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ELECTROMECHANICAL SYSTEM WITH STORAGE OF WIND ENERGY IN HYDRAULIC ENERGY, IN THE DANUBE BOTTLENECK („CLISURA DUNĂRII")

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Abstract: The present study analyses the operation mode, in the maximum power point – MPP, of wind turbine – WT, that operate at various wind speeds, located in the "Clisura Dunarii". The operation mode of the energy pumping storage system is analysed; in the hydraulic accumulation from "Portile de Fier I " hydroelectric power plant in time, at the point of maximum power. A maximum power point – MPP of energy storage is reached, with the flow of electricity in two directions, namely: in the network, or in the hydropower accumulation "Portile de Fier I", depending on the load curve in the national energy system and the potential eolian. In this way there is no problem of power fluctuations that occur at wind speeds variable in time, fluctuations that disrupt the operation of the national power system (SEN), especially at wind speeds significantly variable over time, as in the case of Romania. The system consists in a wind turbine, coupled with a synchronous generator with permanent magnets, (GSMP), which delivers electrical power to an asynchronous motor, (MA), and coupled with a water pump, (PA). In the present paper, the behavior of the system is determined considering the mechanical angular speed/speed, n_{ref} (ω_{ref}), as a reference quantity in a driving system. Thus, an optimal management of the system is achieved, so as to extract the maximum wind energy, at wind speeds variable in time. The driving structure is based on measuring the momentary wind speed.

Keywords: Wind electromechanical system, asynchronous motor, water pump, maximum captured energy, time–varying wind speeds, mechanical inertia, mathematical models, reference speed estimation, storage of wind energy by pumping, hydropower storage "Portile de Fier"

1. INTRODUCTION

This paper analyses the hydro storage of wind energy, optimal storage in terms of energy and without pollution problems.

It analyses the operation in the point of maximum power, MPP, of the wind turbine, TV, at wind speeds variable in time.

At wind speeds that vary significantly over time, the power values captured by the TV are variable over time and this can create instabilities in the power system.

The elimination of these important disadvantages arising from the use of wind energy can be done by storing wind energy in hydro accumulations.

Due to time–varying wind speeds in high–power wind power systems with high moments of inertia, the speed of the wind turbine (TV) and the permanent magnet synchronous generator (GSMP) cannot be changed in a timely manner, so ensure a turbine operation at maximum power points.

In the control system it is expected to obtain a maximum wind energy at wind speeds that vary significantly over time. For this, the wind speed is measured and the value of the mechanical speed / angular speed is calculated for which the captured energy is maximum.

This has been called the reference value and is denoted by n_{ref} (ω_{ref}). The reference mechanical speed / angular speed ω_{ref}, of reference, has a special importance because it allows the optimal conduction of the system, so that the maximum mechanical energy is extracted, at wind speeds variable in time.

Configuration of the wind system, with storage in the reservoir from the hydropower plant Iron Gates I, is given in figure 1, with the following components:

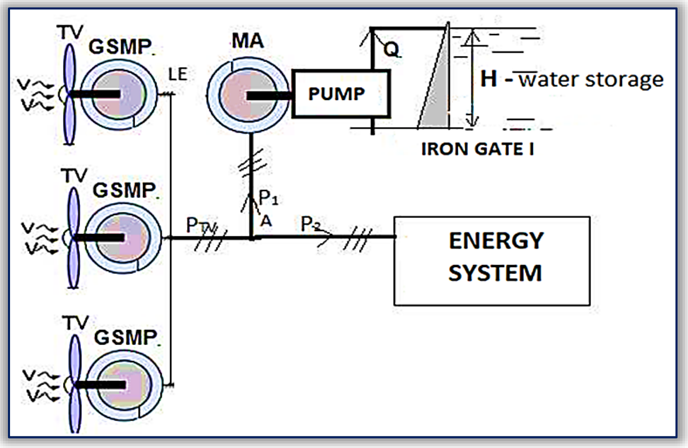

Figure 1. Configuration of the wind system with storage in the lake accumulation from the hydropower plant Iron Gates I

- TV–wind turbines,
- GSMP–synchronous generators with permanent magnets,
- LE–three–phase power line,
- MA–asynchronous motor, or –MSMP–synchronous motor with permanent magnets,

- PUMP – water pump,
- reservoir lake – “Portile de Fier I”;
- Q–water debit;
- H–height of the dam “Portile de Fier I”;

In most works, [5,11–14], the functioning of TV in MPP is analysed, but, at constant wind speeds over time, and without an economically efficient storage of the captured wind energy, regardless of the variation of the wind speed over time.

In areas where time variations in wind speed are significant, capturing maximum wind energy is a complex problem, TV operation at maximum power is possible, with efficient adjustment and a storage system, of captured wind energy, efficiently from an economic point of view, [5–8].

The major problem that arises in capturing a maximum wind energy is the adaptation of the TV speed to the wind speed, [1–4], knowing the dependence of the optimal mechanical angular speed, of the TV, ω_{OPTIM}, on the wind speed, V, meaning the function, ω_{OPTIM} (V).

In detail, this problem must be periodically analysed on TVs in operation, with specific methods, which, however, are often approximate, or are secreted by the companies that own the TV parks.

The high mechanical inertia, characterized by the high value of the total moment of inertia, J and the variable wind speed over time, pose difficult problems for the currently used control system, which it must ensure an operation in the optimal area from the energy point of view, [1–4].

With a high–performance storage system, treated in this paper, the TV operates at the maximum power point, MPP, because it is no longer necessary to cap the power, by National Energy Dispatcher, [12–14].

The value of the power from the TV shaft, $P_{TV}(\omega,V)$, depends on the value of the wind speed, V and on the value of VUM ,ω, in the form, (1), [11–14]:

$$P_{TV}(\omega,V) = a(V/\omega - b)e^{-c(V/\omega)}V^3 \quad (1)$$

where: the values of parameters a, b and c are determined by different methods.

The $P_{TV}(\omega,V)$, function is also the mathematical model of TV, MM–TV and is used in the analysis various operating modes.

- Remark 1

Knowing, as accurately as possible, the function of $P_{TV}(\omega,V)$, is essential in obtaining some valid results. It is possible that the construction company will give this function, however its applicability is limited because the values of parameters a, b and c have been determined in different conditions from those in operation and, for this reason, it is correct that the values of these the parameters to be determined from the experimental data, from the TV locations in operation. From TV power characteristic, for wind speed V, at the maximum value of the PTV function, se get optimal VUM, OPTIM. Knowing the characteristics of TV power, for different values of wind speed, you can get the optimal VUM dependence, OPTIMUM, wind speed, function ω_{OPTIM} (V). Knowledge of this function is essential in achieving a management system high performance, with ω_{OPTIM} reference size.

Knowing the $P_{TV}(\omega,V)$, and ω_{OPTIM} (V) functions can ensure an operation in the area optimal, from an energy point of view.

By simulation, based on mathematical models, the functioning of the system is analysed wind, at wind speeds varying significantly over time.

2. MATHEMATICAL MODELS FOR WIND TURBINE, ELECTRIC GENERATOR AND ASYNCHRONOUS MOTOR

To analyze the operation of the GSMP+ MA+ PA+ TV system, at wind speeds variables over time, the following original mathematical models are used:

— Mathematical model of TV and deduction of mechanical angular speed reference ω_{ref}.

Using the results from [2] for the mechanical characteristic of the TV, a model is used mathematical form (2):

$$M_{TV} = (-9.5541 \cdot 10^{-2} \cdot V^{0.6} \cdot \omega + 2.25\, V^{1.8}) \frac{20}{314} \quad (2)$$

based on the experimental mechanical characteristics, obtained in the stable area and given in figure 2, for 3 wind speeds: V = 9, 12, 15 [m/s], we have ecuations (3, 4, 5)

$$M_{TV} = (-9.5541 \cdot 10^{-2} \cdot 15^{0.6} \cdot \omega + 2.25 \cdot 15^{1.8}) \frac{20}{314} \quad (3)$$

$$M_{TV} = (-9.5541 \cdot 10^{-2} \cdot 12^{0.6} \cdot \omega + 2.25 \cdot 12^{1.8}) \frac{20}{314} \quad (4)$$

$$M_{TV} = (-9.5541 \cdot 10^{-2} \cdot 9^{0.6} \cdot \omega + 2.25 \cdot 9^{1.8}) \frac{20}{314} \quad (5)$$

The value of the mechanical angular speed / speed for which the captured energy is maximum was called the reference value and is noted with n_{ref} (ω_{ref}).

The deduction of ref can be done by maximizing the mechanical energy Wm over a period of time T.

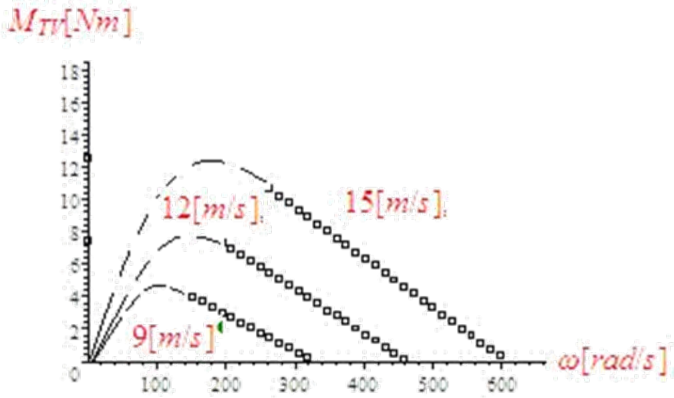

Figure 2. Experimental mechanical characteristics

where: V – wind speed; ω – mechanical angular velocity at GSMP.

— Mathematical model of the permanent magnet synchronous generator (GSMP)

GSMP is characterized, in the orthogonal model, by the equations (6)[5]:

$$\begin{cases} -U\sqrt{3}\,\sin\theta = R_1 I_d - \omega L_q I_q \\ U\sqrt{3}\cos\theta = R_1 I_q + \omega L_d I_d + \omega\,\Psi_{MP} \\ M_{motor} = p_1\left(L_d - L_q\right) I_d I_q + I_q \Psi_{MP} \end{cases} \tag{6}$$

where: R_1– stator winding resistance; L_d – inductance of stator winding in the axis d; L_q – own inductance of the rotor winding in the q axis; p_1 – number of pairs of poles, MP – permanent magnet flux

— Mathematical model of the asynchronous motor (MA)

In MA the equations of the orthogonal model are of the form (7):

$$\begin{cases} U_d = R_1 I_d - \omega_1 L_1 I_q - \omega_1 M I_{qr} \\ Uq = R_1 I_q + \omega_1 L_1 I_q + \omega_1 M I_{dr} \\ 0 = -M(\omega_1 - \Omega) I_q + R_2 I_{dr} - L_2(\omega_1 - \omega) I_{qr} \\ 0 = M(\omega_1 - \Omega) I_d + L_2(\omega_1 - \omega) I_{dr} + R_2 I_{qr} \\ M_{MA} = p_1 M\left(I_q I_{dr} - I_d I_{qr}\right) \end{cases} \tag{7}$$

where: R_1 – stator winding resistance; R_2 – rotor winding resistance; L_1 – own inductance of stator winding in axis d and q; L_2 – own inductance of rotor winding in axis d and q; M – mutual inductance between stator winding and rotor winding, p_1 – number of pole pairs.

— Equations of the GSMP MA PA system

The mechanical power received by the GSMP from the TV, PT, is transformed into electrical power P_G and transmitted to MA.

▪ Case study at V = 15 [m/s]

By measuring the average wind speed: V_{MEDIE} = 15 [m/s], the speed/speed is determined mechanical reference angle ω_{ref}, by maximizing the mechanical energy W_m, on a time period T:

$$\omega_{ref} = 11.775\,\frac{\int_0^T (V)^{1.8}\,dt}{\int_0^T (V)^{0.6}\,dt} = 11.775\,\frac{(15)^{1.8}}{(15)^{0.6}} = 303.58[\frac{rad}{s}] \tag{8}$$

and thus all other important functional quantities of system: currents, voltages, powers. At this value for ω_{ref}, the torque at GSMP is (9):

$$M_G = M_{TV-MEDIU} = (-9.5541\cdot 10^{-2}\cdot(15)^{0.6}\cdot 303.58 + 2.25\cdot(15)^{1.8})\frac{20}{314} = 9.3803[Nm] \tag{9}$$

The connection equations between GSMP and MA are (10):

$$I_d^2 + I_q^2 = I_1^2 + I_2^2 \text{ – the equality of stator values} \tag{10.1}$$

$$U_d^2 + U_q^2 = U_1^2 + U_2^2 \text{ – the equality of stator voltages} \tag{10.2}$$

The connection equation between MA and PA is given by (11):

$$M_A \cdot \Omega = \rho \cdot g \cdot Q \cdot H = 9800 \cdot Q \cdot 11 = P_{MA} \text{ at a level difference: } H = 11[m] \tag{11}$$

The GSMP loading is done by imposing power on the ax MA: P_{MA}, resulting in the flow value, Q.

The balance of power is as follows:

≡ the mechanical power given by the turbine is: P_T = 2847. 7 [W]

≡ the electric power given by GSMP is: P_G = – 2745. 9 [W],

≡ the mechanical power given by MA is by (12):

$$P_{MA} = M_A \cdot \Omega = \rho \cdot g \cdot Q \cdot H = 9800 \cdot 1.5683 \cdot 10^{-2} \cdot 11 = 1690.6\ [W] \tag{12}$$

Having a value yield: $\eta = 1690.6/2847.7 = 0.59367$

In conclusion, the system can be run according to the following calculation algorithm:

- ≡ measuring wind speed
- ≡ calculation of the mechanical reference angular velocity ω_{ref},
- ≡ calculation of power to TV and GSMP debit rate, from the energy balance,
- ≡ calculation of the torque given by MA and the flow Q, from the pump

3. OPERATION OF THE WIND STORAGE WIND SYSTEM

By modify the water debit rate Q, figure 3, the system can be controlled so that VUM to have the value ω_{ref},

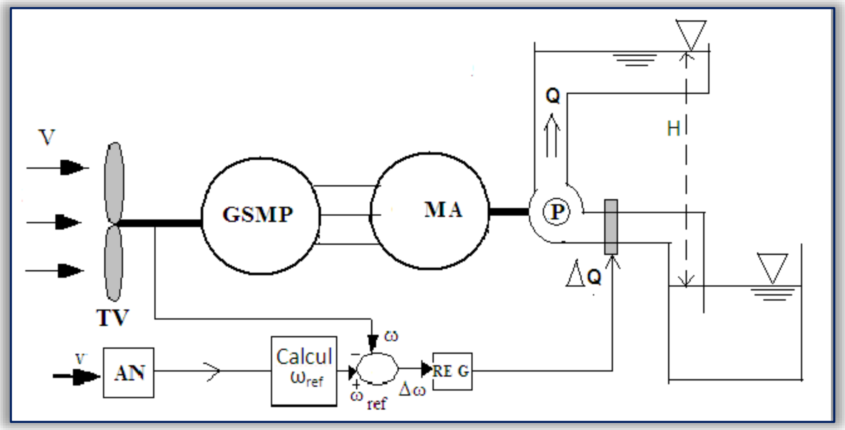

Figure 3. Wind system with hydro storage

Case study at V = 17 [m/s]

At wind speed V_{MEDIE} = 17 [m/s] is obtained (13):

$$\omega_{ref} = 11.775\,\frac{\int_0^T (V)^{1.8}\,dt}{\int_0^T (V)^{0.6}\,dt} = 11.775\,\frac{(17)^{1.8}}{(17)^{0.6}} = 352.78[\frac{rad}{s}] \quad (13)$$

At wind speed $V_{MEDIE-1}$ = 15 [m/s] the debit has the value (14):

$$Q_1 = 1.5683 \cdot 10^{-2}\ [m^3/s] = 15.683\ [l/s] \quad (14)$$

and at the wind speed VMEDIE– 2 = 17 [m/s] the debit has the value (15):

$$Q_2 = 2.8201 \cdot 10^{-2}\ [m^3/s] = 28.201\ [l/s] \quad (15)$$

Considering for the flow a variation of the form (16):

$$Q = aV^2 + bV \quad (16)$$

The dependence of the debit on the wind speed is obtained, figure 4, in the form (17):

$$Q = 0.30667V^2 - 3.554\,6V \quad (17)$$

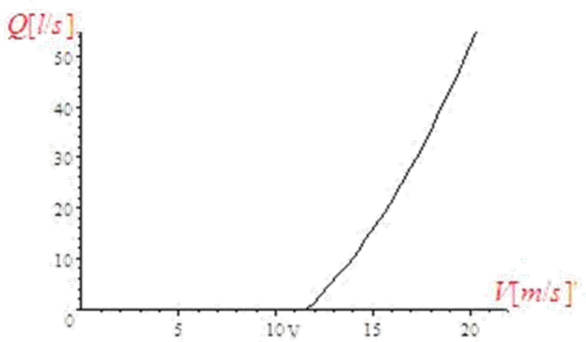

Figure 4. Dependence of flow on wind speed

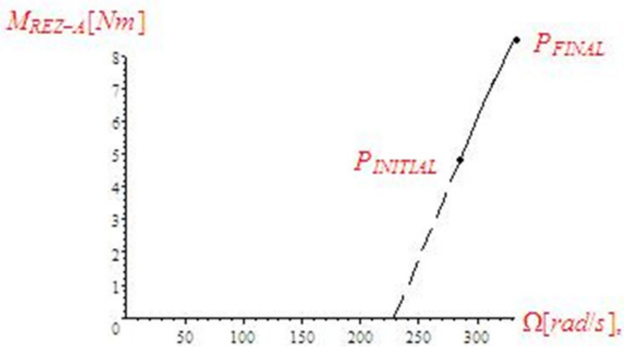

Figure 5. Pump torque variation with Ω

4. SYSTEM DYNAMICS AT VARIATIONS OF WIND SPEED

At wind speed variable in time from V_I =15 [m/s] to V_F =17 [m/s] system TV+GSMP+MA+ PA has two fundamental mechanical differential equations (17, 18):

$$J_1 = \frac{d\omega}{dt} = M_{TV} - M_{GSMP} \text{ – the equation of motion for the GSMP + TV subsystem} \quad (17)$$

$$J_2 = \frac{d\Omega}{dt} = M_{MA} - M_{PUMP} \text{ – the equation of motion for the MA + PA subsystem} \quad (18)$$

where: J_1 – moment of inertia for GSMP + TV; J_2 – moment of inertia for MA + PA.

By modifying the wind speed from V_I = 15 [m/s] to V_F = 17 [m/s] the M_A is changed from the $M_{A-INITIAL}$ = 5.717[Nm] to the $M_{A-FINAL}$ = 9.0767[Nm] and therefore for the MA + PUMP subsystem, according to figure 5, shaft resistant torque MA is (19):

$$M_{REZ-A} = (8.5577 \cdot 10^{-2} \cdot \Omega - 19.586) \quad (19)$$

The equation of motion for the MA + PA subassembly is obtained in the form (19):

$$J_2 = \frac{d\Omega}{dt} = M_{MA} - M_{PUMP} \quad (19.1)$$

or:

$$50 \cdot \frac{d\Omega}{dt} = M_{MA} - (8.5577 \cdot 10^{-2} \cdot \Omega - 19.586) \quad (19.2)$$

The value of the torque M_{MA} depends on the voltage U and the frequency $f = \omega/2\pi$ from GSMP, which are determined by the change of torque, (moment M), from TV, from: $M_{TV} = 9.38$ [N/m] to $M_{TV} = 11.751$ [N/m].
The motion equation for subansambly TV + GSMP is (20):

$$J_1 \frac{d\omega}{dt} = M_{TV} - M_{GSMP} \quad (20.1)$$

or:

$$80 \cdot \frac{d\omega}{dt} = M_{TV} - M_{GSMP} \quad (20.2)$$

or:

$$80 \cdot \frac{d\omega}{dt} = 8.6362 \cdot 10^{-2}\,\omega + 42.218 - (4.8185 \cdot 10^{-2}\,\omega - 5.2477)$$ – only for the grup TV + GSMP (20.3);

For the grup MA + PA we have ecuation (21):

$$50 \cdot \frac{d\omega}{dt} = 0.6635 \cdot (4.8185 \cdot 10^{-2}\omega - 5.2477) \cdot \omega/\Omega - (8.5577 \cdot 10^{-2}\Omega - 19.586)$$ – for the grup MA+ PA (21).

By solving the two equations of motion we obtain the time variations of ω and Ω, given in figures 6 and 7.

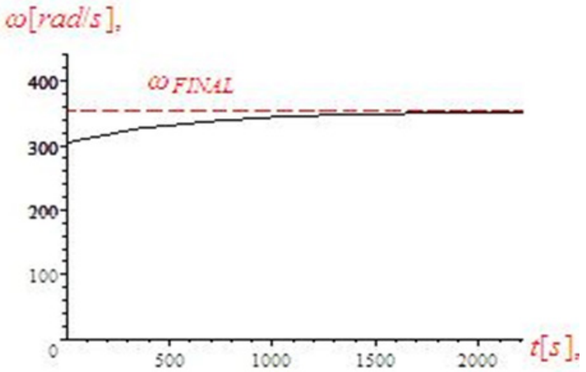

Figure 6. The variation of ω in time

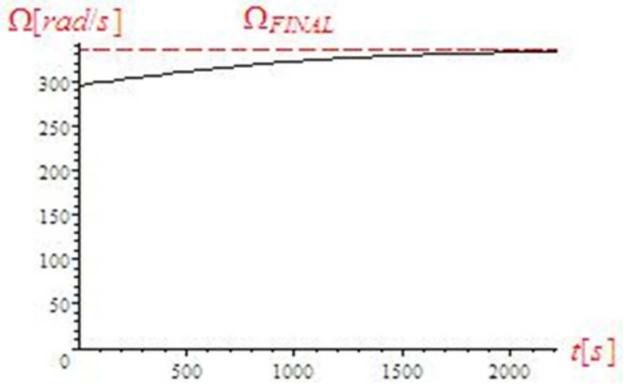

Figure 7. The variation of Ω in time

Observations:

1) VUM, ω, from GSMP reaches the final value: $\omega_{FINAL} = 352.78$ [rad/s] in a time $t_\omega = 1800$ [s] = 0. 5 [h];
2) VUM, from MA + PA reaches the final value: $\Omega_{FINAL} = 334.93$ [rad/s] in the same interval time $t_\Omega = 1800$ [s] = 0. 5 [h].

In the time interval of 0.5 [h] the water debit changes over time as in the figure above down:

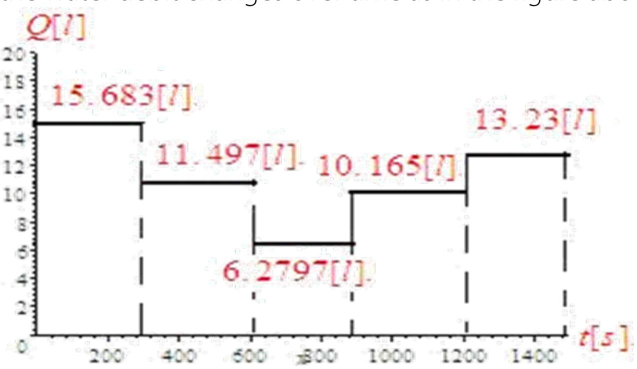

Figure 8. The variation of debit in time

By storing wind energy in hydraulic energy, a high–performance energy system is achieved in which the fluctuations of the wind speed are not disturbing.

5. CONCLUSIONS

The operation at the point of maximum power of the wind turbine was analysed, at wind speeds variable in time, in the "Clisura Dunarii". By changing the water debit Q the system can be controlled so that VUM has the optimal value and in this way to achieve a capture of maximum wind energy. Hydraulic energy obtained from wind energy can be used both for power purposes and for other purposes such as: irrigation, domestic water supply. The operation of the wind system with electricity storage was analysed by pumping, in the hydraulic accumulation from the "Portile de Fier I" hydroelectric power plant. With the method presented, regardless of the wind speed values and the restrictions imposed by the National Energy Dispatcher, the wind turbines operate at the maximum power point. It captures a maximum wind energy, with the debiting of electricity in two directions: in the grid, or in the hydropower storage "Portile de Fier I", depending on the load curve in the national energy system and the wind potential. The wind system captures a maximum wind energy. The simulation demonstrated the validity of the proposed system.

Note: This paper was presented at CNAE 2022 – XXth National Conference of Electric Drives, organized by University POLITEHNICA Timisoara, Faculty of Faculty of Electrotechnics and Electroenergetics (ROMANIA), in Timisoara, ROMANIA, in 12-13 May, 2022.

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