance of the baseplate outer surface to the air, °C/W
R_{bf}--*T*hermal resistance of the baseplate, °C/W
R_{cb}--Thermal resistance of heat source to the baseplate outer surface, °C/W
R_{fa}--Thermal resistance of fins to the air, °C/W
Re--Reynolds number, $V_a s/v$
s--Fin spacing, m
t_a --Fin thickness in root, m
t_b--Baseplate thickness, m
T--Temperature, °C
T_a--Air temperature, °C
T_b--The outer surface temperature of baseplate, °C
T_f--The inner surface temperature of baseplate, °C
T_i--The temperature of the heat source, °C
$\triangle T_a$--The temperature rise of air, °C
$\triangle T_s$--The temperature rise of heat sink, °C
V_a--Average velocity in fin channel, m/s
V_{a1}--Inlet and outlet velocity of heat sink, m/s
V_{amax}-- Maximum velocity in fin channel, m/s
W--Heat sink width, m
W_s--Heat source width, m

Greek Symbols

ρ_a--Air density, kg/m^3
η_f--Fin efficiency
ε--Contraction ratio
v--Kinematic viscosity, m^2/s

1. Introduction

Compared with constant-voltage constant-frequency AC power supply and constant-voltage variable-frequency AC power supply, 270V high-voltage DC power supply has higher efficiency, and its power generation and distribution equipments are smaller for high power aircraft power supply.[1] 270V high-voltage DC power supply has been one of the main development trends. Meanwhile, on-board equipment still has a certain requirement for 28V low-voltage DC power. Therefore, DC 270V to DC 28V converter is a crucial equipment.

In this paper, the application background of the air-cooled design is a DC 270V to DC 28V converter, which works in 100kHz and has 4kW output power. An air-cooled heat dissipation structure adopting centrifugal fan and heat sink with striped fins is proposed. The calculation process of fan air volume and air pressure is presented. Finally, the air-cooled design is verified by experimental results.

2. Losses of Converter

The simplified circuit of DC 270 V to DC 28V converter is shown in Fig 1. Capacitance C_i is used to smooth input voltage V_i. Transistors V_1 to V_4 compose the full-bridge, which is used to convert 270V input DC V_i into 100 kHz high-frequency AC v_1. Transformer T is used to realize the initial adjustment

IOP Conf. Series: Earth and Environmental Science **252** (2019) 032086 doi:10.1088/1755-1315/252/3/032086

of input and output voltage, the isolation of input and output, and the output of high-frequency AC v_2. Diodes D_1, D_2 and inductances L_1, L_2 compose the high-frequency rectifier, which converts high-frequency AC v_2 into output DC V_o. Capacitor C_b is used to suppress the DC magnetic bias of transformer. An auxiliary circuit consisting of inductance L_r and diodes D_{a1}, D_{a2} is used to suppress the peak of reverse voltage on rectifier diodes D_1, D_2. This converter adopts phase-shift full-bridge control. Capacitors C_1-C_4 in parallel with transistors V_1-V_4 respectively are used to realize soft switching of transistors. Inductance L_r is also beneficial to make lagging bridge arms consisting of V_3 and V_4 achieve soft turn-off easier. The control circuit detects the output voltage V_o, and adjusts the phase shift angle of the primary bridge to keep output voltage V_o in desired value. The main components of the converter are shown in Table 1. The main component losses of the converter are shown in Table 2.

The conduction loss of each transistor in V_1-V_4 is 25W, and the switching loss is 20W. The windings ratio of transformer T is 6:2. The transformer adopts two PEE64 magnetic cores. The iron loss and copper loss of transformer T are 7W and 12W respectively. Inductance L_r adopts a PEI58 magnetic core, and the number of turns is 2. The iron loss and copper loss are 2.1 W and 1.4 W respectively. Any one of the inductances L_1, L_2 adopts a PEE64 core. The number of turns is 2.The iron loss and copper loss are 1W and 8W respectively.

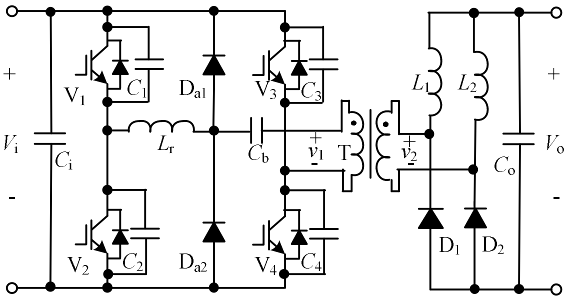

Fig.1 Simplified circuit of the DC 270 V - DC 28V converter

Table 1 Main components of converter

V_1~V_4	C_i	C_1~C_4	C_b	T
APT40GP60JDQ2	22 μF	7.5 nF	33μF	6:2
D_1, D_2	L_1, L_2	L_r	C_o	D_{a1}+D_{a2}
4×(DSS2×101-02A)	4.5 μH	2.3 μH	6000 μF	DSEI2×30-06C

The upper limit working temperature of power semiconductor devices V_1-V_4 and D_1, D_2 is 150°C. In order to guarantee its reliability, the temperature of heat sink's baseplate should be usually less than 110°C. Magnetic elements T, L_r, L_1 and L_2 are composed of ferrite material, and its Curie temperature is 240°C. The upper limit working temperature of Magnetic elements' windings is 180°C. So it is reasonable that the magnetic components work below 150°C. Due to that the upper limit ambient temperature of the converter is 65°C to 70°C, the temperature rise of heat sink's baseplate should be less than 35°C, and the temperature rise of magnetic components should be less than 70°C.

Table 2 Main components loss of converter

V_1~V_4	T	D_1+D_2	L_r	L_1+L_2
180 W	19 W	100 W	3.5 W	18 W

3. Air-cooled structure and analysis model

According to the loss distribution shown in Table 2, the structure of air-cooled heat dissipation is shown in Fig2. Fig2(a) shows the distribution of the main components on the surface of the heat sink. The

IOP Conf. Series: Earth and Environmental Science **252** (2019) 032086 doi:10.1088/1755-1315/252/3/032086

dotted line envelope represents the centrifugal fan embedded in the heat sink fins, and the direction of air flow is shown as the arrows. The side view shown in Fig 2(b) is viewed from cross section A_1. The arrow in Fig 2(b) indicates the air flow direction between the heat sink fins. The air enters the gap between heat sink baseplate and fans in the lower left-side, flows through the fan, and then flows out through the gaps of fins in the upside. The air flow length L_f is approximately equal to the width of heat sink. The fins at the bottom are truncated to place the fan. The effective heat dissipation area of the lower fins is smaller than that of the upper fins. Therefore, the power semiconductor devices with high loss are mainly arranged in the upper region.

Fig.2 shows that the primary full-bridge consisting of transistors V_1-V_4 has the maximum loss and is located in edge of the heat sink. This region is the most severe region of heat dissipation. Therefore, this area is the focus of heat dissipation design in the following analysis.

The thermal resistance model is shown in Fig.3. L_s and W_s represent the equivalent heat source length and width of the primary full-bridge respectively, and L and W represent the length and width of the equivalent heat sink respectively. The height and root thickness of the fins are H and t_a respectively. The space between the fins is s. A_i and A_o are the outside area of the heat sink baseplate and the total surface area of the fins respectively, and the thickness of the baseplate is t_b. In Fig3(b), T_i, T_b, T_f and T_a represent the temperature of the heat source, the outer surface of the baseplate, the inner surface of the baseplate and the air respectively. R_{cb}, R_{bf}, R_{fa} and R_{ba} represent the thermal resistance of heat-source to outer surface of baseplate, baseplate, fins to air and outer surface of baseplate to air respectively [2].

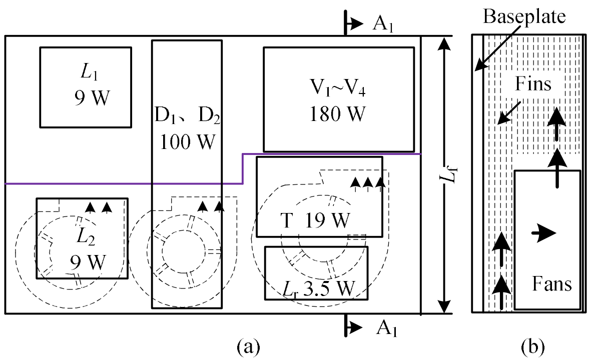

Fig.2 Structure of air-cooled, (a) front view, (b) side view

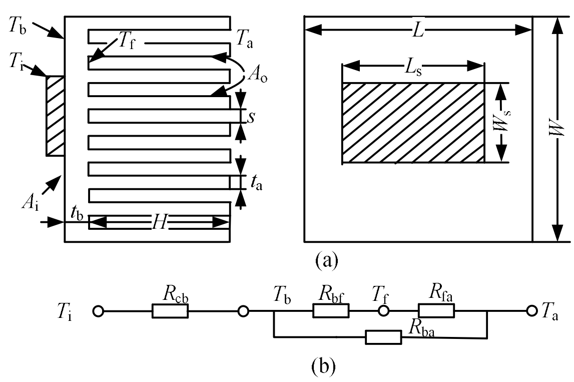

Fig.3 Thermal resistance model, (a) equivalent structure of heat sink, (b) equivalent thermal resistance

The thermal resistance R_{cb} is diffusion thermal resistance. Due to that the calculation of R_{cb} is complicated. 10 °C to 15 °C of temperature loss is allowed to assess the effect of R_{cb}, when heat dissipation power of the devices in unit area is distributed as evenly as possible. The thermal resistance

R_{ba} value of the outer surface of the baseplate to air is large and has little influence on the overall heat dissipation analysis. R_{ba} can be ignored. In engineering applications, the thermal resistance R_{bf} of baseplate and the thermal resistance R_{fa} of fins to air should be mainly considered. The expressions are shown in Eq. (1) and Eq.(2) respectively.

$$R_{\mathrm{bf}} = t_{\mathrm{b}} \big/ \left(k_{\mathrm{f}} A_{\mathrm{i}} \right) \tag{1}$$

where, k_f is the heat conductivity of the heat sink.

$$R_{\mathrm{fa}} = 1 \big/ \left(h A_{\mathrm{o}} \eta_{\mathrm{f}} \right) \tag{2}$$

where, h is the heat transfer coefficient of heat sink to air, η_f is the heat sink efficiency.

4. Design process

The design process of air-cooled heat dissipation of the primary full-bridge region includes the following steps. [3,4]

Step 1) Losses should be calculated. According to Table 2 and considering the corresponding margin, 240W is chosen as the dissipation power of the full-bridge transistors for the heat dissipation design.

Step 2) A heat sink should be selected first. Nu should be calculated with an air velocity, and then the heat transfer coefficient h should be obtained. The heat sink parameters are shown as following. Average fins thickness t_a=2.5mm, fin spacing s=4.8mm, baseplate thickness t_b=7mm, fins height H=40mm, the heat sink's equivalent width W=140 mm, thermal conductivity k_f=160W/(m·°C), the heat sink's equivalent length L=140mm, the heat sink's equivalent total surface area A_o=1.53m^2, and fin number n_f=19. The heat sink fins has stripes along the direction of air flow to increase the surface area of heat dissipation. The ratio of the surface area of fins with stripes and the surface area of smooth fins is defined as the stripe coefficient c_1, and the calculation of c_1 is shown as Eq. (3). The calculation result is that c_1=2.06.

$$c_1 = A_{\mathrm{o}} \big/ \left(2 n_{\mathrm{f}} L H \right) \tag{3}$$

Assuming V_a=5m/s, where V_a is average velocity in fin channel. The Reynolds number is shown as Eq.(4).

$$Re = V_{\mathrm{a}} s \big/ \nu \tag{4}$$

where, ν is kinematic viscosity. The value of ν is 17×10^{-6} m^2/s when ν is calculated by air kinematic viscosity in 40°C. The calculation result is that Re=1412.

Eq.(4) show that $Re < 2200$. So air flow for air-cooled heat dissipation can be treated as laminar flow[5]. The Nusselt number is shown as Eq.(5).

$$Nu = \left[23.4 \left(x^{+} \right)^{-3} + \left(x^{+} \right)^{-1.28} \right]^{-1/3} \tag{5}$$

where, $x^+=Re\cdot s/L$=48.4.The calculation result is Nu=5.18.

When air temperature is 40°C, the air thermal conductivity is about 2.75×10^{-2} W/(m·°C). So heat transfer coefficient is shown as Eq.(6).

$$h = Nu k_{\mathrm{a}} \big/ s \tag{6}$$

The calculation result is that h=29.7W/(m^2·°C).

Step 3) Fin efficiency should be calculated. When h is known, the fin efficiency η_f can be got from Fig.4[4]. The heat sink adopt rectangular fin. The horizontal coordinate in Fig.4 is shown as Eq.(7).

$$\sqrt{c_1 h/(k_f A_V)}H^{3/2} \tag{7}$$

where, A_v is longitudinal cross-sectional area of fins, and $A_v=t_a H$. The calculation result is 0.49. According to Fig.4, the fins efficiency η_f=0.86.

Step 4) Thermal resistance should be calculated. According to the thermal resistance model, baseplate thermal resistance R_{bf} and convection thermal resistance R_{fa} betweem fins and air are mainly focused. They are shown as Eq.(8) and Eq.(9) respectively. The calculation result are that $R_{bf}=2.2\times10^{-3}$°C/W and $R_{fa}=91\times10^{-3}$°C/W.

$$R_{bf} = t_b/(k_f A_i) = t_b/(k_f WL) \tag{8}$$

$$R_{fa} = 1/(hA_o \eta_f) \tag{9}$$

Step 5) Pressure drop of the heat sink should be calculated [6,7]. The heat sink's compactness factor $\varepsilon=s/(s+t_a)$ =0.67, $K_c=0.8-0.4\varepsilon^2$ =0.62, $K_e=(1-\varepsilon)^2-0.4\varepsilon$=-0.12. The pressure drop of inlet and outlet is $\triangle p_1$, Which is shown as Eq. (10). Core pressure drop is $\triangle p_c$, Which is shown as Eq. (11).

$$\Delta p_1 = (K_c + K_e)\rho_a V_{a\max}^2/2 = 0.5\rho_a V_{a\max}^2/2 \tag{10}$$

where, ρ_a is air density and its value is 1.13 kg/m^3 at 40°C. V_{amax} represents maximum velocity in fin channel. It is approximately equal twice of V_a for laminar flow.

$$\begin{aligned}\Delta p_c &= \left[4f_{app}\cdot 2Re/(4x^*)\right]\left(\rho_a V_{a\max}^2/2\right)\\ &= 1.46\rho_a V_{a\max}^2/2\end{aligned} \tag{11}$$

where, $x^*=Re\cdot s/L_f$, L_f is air circulation length in heat sink and approximately equal to the width of the converter. L_f= 235 mm.

$$\begin{aligned}2f_{app}Re &= 23.7366 + 0.219847\times(4x^*) - 6.43526\\ &\times10^{-3}\times(4x^*)^{1.5} + 7.39124\times10^{-5}\times(4x^*)^2\\ &-3.81290\times10^{-9}\times(4x^*)^3\end{aligned} \tag{12}$$

where, f_{app} is apparent friction factor.

Total pressure drop is shown as Eq. (13). The calculation result is that $\triangle p$=117Pa.

$$\Delta p_a = \Delta p_1 + \Delta p_c \tag{13}$$

According to the principle of flow conservation, the velocity at the outlet of the heat sink is shown as Eq. (14). The calculation result is that V_{a1}=3.63m/s.

IOP Conf. Series: Earth and Environmental Science **252** (2019) 032086 doi:10.1088/1755-1315/252/3/032086

$$V_{a1} = V_a \varepsilon \tag{14}$$

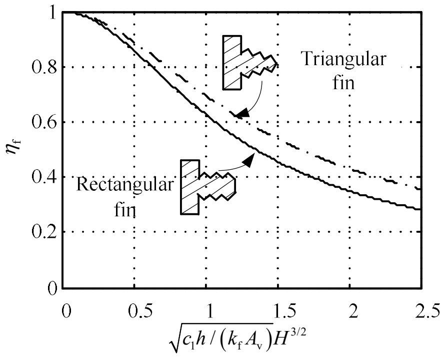

Fig.4 Efficiency curves of striped fins

Step 6) Volumetric flow rate and air temperature rise should be calculated. Volumetric flow rate Q is shown as Eq.(15).The calculation result is that Q=1.22m^2/min.

$$Q = 60 V_{a1} \times WH \tag{15}$$

The temperature rise of inlet and out let air is shown as Eq.(16). The calculation result is that $\triangle T_a$=9.8°C.

$$\Delta T_a = 60P / (\rho_a c_a Q) \tag{16}$$

Where, c_a is the specific heat capacity of air and its value is 1000 J/(kg·°C).

Step 7) The results at different wind velocity should be calculated by Step1) to Step 6). Table 3 shows all the parameter values of V_a with 0.5 m/s as step. In Table 3, the temperature rise of heat sink is calculated by Eq. (17).

$$\Delta T_s = P \times (R_{bf} + R_{fa}) \tag{17}$$

where, P is power, and P=240 W.

According to Table 3, when the wind velocity V_a=5m/s, the temperature rise of the heat sink is 22.3°C, and the thermal resistance of heat sink can meet the requirement of heat dissipation. At this time, the corresponding volumetric flow rate Q is1.22m^3/min, and static pressure $\triangle p$ is 117 Pa. Finally, a fan BFB1224GH of 24V/1.6A is selected for the primary full-bridge heat dissipation. The parameters of BFB1224GH are that rated volumetric flow rate Q_m is 1.71m^3/min, rated static pressure p_m is 1019Pa, and rated power is 38.4W. When the static pressure $\triangle p$= 196Pa, the air volume Q=1.4m^3/min, which can be obtained by viewing the fan character curve. It can meet the requirement of heat dissipation.

Table 3 Parameter values in different air velocity

	V_a m/s						
	3	3.5	4	4.5	5	5.5	6
x^+	29.0	33.9	38.7	43.6	48.4	53.2	58.1
Nu	4.11	4.41	4.69	4.95	5.18	5.41	5.62
h W/(m·°C)	23.6	25.3	26.9	28.3	29.7	31.0	32.2
η_f	0.89	0.88	0.87	0.87	0.86	0.86	0.85
$R_{fa}\times10^3$ °C/W	111	104	99	94	91	87	85
$\triangle p_a$ Pa	55	69	84	100	117	136	156
Q m^3/min	0.73	0.85	0.98	1.10	1.22	1.34	1.46
$\triangle T_s$ °C	27.2	25.6	24.3	23.2	22.3	21.5	20.8
$\triangle T_a$ °C	16.4	14.1	12.3	10.9	9.8	8.9	8.2

5. Experimental results

The converter is constructed according to the circuit shown in Fig.1 and the structure shown in Fig.2. The models of large fan and two small fans are BFB1224GH and BFB1024H respectively. When the output is 4kW and room temperature is 21°C, the main components temperature is shown as in Table 4. The baseplate temperature in Table 1 is the baseplate temperature of the primary full-bridge region. Temperature data is obtained by Fluck Ti30 thermal imager.

Table 4 Main components temperature in room temperature

Points	T °C	Points	T °C
T's core	81	T's windings	72
L_r's core	57	L_r's windings	58
L_1's core	57	L_1's windings	73
baseplate	46		

Experiments at different ambient temperatures are carried out in the temperature test chamber. The baseplate temperature of primary full-bridge is shown in Table 5. Where, the temperature is measured by the LM35 temperature sensor.

The Experimental results in Table 4 and Table 5 show that the baseplate temperature rise $\triangle T_s$ of the heat sink is less than 35°C. The temperature rise of magnetic components is less than 70°C. The converter can work reliably at 70°C ambient high temperature.

Table 5 Baseplate temperature in different ambient temperature

	Ambient temperature °C			
	14	55	65	73
T_s °C	39	82	94	104
$\triangle T_s$ °C	25	27	29	31

6. Summary

(1) According to the circuit structure of converter, the loss of main components was given, and an air-cooled heat dissipation structure was proposed. The centrifugal fan was embedded into the heat sink, and the fins of heat sink with stripes were adopted to expand the surface area of air-cooled heat dissipation.

(2) The primary full-bridge, the worst heat dissipation region, was selected as an example, the heat resistance model of air-cooled heat dissipation was constructed, the design process of air-cooled heat sink was illustrated, and then the pressure and volume of the fan were determined.

(3) The experimental results verified that the baseplate temperature rise of the heat sink was less than 35°C. The temperature rise of magnetic components was less than 70°C. The converter can work reliably at 70°C ambient high temperature. The power semiconductor devices and magnetic components have favorable thermal reliability.

Acknowledgments
This work was financially supported by Pre-research Project of Military Equipment for the 13th Five-year Plan, China (No.31512040130); Pre-research Project of Air Force Equipment for the 13th Five-year Plan, China (No.303040304).

References
[1] Yan Yangguang, Qin Haihong, Gong Chunying, et al. More Electric Aircraft and Power Electronic [J]. Journal of Nanjing University of Aeronautics & Astronautics, 2014, 46(1): 11-18.
[2] Z. P. Duan, Y. S. Muzychka. Experimental investigation of heat transfer in impingement air cooled plate fin heat sinks [J]. Journal of Electronic Packaging, 2006, 128(4): 412-418.
[3] Xue Kaichang. Research on Reliability Key Technologies of Geoelectric Field Grounded Source Transmitter [D]. Changchun: Jilin University, 2015.
[4] K. C. Xue, S. Wang, J. Lin, et al. Loss analysis and air-cooled design for a cascaded electrical source transmitter [J]. Journal of Power Electronics, 2015, 15(2): 530-543.
[5] Dai Guosheng. Heat transfer [M]. 2nd ed., Beijing: High Education Press, 2011.
[6] S. Y. Kim, R. L. Webb. Analysis of convective thermal resistance in ducted fan-heat sinks [J]. IEEE Transactions on Components and Packing Technologies, 2006, 29(3): 439-448.
[7] S. W. Karng, J. H. Shin, H. S. Han, et al. Thermal performance of a thermoelectric air-cooling system with heat sinks [C]. 12th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. Las Vegas: IEEE, 2010: 1-7.