3rd International Conference on Automation, Control, Engineering and Computer Science (ACECS'16)
Proceedings of Engineering & Technology (PET)
pp. 669-674

3D Finite Element Modelling of Single-Sided Axial-Flux Permanent-Magnet Synchronous Machine

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***Abstract*— The single-sided construction of a disc-type machine is simpler than the double-sided one. The axial-flux machine has many advantageous aspects that qualify it above the radial-flux machine for many applications. Instead of using analytical approach, finite element method (FEM) can calculate accurately some of the equivalent circuit parameters and losses of the axial-flux machine. This paper presents a (3-D) finite element modeling of single-sided axial-flux permanent-magnet synchronous machine by the mean of ANSYS software which include an analytical, (2-D) and (3-D) electromagnetic design tools. This kind of software offer the possibility to compare the analytical results of pre-model with the (3-D) FEM ones.**

***Keywords*— Axial-flux machine, permanent-magnet, single-sided, finite element method, ANSYS.**

I. Introduction

The technological advances of the surface mounted axial-flux permanent-magnet synchronous machines (AFPMSM) has been stagnant for some time compared to the growing activity of the conventional radial-flux permanent-magnet synchronous machines because of the deficiency of the fabrication technology. The limitations are due to the strong axial magnetic attraction between the stator and rotor, which causes the deflection of rotor discs and fabrication difficulties such as high cost, lamination in the slotted stator, and the assembly process [1].

Nonetheless, radial-flux machines know many inherent limit as mentioned in [2] such as, much of the rotor core around the shaft is hardly utilized as a magnetic circuit. The heat from the stator winding is transferred to the stator core and then to the frame. A poor heat removal through the stator air gap, rotor and shaft without applying an adequate cooling system. These limitations and many others are deeply attached to the radial-flux machines and cannot easily be removed unless a new topology is adopted.

Despite Davenport has claimed in 1837 the first patent for the radial-flux machine, the axial-flux machine was the first invented in 1831 by Faraday as the earlier electrical machine [3]. Now, because of the discovery of new materials, improvement in manufacturing technology and innovation, the axial-flux PMSM are widely used and the research communities never cease to develop it. The AFPMSM is recognized as having better power density than the radial-flux machine and more compact [4]. In addition, it has a better ventilation and cooling arrangement.

Moreover, the AFPMSM offers a higher torque-to-weight ratio due to the application of less core material, smaller size, planar and easily adjustable air gap, lower noise, and lower vibration which rank it superior to the conventional radial-flux machines [5].

From a construction point of view, the AFPMSM can be designed as single-sided, double-sided or multi-disc structure. It can be with inner rotor or inner stator. In addition, the stator can be with or without iron-core armature. As summarized in Fig. 1.

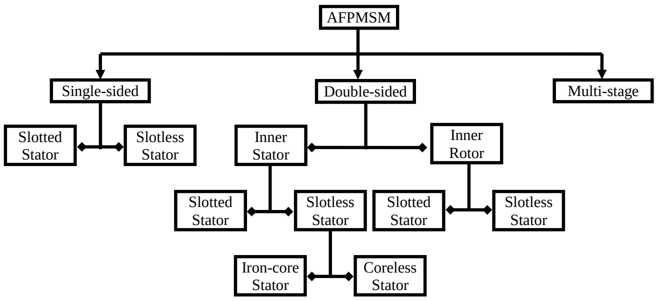

Fig. 1 Axial-flux PMSM topologies

The AFPMSM topologies have been extensively studied and analyzed. However, despite the significant development in the AFPM machine technology, a gap still exists in industrial applications and some key aspects in the analysis and design of such machines are being published in many papers [6].

Since the computer innovation are made in electrical engineering applied software, modeling electrical machines can be done using analytical [7], two-dimensional (2D) finite element method (FEM) [8] or three-dimensional (3D) FEM analysis [9-11]. In industrial application, an analytical approach or 2D FEM is generally used in computations due to their speed compared to the 3D FEM. In modeling axial-flux PMSM, the requirements related to the speed and accuracy of the computations are divergent. An axial-flux machine is an inherent 3D geometry from the point of modeling. Thus, analytical or 2D finite element analysis, are applied to the radius of the machine, has a lack of accuracy in computations. However, the 3D FEM analysis has larger time consuming. To improve this situation, ANSYS is a Multiphysics FEM software that offers a suitable application for electrical machine designers. ANSYS has created a comprehensive simulation platform as shown in Fig. 2 and it gather electromechanical system solution.

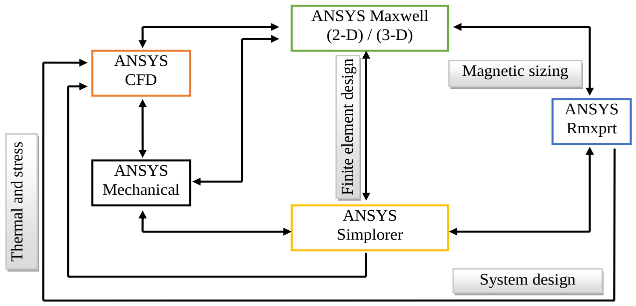

Fig. 2 ANSYS simulation platform

In this paper, the single-sided AFPMSM is designed and simulated using FEM software ANSYS. The first part represents the seizing equation and the different electrical and geometrical data of the machine. In addition, the adopted winding arrangement was described and the analytical prototype of the machine using RMxprt was presented. The second part describes the different steps of the FE modelling phase. Finally, the FE model was simulated and the magnetic fields were analysed and the transient curves were presented and compared to the analytical ones.

II. Electromagnetic Design of the Single-Sided AFPMSM

Axial-flux permanent-magnet synchronous machines are disc-type machines; they are an alternative to the cylindrical radial-flux machine due to its pancake shape, compact construction and high power density. AFPMSM are composed from: stator core, winding coils, permanent magnets, rotor core and shaft mechanism. A 3D representation of the machine is shown by Fig. 3.

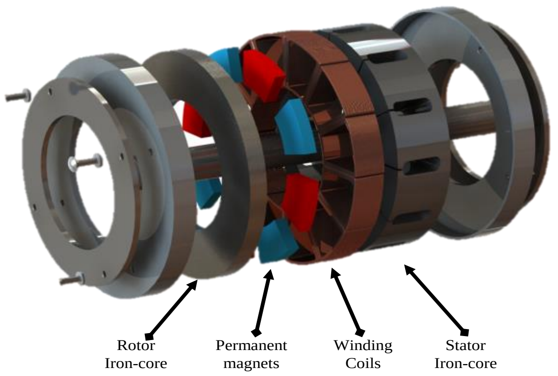

Fig. 3 3D exploded view of the single-sided AFPMSM

A. Machine design and operating parameters

The seizing equation represents an essential step in the designing of the AFPMSM by defining suitable dimensions of the stator, the rotor and the permanent magnet volume. In fact, there is various constraints to determine the geometry of the components such as the rated/max speed, the rated/max torque, the phase current, the line-to-line voltage, etc. By neglecting the leakage and resistance inductance of the stator, the output power is determined by Eq. (1).

$$P_{out} = \eta \frac{m}{T}\int_0^T e(t)i(t)dt = \eta m K_p E_{pk} I_{pk} \qquad (1)$$

Where η is the machine efficiency, m is the number of phases, T is the period of one EMF cycle, e(t) is the air-gap EMF, i(t) is the phase current, K_p is the electrical power factor, E_{pk} and I_{pk} are respectively the peak of phase air-gap EMF and current. For a general purpose sizing equation for the AFPMSM can be expressed by Eq.(2).

$$P_{out} = \frac{1}{1+K_\phi}\frac{m}{m_1}\frac{\pi}{2}K_e K_i K_p K_L \eta B_g A \frac{f}{p}(1-\lambda^2)(\frac{1+\lambda}{2})D_0^2 L_e \qquad (2)$$

Where K_φ is the electrical loading ratio, m_1 is the number of phases for each stator, K_i is the current factor, K_L is the aspect ratio coefficient, λ is the diameter ratio and Le is the axial length. The AFPMSM power density for total volume is defined by Eq.(3).

$$P_{Den} = \frac{P_{out}}{D_{tot}^2 L_{tot}\frac{\pi}{4}} \qquad (3)$$

Where D_{tot} and L_{tot} are respectively the total outer diameter and the total length of the machine.

In Tab.1 the different design parameters of the axial machine such as the stator and rotor dimensions, the winding architecture and the PM volume are presented.

TABLE I
Axial-Flux Machine Design Parameters

	Parameters	Values
Stator	Length (mm)	30
	Din (mm)	70
	Dout (mm)	120
	Steel type	D23_50
	Stacking factor	0.95
Rotor	Length (mm)	10
	Din (mm)	70
	Dout (mm)	120
	Steel type	D23_50
	Stacking factor	0.95
Winding	Winding layer	2
	Parallel branches	1
	Conductors per slots	380
	Coil pitch	1
	Number of strands	2
	Wire warp (mm)	0
	Wire size (mm)	0.269
PM	Length (mm)	25
	Thickness (mm)	8
	Embrace	0.7
	Magnet type	XG96/40

The single-sided axial-flux machine can operate at rated speed 1500 rpm for a rated power of 550 W. The different electrical parameters are listed in Tab.2.

TABLE II
AXIAL-FLUX MACHINE ELECTRICAL DATA

Parameters	Values
N° Poles	8
N° Slots	18
N° Phases	3
Phase connection	Y3
Air-gap	1 mm
Rated power	550 W
Rated speed	1500 rpm
Rated voltage	220 V
Frequency	100 Hz
Temperature	75°C

B. Winding arrangement

The winding used for the slotted single-sided AFPMSM is called non-overlap winding. This type of windings use a concentrated coils with coil pitch equal to 1 as presented in Fig. 4.

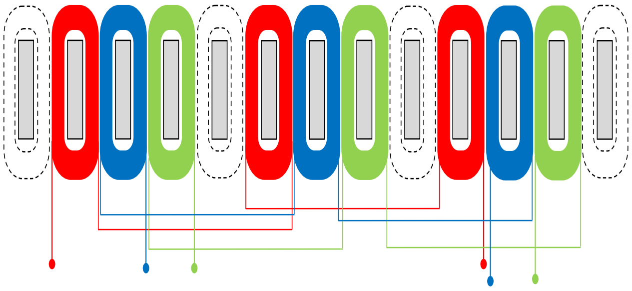

Fig. 4 AFPMSM winding configuration

We use a double layer non overlap winding which means that two coils are sharing one slot. With two coil layers per slot, all teeth are wound. For the studied AFPMSM design there a number of slots equals to Z = 18, and the number of pole pairs is 2p = 8 and the number of phases is m = 3, so the number of slots per pole and per phase is

$$q = \frac{Z}{2mp} \tag{4}$$

Which in this case of design q = 3/4.

The ratio between the number of phases and the number of slots is given by:

$$r = \frac{Z}{m} \tag{5}$$

Therefore, each one of the phases can use 6 stator slots, and 3 concentrated coils.

C. RMxprt rapid prototyping

RMxprt is an analytical design tool included in ANSYS dedicated for electric machines. It can calculate machine performance, make material and size decisions, it offers optimization process for rotation electric machines. Therefore, many curves can be extracted such as the output torque Fig.5, air-gap flux density Fig.6, the winding voltage and current under load Fig.7 and Fig.8.

The analytical results help in the design process with a basic model without errors when moving to the FEM.

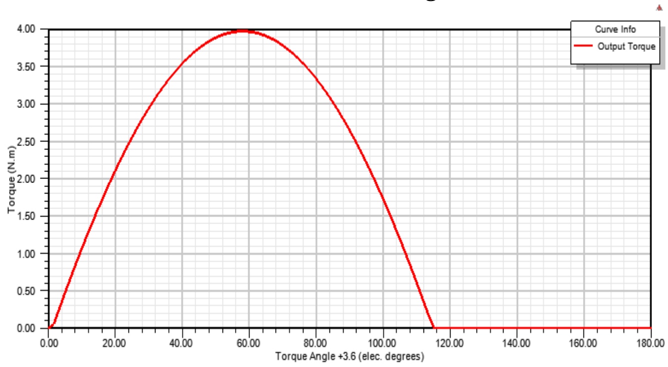

Fig. 5 Analytical computation of the torque for the studied machine

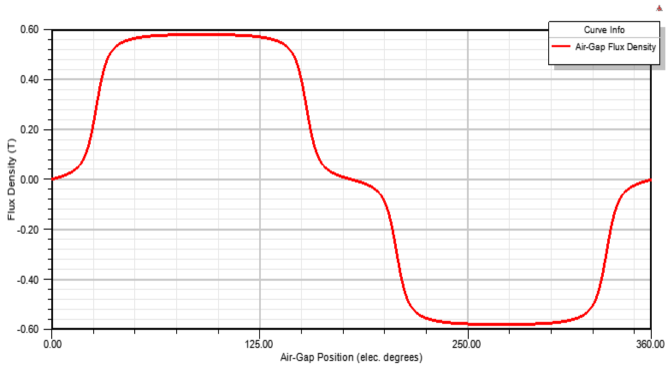

Fig. 6 Air-gap flux density of the studied machine

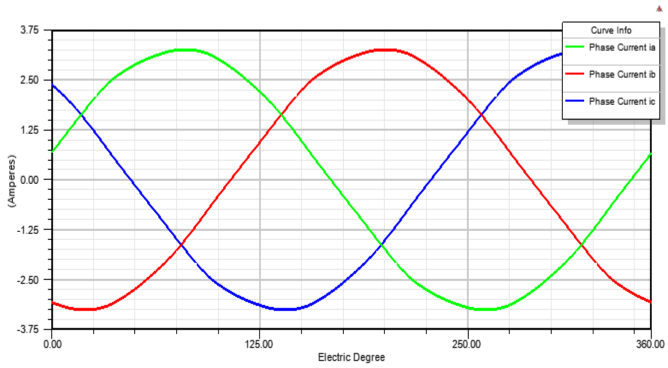

Fig. 7 Winding current under load

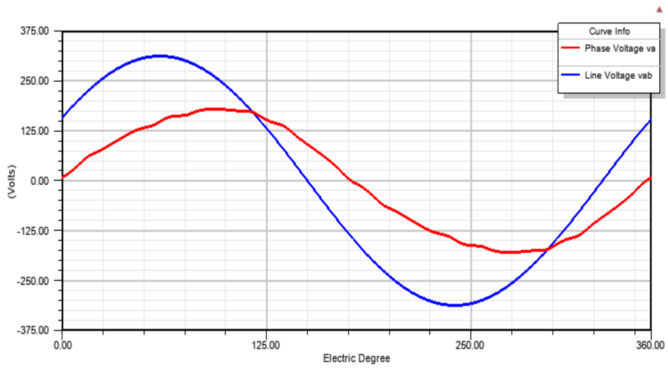

Fig. 8 Winding voltage under load

III. 3D FINITE ELEMENT MODELLING

The single sided AFPMSM is modelled in 3D environment for .two main reasons; the first is due to its disc-type shape unlike the conventional radial flux machine with cylindrical axis form. The second reason is the accuracy that offer the 3D FE analysis compared to the 2D method or the analytical one. Nonetheless, using this method no electromagnetic elements are neglected.

A. Geometry design

The first step in the FE analysis process is drawing the 3D form the single sided AFPMSM base on the dimensions data described previously. The different parts are shown in Fig.9.

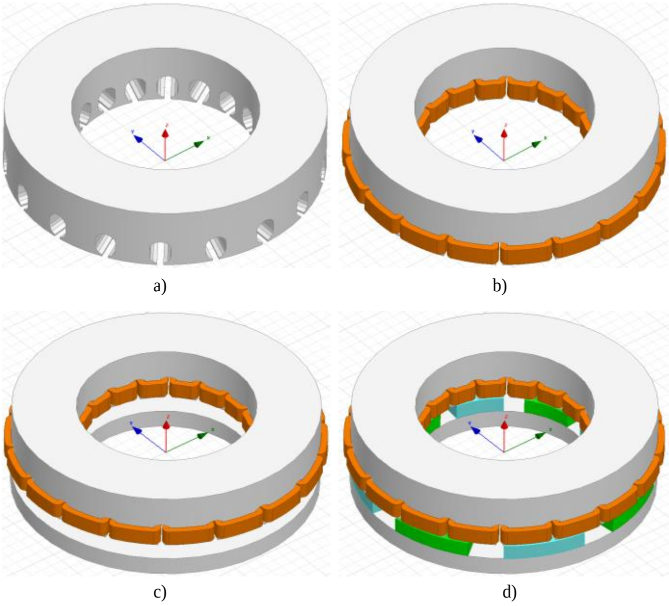

Fig. 9 AFPMSM geometrical part; a) stator core b) coils c) rotor core d) PM

B. Material assigning

The different materiel type used for the machine must be assigned from the ANSYS library. The iron core for the stator and rotor are the same named D23_50 with a mass density of 7820 kg/m^3, this electrical steel has a stacking factor of 0.95. The permanent magnet used are NdFeB type with code name XG96/40 with 1.59155 its relative permeability and a magnitude equals to -350000 A/m. The coils material type is copper with bulk conductivity of 58000000 Siemens/m.

C. Boundaries and symmetry

The AFPMSM is a multi-pole rotating machine, and for time consumption reason, the electromagnetic analysis can be reduced to an even number of poles by employing periodic boundary conditions. The model in our study is divided to half to accelerate the simulation time, but the results curves and values will consider the complete model of the machine.

D. Meshing

In order to apply the excitation and move to the post processing phase, the described model must be discretised by employing a meshing strategy. The mesh density must obey to the accuracy versus time of simulation needs. The different parts of the machines are meshed separately with different resolution shown in Fig. 10.

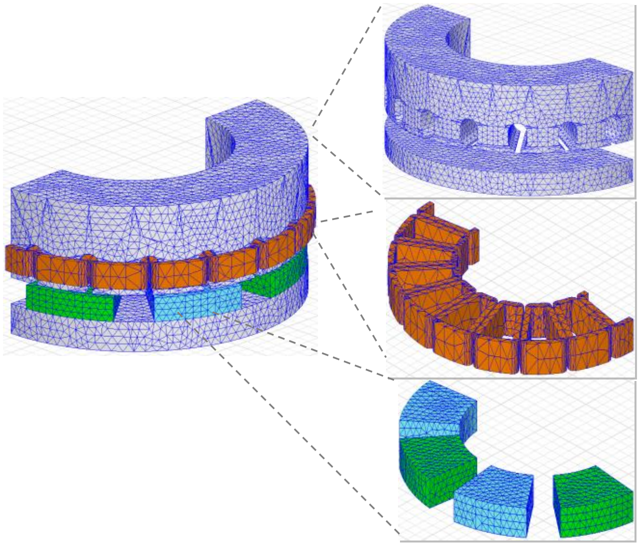

Fig. 10 Meshing operations

IV. SIMULATION RESULTS

The post processing step consist of analysing the magnetic field plots and the transient plots of the studied machine generated by the solver.

Fig.11 shows the saturation of the magnetic flux density in the surface mounted PM area at the rated speed.

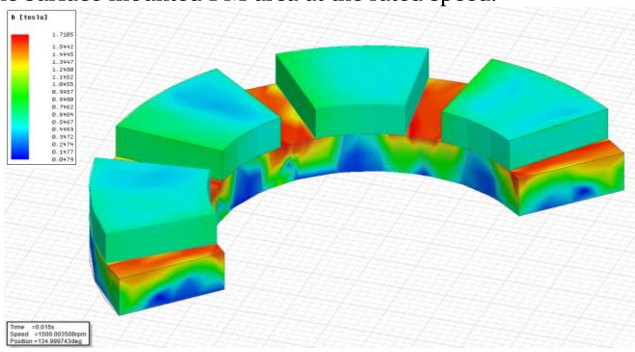

Fig. 11 Magnitude of the B field for the AFPMSM

The current flow density vector J is presented in Fig.12 showing the excited coils through the non overlap winding.

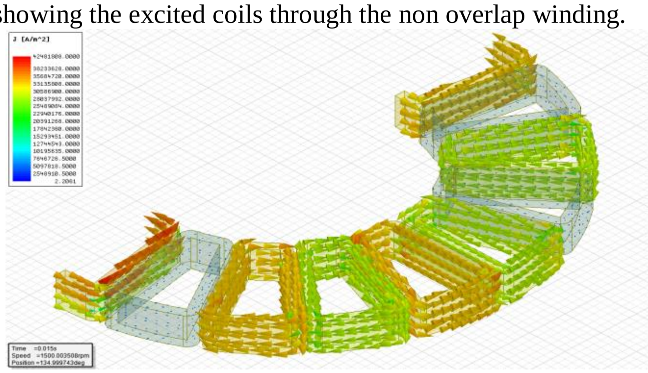

Fig. 12 Current density vector J for the AFPMSM

The magnetic field H is present in Fig.13. The major magnetic saturation is applied on the surface of the permanent magnets.

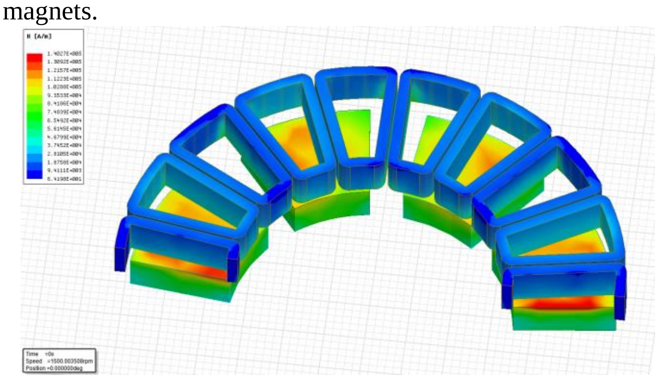

Fig. 13 Magnitude of the H field for the AFPMSM

The transient plots generated by the solver represent the three phases stator current Fig.14 and the induced EMF Fig.15 under load, and the moving torque Fig.16.

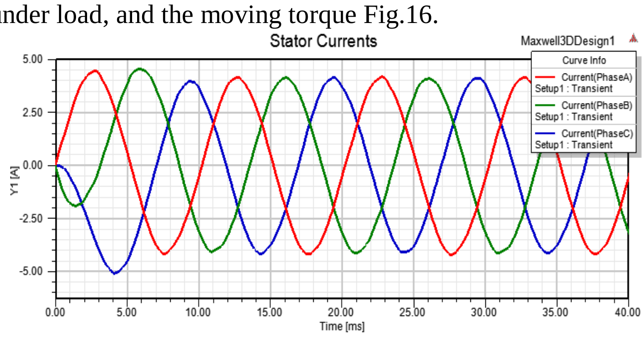

Fig. 14 Stator current of the three phases

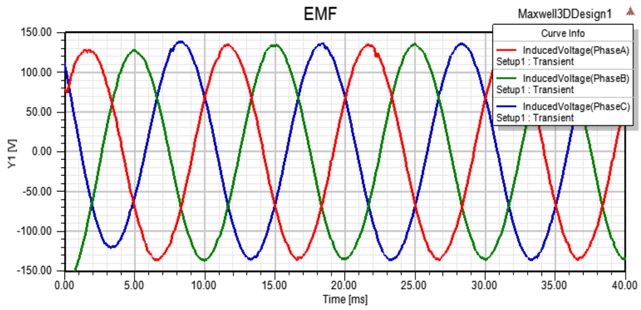

Fig. 15 Induced EMF voltage of the three phases

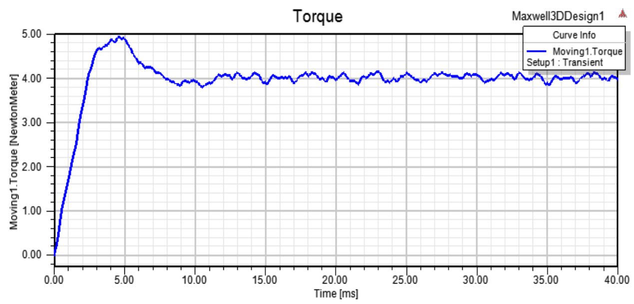

Fig. 16 Moving torque of the AFPMSM

The transient results obtained from the finite element method are more accurate than the analytical ones. The magnetic fields show the saturation zones and the nominal ones which allow the possibility for further optimization regarding the working domain of the machine

V. Conclusion

In this paper, finite element designing and simulation for the single-sided axial-flux permanent magnet synchronous machine are performed in ANSYS platform. A rapid prototyping of the machine was generated using RMxprt tool. Then the different 3D geometrical parts of the machine was established and the different materials for the iron core and the coils and the magnets were assigned. Afterwards the boundaries and symmetry conditions were applied to reduce the simulation time. The discretization of the model was made by employing an adaptive meshing operation and finally the model of the AFPMSM was simulated and both magnetic and transient plots were generated.

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