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A REVIEW OF INCREMENTAL CONDUCTANCE METHOD FOR MPPT TRACKING OF WIND ENERGY CONVERSION SYSTEM

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ABSTRACT

Between solar and wind energy sources, the latter has been attracting much attention, particularly for distributed generation applications. Wind is a variable form of energy, varying throughout the day as well as with seasons. Any wind energy conversion system can either run at a constant speed or at varying speeds. The systems operating at constant speed are generally not used because of their inability to track the changes in wind velocity. This results in poor efficiency for the overall system. With the advances in power electronics, variable speed operation has become possible. For wind generation systems functioning at varying speeds, different types of electric generators can be used. Popular among them are doubly fed induction generator (DFIG), squirrel cage induction generator (SCIG) and permanent magnet synchronous generator (PMSG). The features which make the PMSG advantageous over the other two types have been presented. Controllers are deployed for maximum power point tracking to extract the maximum feasible power from the wind irrespective of the wind speed. Many MPPT techniques have been proposed in literature and extensive research is being done to improvise the existing techniques for better results. This paper introduces a novel approach to apply incremental conductance method, which has been used extensively in photovoltaic systems till now, to wind energy systems. A certain power conditioning topology required to implement this method has been mentioned. Also a comparative account has been presented between the above method and the more commonly used perturb-and-observe method. The proposed method can prove to provide better results in certain conditions of wind speed variation.

Keywords: Comparative Analysis, Incremental Conductance Method, Intermediate Boost Converter, Maximum Power Point Tracking, Permanent Magnet Synchronous Generator.

I INTRODUCTION

Global energy demands are escalating fast and so is the price of fossil fuels. Keeping in view the international norms for pollution control, presently the focus has shifted to renewable energy sources to meet this steep energy deficit. Popular among them are the solar and wind sources. Both of these energy sources are available abundantly in nature and are environmentally benign. The cost of setting up of a wind energy power plant is lower compared to its solar counterpart, so it often gets the main role in power generation [1]. A point to be noted is the nonlinear output torque-speed characteristics of a wind turbine. Due to this inherent system nonlinearity, the power output from the wind turbine varies with the change in wind speed. As a result, the system does not run at its maximum efficiency under all wind speed conditions. To optimize the system efficiency for any given wind speed, methods are employed to maintain the output power at its maximum value at that wind speed. These are called *Maximum Power Point Tracking (MPPT)* methods.

Electric generators driven by wind turbines convert the wind energy into its electrical form. The point of maxima achievable in the turbine output power- shaft speed curve of a wind energy system is called the *Maximum Power Point (MPP)*. MPPT techniques aim at location of this MPP either through “calculation models or by search algorithms” [2]. They maintain the operating point of the wind turbine at its MPP irrespective of the wind speed by suitably changing the speed of the generator.

Various techniques for MPPT in Wind Energy Conversion System (WECS) have been proposed in literature [3]-[6], namely, the Incremental Conductance (IC) [2], the Wind Speed Measurement, the Power Signal Feedback [6], the Perturb and Observe (P&O) [7] etc. Presently the P&O technique is the most widely used in WECS.

Extensive research has been done on implementing IC algorithm for MPPT in PV systems, but it has not yet been studied for large scale WECS. This paper discusses the possible implementation of IC method for MPPT tracking of a wind energy system using grid connected permanent magnet synchronous generator (PMSG). This method can prove to be a better alternative to perturb and observe method under certain conditions of wind speed variation [8]. Further, a comparative account of the above two methods has been discussed in this paper.

II SYSTEM OVERVIEW

The energy of wind is in the kinetic form. When wind flows past the blades of a wind turbine, it rotates the turbine. The expression for *power contained in the wind* P_{av}, is given by [1];

$$P_{av} = \frac{1}{2}\rho A V_w^3 \tag{1}$$

where, ρ is the density of air, A is the area swept by the wind turbine blades and V_w is the wind speed.

It is not possible to extract 100% power from the wind. An index of measurement of the conversion efficiency of a wind turbine is given by the *wind turbine power coefficient* C_p, which is defined as;

$$C_p = \frac{P_m}{P_{av}} \tag{2}$$

where, P_m is the mechanical power output of the turbine.

By applying fluid mechanics, the value for the theoretical maximum of this conversion factor can be calculated to be 0.593. This limit is called the *Betz limit*. It means that no wind turbine can convert more than 59.3% of the kinetic energy of the wind into mechanical energy [9].

Accounting for the efficiency of generator coupled to the turbine in C_p, (2) can be modified as;

$$C_p = \frac{P_e}{P_{av}} \tag{3}$$

where, P_e is the electrical power output of the system.

The *tip speed ratio (TSR)* can be mathematically expressed as;

$$\lambda = \frac{\omega_m . R}{V_w} \tag{4}$$

where, ω_m is the turbine rotational speed, R is the rotor radius. *TSR* is related to efficiency of a turbine.

The factor C_p is a transcendental function of *blade pitch angle (β)* and *tip speed ratio (λ).* The following analytical function for power coefficient has been used in this paper as demonstrated in [10];

$$C_p = 0.5\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \tag{5}$$

where, $\lambda_i = \left(\frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}\right)^{-1}$ (6)

The electrical power output is given as;

$$P_e = \frac{1}{2}C_p(\beta,\lambda)\rho A V_w^3 \tag{7}$$

The performance of any wind turbine can be described by a family of curves called the C_p-λ curves. The C_p-λ curves for various values of blade pitch angle are shown in Fig. 1.

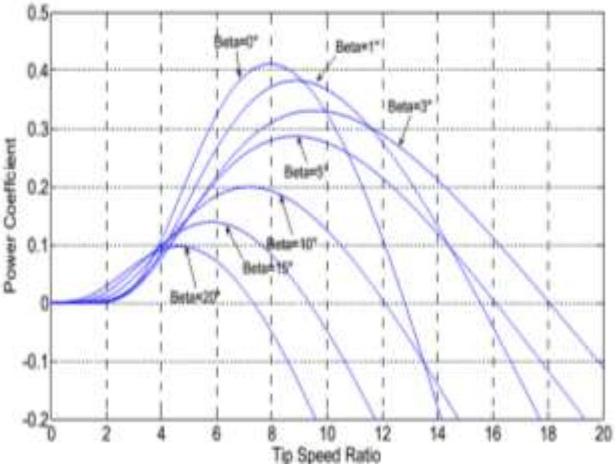


Fig 1: Cp-λ characteristics for different values of pitch angle [3]

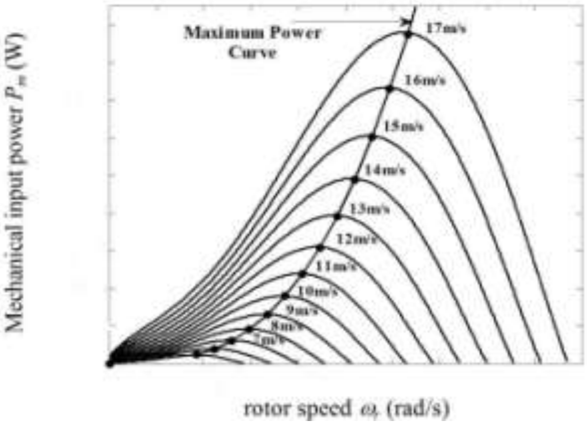


Fig 2: Mechanical power output of the wind turbine versus rotor speed for different wind speeds [3]

For a wind turbine with constant blade pitch, the angle β is set at zero. C_p then becomes a function of λ only. Consequently, maximum power output occurs at one tip speed ratio only as denoted in Fig. 2. This value for *TSR* is called the *optimum TSR* and is denoted as λ_{opt} [4]. The turbine speed corresponding to λ_{opt} is ω_{opt}. Using (4) it can be verified that, for tracking the *MPP* at all wind speeds, the rotational speed must also vary accordingly so that tip speed ratio is maintained at its optimal value at all times. Such variation of operating speed is not possible with fixed speed wind generation systems. On the other hand, variable speed turbines, with the help of suitable control system, have the ability to "*follow*" the instantaneous variations in wind speed by accordingly changing their rotational speed and thus are able to maintain the point of operation at the optimum tip speed ratio, λ_{opt} [11]. Thus MPPT is achieved at different wind speeds.

III SYSTEM CONFIGURATION AND MODELING

3.1 Wind Energy Conversion System

The components of a typical WECS that produces electrical power are wind turbine, drive train mechanical connection, generator and load. When wind blows, the main shaft in the drive train starts to rotate. The gearbox turns the rotational speed to higher level so that it is suitable to drive the generator. The load may be an isolated one or the grid itself. Two broad categories of wind generation systems are: *fixed speed systems* and *variable speed systems*.

As pointed out earlier, for higher efficiency the operating speed of the system must vary with the simultaneous variation in wind velocity, hence the use of variable speed generating systems is the most popular trend in WECS. Mostly two types of variable speed generators are widely used: *Doubly Fed Induction Generator (DFIG)* and *Direct-driven Permanent Magnet Synchronous Generator (PMSG).* Both of them are able to generate high quality electrical power even when wind speed varies. The latter offers some advantages in terms of cost and reliability over induction generators (IG) [12, 13]. Due to the high power density of PMSG, the generator can be driven at low speeds and thus the need for a gear-box is eliminated. Gearbox is the most expensive part in wind turbine which requires scheduled maintenance and very costly repairs [14]. PMSG weighs less, has less mechanical loss and requires less space than comparable IG because of this design.

The model usually consists of wind generation model, three phase rectifier, three phase inverter, load and controller (MPPT). The topology for a wind driven PMSG is shown in Fig. 3.

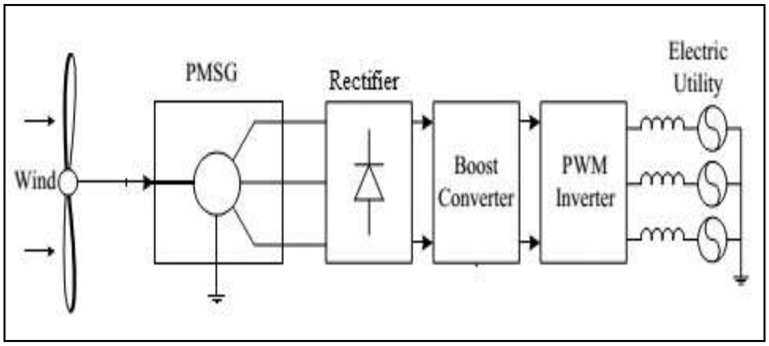


Fig 3: Modeling of wind driven PMSG [16]

3.2 Grid Integration Schemes

The generated power at any instant varies due to the random nature of the wind source. This causes stability problems. To overcome this concern power electronic interface is necessary [15]. The implementation of IC method requires a DC to DC conversion stage but the output power of PMSG is AC. For conversion of AC to DC, various topologies have been proposed in literature. The four topologies for grid connection of PMSG are presented as below [8]:

- Back to Back converter

This is the most commonly studied connection. Fig. 4 shows the back to back converter (BBC) connection for a WECS using permanent magnet synchronous generator. Both the grid side inverter and the generator side rectifier are controlled.

- Intermediate buck-boost converter

Fig. 5 shows the intermediate buck-boost converter (IBBC). This topology uses an uncontrolled bridge rectifier, DC-DC buck-boost converter and DC-AC inverter.

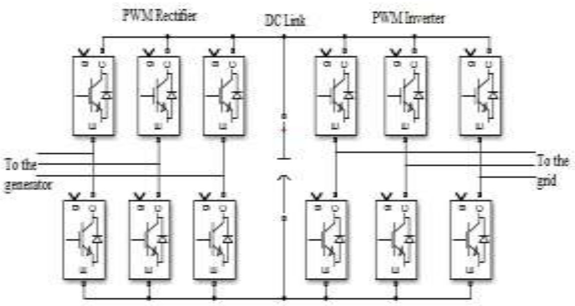


Fig 4: Back to back converter

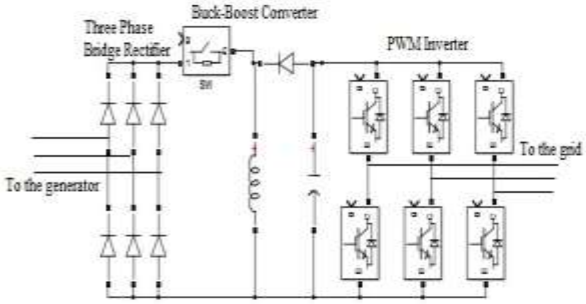


Fig 5: Intermediate buck-boost converter

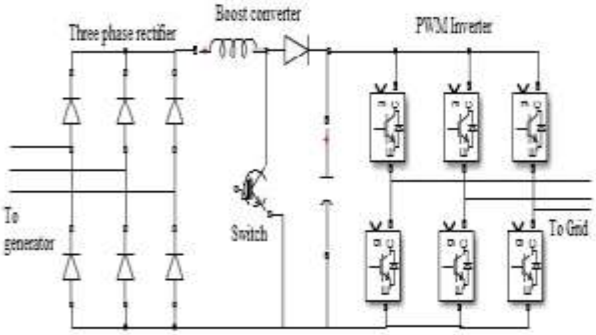


Fig 6: Intermediate boost converter

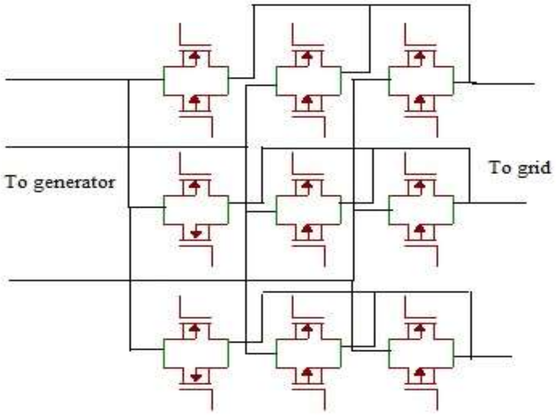


Fig 7: Matrix Converter

- Intermediate boost converter

Fig. 6 presents the intermediate boost converter (IBC). An uncontrolled rectifier, DC-DC boost converter and DC-AC controlled inverter are used for grid integration.

- Matrix converter

A bidirectional matrix converter (MC) is shown in Fig. 7 that can convert AC to AC directly.

3.3 Reliability of Grid Connection Topologies

The probability that a system or component will perform its desired functions under the stated operating conditions for a specified period of time is a measure of its reliability. For grid connection, the topology with the maximum reliability should be chosen in order to minimize the maintenance and operational costs. Reliability of the proposed four types of grid integration of PMSG over time has been shown in Fig. 8. The intermediate boost converter possesses higher reliability than the other types [17]. It can be seen that the reliability of all converters except IBC falls by more than 80% within a period of one year. Matrix converter has a complex architecture and hence is seldom used. The IBC consists of three components, namely, rectifier, boost converter and inverter. Reliability studies have shown that inverter is the least and rectifier is the most reliable component of the converter system. Since the inverter system is common to all the converter schemes, the overall reliability is dependent on the type of rectifier used. IBC, which uses a simple diode bridge rectifier, is a good alternative to the back to back converter. Due to its higher reliability over other topologies, it is proposed to introduce Incremental Conductance algorithm to WECS by using the Intermediate Boost Converter topology.

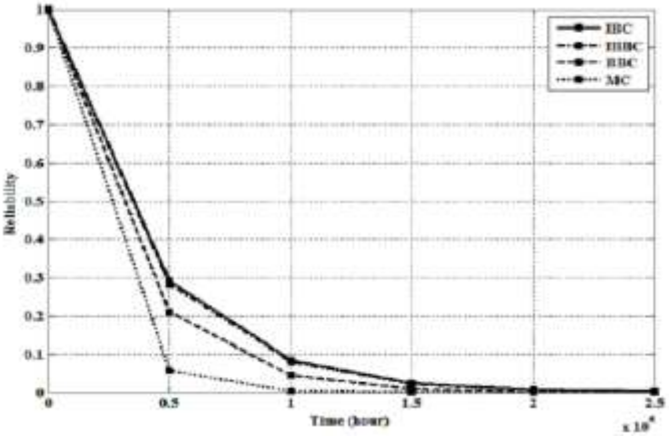


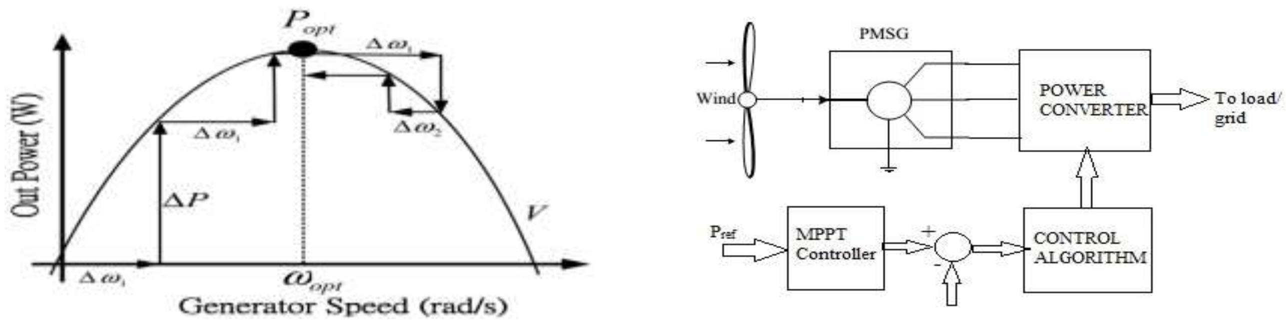
Fig 8: Reliability of converters over time [17]

3.4 Maximum Power Point Tracking

Two tracking techniques are presented as below:

3.4.1 Perturb-&-Observe Method

It is also known as Hill Climb Search (HCS) method. In this control algorithm, the point of peak power output is continuously searched. The relation between the changes in power and rotational speed, i.e., *ΔP/Δω* is determined. Based on the location of the operating point and the sign of the quantity *ΔP/Δω*, the necessary control signal is generated which drives the system to the MPP. Fig. 9 shows the concept of HCS control for a WECS [6].



(a) (b)

Fig 9: P&O method (a) electrical output power versus rotor speed curve (b) WECS with HCS control

3.4.2 Incremental Conductance Method

At MPP, the value of C_p is a constant. From (1), (2) and (4) maximum turbine output power P_{max} is proportional to the cube of wind speed V_w and hence to the cube of optimum rotor speed ω_{opt} which keeps the TSR at its optimal value λ_{opt}.

$$P_{max} \propto V_w^3 \propto \omega_{opt}^3 \tag{8}$$

$$\omega_e = p\omega_{opt} \tag{9}$$

$$V_{ac} = E - I_{ac}(R_s + j\omega_e L_s) \quad = K_e\varphi\omega_{opt} - I_{ac}(R_s + j\omega_e L_s) \tag{10}$$

$$V_{dc} = \frac{3\sqrt{3}}{\Pi} V_{ac} \tag{11}$$

The symbols are defined as:

ω_e: angular speed of generator in electrical radians/second.

p: number of poles of generator

K_e: a coefficient

φ: flux per pole in the machine

V_{ac}: ac voltage output of generator

I_{ac}: ac current output of generator

E: induced voltage in the stator of generator

R_s: stator resistance

L_s: stator inductance

V_{dc}: rectified output voltage

Based on equations (1), (2), (9), (10) and (11) the optimal value of the dc voltage V_{dc-opt} after ac to dc conversion is proportional to the optimal rotor speed ω_{opt} .

$$V_{dc-opt} \propto \omega_{opt} \tag{12}$$

From (8);

$$P_{max} \propto V^3_{dc-opt} \tag{13}$$

(13) establishes the relation between output power and the dc output voltage of the rectifier. Thus by varying the duty ratio of the converter, V_{dc} changes and hence P_m will follow.

The IC method is discussed below;

$$P = VI \tag{14}$$

where, *P* is power, *V* denotes voltage and *I* denotes current.

$$\frac{dP}{dV} = \frac{dVI}{dV} = I + V\frac{dI}{dV} \tag{15}$$

Referring $\frac{dP}{dV}$ to $\frac{dP}{d\omega}$ based on (12) as shown in Fig. 2, the following three conditions may arise:

- When $\frac{dP}{dV} = 0$ the MPP is reached.
- When $\frac{dP}{dV} > 0$ the point is to the left of MPP.
- When $\frac{dP}{dV} < 0$ the point is to the right of MPP.

Whenever $\frac{dP}{dV} \neq 0$ appropriate control action will be taken as shown in Fig.10.

If $\frac{dP}{dV} = 0$ then $-\frac{I}{V} = \frac{dI}{dV}$ (16)

$\frac{I}{V}$ is the instantaneous conductance of the turbine-generator set.

$\frac{dI}{dV}$ is the incremental change in conductance.

By changing the duty ratio of the DC-DC converter the conductance of the circuit will change. When the incremental change in conductance equals the negative of instantaneous conductance the optimal duty ratio is found and maximum power is extracted from wind.

For the proposed model of WECS using IBT, MPPT control is implemented as described below. The successive electrical power output is measured. Following comparison of these measurements, the duty ratio of the dc-dc converter is adjusted accordingly. Hence the rectified output voltage V_{dc} of the converter changes simultaneously. Then the actual power output is compared with the value from the previous cycle. If the change is positive and increasing, the perturbation will continue in the same direction in the subsequent cycle. This will cause the rotational speed to increase. If the change is decreasing, the direction of the search will be reversed. When the quantity *ΔP/Δω* equals zero, it means that the optimum rotor speed for that particular wind speed has been reached. At this point, the MPP has been tracked and the operating point will settle around this point [18].

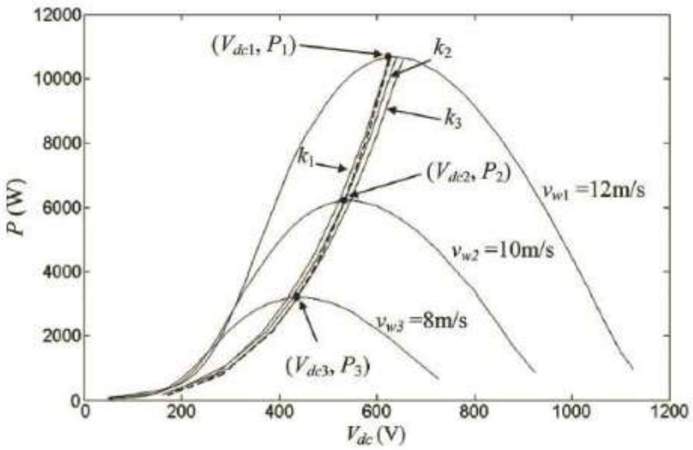


Fig 10: Generated power versus rectifier output voltage curve for a wind turbine driven PMSG; k is the duty ratio of the converter [19]

3.4.2 Comparison of P&O and IC method

Firstly, in HCS method the input data are power and voltage, and in the IC method voltage and current are its inputs. Secondly, the condition that $dV = V(k) - V(k-1)$ is infinitesimal is not considered in HCS method whereas it is taken care of in IC method [20].

The quantity $dV=V(k)-V(k-1)$ is the denominator of $\frac{dP}{dV}$ in (15). If dV is not infinitesimal, the sign of change in duty ratio is decided by whether $-\frac{I}{V}$ is greater or smaller than $\frac{dI}{dV}$. If dV is very small, while dI is also small, no action will be taken. If dV is very small, while dI is above the tiny threshold, the sign of $\frac{dP}{dV}$ is decided by dI because the absolute value of the second term in (15) is huge while I in the first term can be ignored and V in the second term is positive. This method assumes that dV is positive when it is infinitesimal. When the system is working in this condition, there is 50% probability that the controller takes the correct direction to change duty ratio. If wrong action is taken, there will be a drop in load power, but the system will recognize the mistake by observing the control result and make correction in the next cycle. In HCS method, when dV is infinitesimal, wrong control action based on inaccurate measurement of voltage because of sensor limitation is likely to be made.

IV CONCLUSION

Till date the most commonly used grid integration topology for WECS is the Back to Back converter. Intermediate boost converter topology with higher reliability than back to back converter can be a suitable replacement. With this type of DC to DC converter stage, it is possible to implement IC algorithm in MPPT of wind generation systems. This technique can prove to be a better alternative to the P&O technique in applications where high sensitivity to wind speed variations is required. The two techniques are also equivalent in terms of the costs and the software complexity involved. Verification of the discussed topology can be done by simulation. Further study can be done on control of DC to AC converter focusing on providing high power factor and high quality power.

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