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DEVELOPMENT OF INTELLIGENT CONTROLLER FOR POWER RIPPLE MITIGATION OF DFIG BASED WIND ENERGY SYSTEM

Garima Vyas[1], Shripati Vyas[2]
Email Id: garima29vyas92@gmail.com
[1,2]Department of Electrical Engineering, Geetanjali Institute of Technical Studies, Udaipur, Rajasthan, India

ABSTRACT: This study offers an adaptive neuro-fuzzy controller (NFC) for a wind energy conversion system (WECS) based on a doubly fed induction generator (DFIG) that may run in standalone mode. The adaptive-network-based fuzzy inference system (ANFIS) architecture is the foundation upon which the NFC is built since it offers the singular benefit of rapid convergence while integrating the resilience of fuzzy logic and flexibility of neural network algorithm. The load side converter (LSC) control of ANFIS is intended for the independent operation of DFIG-WECS. By keeping output voltage consistent, the suggested approach shows increased dynamic performance under conditions of fluctuating wind speed and load. Due to the precise control of the LSC, the supply frequency to the load is kept consistent even while the turbine rotation changes with changing wind speed. The rotor side converter's proportional-integral (PI) control maintains the flux alignment. The simulation outcomes demonstrate the controller's exceptional performance through its effective management of supply frequency and load-voltage under variations in wind speed and demand load power.

KEYWORDS: Doubly-fed Induction Generator, Wind Energy, Standalone mode, Neuro-Fuzzy Controller.

1. INTRODUCTION

Due to its ability to operate over a larger speed range than its competitors, doubly fed induction generators are now widely used in wind energy conversion systems (WECS) [1]. High magnetising currents are drawn from the electrical grid by traditional squirrel cage asynchronous generators. On the other hand, DFIG makes it easier to operate in sub-synchronous or super-synchronous modes, use low-power converters on the grid side or rotor side, and control actual and reactive power independently. DFIG can function in a freestanding (in a remote place) or grid-connected mode depending on the demand (where existing grid is available). The generator should be able to supply power to the local backup store and base load during standalone operation.

The intermittent nature of wind flow makes it impossible for the wind generator to operate alone without the assistance of additional power sources. For standalone operation of DFIG powered WECS, various alternative energy sources have been selected, including flywheel-based energy storage [2], turbine driven by water flow [3], hybrid energy storage backed by a diesel engine [4], and photovoltaic panel [5]. However, the battery storage-based standalone wind turbine power system became more well-liked due to its simplicity of operation and practical storage space [6–8].

Power electronics interfaces are built into the machine to control voltage and frequency in order to handle power variations from the energy source. Different control strategies have thus far been put out for the control operation of DFIG, whether it is feeding the grid or operating as a standalone load. In the literature, power management methods like direct power control [10] and vector control [9] have been proposed to control the power output of DFIGs operating in standalone mode under balanced and unbalanced conditions.

Only a few studies on the standalone mode operating of DFIG in wind power islanding mode under variable speed conditions have been found, in contrast to the numerous research endeavours on grid-connected DFIG-WECS [11–13]. DFIG's dc voltage regulation in SA mode is proposed in [14] using a direct torque control approach. The model, however, uses a PI controller alone, and its output shows torque pulsation. Iwanski [13] has suggested a PLL-based angle loop control for better frequency management.

A direct voltage control based on negative-sequence compensation was suggested by researchers in a different study to accommodate asymmetric loads [15]. The performance of the wind power control under fluctuating wind speed or applied torque hasn't been demonstrated in the concept, though. For solo functioning of DFIG, intelligent control methods like neural networks (NN), neuro-fuzzy controls (NFC), or adaptive network-based fuzzy inference systems (ANFIS) have not yet been substantially studied.

ANFIS, one of the NFC methods, offers flexibility in selecting the membership functions and quick convergence because of its hybrid learning. ANFIS architecture also combines the capability of fuzzy reasoning in addressing uncertainties and the learning capacity of neural networks from complex systems, giving it the distinctive property of modelling a highly nonlinear system [16]. As a result, it has been shown that ANFIS is a viable option for addressing the nonlinearities and uncertainties associated with induction machines, such as fluctuating wind speed, an imbalanced load, fault circumstances, etc.

As a result, this article suggests the ANFIS-based NFC approach for converter control. In this study, a neuro-fuzzy network-based control scheme based on ANFIS is designed for the standalone operating mode of DFIG-WECS, where the load side converter is driven. The proposed controller seeks to set a specific value for the terminal voltage and frequency. The transient response of the DFIG-WECS with the planned PI controller under varying demand power and fluctuating wind speed conditions is used as the example input-output data for training the ANFIS structure. The suggested ANFIS structure is trained using a back-propagation and least squares function algorithm and a Gaussian type of function as the membership function. The controller's robustness is tested in a simulation with varying circumstances. The real-time experimental model of the suggested approach is currently being created by the authors.

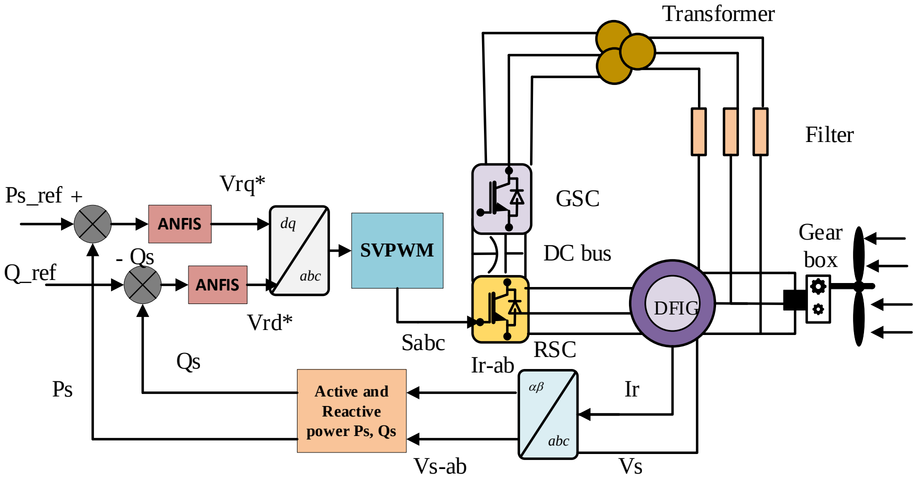

Fig. 1.1 Overall Configuration of the ANFIS based DFIG-WECS

2. PROPOSED DFIG-WECS CONFIGURATIONS FOR SA MODE

In DFIG-based WECS, the generator is powered by the wind turbine, which also converts rotational mechanical energy into electrical energy. The generator's stator is directly connected to the grid, while the rotor interfaces with the grid via a power converter device with a limited amount of power [17]. To change the turbine rotor's low speed to the generator's high speed, a gear box is required. To attain a high conversion ratio to couple the turbine shaft and rotor of the generator, the gear box is typically multi-staged. At the rotor side and the grid side are two back-to-back converters that can be independently regulated.

When the end customers are located far from the national supply grid, an isolated generation system is necessary. The system must have enough storage space to accommodate power variations from the available wind energy source for a standalone use of WECS. So, in addition to the dc bus capacitor, additional storage devices like batteries and fuel cells are attached. DFIG-based WECS's independent operation is shown in Fig. 1. Table-I lists the load, DFIG, and wind turbine specifications that were used in the simulation. A unique ANFIS-based NFC technique is designed to manage the converters for isolated operation of DFIG in order to deal with induction machine nonlinearities, uncertainties in wind speed, and load circumstances.

The d-q axis voltage and flux equations [17] in a synchronous rotating reference frame can be used to derive the dynamic model of the DFIG, as shown in (1)- (8). By substituting the arbitrary speed with the synchronous speed s, the DFIG arbitrary reference frame model can be converted into the d-q transformation model.

$$v_d = R_s \mathrm{i}_{ds} + p f_{ds} - \omega_s f_{qs} \qquad (1)$$

$$v_q = R_r \mathrm{i}_{dr} + p f_{qs} + \omega_s f_{ds} \qquad (2)$$

$$v_d = R_r \mathrm{i}_{dr} + p f_{dr} - (\omega_s - \omega_r) f_{qr} \qquad (3)$$

$$v_q = R_r \mathrm{i}_{qr} + p f_{qr} + (\omega_s - \omega_r) f_{dr} \qquad (4)$$

The d-q axis flux linkages can be related to the corresponding currents by the equations mentioned in (5)-(8),

$$f_{ds} = (L_{ls} + L_m)\mathrm{i}_{ds} + L_m \mathrm{i}_{dr} = L_s \mathrm{i}_{ds} + L_m \mathrm{i}_{dr} \qquad (5)$$

$$f_{qs} = (L_{ls} + L_m)\mathrm{i}_{qs} + L_m \mathrm{i}_{qr} = L_s \mathrm{i}_{qs} + L_m \mathrm{i}_{qr} \qquad (6)$$

$$f_{dr} = (L_{lr} + L_m)\mathrm{i}_{dr} + L_m \mathrm{i}_{ds} = L_r \mathrm{i}_{dr} + L_m \mathrm{i}_{ds} (7)$$

$$f_{qr} = (L_{lr} + L_m)\mathrm{i}_{qr} + L_m \mathrm{i}_{qs} = L_r \mathrm{i}_{qr} + L_m \mathrm{i}_{qs} \qquad (8)$$

where,

$v_{ds}, v_{qs}, v_{dr}, v_{qr}$—d-q axis stator and rotor voltages (V)

$\mathrm{i}_{ds}, \mathrm{i}_{qs}, \mathrm{i}_{dr}, \mathrm{i}_{qr}$— d-q axis stator and rotor currents (A)

$f_{ds}, f_{qs}, f_{dr}, f_{qr}$ – d-q axis stator and rotor flux-linkages (Wb)
R_s, R_r— stator and rotor winding resistances (Ω)
ω_s, ω_r—synchronous and rotor electrical angular speed (rad/s)
p —derivative operator ($p = d/dt$).
$L_s = L_{ls} + L_m$ —Stator self-inductance (H)
$L_r = L_{lr} + L_m$ —Rotor self-inductance (H)
L_{ls}, L_{lr}— Stator and rotor leakage inductances (H)
L_m— Magnetizing inductance (H)

3. PROPOSED ANFIS STRUCTURE

Before being applied to a practical wind-turbine system, the linear controller design for DFIG-WECS may require additional adjusting. Since a genuine DFIG-WECS contains numerous dynamics that are not entirely understood, it is quite challenging to create the ideal simulation model for it [18]. An authentic input-output data set can be used to recreate the membership functions of a fuzzy inference system to create an adaptive neuro-fuzzy inference system. The gradient descent approach yields variable parameters for the membership functions [19].

For estimating the membership function parameter, ANFIS networks combine least squares estimation and back propagation. Fig. 3.1 depicts a schematic of the proposed ANFIS architecture. [20] has information about the ANFIS structure in detail. A data-driven designing approach for the Takagi-Sugeno-Kang (TSK) fuzzy model has been presented in the suggested controller.

Rule 1: If (x is A_1) and (y is B_1) then $f_1 = p_1x+q_1y+r_1$
Rule 2: If (x is A_2) and (y is B_2) then $f_2 = p_2x+q_2y+r_2$

Here, r_i, p_i and q_i are the design parameters determined during the period of training phase.

Figure 4 depicts the overall block diagram of the ANFIS controller system used for the two-rule fuzzy system. There are two adaptive levels in the block structure (Layers 1 and 4). Three movable parameters for the input membership functions are present in Layer 1. (ai, bi and ci). These parameters were developed first. Three movable first degree polynomial-related parameters (ri, pi, and qi) are included in layer 4. The term "result parameters" refers to these variables.

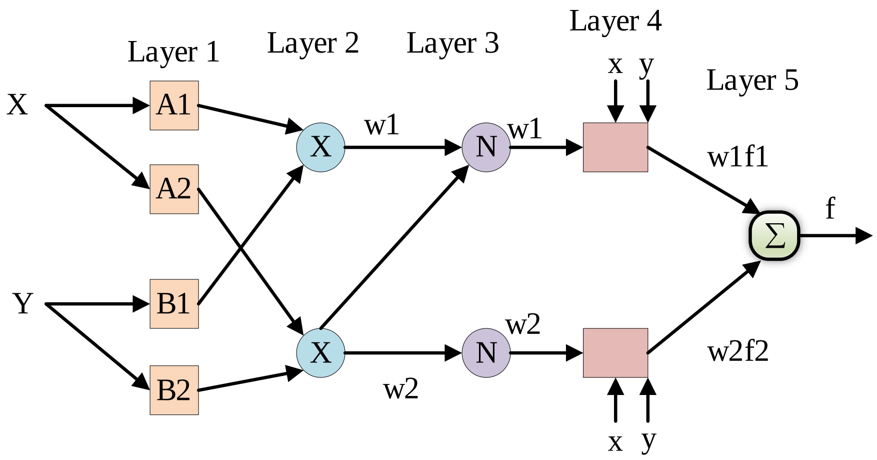

Fig. 3.1 The architecture of the ANFIS

The duty of learning or training algorithm for ANFIS is to change all the adjustable parameters to compare ANFIS output with trained data.

Layer 1: Each node produces the membership grades of a linguistic label. An example of a membership function is the generalised bell function. By changing the values of the parameters, the shape of the bell-shaped function varies. Parameters in that layer are called premise parameters.

Layer 2: Each node calculates the firing strength of each rule using the min or prod operator. In general, any other fuzzy AND operation can be used.

Layer 3: The nodes calculate the ratios of the rule's firing strength to the sum of all the rules firing strength. This results in a normalised firing strength.

Layer 4: The nodes compute a parameter function on the layer 3 output. Parameters in this layer are called consequent parameters.

Layer 5: Normally a single node that aggregates the overall output as the summation of all incoming signals.

4. SIMULATION MODEL

Using MATLAB, a 9 MW wind farm comprised of 6 X 1.5 MW machines is modelled and simulated. This farm is linked to a 25 kV distribution system, and a 25 kV, 30 km, 3-phase line transports 9 MW to a 120 kV grid. The wind speed in the simulation is held constant at 15 m/s. A torque controller is used to maintain 1.2 pu as the machine speed. The wind turbine's reactive power output is held constant at zero. In Fig. 4.1, a Simulink model of a 9 MW wind farm is displayed. Table-4.1 and provide, respectively, the machine's parameters.

Table-4.1 Parameters of DFIG based WECS

Stator voltage (Vs)	575V
Rotor voltage (Vr)	1975V
Frequency (f)	60Hz
Nominal power (P)	1.5MW
Stator resistance (Rs)	0.023**Ω**
Rotor resistance (Rr)	0.016**Ω**
Stator inductance (Ls)	0.018H
Rotor inductance (Lr)	0.016H
Mutual inductance (Lm)	2.9H
Pole pair (p)	3

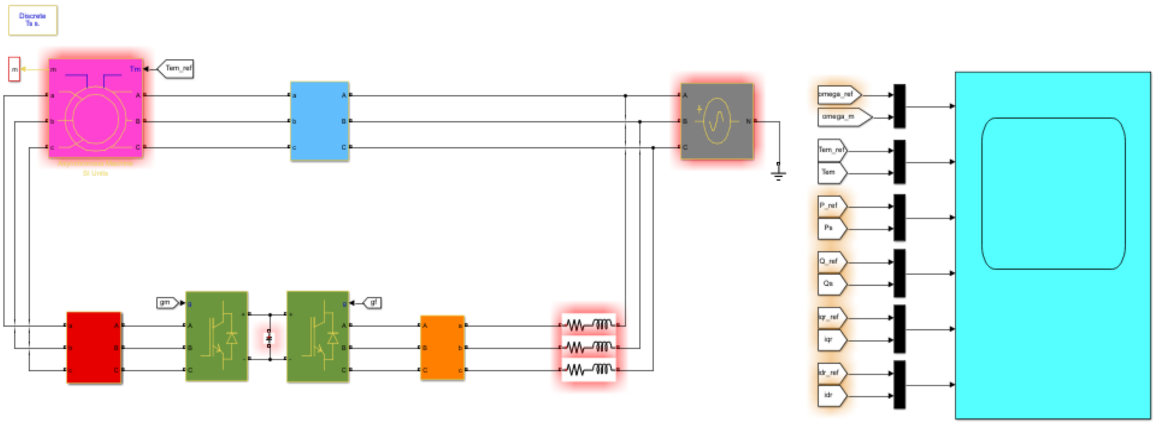

Fig. 4.1 Simulink Model of DFIG Wind Farm

5. RESULT AND DISCUSSION

In a simulation, the effectiveness of the suggested ANFIS controller-based DFIG-WECS is examined under various operating conditions, such as changeable wind speed and load variation in standalone mode. The LSC control aims to maintain a constant level of output voltage and frequency for the DFIG. It is assumed that the load power demand will always be smaller than the power produced by the wind turbine in order to simplify the control algorithm. Additionally, filtering capacitors are needed to get rid of the harmonic switching frequencies that the load-side and rotor-side converters both create.

A portion of the reactive power required for magnetization is also supplied by the capacitors. The filtering circuit is not displayed in the control structure to simplify the suggested approach. LSC control algorithm for DFIG-operated WECS with isolated load based on ANFIS. The integrated neuro-fuzzy algorithm has the ability to learn, which allows the suggested controller to follow changes in wind turbine speed and variations in power demand.

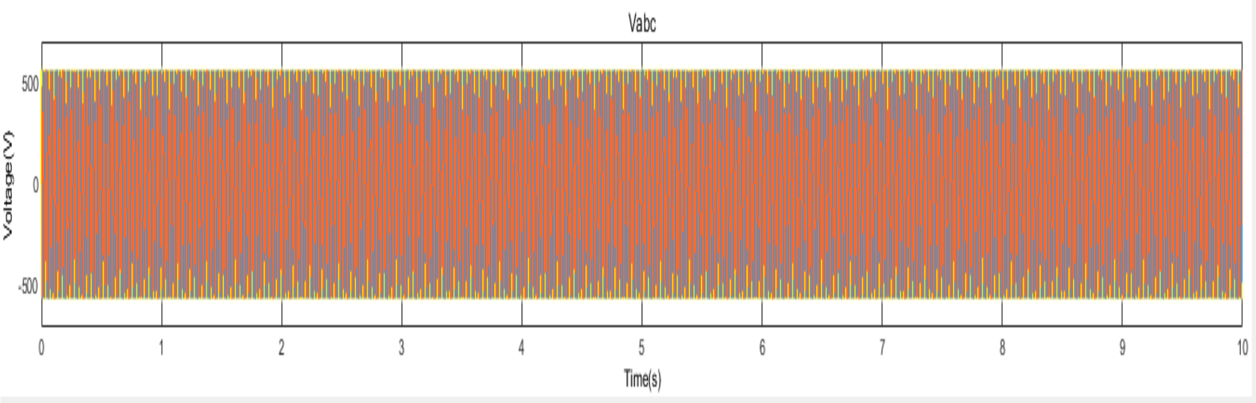

Fig. 5.1 Grid Output Voltage

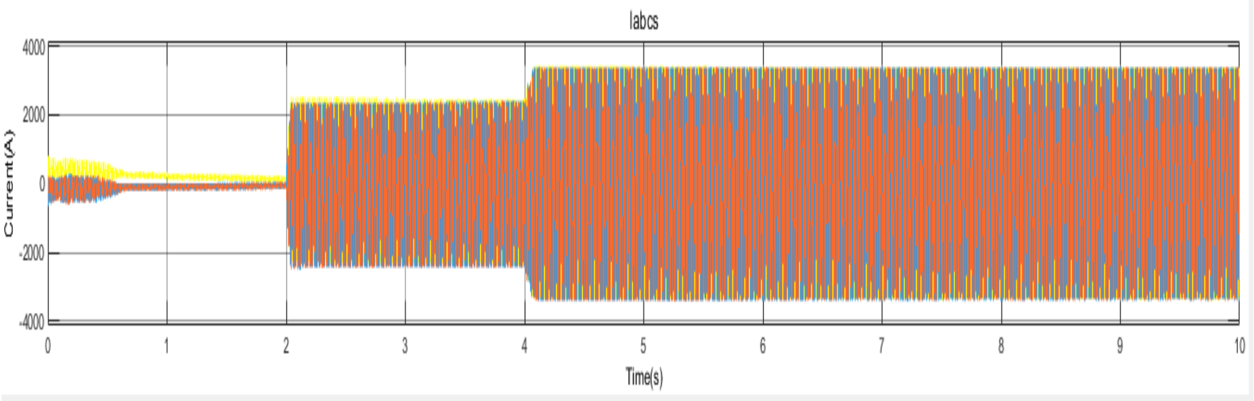

Fig. 5.2 Stator Current

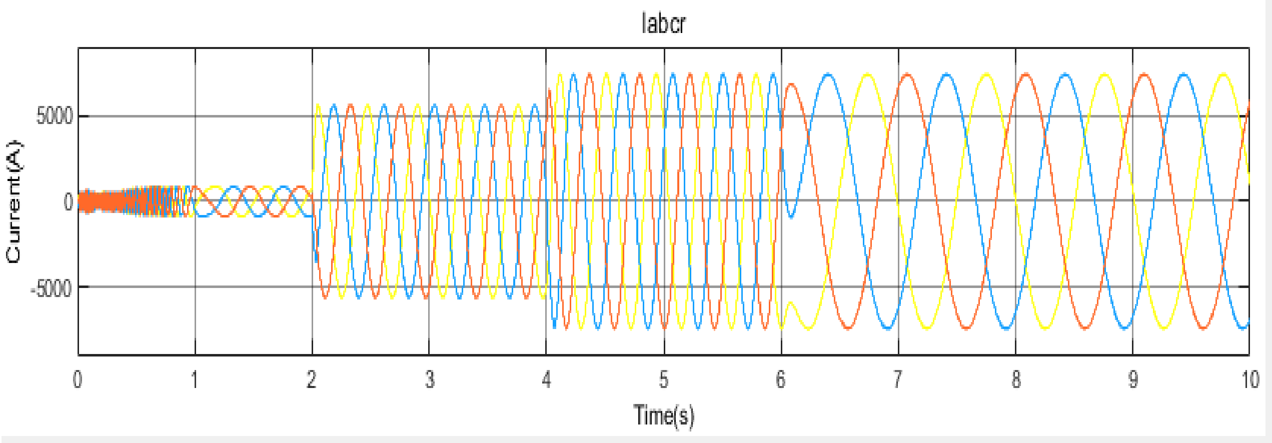

Fig. 5.3 Rotor current

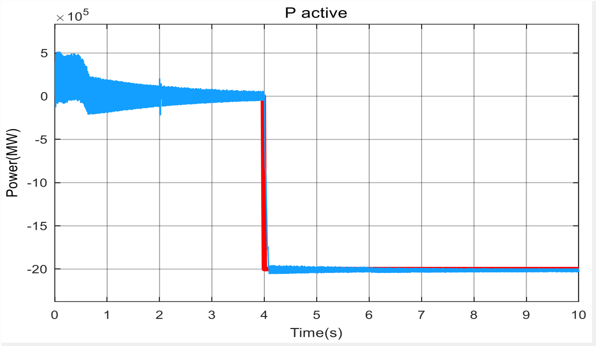

Fig. 5.4 Active power

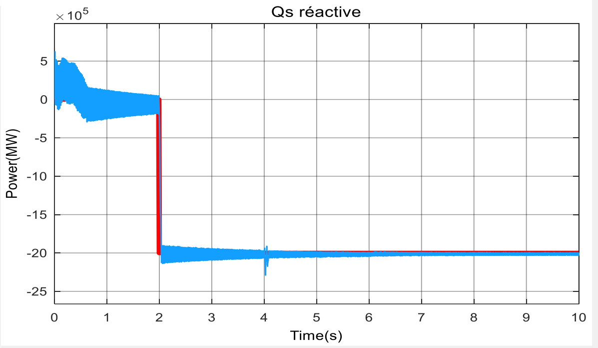

Fig. 5.5 Reactive power

CONCLUSION

This research presents a unique ANFIS-based NFC solution for DFIG-operated WECS. Under various dynamic operating situations, the suggested controller's performance for an isolated load has been examined. The simulation findings indicate that by modifying the rotor speed and machine torque in response to changes in wind speed, the LSC and GSC controller work together to regulate real and reactive power. Additionally, the suggested controller can maintain constant voltage and frequency at the load end even when the required power demand and wind speed abruptly change. The suggested controller's built-in learning ability ensures the adaptive compensation required by the nonlinearity of DFIG-WECS and overall system unpredictability. In the standalone working mode of DFIG-WECS, the study of the suggested scheme points to the superiority and reliability of the provided ANFIS architecture-based controller. The standalone DFIG-WECS based on the real-time lab model of the ANFIS controller is now being tested.

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