Maximum Power Extraction Schemes & Power Control in Wind Energy Conversion System

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Abstract— Nowadays research focus is towards the Variable speed power generation in instead fixed speed power generation in wind energy conversion system. With variable speed, there will be 20-30% increase in the energy capture compared to the fixed-speed operation. For Variable speed wind energy conversion system the maximum power point tracking (MPPT) is a very important requirement in order to maximize the efficiency. Every year a number of publications appear in various journals and conferences/seminars claiming to offer better and faster MPPT techniques for wind energy conversion system (WECS). On the other hand, wind turbines are designed to give maximum output at wind speeds around 15 m/s (30 knots or 33 mph). For stronger winds it is necessary to dissipate part of the excess energy of the wind to avoid damaging the wind turbine. So all wind turbines are designed with some power control mechanism. This paper provides the brief idea about the power control techniques on modern wind turbines and a comprehensive review and critical analysis of MPPT techniques, which is very helpful for present researcher and students working in this area.

Index Terms— MPPT, HSC, PSF, WECS.

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1 INTRODUCTION

Variable-speed wind turbines are designed to operate at an optimal rotation speed as a function of the wind speed. The power electronic converter may control the turbine rotation speed to get the maximum possible power by means of a maximum power point tracking (MPPT) strategy. It is also possible to avoid exceeding the nominal power if the wind speed increases by means of Power Control mechanism of Wind Turbines Therefore all wind turbines are designed with some power control mechanism. The power generated by a wind turbine can be expressed as; $P=0.5\rho\pi R^2V^3C_P$ (λ, β); where ρ = air density ; Kg/m^3, R= turbine rotor radius, V= wind speed, & C_P=turbine power coefficient that represents the power conversion efficiency of a wind turbine. The physical meaning of the C_P curve is the ratio of the actual power delivered by the turbine and the theoretical power available in the wind. C_P is a function of the tip speed ratio (TSR), λ, as well as the blade pitch angle (β) in a pitch controlled wind turbine. λ is given by: $\lambda = Rv_r/V$, where v_r is the rotational speed of the wind turbine. $C_{P\max}$ (theoretical) = 16/27, is the maximum theoretically possible turbine power coefficient. In practice, it is 40%–45% [1]. The rotor efficiency curve $C_P(\lambda)$ is a nonlinear function of the TSR (λ) which is determined by the blade design, and the pitch angle. There is a value of λ for which C_P is maximum, therefore maximum the power for a given wind speed. Because of the relationship between C_P and λ, for each wind velocity, there is a turbine speed that gives a maximum output power.

2 POWER CONTROL TECHNIQUES IN WIND TURBINES

Wind turbines are designed to give maximum output at wind speeds around 15 m/s (30 knots or 33 mph). A good wind turbine can start spinning in 5 mph (in between 2 to 3 m/s) winds. For stronger winds it is necessary to dissipate part of the excess energy of the wind to avoid damaging the wind turbine. Therefore all wind turbines are designed with some power control mechanism. Basically there are three types of power control Techniques in modern wind turbines, which are as follows;

2.1 Pitch Controlled Wind Turbines

In a pitch controlled wind turbine the electronic controller of turbine checks the power output of the turbine several times per second. When the power output cross a threshold limit, it sends an actuating signal to the blade pitch mechanism which quickly turns the rotor blades slightly out of the wind. On the other hand, the blades are turned back into the wind whenever the wind goes down again. Thus the rotor blades have to be able to twist around their longitudinal axis (to pitch). The pitch mechanism is usually operated using hydraulics. Variable speed pitch-regulated wind turbines have two methods for affecting the turbine operation, namely speed changes and blade pitch changes. Power optimization strategy, employed when the speed is below the rated wind speed, to optimize the energy capture by maintaining the optimum tip speed ratio. Power control strategy, used above the rated wind speed of the turbine is for limiting the output power by changing the blade pitch to reduce the aerodynamic efficiency. The maximum rate of change of the pitch angle is in the order of 3 to 10 degrees/second. The Pitch angle controller has a slight overspeeding of the rotor above its nominal value can be allowed without causing problems for the wind turbine structure [2]. The pitch angle controller employs a PI controller [3], [4].

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2.2 Stall Controlled Wind Turbines

In (Passive) stall controlled wind turbine’s rotor blades bolted onto the hub at a fixed angle. . Here aerodynamically designed rotor blade ensure that the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not in front of the wind. This stall prevents the lifting force of the rotor blade from acting on the rotor [5]. In stall controlled wind turbine, the blade is twisted slightly as you move along its longitudinal axis to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value. The fundamental advantage of stall control is that it avoids moving parts in the rotor itself, and a complex control system. On the other side, stall control represents a very complex aerodynamic design problem, and also related design difficulty in the structural dynamics of the whole wind turbine, e.g. to avoid vibrations due to stall. In a fixed speed stall-controlled wind energy conversion system, the turbine output power peaks somewhat higher than the rated limit, then decreases until the cut-out speed is reached. This characteristic provides an element of passive power output regulation, ensuring that the generator is not overloaded as the wind speed reaches above nominal values [6].

2.3 Active Stall Controlled Wind Turbines

The larger wind turbines (1 MW and above) are being developed with an active stall power control mechanism. Theoretically the active stall machines look like pitch controlled machines, since they have pitchable (able to turn) blades. At low wind speeds, in order to get a reasonably large amount of turning force, the machines will generally be programmed to pitch their blades just like a pitch controlled machine, but in pitch controlled machine uses only a few fixed steps depending upon the wind speed [6]. When the machine reaches its rated power, the machine will pitch its blades in the opposite direction, i.e. it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall and wasting the excess energy in the wind. One of the advantages of active stall is that one can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the machine at the beginning of a gust of wind. Another advantage is that the machine can be made to run almost exactly at rated power at all high wind speeds. The pitch mechanism is usually operated using hydraulics or electric stepper motors [7].

2.4 Other Power Control Methods

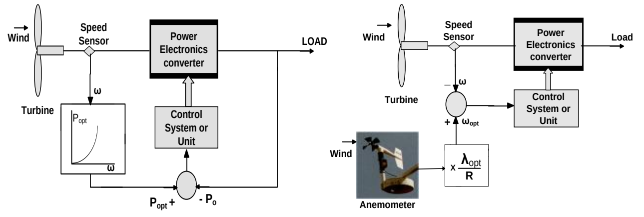
Some older wind turbines use ailerons (flaps) to control the power of the rotor. In this case the geometry of the wing airfoil is altered to provide increased or decreased air lift. Another theoretical possibility is to yaw the rotor partly out of the wind to decrease power. This technique of yaw control is in practice used only for tiny wind turbines (1 kW or less), as it subjects the rotor to cyclically varying stress which may ultimately damage the entire structure. To control yaw, there are passive yaw control to change the direction of wind automatically by the influence of wind, and active yaw control to follow the direction of wind by hydraulic or electric motors. The active method is mainly used for large wind turbines. Simple passive yaw control systems for small horizontal-axis wind turbines are tilt-up mechanisms, gravity operated furling tails with offset wind rotor systems, side-vanes with offset wind rotor systems, and spring loaded tails with offset wind rotor systems. Among of these mechanisms, the small wind turbines with a tilting hinged tail and offset pivot have better, more efficient regulator ability and a much simpler structure [8]. This mechanism is entirely passive, fail safe, robust, and simple to construct and maintain [9]. Some of the authors is used intelligent control theory for yaw control strategy of large-scale wind turbine generator

3 MAXIMUM POWER POINT TRACKING (MPPT)

The maximum extractable power depends not only on the strength of the source (i.e. wind) but also on the operating point of the WECS. The concept of MPPT is to optimize the generator speed relative to the wind velocity intercepted by the wind turbine such that the power is maximized. Variable-speed wind turbines are designed to operate at an optimal rotation speed as a function of the wind speed. The power electronic converter may control the turbine rotation speed to get the maximum possible power by means of a MPPT strategy. Following methods are used in WECS for MPPT:

3.1 The Lookup Table Based Techniques

The most widely used MPPT techniques are lookup table based. They need either a pre-programmed 2D lookup table with stored values of optimal generator speed and the corresponding maximum power (torque) at various wind velocities; or a cubic (quadratic) mapping function to provide reference signal for optimal turbine power (torque) at the operating generator speed, as shown in fig.1



(a) (b)

Fig. 1. Lookup table based MPPT techniques; (a) Power Signal Feedback and (b) Tip Speed Ratio control

Thus they require a speed sensor or observer. Typically the most popular approach is the power signal feedback (PSF) [13] which uses either a 2D lookup table with the maximum power in the ordinate or a mapping function employing the product of the cube of measured generator speed with the optimum proportionality constant. The optimal torque (OT) technique available in [12] makes use of the quadratic optimal torque curve. However both the techniques (i.e. PSE and OT) are very much similar in performance and complexity of implementation. Another commercially used lookup table based MPPT is the Tip Speed Ratio (TSR) control. This technique requires an additional anemometer for the wind speed measurement and also has a pre-known value of the optimal tip speed ratio to convert the wind velocity measurement into its corresponding reference for optimal generator speed. Due to the nonnegligible inertia of WECS, the generator speed changes a bit lazily as compared to the change in wind. This means that the reference signal for PSF and OT techniques cannot be set immediately with the change in wind because the sudden change in wind may not cause a sudden change in generator speed. On the other, the TSR control technique can give the fastest control action because it directly measures the wind speed and gives the control reference instantaneously; therefore gives more energy. Though the accurate wind measurement is not a small task especially in case of large wind turbines. The anemometer provides limited measurements of wind speed only at the hub height and cannot cover for the whole span of large blades [15]. In addition, due to the interaction between the rotor and the wind, this usual placement of anemometers on nacelles leads to inaccurate wind speed measurements in both upwind and downwind turbines. Plus the additional requirement of a wind speed sensor makes TSR control more costly than PSF. In these lookup table based MPPT, the stored optimal values of wind speed is to be constants. But, it is not true. There are a number of factors, such as Change in the air density [14], aging factor, Variable efficiencies of generator and converter subsystems [17], that can cause change in these values and as a result the stored curve or mapping function may not remain valid for the optimal power extraction.

3.2 The State Space Linearization & Nonlinear State Space Based Techniques

In the control of WECS, there are various applications of linear and nonlinear state space control theory. Feedback linearization with optimal control theory is used in [18] whereas feedback linearization theory with sliding mode control is used in [19]. In [20], TSR control along with input-output feedback linearization is employed to get rid of the effects of nonlinearity due to magnetic saturation. In [21], a disturbance observer for estimation of parameter uncertainties by means of feedback linearization is used. Few publications employed sliding mode or passivity based variable structure control (VSC) of Wind Energy Conversion System [22]-[25]. In a particular well defined wind turbine and generator, the state space techniques possibly will provide robustness against disturbances. But in the formulation of these techniques, we require system modeling which may not be available or known in general and is quite complicated; particularly in the case of WECS driven by the new kinds of special machine whose mathematical models are not well-known so far. Therefore these techniques are hard to implement and their system specific dependency makes them sensitive to the drift or modifications in the system's parameters.

3.3 The Neural Network-Fuzzy Logic Based Techniques

Control systems for variable-speed wind turbines are progressively evolving toward effective and innovative control systems based on soft-computing methodologies, such as fuzzy systems and artificial neural networks. Actually, Fuzzy control algorithms offer many advantages over traditional controls since they give fast convergence, they are parameter insensitive, and accept noisy and inaccurate signals. [16]-[22]. Artificial neural networks (ANNs) are particularly useful to implement nonlinear time-varying input–output mapping. In the past, ANN has been applied for various control, identification, and estimation schemes in power electronics and drives. For example, feedforward ANNs were selected for implementation of pulse width-modulation (PWM) techniques [23], [24]. The ANN-based PWM has advantages of fast parallel computation, learning capability, and fault tolerance, which are not possible by standard PWM implementation methods. Also, ANN gives an alternative method of observing the input–output relationships of alternating current (ac) induction machines (IMs), whose parameters vary with time and operating conditions [25]. For the WECS application, ANN shows high promise for simplification of feedback signal processing. ANN can also be trained off-line and/or on-line to follow existing controllers [26]. The cost may be good enough, but the speed is slow for complicated real-time applications. Another alternative is the use of an ANN application-specified integrated circuit (ASIC). Although the speed requirement is good enough, the cost is very high for most applications. Fuzzy logic MPPT controller [18]-[22] is basically the extended adaptation of the hill climb searching (HCS) or perturb & observe (P&O) control which will be explained later. In HCS, the control decision based on only one "IF-ELSE" statement, while intelligent fuzzy logic control is governed by a set of rules which chooses different control action based on the state of the system at that instant. Similar to HCS, fuzzy control does not need to identify system parameters or equations. However, fuzzy logic controller may require speed sensors. Fuzzy control needs to define plenty of boundaries and gains. The ANN requires an additional wind velocity sensor for its training apart from the generator speed sensor which is again not a good feature.

3.4 The Neural Network-Fuzzy Logic Based Techniques

The hill shaped power curves of WECS show unique maxima with respect to its control variable (generator speed or converter duty ratio). Therefore a straightforward discrete time hill climb searching (HSC) control can be employed by perturbing the control variable and observing the resulting increase or decrease in power [13], [14]; as given in fig.2. Hill climb searching (HCS) or P&O is the simplest MPPT technique that does not need any past knowledge of the system or any additional sensor apart from the measurement of the power which is used to maximization. Thus it can be useful to any renewable energy conversion system that shows a unique power maximum. But it is only possible in the slow varying systems. In rapidly changing wind conditions, there are two critical problems with HCS which considerably decline its perfor-

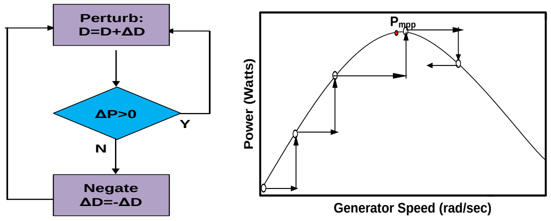


Fig. 2. Law of HCS MPPT: Continue perturbing the control variable in the same direction until the power is decreased

mance [17]. The first problem is larger perturbation step size. It increases the speed of convergence but degrade the efficiency η_{mppt} of the MPPT through amplifying the oscillations ΔP_{mpp} around the maximum power point (MPP) P_{mpp}. It is due to that HCS control does not stop at P_{mpp} and consequently the oscillations are unavoidable feature of the HCS control. A smaller step size improves the efficiency but the controller becomes slower and may become incompetent of tracking maximum power point in rapidly varying wind conditions. Being blind to the wind change, the HSC rule can be confusing as the sign might get determined by the change in wind rather than the applied perturbation. This incorrect decision leads to the malfunction in keeping track of MPP and the HCS control moves downward.

3.5 HYBRID Hill Climb Searching/ Lookup Table Based Techniques

The lookup table based MPPT and HCS are the most feasible of MPPT techniques which can be more capable if their drawbacks can be removed through some smart advancement. Therefore the bulk of the research papers on MPPT employed the hybrid versions of HCS and PSF. The following section presents a brief analysis of the same.

I. Variable Step Size Hill Climb Searching [27], [28]

A fixed step size HCS always suffers from tracking speed versus control efficiency transaction. In [27], the constant step size is replaced by the scaled measure of the slope of power with respect to the perturbed generator speed $\Delta P/\Delta\omega$. The main features of the method used in the proposed MPPT system [27] are: (i) Variable step tracking i.e. the tracking step size is changeable according to the change of wind speed; (ii) The dead time effect of the inverter is avoided by synchronizing the MPPT controller to the rotating speed of the generator; (iii) a low pass filter is used at the output of the MPPT controller to limit the fluctuation of the reference rotating speed. As a result the system has high-efficiency, lower-cost and fast stable tracking speed. But in reality it is only feasible for a constant or very slowly changing wind. Otherwise $\Delta P/\Delta\omega$ will not give a accurate measure of the distance from the maximum because the operating point shifts from one power curve to another for different wind velocities. Therefore the technique is to result in needless large or small step size during changing wind, resulting into big deviation from the maximum

II. Dual Step Size Hill Climb Searching [29]

Authors in [29] proposed an alternative approach for the variable step size HCS. Here only two discrete values perturbation step, instead of the constant, are used in a way that until the maximum is achieved or if the wind change is detected then the algorithm uses a larger step size, otherwise it is switched to a smaller one. The variable step HCS shows better performance, if there is no or very sluggish change in wind speed. But practically it is very rare to occur and therefore the dual step size HCS gives a bit better alternative as it does not undergo much away from the needless fluctuations in the command signal with the variations in wind speed. However the realization of the algorithm requires sensing the change in wind. One of the uniqueness of this algorithm or technique is that for the true peak recognition it does not just use $\Delta P<0$ but in addition the checks on the current and the previous samples of the change in wind speed.

III. Search-Remember-Reuse HCS [30]

In [30], HCS turns into a lookup table based technique by online training of a memory table. At starting it is just like the conventional HCS which rephrases as maximum power error driven (MPED) control. Then a memory is maintained in the structure of triplet (i.e. Maximum Power, Rectified Generator Voltage V_{dc}, and Current Control Value). The important feature of [30] is that it carries out MPPT for the turbine mechanical power Pm instead of the output electrical power Po assuming that large inertia of WECS. The technique does not have an appropriate peak detection mechanism. Similar to almost all other related publications, [30] also assumes a constant optimal characteristic of the system which can become mistaken as already explained above in the analysis of the lookup table based MPPT.

IV. Modified HCS to avoid Generator Stall [31]

A faster control indexed HCS driven control is given in [31] for MPPT. The fast index is projected as an exponential function of the differential generator speed & thus it causes sharp increase or decrease of generator current command on abrupt increase or decrease of wind speed correspondingly. This amplified fast control is termed as Maximum Power Differential Speed (MPDS). The MPDS in [13] sharply increases the generator speed to avoid stall. Nevertheless this control will lead farther away from MPP if the system is operating in the right hand area with respect to the cubic optimal power curve. Likewise in the increase in wind speed the proposed MPDS increases the turbine torque by reducing the generator speed. This will be harmful for MPPT if the system is now operating in left half plane.

V. Modified PSF to avoid Generator Stall [32]

Authors presented the scheme to compensate the measured power by a constant value to avoid stall [32]. Furthermore, it feedbacks the derivative of the stator frequency to increase the sensitivity of the system for the change in wind. In the proposed sensorless scheme, the inverter input working voltage is obtained by a “power-mapping” method. The “power-mapping” technique is analogous to the one-dimensional lookup table with one input (P_{dc}) and one output (estimated voltage, V_{dc}). The additional constant value to keep away from stall will make the algorithm unable to achieve MPP as there is always be an offset in the TSR with respect to its optimal value. The derivative of stator frequency will become zero at MPP. But practically this is merely true when wind speed is constant or changing very gradually, otherwise the derivative gain will never become zero. In addition it may cause unwanted overshoots in the control variable.

VI. Modified OT for Fast Tracking [33]-[35]

A fascinating alteration of the optimal torque control law is given in [33], [34] which are also employed in [35]. Rather than the conventional OT command $T = k\omega^2$, a net torque term accountable for the acceleration or deceleration of generator speed is also included given as; $T=k\omega^2-\hat{G}(T_m-k\omega^2)$; where T_m is the mechanical torque captured by the wind turbine & $\hat{G}$ is a positive definite gain to adjust the role of the net torque $T_m-k\omega^2$ during the transient state. This technique aids the tracking speed by producing a larger difference between the new available torque T_m (due to change in wind) and the torque command; it decreases the torque control signal with the increase in aerodynamic torque and vice versa. The drawback of this alteration however is that now it is requisite to have a measure of turbine mechanical torque which is either calculated by means of Newtonian equation as in [34] or estimated via torque observer as in [35]. In both the cases we require to know the system parameters for example the turbine inertia *J*, which may change over time due to aging.

VII. Adaptive TSR Control [36]

The technique given in [36] initiates the TSR control with an approximated optimal TSR value. Afterward when the measured wind velocity is found to be stable enough, then the algorithm switches to HCS to search for the real optimal point. When accurate peak is reached, then; i) a memory table of the optimum generator speed with the analogous wind velocity is updated & ii) the TSR is corrected. The given algorithm has two major concepts that permit fast and efficient maximum power extraction. The first concept is to merge the use of the turbine fundamental TSR equation in conjunction with the Hill Climb Searching (HCS) methodology. The 2nd concept employed in the algorithm is the memory feature that allows it to adjust to its given turbine. This technique is the best until now in terms of fast and accurate tracking without the need of any pre-programmed system characteristics. But this algorithm suffers from the same issues as of TSR control concerning the wind speed measurement such as use of an anemometer and rotor speed sensor.

VIII. Adaptive OT Control [37]

The authors in [37] uses HCS in the optimal torque (OT) control by perturbing the proportionality gain of the optimal torque equation & observing the variation in the estimated measure of power coefficient C_p to choose for the next perturbation. The projected estimate of C_P is calculated by taking the ratio of the average mechanical power over the average wind power. This averaging is done over a very long time period to average out the wind variation effects. In [36], the perturbation of the OT gain is not done continuously however periodically after a very long time period. The choice for the next perturbation depends on the variation in the C_P estimate. If there is no averaging, the algorithm will act like a conventional HCS which is most probable to go lost in fluctuating wind. Moreover it additionally requires an anemometer.

IX. Limit Cycle Based HCS [38]

It is an application of the "limit cycle MPPT technique" which is previously proposed for the photovoltaic system. The dc output power of the rectifier is controlled by additional boost chopper & PWM inverter stages. The proposed MPPT is performed via an integrator ramping up or down the current control signal of the load side inverter according to the error in the dc link voltage synchronized by the generator side chopper. The current control ramps up till the maximum power is achieved and if it is increased further then the dc link voltage cannot be kept at constant because the power equilibrium cannot be maintained. In this fashion the MPPT exhibits non linear oscillations about MPP called limit cycle. The good point of the proposed technique over the conventional HCS is its hardware simplicity as it does not need a power calculator and the whole algorithm can be implemented using low-cost analog elements. On the other hand it does suffer from all those failures of conventional HCS.

X. Disturbance Injection Based HCS [39]

As the name implies, this algorithm proposes to inject a sinusoidal perturbation rather than the constant step. The output power is then sampled at $\pi/2$ and $3\pi/2$ of each cycle, the difference of which make a decision about the next perturbation. This technique does not offer any added advantage over conventional HCS. Instead it adds up the following shortcomings; 1) this requires to measure samples at two time instances to make a decision about the next perturbation. So this algorithm is slower than HCS; 2) the algorithm will merely work for constant or very slow changing wind, if not the samples at $\pi/2$ and $3\pi/2$ will give the wrong idea about the tracking.

XI. Self Tuning Sensorless Adaptive HCS [40]

In [40], a novel self tuning adaptive step size HCS algorithm is proposed. The proposed novel MPPT algorithm uses the fact that the mechanical power P_m of a constant-pitch variable-speed wind turbine has a unique optimal power curve P_{opt} which exhibits a cubic function of the generator speed ω ($P_{opt} = k_{opt}.\omega^3$) [40]. The size of the step can be calculated through the measure of how far the working point lies from the optimal curve. Once a peak is detected then it extracts the optimal curve constant k_{opt} through measured output electrical power and estimated generator speed. It can effectively deal with the fast changing wind as well as the inconsistent efficiency of the system. Though there are two limitations of this technique; a) large inertia of WECS and fast rate of change of wind may cause longer time to find a k_{opt}. b) The limit ε employed to detect the wind change requires a test run for its tuning.

4 CONCLUSION

Nowadays, the most common wind turbine configurations are based on the variable-speed pitch-control and the fixed-speed stall-control concepts. The variable-speed pitch-control concept is the currently preferred option mainly because of its good power control performance, low mechanical stresses and emergency-stop power reduction features.A systematic review and analysis of the techniques available for MPPT in WECS has been given in this research paper. This review paper spans all the possible publications till date. The analysis concludes the two best techniques to be [34] and [41]. Both the algorithms have adaptive tracking with self-tuning capability. But [34] needs both wind speed and generator speed sensors. While [40] has a clear edge over [34] and all the rest for being absolutely mechanical sensorless. Furthermore, in contrast to [34], the algorithm of [40] does not construct a lookup table and therefore is easy on the memory requirements.

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