Fault-tolerant Control of a Wind Turbine with a Squirrel-cage Induction Generator and Stator Inter-turn Faults

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Abstract—Faults of wind turbine generator electromechanical parts are common and very expensive. This paper introduces a fault-tolerant control scheme for variable-speed variable-pitch wind turbines that can be applied to any type of generator. We focus on generator stator isolation inter-turn fault that can be characterized before triggering the safety device. A simple extension of the conventional control structure is proposed that prevents the fault propagation while power delivery under fault is deteriorated as less as possible compared to healthy machine conditions. Presented fault-tolerant control strategy is developed taking into account its modular implementation and installation in available control systems of existing wind turbines to extend their life cycle and energy production. Simulation results for the case of a 700 kW wind turbine are presented.

I. INTRODUCTION

Increasing interest in renewable energy sources and their growing impact on today's energy production motivated different branches of science to make contributions in price reduction, energy quality and market competence of renewables. After a huge breakthrough and an average growth rate of 27% in last 5 years, wind energy today is a well-tested technology with total world installed capacity of about 197 GW in 2010 [1].

Because low-turbulent and strong winds are favorable, remote locations are best suitable for wind turbines. This introduces difficult and expensive maintenance procedures and rises availability concerns. Different fault-tolerant control algorithms have been introduced in [2] and they mostly propose different kinds of redundancies for sensors and electronic components. Focus here is on generator electromechanical faults, which are besides gearbox and power converters faults the most common in wind turbine systems [3].

Due to the lowest failure rate among all kinds of machines [3], many already installed wind turbines have a squirrel-cage induction generator (SCIG). In our recent papers [4] and [5] we proposed a general idea of fault-tolerant control algorithm for generator electromechanical faults and its application in suppressing the rotor-bar defect in SCIGs. Algorithm is based on proper extension of widely adopted control strategies used in wind turbines, mainly on torque control loop with field-oriented control (FOC).

Focus of this paper is to research and develop a faulttolerant control strategy for stator isolation faults that cause about 20% of machine faults [6]. We introduce a modulation of the generator flux using already available control system in order to suppress the fault propagation and to keep the electrical energy production possible under emergency circumstances.

There are two main issues which hinder the proposed faulttolerant control algorithm application on suppressing stator isolation faults:

- very slow dynamics of machine rotor-flux transients, which are dependent on the rotor time constant,
- whole procedure needs to be performed with the high frequency of voltage supplied to the machine stator.

Main advantage, as well as the motivation, is that proposed algorithm is not only restricted to an SCIG but can be applied to any type of generators used in wind turbines (doubly-fed induction machine, synchronous generator with wound rotor, synchronous generator with permanent magnets).

This paper is organized as follows. The stator inter-turn isolation fault is briefly described in Section II. Section III presents the mathematical model of wind turbine, as well as most-widely-adopted wind turbine control strategy. In Section IV a mathematical model of an SCIG is described explaining the theoretical basis used to form a control system extension. A fault-tolerant approach and control algorithm that enables wind turbine operation under stator isolation fault is proposed and described in Section V. Section VI provides simulation results.

II. STATOR ISOLATION FAULT

Some of the most common causes of stator isolation faults are moisture in the isolation, winding overheating, or vibrations (especially due to fallen stator slot wedge). Modern voltagesource inverters also introduce additional voltage stress on the inter-turn isolation caused by the steep-fronted voltage surge [7], [8].

There are two main kinds of stator faults (Fig. 1). One is the isolation fault and short circuit between two different machine phases. The time elapsed between fault occurrence and triggered safety device is about one third of a second. If there is a short circuit between turns of the same phase the time elapsed between incipient fault and triggered safety device



Fig. 1. Sketch of a stator slot including two turns of the same phase (aa) and two turns of different phases (ab).

is about several minutes or even much longer, depending on the stator winding method [9]. This may give enough time for fault detection and adequate autonomous reaction provided by control system to suppress the fault from further spreading on other wind turbine components.

The fault is manifested as a shorted turn in the phase winding with very low resistance. It results in high currents that flow through that turn and cause machine torque reduction and local overheating. The goal of considered fault-tolerant control is to keep the current in the shorted turn below its rated value and stop the fault from spreading on other components. This would cause machine to operate at below-rated power but would also prolong the machine lifetime until scheduled repair, which is very important for remotely-located wind turbines.

III. WIND TURBINE CONTROL SYSTEM

Modern variable-speed variable-pitch wind turbines operate in two different regions. One is so-called low-wind-speed region where torque control loop adjusts the generator torque to achieve desired wind turbine rotational speed in order to make the power production optimal. Other region is high-windspeed region where the power output is maintained constant while reducing the aerodynamic torque and keeping generator speed at the rated value. For this task a pitch control loop is responsible. Both control loops are shown in Fig. 3

The ability of a wind turbine to capture wind energy is expressed through a power coefficient C_P which is defined as the ratio of extracted power P_t to wind power P_V :

$$C_P = \frac{P_t}{P_V}.$$
 (1)

The maximum value of C_P , known as Betz limit, is $C_{Pmax} = \frac{16}{27} = 0.593$. It defines the maximum theoretical capability of wind power capture. The real power coefficient of modern commercial wind turbines reaches values of about 0.48 [10]. Power coefficient data is usually given as a function of the tip-speed-ratio λ and pitch angle β (Fig. 2). Turbine power and



Fig. 2. Power a) and torque b) coefficients for an exemplary 700 kW variable-pitch turbine.



Fig. 3. Control system of a variable-speed variable-pitch wind turbine.

torque are given by [11], [12]:

$$P_t = C_P(\lambda, \beta) P_V = \frac{1}{2} \rho R^2 \pi C_P(\lambda, \beta) V^3, \qquad (2)$$

$$T_t = \frac{P_t}{\omega} = \frac{1}{2}\rho R^3 \pi C_Q(\lambda, \beta) V^2, \qquad (3)$$

where $C_Q = C_P/\lambda$, ρ , R, V and ω are torque coefficient, air density, radius of the aerodynamic disk of a wind turbine, wind speed and the angular speed of blades, respectively, and $\lambda = \frac{\omega R}{V}$.

In this section only the basic control concept of modern wind turbines is presented. For more information about wind turbine modelling and control system design see [10]-[13].

IV. MATHEMATICAL MODEL OF AN AC MACHINE

There are several approaches in modelling an AC induction machine [14]. One of the most common is the representation of machine stator and rotor phases in the two-phase common rotating (d, q) coordinate system, which is suitable for field-oriented control application. A rotor-based field-oriented control (RFOC) implies that the common rotating (d, q) frame is aligned with rotor flux linkage:

$$\bar{\psi}_r = \psi_{rd} + j0,\tag{4}$$

and the complex value of $\bar{\psi}_r$ becomes a scalar ψ_{rd} .

Mathematical model of an AC squirrel-cage induction machine used for RFOC can be represented with following equations [14]:

$$u_{sd} = k_s i_{sd} + \sigma L_s \frac{di_{sd}}{dt} - \frac{1}{T_r} \frac{L_m^2}{L_r} i_{mr} - \omega_e \sigma L_s i_{sq}, \quad (5)$$

$$u_{sq} = R_s i_{sq} + \sigma L_s \frac{di_{sq}}{dt} + \omega_e \frac{L_m^2}{L_r} i_{mr} + \omega_e \sigma L_s i_{sd}.$$
(6)

where $u_{sd,q}$ are stator voltages in d and q axes, $i_{sd,q}$ are stator currents, i_{mr} is a magnetizing current. Parameter $T_r = \frac{L_r}{R_r}$ is a rotor time constant, parameters L_r , L_s and L_m are rotor, stator and mutual inductance, respectively, R_r and R_s are rotor and stator resistances, $\sigma = (1 - \frac{L_m^2}{L_r L_s})$, $k_s = (R_s - \frac{L_m^2}{L_r^2} R_r)$. Variable $\omega_e = 2\pi f$ denotes the speed of machine magnetizing flux rotation with respect to the stator, where f is the frequency of voltage supplied by the inverter. Elements with ω_e represent machine back-electromotive force (EMF).



Fig. 4. Field-oriented control loop.

RFOC equations are given by:

$$i_{mr} = \frac{\psi_{rd}}{L_m},\tag{7}$$

$$i_{sd} = i_{mr} + T_r \frac{di_{mr}}{dt},\tag{8}$$

$$\omega_{sl} = \omega_e - p\omega_g,\tag{9}$$

$$T_g = \frac{3}{2} p \frac{L_m^2}{L_r} i_{mr} i_{sq} = k_m i_{mr} i_{sq},$$
(10)

where $\omega_{sl} = \frac{i_{sq}}{T_r i_{mr}}$ is the slip speed, ω_g is rotor mechanical speed and p is the number of stator pole pairs.

Relation (10) is the key equation for RFOC of an induction machine. Following from (8), the magnetizing current vector i_{mr} is not suitable for fast control action influencing torque because of the time lag T_r and is therefore kept constant in the sub-nominal speed operating region. Torque is controlled only by q stator current component (i_{sq}) .

A decoupling method is applied to (5) and (6) (see [14]) by introducing correction voltages Δu_{sd} , Δu_{sq} and fully decoupled relations are derived:

$$u_{sd} + \Delta u_{sd} = k_s i_{sd} + \sigma L_s \frac{di_{sd}}{dt},\tag{11}$$

$$u_{sq} + \Delta u_{sq} = R_s i_{sq} + \sigma L_s \frac{di_{sq}}{dt}.$$
 (12)

These equations are now suitable for further design of the control loop and proportional-integral (PI) controllers are chosen with integral time constants $T_{Id} = \sigma L_s/k_s$ for *d*current, $T_{Iq} = \sigma L_s/R_s$ for *q*-current and gain K_r . Finally, closed loop dynamics can now be represented as first-order lag system with transfer function:

$$\frac{i_{sd}(s)}{i_{sd_REF}(s)} = \frac{i_{sq}(s)}{i_{sq_REF}(s)} = \frac{1}{1+\tau s},$$
(13)

where τ is a time constant defined with $\tau = \frac{\sigma L_s}{K_r}$.

V. FAULT-TOLERANT CONTROL

In order to stop the fault from spreading the current flowing through shorted turns must be kept below nominal value, as stated before. The current flow is caused by induced voltage due to variable magnetic flux. In three-phase coordinate system (a, b, c) stator voltage equation is defined with:

$$u_{sx} = i_{sx}R_s + \frac{d\psi_{sx}}{dt} \approx \frac{d\psi_{sx}}{dt}.$$
 (14)

Generally, the stator flux is considered sine-wave (in the fundamental-wave approaches, such as FOC) with amplitude

 $|\psi_s|$, angular frequency ω_e and phase offset φ_x . The flux in phases a, b, c is represented with:

$$\psi_{sx}(t) = |\psi_s|(t)\sin(\omega_e t + \varphi_x). \tag{15}$$

Flux amplitude envelope denoted with $|\psi_s|(t)$ in (15) is timevariable and must be taken into account when calculating the flux derivative for fault suppression:

$$\frac{d\psi_{sx}(t)}{dt} = \frac{d|\psi_s|(t)}{dt}\sin(\omega_e t) + |\psi_s|(t)\omega_e\cos(\omega_e t).$$
 (16)

Considering the design of fault-tolerant control strategy, one approach is to use wind turbine pitch control to restrict flux rotational speed never to exceed maximum allowed value defined with product $|\psi_s|\omega_e$. Other approach is to weaken the machine flux, which would result in reduced torque and increased speed. Wind turbine pitch control can be then used to lower the aerodynamic torque in order to impose the torque balance. The weakened flux is shown in Fig. 5 as *Faulty A* waveform. In both cases, flux amplitude is kept constant at some value. Both approaches lower the generator power production significantly and possibly unnecessarily. In the sequel we present a method for achieving the maximum power production while suppressing the fault at the same time.

The goal for suppressing the fault is formed as a restricted value of flux derivative as in (14):

$$\left|\frac{d\psi_{sx}}{dt}\right| \le k. \tag{17}$$

From (17) it follows that in order to stop the fault from spreading, the stator flux waveform must never be allowed to exceed a restriction shaped as a triangular waveform |kt| shown in Fig. 5 (dash-dot). The restriction also represents the flux waveform that enables maximum power production in the faulty machine state. Therefore, our goal is to utilize the existing control strategy and FOC to achieve that triangular waveform. The value k is determined based on fault identification procedure through machine fault monitoring and characterization techniques [15].

An appropriate flux amplitude envelope is chosen such that $\left|\frac{d\psi_{sx}}{dt}\right| = k$ is ensured (for phase *a* with $\varphi_a = 0$):

$$|\psi_s|(t) = \frac{\frac{k}{\omega_e}\omega_e t}{\sin(\omega_e t)},\tag{18}$$

with minimum absolute value at angles $\omega_e t = 0, \pi, ...,$ and maximum at $\omega_e t = \pi/2, 3\pi/2...$:

$$\begin{aligned} |\psi_s|(0) &= \frac{k}{\omega_e}, \\ |\psi_s|\left(\frac{\pi}{2}\right) &= \frac{k}{\omega_e}\frac{\pi}{2}. \end{aligned}$$
(19)



Fig. 5. Stator flux waveforms for healthy and faulty machine.

With modulated amplitude (18) the flux waveform from (15) obtains the form:

$$\begin{aligned}
\psi_{sa}(t) &= kt, & t \in \left[-\frac{\pi}{2\omega_e}, \frac{\pi}{2\omega_e}\right] \\
\psi_{sa}(t) &= -kt + k\pi, & t \in \left[\frac{\pi}{2\omega_e}, \frac{3\pi}{2\omega_e}\right]
\end{aligned}$$
(20)

Transformed to the (d,q) and RFOC domain, stator flux linkage is defined with:

$$\begin{aligned}
\psi_{sd} &= \sigma L_s i_{sd} + \frac{L_m}{L_r} \psi_{rd}, \\
\psi_{sq} &= \sigma L_s i_{sq},
\end{aligned} \tag{21}$$

and relation $|\psi_s| = \sqrt{\psi_{sd}^2 + \psi_{sq}^2}$ holds. Changing the ψ_{rd} is very slow due to large rotor time-lag T_r ,

so we choose to manipulate the flux ψ_{sx} only through machine fast dynamics (13). Proper values of current components i_{sd} and i_{sq} are chosen to achieve the triangular form in Fig. 5. With this approach, minimum and maximum achievable fluxes are for the case when i_{sq} is set to zero and i_{sd} to rated value of machine stator currents amplitude $\mp |i_{sn}|$:

$$\psi_{s_min,max} = \mp \sigma L_s |i_{sn}| + \frac{L_m}{L_r} \psi_{rd}.$$
 (22)

However, desired machine torque and corresponding i_{sq} must also be included into consideration. Due to saturation, the maximum flux is also restricted with the rated value of stator flux. The value of ψ_{rd} is considered constant during the manipulation of stator flux. In practice it is influenced by changing the i_{sd} current and it slowly fluctuates around mean value of the chosen ψ_{rd} .

If parameter k from the fault condition (17) is too large or chosen ψ_{rd} value limits the freedom for desired fast dynamics, desired amplitude scope shown in Fig. 6 with peak values (19) is not achievable. Therefore the minimum value is set to ψ_{s_min} and when the amplitude envelope $|\psi_s|(t)$ reaches value of ψ_{s_max} (at time instant t_m) it is fixed to that value. Stator flux takes the form presented as *Faulty B* in Fig. 5. The amplitude envelope is shown in Fig. 6 with dashed line representing the case when triangular waveform is achievable and full line for the case of *Faulty B* waveform. The time instant t_m can be obtained from condition:

$$kt_m = \psi_{s_max} \sin(\omega_e t_m). \tag{23}$$

Considering (16), influence of the static part $|\psi_s|(t)\omega_e \cos(\omega_e t)$ of equation is examined. In the sequel we consider the dynamic part $\frac{d|\psi_s|(t)}{dt}\sin(\omega_e t)$. Derivative of flux amplitude envelope (18) from Fig. 6 is:

$$\frac{d|\psi_s|(t)}{d(\omega_e t)} = \frac{k}{\omega_e} \frac{\sin(\omega_e t) - \omega_e t \cos(\omega_e t)}{\sin^2(\omega_e t)}.$$
 (24)

The flux amplitude derivative reaches its maximum value of $\frac{k}{\omega_e}$ at time instant $t = \frac{\pi}{2\omega_e}$. For values of ω_e that require application of fault-tolerant algorithm the dynamic part has much less influence (up to several hundred times) on flux derivative than the static part.

Fastest achievable transient of currents is determined with inverter limitation. Considering the worst case scenario, highest outputs from currents PI controllers described in previous section are attained at the beginning of the transient with values



Fig. 6. Flux amplitude from (18) chosen to achieve $\left|\frac{d\psi_s}{dt}\right| \leq k$.

of $u_{sd,q} + \Delta u_{sd,q} = K_r(i_{sd,q_REF} - i_{sd,q})$. Respecting the maximum available voltage supplied to one phase U_{max} that arise from maximum voltage U_{dc} of the dc-link (see Fig. 4) and corresponding U_{sd_max} and U_{sq_max} voltages, maximum values of $(i_{sd,q_REF} - i_{sd,q})$ can be roughly calculated as:

$$i_{sd_REF} - i_{sd} = \frac{1}{K_r} \left(|U_{sd_max}| + \frac{1}{T_r} \frac{L_m^2}{L_r} i_{mr} + \omega_e \sigma L_s i_{sq} \right),$$
(25)
$$i_{sq_REF} - i_{sq} = \frac{1}{K_r} \left(|U_{sq_max}| - \omega_e \frac{Lm^2}{L_r} i_{mr} - \omega_e \sigma L_s i_{sd} \right).$$
(26)

The flux derivative can be expressed as:

$$\frac{d|\psi_s|(t)}{dt} = \frac{d|\psi_s|(t)}{di_{sd}} \cdot \frac{di_{sd}}{dt} + \frac{d|\psi_s|(t)}{di_{sq}} \cdot \frac{di_{sq}}{dt}.$$
 (27)

By including the flux derivative with respect to currents from (21) and currents time derivatives that arise from (13), (25) and (26) $\left(\frac{di_{sd,q}}{dt} = \frac{i_{sd,q_REF} - i_{sd,q}}{\tau}\right)$, the maximum possible $\frac{d|\psi_s|(t)}{dt}$ by far exceeds the needed condition of $\frac{k}{\omega_e}$ (about hundred times for the worst case in our simulations).

Therefore by disregarding the dynamical part in (16), available generator electrical speed is chosen from product $|\psi_s|\omega_e$:

$$\omega_e \le \alpha \frac{k}{\psi_{s_min}},\tag{28}$$

where $\alpha = 0.9$ is a redundancy factor that ensures possibility of manipulation with i_{sd} and i_{sq} currents. The factor places the minimum value of $|\psi_s|(t)$ little above ψ_{s_min} as shown in Fig. 6.

Using the described method, an exemplary graph of available speed-torque points under machine fault is shown in Fig. 7. Normal operation of the healthy generator is bounded with rated machine torque T_{gn} and rated speed ω_{gn} and pitch control is responsible to keep the operating point between boundaries. The curve denoted with *Optimum power* represents optimal operating points of wind turbine at which the power factor coefficient C_p and power production is at maximum value.

For the case of diagnosed fault, dashed area denotes all available generator torque values that can be achieved for certain generator speed. Below speed ω_g^* generator is operating in the safety region and no fault-tolerant control is needed. It follows that up to the speed ω_{g1} it is possible to control the wind turbine in the faulty case without sacrificing power production. However, from that speed onwards it is necessary to use blades pitching in order to limit the aerodynamic torque and to keep the power production below optimal in order to suppress the fault from spreading. The speed control loop is



Fig. 7. Available torque-speed generator operating points under fault condition (shaded area).

modified such that instead of reference ω_{gn} the reference ω_{g1} is selected. Interventions in classical wind turbine control that ensure fault-tolerant control are given in Fig. 8.

Desired generator torque reference dictated by the wind turbine torque control loop determines adequate value of ω_e and i_{mr} (or ψ_{rd}) used to achieve correct ψ_{s_min} and ψ_{s_max} . Proper current references i_{sd_REF} and i_{sq_REF} are then calculated to obtain desired stator flux wave. The algorithm is given in the sequel:

Algorithm 1 Fault-tolerant control for stator fault

- 1. Choose correct ψ_{s_max} as a lower value between rated flux ψ_{sn} and (19) with diagnosed fault condition k and current flux rotational speed ω_e ;
- 2. Find angle $\omega_e t_m$ from (23) and calculate approximate mean value of stator flux $\psi_{s_mean} = \frac{1}{n} \sum_{i=1}^{n} \psi_{si}$ with ψ_{s_min} from (19) and ψ_{s_max} ;
- Obtain i_{mr_mean} from ψ_{s_mean}; i_{sq_mean} from desired torque T_{gref}, i_{mr_mean} and (10) respecting the maximum allowed slip value (9); i_{sd_max} from ψ_{max} and (21);
- 4. If $i_{sd_max} > \sqrt{i_{sn}^2 i_{sq_mean}^2}$ decrease ψ_{s_max} by a small value ϵ and go back to step 2., iteratively;
- 5. Calculate i_{sd_REF} from (18) and (21) with i_{mr_mean} and i_{sq_mean} , set $i_{sq_REF} = i_{sq_mean}$;
- 6. Compute ω_{g1} as a speed coordinate of the intersection point of $T_{av}(\omega_g)$ and of the normal wind turbine torque controller characteristics, compute $\omega_1 = \omega_{g1}/n_s$ where n_s is the gearbox ratio. Set $\omega_{ref} = \omega_1$.

Step 5. is executed at each discrete time step, while other steps are executed once in every stator flux modulation period (Fig. 6) for less computational effort.

VI. SIMULATION RESULTS

This section provides simulation results for a 700 kW MATLAB/Simulink variable-speed variable-pitch wind turbine model with a two-pole 5.5 kW SCIG scaled to match the torque and power of 700 kW machine.



Fig. 8. Control system of wind turbine with fault-tolerant control strategy.

Generator parameters are: $L_s = L_r = 0.112$ H, $L_m = 0.11$ H, $R_s = 0.3304 \Omega$, $R_r = 0.2334 \Omega$ and PI controller gain is $K_r = 6$. Turbine parameters are: $C_{Pmax} = 0.4745$, R = 25 m, $\lambda_{opt} = 7.4$, $\omega_n = 29$ rpm, $T_{tn} = 230.5$ kNm with gearbox ratio $n_s = 105.77$. Stator flux rated value is $\psi_{sn} = 0.625$ Wb and sample time is chosen $T_s = 10^{-4}$ s. Moment of inertia of wind turbine and generator, reduced to the generator side is $J = 72.11 \text{ kgm}^2$.

In the sequel simulation results with diagnosed fault and $\left|\frac{d\psi_{sx}}{dt}\right| = k = 100$ Wb/s are presented. The i_{sq} current is chosen as constant value in order to maintain the desired torque. Therefore stator flux is manipulated only by i_{sd} as presented in Fig. 9.

Stator flux amplitude envelope from (18) is shown in Fig. 10 and corresponding stator flux waveforms in phases a, b, c are shown in Fig. 11. Following from figures, the required restriction formed as described triangular waveform is satisfied in shorted phase (phase a). Phase currents calculated to achieve desired flux waveforms are shown in Fig. 12. Currents follow a sinusoidal shape with deviations at peak values. With better tracking performance of i_{sd} with respect to the reference value in Fig. 9 or by compensation of the referent value with included prediction procedure, more symmetric waveforms of flux, as well as those of currents, in phases a, b, c can be achieved.

Fig. 13 shows that proposed fault-tolerant algorithm introduces torque oscillations in the system. This occurs due to rapid changing of i_{sd} and its reflection on machine rotor flux ψ_{rd} . Proper modulation of i_{sq} current can overcome this problem. However, because of very large moment of inertia of the wind turbine, torque oscillations have negligible influence on wind turbine rotational speed.

VII. CONCLUSIONS

We introduced a fault-tolerant control strategy for variablespeed variable-pitch wind turbines. The focus is on a squirrelcage generator with diagnosed short-circuit between turns of the same phase. An extension of the conventional control structure is proposed that prevents the fault propagation and enables faulty wind turbine operation with reduced power. The power delivery under fault is deteriorated as less as possible compared to healthy machine conditions.

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Fig. 9. Direct current component. Dashed is referent value.



Fig. 10. Stator flux magnitude $|\psi_s|(t)$.



Fig. 11. Stator flux in phases a, b, c.

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Fig. 13. Wind turbine generator torque and rotational speed.

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