A Novel Maximum Power Point Tracking Algorithm for Wind Energy Conversion System

S. Ahmed, M. A. Rashid, Member, IAENG, S. B. Mohamed, S. B. Yaakob

Abstract—**This paper presents a novel efficient maximum power point tracking algorithm for wind energy conversion system. Conventional techniques to obtain maximum power are susceptible to the mechanical disturbances. Conversely, the perturbation algorithm requires high accuracy of turbine power characteristics. Therefore, a variable speed-variable pitch wind turbine in conjunction with permanent magnet synchronous generator and sensor-less maximum power point tracking has been proposed in this paper. A nonlinear optimum relationship between output power and dc voltage has been developed in this research work. On the basis of mathematical relationship, a new perturbing parameter has been introduced for more effective tracking scheme. The proposed system has been verified on simulation interface, and compared with the conventional perturbations. The comparison results show that the proposed technique increases the overall output power of the system by 5-7%.**

Index Terms—**Wind energy conversion system, Distributed generation, Micro-grid, Maximum power point tracking.**

I. Introduction

DISTRIBUTED generations and renewable energy are becoming the fastest growing field of the energy industry due to the recent technical improvements. A large number of small scale generation units, located at user's site, are integrated in a distributed generation system in order to meet the growing customer's need for electricity with the emphasis on power quality including reliability [1]. It encompasses a wide range of renewable and non-renewable sources such as internal combustion engine, gas turbine, wind turbine and solar energy [2], [3].

The renewable energy like solar energy, water power, wind power, biomass energy, terrestrial heat, sea waves, morning and evening tides, etc. can be recycled [4]. Among the renewable energy sources, the wind energy has become popular in the field of distributed generation and micro grid concept due to their capability of providing power in both grids connected and island modes [5]. Wind turbines can provide power seamlessly, which has made it the most important source and probably the most utilized one among all renewable technologies. Now a day, it has been a complement to other pollution free power generation system in the civilized society.

In a Wind Energy Conversion System (WECS), the energy associated with wind is converted into the electrical power using an alternator, which is then fed to the local grid through power converter [6]. The power converter ensures continuous power transfer between grid connected and island mode, whereas the dc to dc converter is controlled in a way that it produces the maximum power from wind [7].

According to Betz's law, only 59.3% of total available wind energy can be converted into mechanical energy considering no mechanical losses in the system [8]. However, in most cases about 20% - 60% of the Betz's limit can be obtained from wind turbines [9]. However, the conventional way to get the maximum power from wind is based on the optimum mathematical relationship. The turbine output power is a function of rotor speed if the wind speed is assumed to be constant. Thus controlling the rotor speed allows control over power production from the generator [10]. There are several other mathematical relationships suitable for maximum power tracking. In many cases electromagnetic torque vs. power relation is used to obtain the maximum power [11].

Maximum power tracking by controlling the rotor speed or electromagnetic torque requires the use of a rotary encoder which not only increases the total cost but also makes the system prone to mechanical noise. Besides, such mechanical devices require continuous monitoring and maintenance. Therefore, a speed sensor-less scheme was invented [12]. It resolves the problem associated with mechanical sensors but falls short in response time and accuracy. Because such systems often depend heavily on wind speed measurement and measuring wind speed with required precision is costly.

Typical WECS consists of rectifier, boost chopper and Pulse Width Modulation (PWM) inverters. In this configuration, both dc voltage and dc current provides suitable relationship for Maximum Power Point Tracking (MPPT) [13], [14]. Fuzzy logic and PI controller is widely used to find optimal operating conditions for photo voltaic (PV) and WECS [15], [16]. In this paper, a mathematical model of a WECS is established and a relationship between dc voltage and output power is derived from there. This mathematical relation provides an optimal model for maximum power tracking. This paper also demonstrates the implementation of the developed mathematical model through simulation by MATLAB/SIMULINK interface.

Furthermore, this paper introduces a novel algorithm,

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which provides a faster searching option compared to the conventional Perturbation and Observe (P&O) and look up table approaches. The validity of the proposed algorithm for control system was analyzed and investigated by comparing it with the conventional tracking system. A compressive conclusion was drawn finally from the detailed analysis conducted in this research work.

II. Mathematical Modeling of Wind turbine

The monotonic characteristic of wind turbine is suitable for finding maximum power using conventional search algorithm. The power output to grid is initially controlled by the pitch controller and then by power electronic converter. From the basic understanding of the physics of WECS, it is established that input power P_w can be expressed as [17].

$$P_w = 0.5\rho\pi R^2 V_w^3 \quad (1)$$

where R is the turbine blade radius, V_w is wind speed and ρ is air density in the vicinity of turbine. The turbine input torque is expressed as

$$T_{wind} = \lambda/\Omega_w \quad (2)$$

$$T_{wind} = 0.5\rho\pi R^3 V_w^2 \quad (3)$$

where Ω_w is the angular velocity of the turbine and λ is tip speed ratio. The tip speed is defined as

$$\lambda = R\Omega_w/V_{w.} \quad (4)$$

The turbine converts this wind power into mechanical power P_{mech} and is given by the following equation,

$$P_{mech} = 0.5\rho\pi R^2 V_w^3 C_p \quad (5)$$

where C_p is the input power coefficient which depends on the tip speed ratio λ and blade pitch angle β,

$$C_p(\lambda,\beta) = c_1\left(\frac{c_2}{\lambda_i - c_3\beta - c_4}\right)e^{-\frac{c_5}{\lambda_i}} + c_6\lambda \quad (6)$$

here c_1=0.5167, c_2=116, c_3=0.4, c_4=5, c_5=21 and c_6= 0.0068.

Tip speed ratio and pitch angle are related by the following equation,

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (7)$$

The relationship between power coefficient, pitch angle and tip speed ratio is shown in Fig.1.

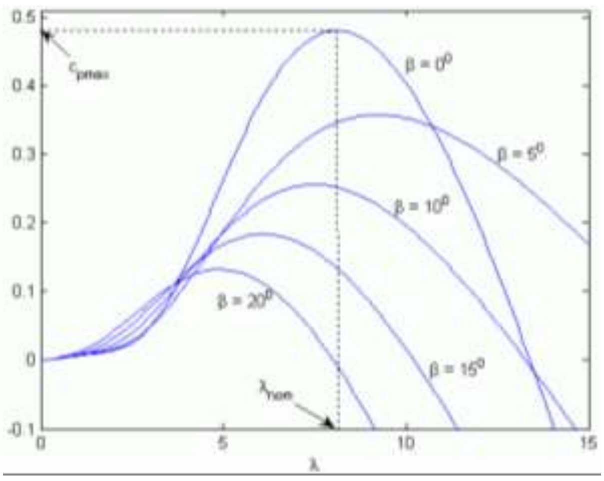


Fig.1 Relationship between the power coefficient and the tip speed ratio λ

It can be said from Fig.1 that the power extraction will be maximum when the pitch angle of the blade is zero degree.

At maximum power, the tip speed ratio has a fixed value. The output power, P is obtained from equation (4) and (5), which is shown in equation (8).

$$P = k_1\Omega_w^3 \quad (8)$$

Using equations (3) and (4), the output torque can be derived as

$$T = k_2\Omega_w^2 \quad (9)$$

As of now, most of the MPPT algorithms are based on equations (8) and (9) even though such algorithm has slow convergence and are subjected to mechanical wear and tear [18].

In modern WECS as shown in Fig.2, the mechanical power produced by the rotating wind turbine is directly fed to a permanent magnet generator. Although the conventional induction generator has the advantage of robust construction and maintenance free operation, it has some limitations like low power factor and need for external excitation source. Introducing permanent magnet synchronous generator (PMSG) into conventional WECS enables a gearless scheme. The slow speed of the turbine can be compensated by a larger rotor with multiple poles so that it can produce a large amount of current [19].

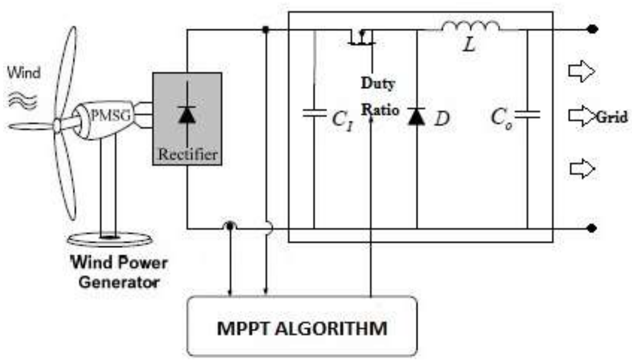


Fig. 2 Overview of a typical wind energy conversion system

The alternating power produced in PMSG is then converted to DC using a simple diode bridge rectifier; this reduces cost associated with sophisticated converters and their controls. The back emf in PMSG, for a constant flux is given by the following equation,

$$E = \left(\frac{1}{\sqrt{2}}\right)\Omega_w p\phi \quad (10)$$

where E is the back emf of the generator, p defines the number of poles that the generator has and ϕ signifies the flux associated with the generator. The mathematical expression for average dc voltage V_{dc} of a diode bridge rectifier is taken from [20].

$$V_{dc} = \frac{3\sqrt{6}}{\pi}E - \frac{3}{\pi}\Omega_w p L_s I_{dc} \quad (11)$$

From equation (10) and (11), it can be derived that

$$V_{dc} \propto \Omega_w \quad (12)$$

It is then evident from equation (8) and (12) that

$$P = k\,V_{dc}^3 \quad (13)$$

An algorithm for MPPT can be achieved using this relation between total power and dc voltage, which eliminates mechanical disturbances and enables quick tracking of maximum power point.

There are many algorithms to use the above described relations for maximum power tracking [21]. The P&O also known as the hill climbing approach is the most common among them. In this method one dictating parameter is increased or decreased depending on the successive measurement of power produced by the system. This searching method is widely used in photovoltaic system but the high inertia associated with wind turbine makes this approach slow and untidy. Some algorithms involve two dimensional look up table searching, but it requires extensive field experimentation and prior knowledge of the system.

III. Proposed Control System

A. MPPT Algorithm

Tracking of maximum power in WECS can be achieved by using equation (13). The relationship between power and turbine shaft speed of WECS is presented in Fig. 3.

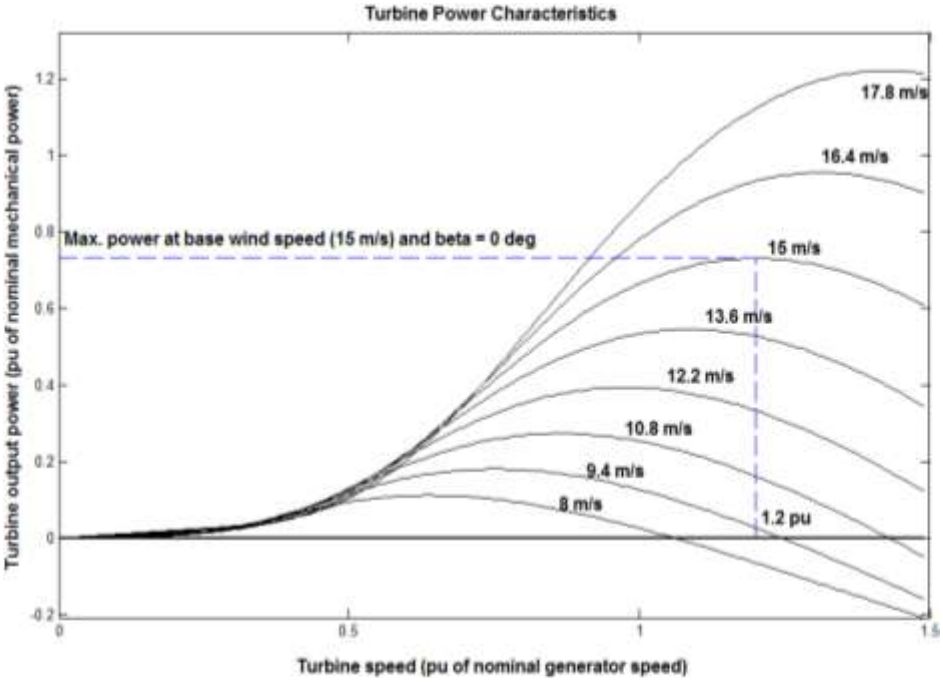


Fig.3 Turbine output power vs. rotor speed characteristics.

From equations (8), (12) and (13) it can be said that the voltage-power relationship will be almost similar to that of shaft speed and power. The simulation results also suggest the same.

The average dc voltage and power relation for different wind speed V_{w1}, V_{w2} and V_{w3} is given in Fig. 4.

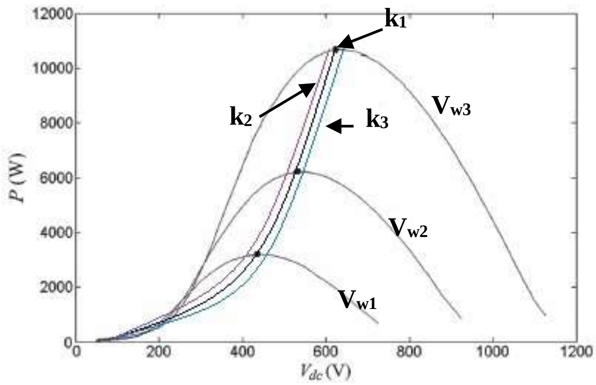


Fig. 4 Power vs dc voltage curves of WECS at different wind speed.

Output power reaches maximum value for a particular value of dc voltage, assuming that the wind speed remains constant. In practical experience as the wind speed varies, changing the dc voltage accordingly can yield maximum power at that wind speed [19].

However, it is also noticeable that varying constant *'k'* also yields a tracking algorithm as we already know the system behavior.

$k_1 = \frac{P_1}{V_{dc1}^3}$; $k_2 = \frac{P_2}{V_{dc2}^3}$; $k_1 = \frac{P_3}{V_{dc3}^3}$

As seen from Fig. 4, the maximum power points form an exponential shape, it can then be assumed that

$$k = ae^{\theta} \tag{14}$$

Replacing the value of 'k' in equation (13) we obtain,

$$P = (ae^{\theta})\, V_{dc}^3 \tag{15}$$

Now changing θ of equation (15), we get maximum power since "a" is merely a constant that does not change with varying wind speed, and it can be calculated from the rated value of the system. The power through the grid can be controlled by controlling the boost duty ratio of the dc-dc converter. The dc power is then converted into AC power using a voltage regulated inverter before it is fed into the micro grid.

Fig. 5 shows the block diagram of the proposed MPPT controller. The control algorithm is very similar to the conventional P&O except that 'θ' is used as the controlling parameter here. In conventional algorithm, V_{dc} is increased using Newton Raphson formula [14] and the power established changes according to equation (13). In the proposed system, the ‘θ’ is changed linearly to search the optimum operating condition. It reduces the system complexities without hampering the convergence time.

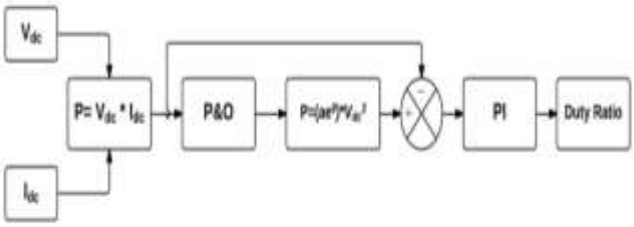


Fig.5 Structural diagram of proposed MPPT controller.

The flow chart of the MPPT control algorithm is shown in Fig. 6. At the beginning of the process, the dc voltage and current are measured from the system. The dc power is then calculated from the measured value, and it is considered as the present value. This present value is compared with the previous value of the dc power. If the difference value is positive, θ is incremented by an amount $\Delta\theta$, whereas in case of negative value it is decremented by the same amount.

At the convergent point of power, the difference will be zero. This value of θ is substituted in equation (15). The difference value of calculated dc power and measured dc power is then used in a PI controller and produces the boost duty ratio signal from the dc/dc converter.

B. Pitch Controller

The pitch of the blade affects the power extraction from wind. The conventional way of controlling pitch involves a PI controller using power feedback from the system [22]. Other systems use Fuzzy logic (FL) to design the controller [23][24]. However, a new Fuzzy-PI controller is designed here to control blade pitch.

This controller uses torque feedback instead of power feedback and simulation results show that this Fuzzy-PI controller has sufficient control over power. It opts the system to a minimum pitch angle, which helps the turbine to extract more power than individual FL or PI controller. Moreover, the fuzzy-PI controller has inherent capability to perform under rapidly varying wind speed, whereas a FL controller fails to show adequate response to turbulent wind signal. The block diagram of the pitch controller is given in Fig.7.

Three input variables are used in the FL controller e.g. wind speed V_w, torque deviation from its reference value ΔT and its variation during a sampled time $\delta\ (\Delta T)$. Here

$$\Delta T = T_e - T_{mech} \tag{16}$$

$$\delta\ (\Delta T) = \Delta T_m - \Delta T_{m-1} \tag{17}$$

The fuzzy interface system variables are given in Fig. 8. Nine membership functions are used to describe the system and build fuzzy rules.

The relation between input and output variables in fuzzy logic is obtained under following considerations. There are a total of 74 logic rules in the “Fuzzy Interface System” proposed here. Some of the rules are explained below:

i. If (ΔT) and $\delta\ (\Delta T)$ both are negative low while wind speed is positive medium low the pitch angle has to be decreased rapidly in order to increase power extraction.
ii. If (ΔT) is negative low and wind speed is positive medium high, the pitch angle has to be increased but rather smoothly than previous condition.
iii. If (ΔT) is positive low and wind speed is positive medium high, the blade angle should be kept constant.
iv. If wind speed is positive high-high, under any circumstance of (ΔT) and $\delta\ (\Delta T)$ the pitch angle has to be increased rapidly.

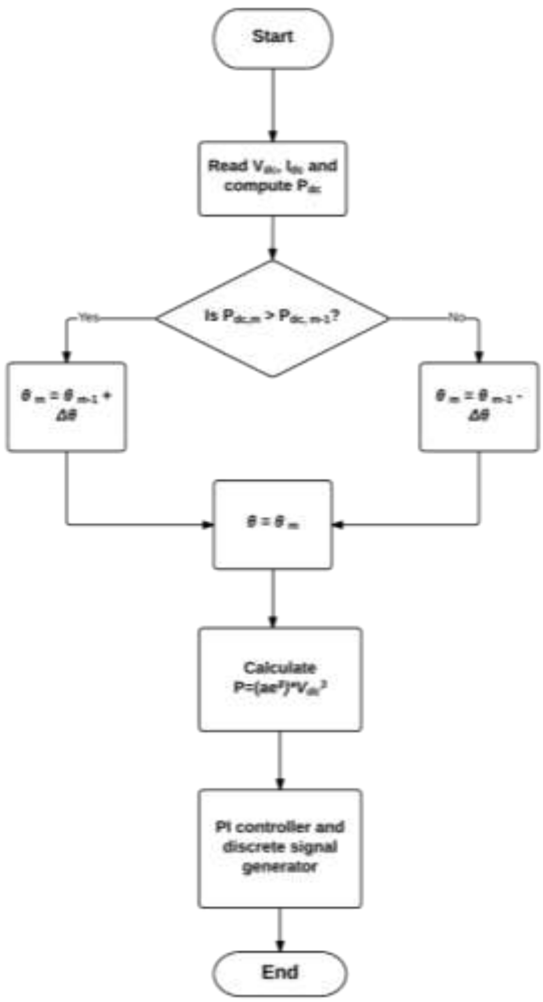


Fig. 6 Flow chart of MPPT control signal generator

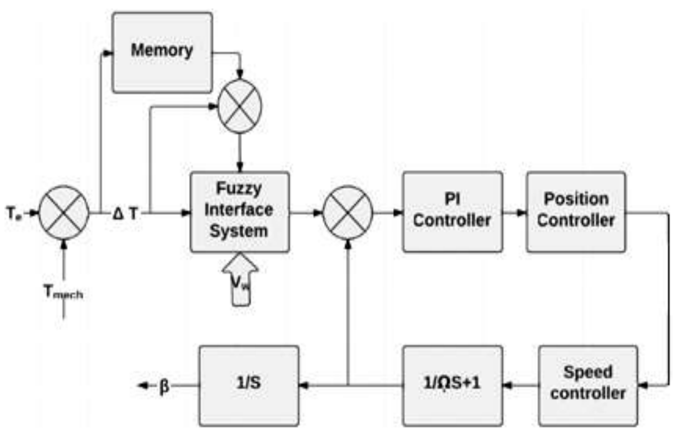
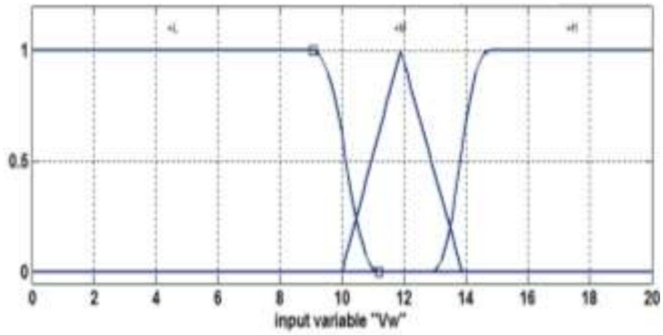
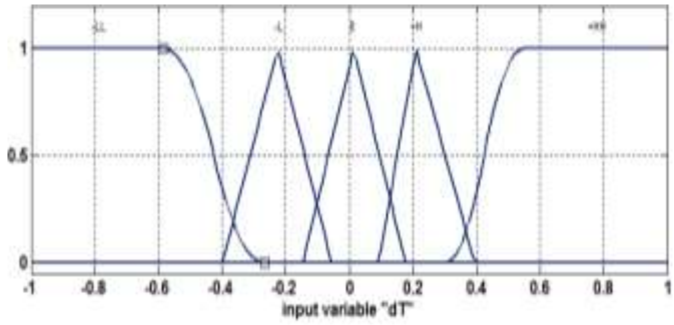


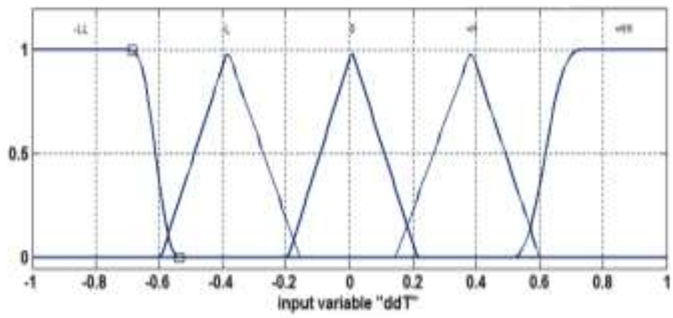
Fig. 7 Overview of Fuzzy-PI pitch controller



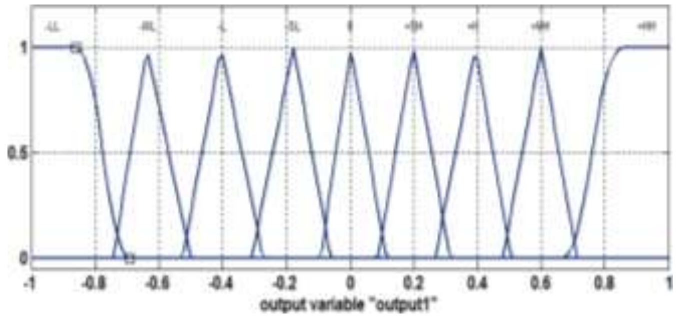
(a)



(b)



(c)



(d)

Fig. 8 Membership functions of Fuzzy-PI controller input and output variables; (a) wind speed input, (b) torque deviation ΔT, (c) difference between successive torque variation, (d) pitch output variable.

The surface view of the fuzzy logic rule set is shown in the Fig. 9. It represents the relationship between preset input variables and output variation based on the fuzzy rules.

C. Grid Side Converter Control

A voltage regulated PWM technique is used to control the grid side converter as shown in Fig. 10.

The design of the controller is focused on maintaining the fixed voltage at the load side. It consists of two basic parts, a voltage regulator which depends on line-line voltage and a discrete PWM signal generator which receives reference signal from voltage regulator. The voltage output at inverter depends on the modulation index. Assuming that the mean value of the modulation index, m = 0.9, and the mean value of the DC voltage is 587 V in steady state, the fundamental component of 50 Hz voltage buried in the chopped inverter voltage is V_{ab}= 587 V ×0.612 ×0.90 = 323 V (*rms*).

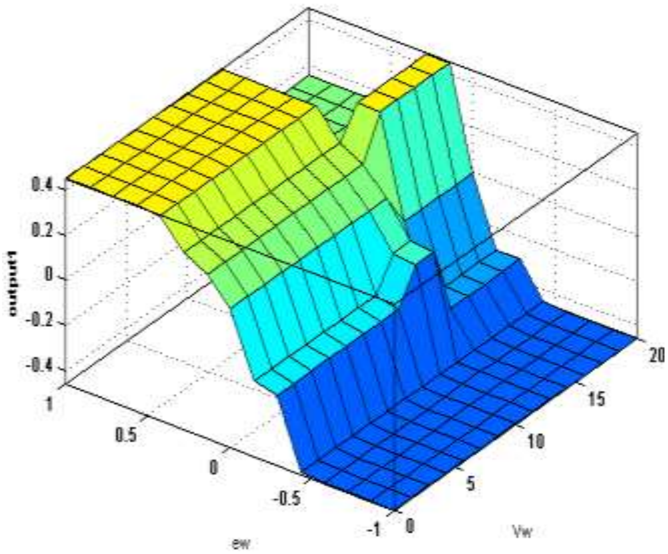


Fig.9 Surface view of the fuzzy logic output vs. input relation.

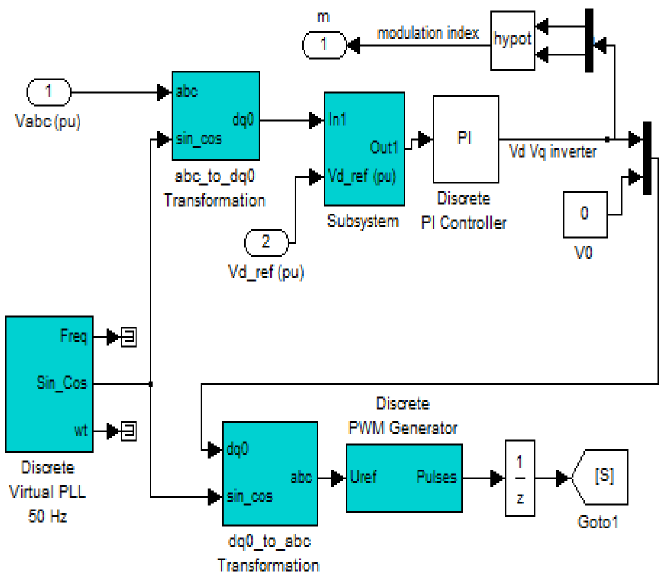


Fig. 10 PWM IGBT inverter controller configuration

IV. Simulation Result

Numerical simulations are performed on wind turbines in order to study the effectiveness of the proposed MPPT technique. The specifications of the wind turbine under consideration are given in Table I. This specification corresponds to the Department of Energy (DOE) General Electric (GE) turbine, located at National Renewable Energy Limited (NREL). The GE 1.5SLE is a variable speed, variable pitch three bladed wind turbine with nominal power rating of 1.5MW and hub height of 80 m (262.5 ft.) [25]. However, a PMSG is integrated in the model instead of asynchronous generator in order to construct a gearless scheme and to make the model suitable for micro-grid distributed generation concept. One essential aspect while designing a wind speed controller is whether the controller can handle the high wind speed during a storm. During storm, the wind speed may reach a critical value which can destroy the structure of the turbine.

TABLE I
WIND TURBINE SPECIFICATION

DOE GE1.5 SLE TURBINE	Rating
Production (NWTC Site)	1,600 MWh/y
Tower Height	80 m (262.5 ft)
Rotor Diameter	77 m (252.6 ft)
Swept Area	4.6k m^2 (50.1k ft^2)
Total Height	119 m (388.8 ft)
Met Tower Height	134.1 m (440 ft)

In case of proposed control, the system cut-off wind speed is 53m/s i.e. at 53 m/s the control system will direct the turbine to present a steep pitch angle so as to reduce the power generation and cut-off.

To simulate this scenario, the wind speed is varied from 8 m/s to 65 m/s (variation of wind speed is done within 0 to 40 seconds) and the output power and rotor speed is observed. This simulation results are shown in Fig.11 & 12.

The controller constantly monitors the rotor speed and wind speed and as soon as they go beyond rated value, it poses a high pitch angle. Resultantly the output power and generator speed falls to zero which is evident from Fig.11 and Fig. 12.

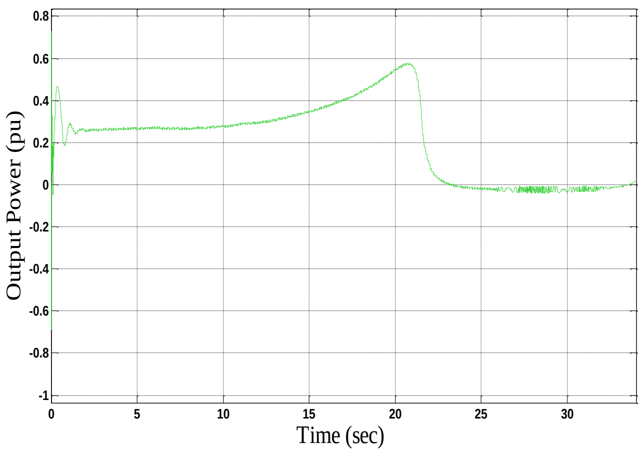


Fig.11 Overall output power of the turbine between cut-in and cut-off wind speed

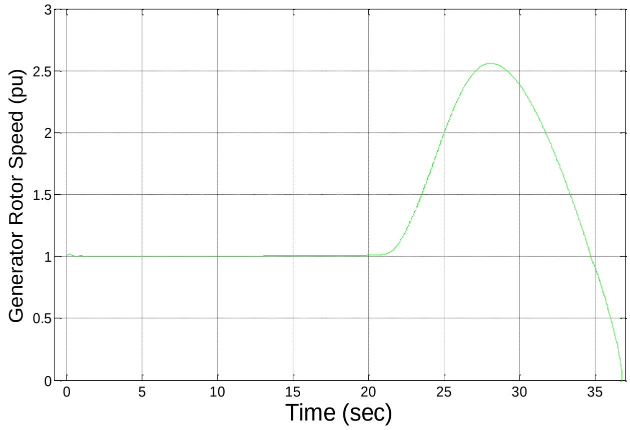
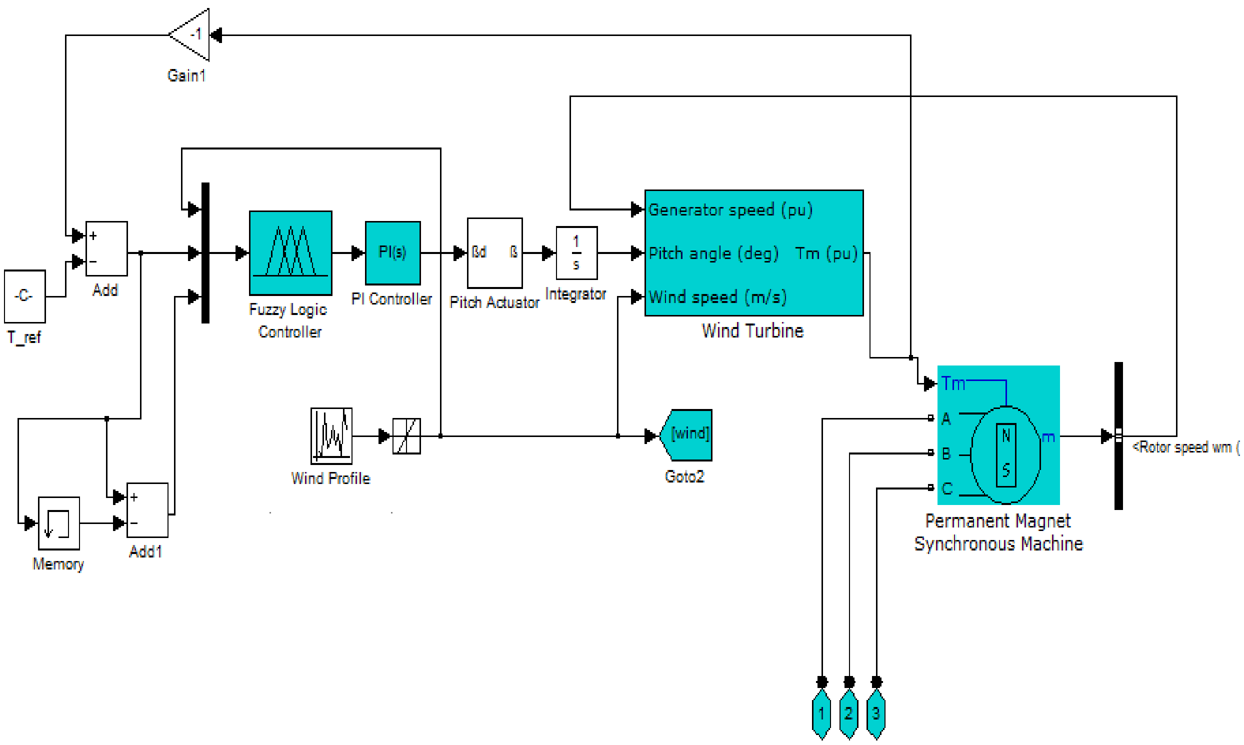
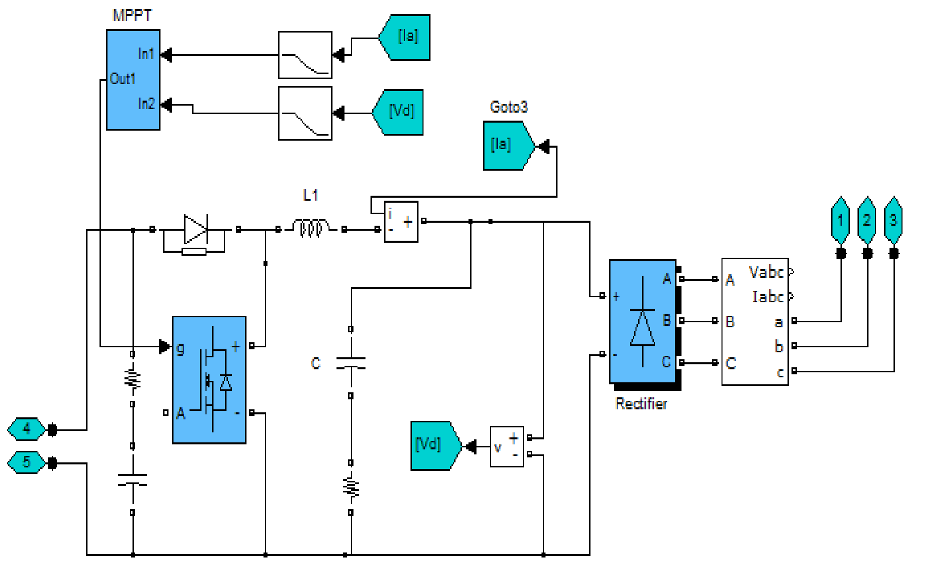


Fig.12 Overall rotor speed of the turbine between cut-in and cut-off wind speed



(a)



(b)

Fig.13 (a) WECS generation block including Fuzzy-PI controller proposed in this paper, (b) dc/dc controller block

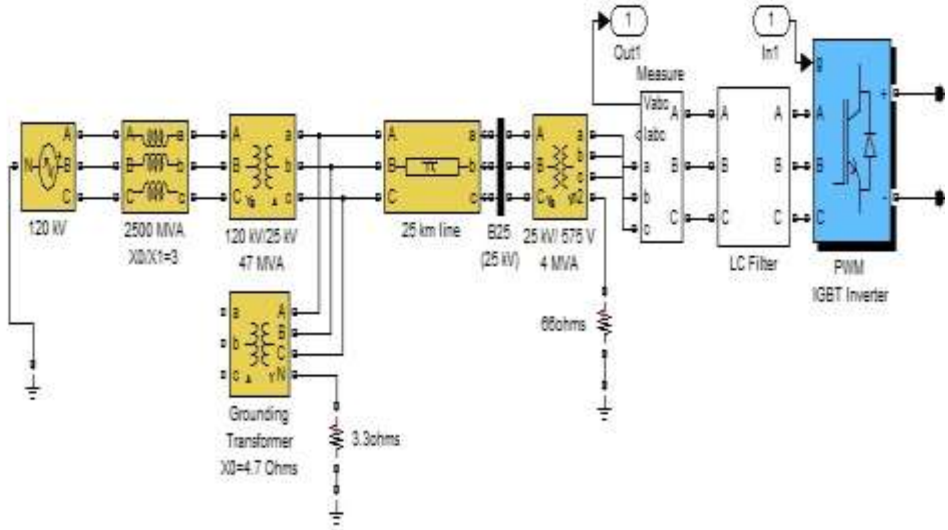


Fig.14 PWM IGBT inverter with a connection to the grid

The WECS model shown in Fig.13 and Fig. 14 can be described in three parts, (a) generation block, (b) control block, (c) load block. The generation block consists of Fuzzy Logic controller, PI controller, wind turbine block, wind profile generator and PMSG as seen from the figure Fig 13(a). This is the primary block of the WECS. The fuzzy logics and controllers used in this block are explained. The power generated at this block is fed to the rectifier where it is converted to dc power. Ripple in dc voltage is controlled by a boost converter. The MPPT controller proposed here can be seen in Fig. 13(b). There the dc voltage and current measured after the rectifier end is fed into the MPPT controller to produce a reference gate control signal for IGBT. Thus by controlling the gate signal of IGBT, the output power of the wind turbine is controlled. The dc-to-dc converter parameters were selected based on the generator power capacity and voltage ripple requirements of the output voltage of converter. The converter parameters are as follows, Low voltage side capacitor C=5000 μF, High voltage side capacitor C_1=3600 μF, Inductor L =2 mH, Switching frequency f_d =20 KHz. The load side of the system is connected to 25 KV transmission line through LC filters.

The simulation results are shown in Fig.15. For comparison with the proposed method the conventional P&O technique as is also simulated. The blue lines in simulation result represent the proposed model whereas the red lines represent conventional approach. All the characteristics have been analyzed in time domain. An essential part of any wind turbine simulation model is the wind speed model since the output power generated by the wind turbine is directly manipulated by it. Typically wind flow of any particular area remains the same over the year. However, the short time behaviour of the wind profile can be influenced by surface condition of tree, building and water areas. These factors combine together to produce turbulence in wind flow. As a result, these factors are an important consideration in the simulation model and a turbulent wind profile should always be preferred over uniform wind functions. In this research work a turbulent wind profile of 13.5 m/s mean speed is generated to observe the effectiveness of the model. The wind profile is shown in Fig. 15(a).

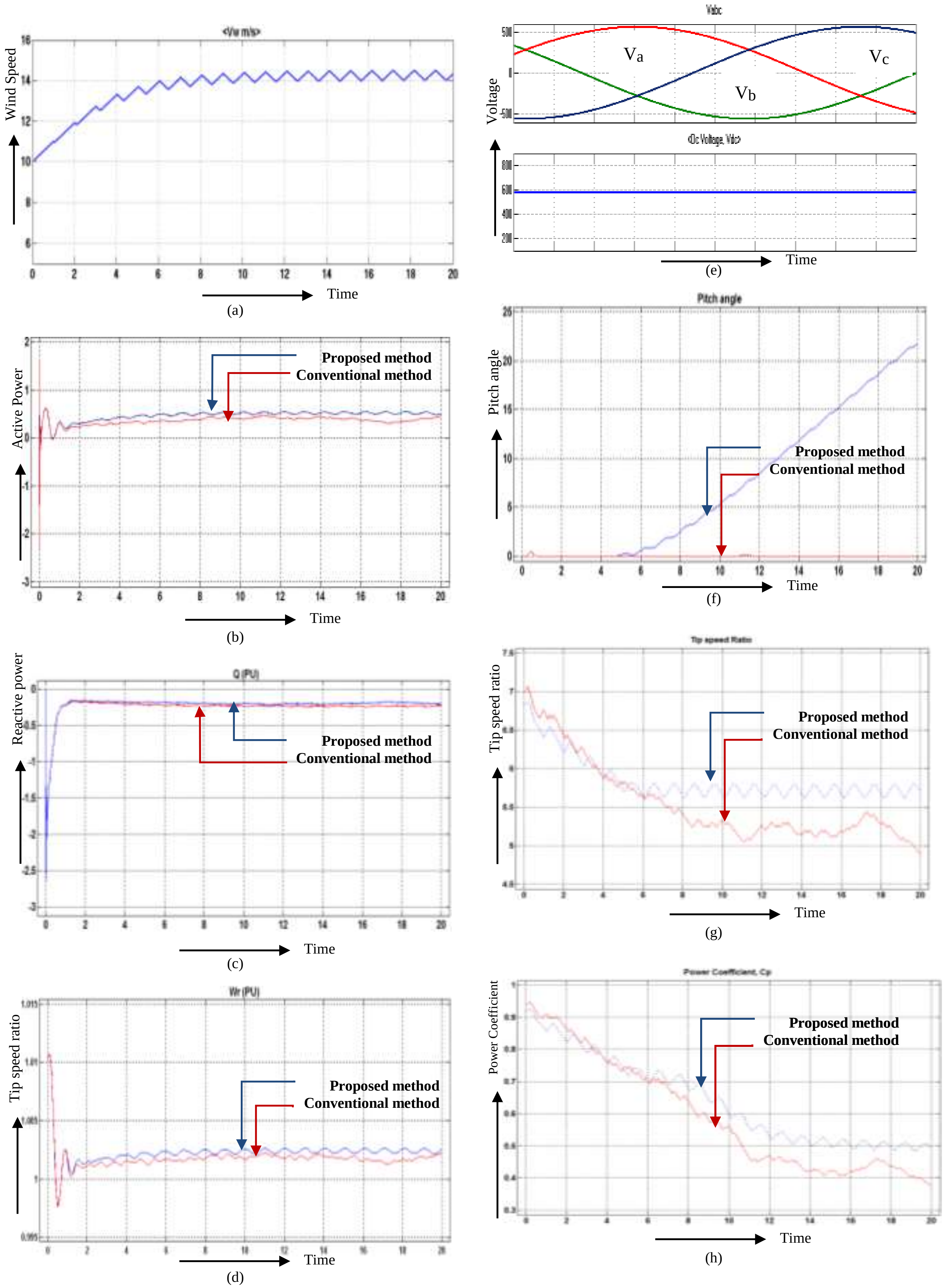


Fig.15 Comparison between Proposed P&O and conventional P&O (a) Wind profile with 13.5 m/s mean wind speed (m/s), (b)Output Power (PU), (c)Reactive Power (PU), (d) Rotor Speed (PU), (e) Ac voltage at the generator terminal and dc link voltage after rectifier, (f) Pitch angle (g) Tip speed ratio (PU), (h) Power coefficient (PU).

As seen from Fig. 15(d) the rotor tracks wind speed better, with the proposed approach. As a result, power extraction from wind is also better in this approach as seen in Fig. 15(b). The reactive power required by WECS system is shown in Fig. 15(c). It is found that the proposed system reduces reactive power consumption by 1% - 2%. Fig.15 (e) shows the ac voltage measured at the generator terminal and dc link voltage after the rectifier. The dc link voltage is kept constant at 575V peak - peak over the range of system operation.

The change in pitch angle with wind speed is shown in Fig. 15(f). Initially the pitch angle remains zero at low wind speed and as the wind speed increases; the pitch angle rises and takes the system towards stall in case wind speed reaches a preset point. The power coefficient and tip speed ratio of wind turbine is shown in Fig. 15(g) and (h).

Power coefficient of wind turbine is a function of rotor speed and wind speed based on equation (4), (6) and (8). As seen from the simulation result, the power coefficient drops whenever wind speed deviates from optimum value. However, it is seen that by using proposed technique; drop in power coefficient (C_p) can be controlled to a minimum level.

V. CONCLUSION

In this paper a WECS model with PMSG is presented which is suitable for distributed generation as well as a standalone unit. A relationship between dc voltage and power is derived and analyzed theoretically to establish the basis for a new MPPT technique. In order to obtain maximum power point, the conventional P&O technique is modified and a new perturbing parameter has been introduced. The proposed method overcomes the shortcomings of conventional approach and combines the advantages of P&O and look up table. The hunting problem of conventional P&O technique is reduced to some extent since it employs a vertical hunting. Simulations were carried out to verify the theoretical analysis and to investigate the differences between two models. It was found that the modified P&O approach proposed in this paper increases the overall system efficiency by 5-7%. It also provides a better response with turbulent wind variation. Simplified optimum mathematical relationship is used in the proposed control algorithm as a result it reduces computational complexity. The proposed method is more suitable for systems with higher inertia to track maximum power.

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