A modified vector control strategy for DFIG based wind turbines to ride-through voltage dips

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Abstract— ***This paper proposes a new indirect power control strategy and a novel crowbar protection technique for the doubly fed induction generator (DFIG) used in the wind power generation systems. The main difficulty for a DFIG to ride through severe unbalanced grid voltage dips is the large transient currents induced in the rotor windings, which may damage the ac excitation converter. The proposed control is capable of suppressing the transient oscillations of fault currents. The crowbar protection is able to limit the peak values of the fault rotor currents under a preset threshold. Simulation results prove that with this control scheme the DFIG is capable of riding through the severe unbalanced grid voltage dips.***

Index Terms— **Doubly fed induction generator; Variable speed wind turbine; Power control; unbalanced grid voltage dips; Crowbar; Voltage dip**

NOMENCLATURE

$V_{ds}, V_{qs}, V_{dr}, V_{qr}$	Stator and rotor voltages in (d,q) reference frame,
$\phi_{ds}, \phi_{qs}, \phi_{dr}, \phi_{qr}$	Stator and rotor fluxes in (d,q) reference frame,
$I_{ds}, I_{qs}, I_{dr}, I_{qr}$	Stator and rotor currents in (d,q) reference frame,
R_s, R_r	Stator and rotor resistances,
M	Mutual inductance,
L_s, L_r	Stator and rotor inductances,
ω_s	grid pulsation (rad/s),
DFIG	Doubly-Fed Induction Generator,
FLC	Fuzzy Logic Controller
ρ	Air density,
$C_p(\lambda)$	Power coefficient;
V	Wind speed.

I. INTRODUCTION

A doubly-fed induction generator (DFIG) is an electrical asynchronous three-phases machine with open rotor windings which can be fed by external voltages. The typical connection scheme of this machine is reported in Fig. 1. The stator windings are directly connected to the line grid, while the rotor windings are controlled by means of an inverter,[1],[2]. This solution is very attractive for all the applications where limited speed variations around the synchronous velocity are present, since the power handled by the converter at rotor side will be a small fraction (depending on the slip) of the overall system power. In particular, for electric energy generation applications, it is important to note that the asynchronous nature of the DFIG allows producing constant frequency electric power with a variable mechanical speed, in addition reduced copper losses and wider operational range are obtained with respect to standard squirrel-cage induction machine [3].

With the massive development of wind energy, the technical requirements for connecting this technology will require the improvement of the fault ride-through capability of grid-connected wind turbines. The task for the grid system operator is to use all generators to ensure the stability of the electrical system.

Faults in the power system, even far away from the location of the turbine, can cause a voltage dip at the connection point of the wind turbine. Even though the performance of the DFIG wind turbine is excellent in normal grid condition, a partial control of the system is obtained because of the relative small rating of the rotor side converter compared to the generator rating. As a result, the dip in the grid voltage will result in an increase of the current in the stator windings of the DFIG. Because of the magnetic coupling between stator and rotor, this current will also flow into the rotor circuit and the power converters. So that it will cause an over current in the rotor windings and over voltage in the DC bus of the power converters [4][5]. Without any protection, this will lead to the destruction of the converters.

Thus the main objective of the control system during grid faults is to limit the rotor over current and the DC bus over voltage. Vector control [6][7], direct torque control (DTC) [8], rotor flux magnitude and angle control (FMAC) [9] as well as some nonlinear control schemes [10][11] have already been applied to the DFIG during grid fault conditions. In this paper, a modified vector control strategy will be proposed and compared with conventional vector control scheme in order to show the influence on the dynamic behavior of the wind turbine system against voltage dips.

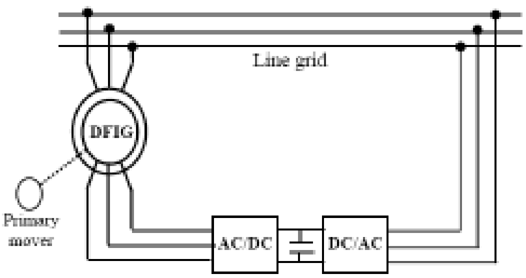

Fig. 1 The typical connection scheme of DFIG

The aim of this paper is to propose a new control technique that would permit to guarantee the controllability of DFIG during severe voltage sags.

II. MODEL OF THE DOUBLY-FED INDUCTION GENERATOR

a. *Modelling of the wind turbine and gearbox*

The aerodynamic power, which is converted by a wind turbine, P_t is dependent on the power coefficient C_p . It is given by

$$P_t = \frac{1}{2} C_p(\lambda).\rho.\pi.R^2 V^3 \quad (1)$$

Where ρ is the air density, R is the blade length and V the wind velocity. The turbine torque is the ratio of the output power to the shaft speed Ω_t , $T_{aer} = \frac{P_t}{\Omega_t}$

The turbine is normally coupled to the generator shaft through a gearbox whose gear ratio G is chosen in order to set the generator shaft speed within a desired speed range. Neglecting the transmission losses, the torque and shaft speed of the wind turbine, referred to the generator side of the gearbox, are given by:

$$T_g = \frac{P_{aer}}{G} \ , \ \Omega_t = \frac{\Omega_{mec}}{G} \quad (2)$$

Where T_g the driving is torque of the generator and Ω_{mec} is the generator shaft speed, respectively. A wind turbine can only convert just a certain percentage of the captured wind power. This percentage is represented by $C_p(\lambda)$ which is function of the wind speed, the turbine speed and the pith angle of specific wind turbine blades [12]. Although this equation seems simple, C_p is dependent on the ratio λ between the turbine angular velocity Ω_t and the wind speed V . This ratio is called the tip speed ratio:

$$\lambda = \frac{\Omega_t.R}{V} \quad (3)$$

A typical relationship between C_p and λ is shown in Fig. 1. It is clear from this figure that there is a value of l for which C_p is maximum and that maximizes the power for a given wind speed. The peak power for each wind speed occurs at the point where Cp is maximized. To maximize the generated power [13],[14] ,it is therefore desirable for the generator to have a power characteristic that will follow the maximum $C_{p\max}$ line.

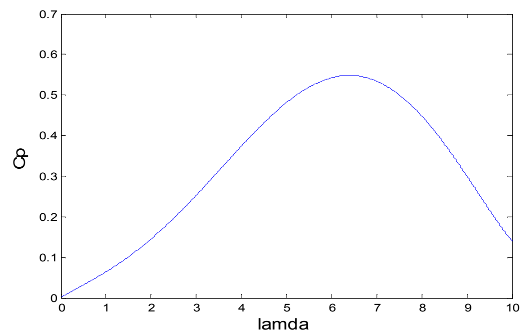

Fig. 2. Power coefficient for the wind turbine model.

b. *Modelling of the DFIG*

The classical electrical equations of the DFIG in the PARK frame are written as follows [10]:

$$\begin{cases} V_{ds} = R_s.I_{ds} + \frac{d}{dt}\phi_{ds} - \omega_s \phi_{qs} \\ V_{qs} = R_s.I_{qs} + \frac{d}{dt}\phi_{qs} - \omega_s \phi_{ds} \end{cases}$$

$$\begin{cases} V_{dr} = R_r.I_{dr} + \frac{d}{dt}\phi_{dr} - (\omega_s - \omega)\phi_{qr} \\ V_{qr} = R_r.I_{qr} + \frac{d}{dt}\phi_{qr} - (\omega_s - \omega)\phi_{dr} \end{cases} \quad (4)$$

Where R_s and R_r are, respectively, the stator and rotor phase resistances, $\omega = P_{dfig}.\Omega_{mec}$ is the electrical speed and P_{dfig} is the pair pole number.

The stator and rotor flux can be expressed as

$$\begin{cases} \phi_{ds} = L_s I_{ds} + M I_{dr} \\ \phi_{qs} = L_s I_{qs} + M I_{qr} \\ \phi_{dr} = L_r I_{dr} + M I_{ds} \\ \phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (5)$$

Where I_{ds} , I_{qs} I_{dr} , and I_{qr} are, respectively, the direct and quadrate stator and rotor currents.

The active and reactive powers at the stator, the rotor as well as those provide for grid are defined as[11]:

$$\begin{cases} P_s = V_{ds}.I_{ds} + V_{qs}.I_{qs} \\ Q_s = V_{qs}.I_{ds} - V_{ds}.I_{qs} \end{cases} \quad (6)$$

$$\begin{cases} P_r = V_{dr} I_{dr} + V_{qr} I_{qr} \\ P_r = V_{qr} I_{dr} - V_{dr} I_{qr} \end{cases} \quad (7)$$

The electromagnetic torque is expressed as

$$T_{em} = P_{dfig}(\phi_{ds} I_{qs} - \phi_{qs} I_{ds}) \quad (8)$$

III. TRADITIONAL CONTROL STRATEGY OF THE DFIG

a. Decoupling of the active and reactive powers

When the DFIG is connected to an existing grid, this connection must be established in the following three steps. The first step is the synchronisation of the stator voltages with the grid voltages, which are used as a reference. The second step is the stator connection to this grid. After that, the connection can be effectively established. Once this connection is achieved, the third step is the regulation of the transit of the power between the DFIG and the grid A d–q reference-frame synchronized with the stator flux is employed [12]. By setting the quadratic component of the stator to the null value as follows:

$$\phi_s = \phi_{ds} \quad \Rightarrow \quad \phi_{qs} = 0 \tag{9}$$

Then the torque is simplified as indicated below:

$$\begin{cases} \phi_{ds} = L_s.I_{ds} + M.I_{dr} \\ 0 = L_s.I_{qs} + M.I_{qr} \end{cases} \tag{10}$$

The electromagnetic torque, and subsequently the active power, will only depend on the rotor current along the q-axis. By neglecting the stator resistance R_s

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s \end{cases} \tag{11}$$

Using Equations (4), (5) and (9) the stator active and reactive power can then be expressed only versus these rotor currents as :

$$\begin{cases} P_s = V_s I_{qs} = -V_s \dfrac{M}{L_s} I_{qr} \\ Q_s = V_s I_{ds} = \dfrac{V_s \phi_s}{L_s} - \dfrac{V_s M}{L_s} I_{dr} \end{cases} \tag{12}$$

IV. CONTROLLERS SYNTHESIS

a. PI regulator synthesis

This controller is simple to elaborate. Fig. 2 shows the block diagram of the system with this controller. The terms K_p and K_i represent respectively the proportional and integral gains.

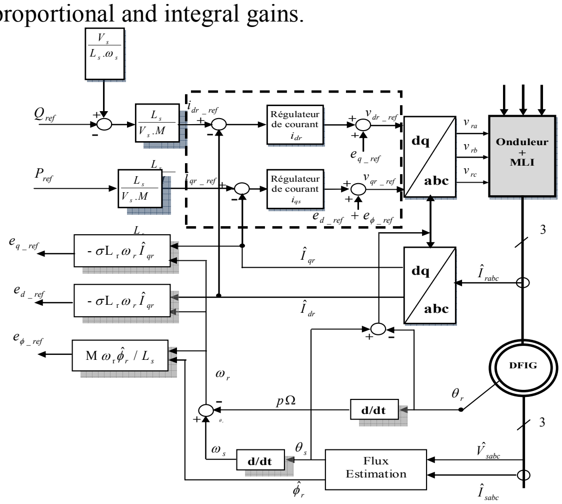

Fig. 3 Diagram of the traditional stator flux vector oriented control

V. NEW DFIG CONTROL MODELS WITH GRID VOLTAGE DYNAMICS CONSIDERED

To design a control system to provide full decoupling and good response under stator voltage variation, it is necessary the dynamics of the stator flux should not be ignored for the design of the current controller.

Note that the quadrature stator flux does not equal to zero during a voltage dip, we can then obtain the following relationship between the stator current and rotor current:

$$\begin{cases} I_{ds} = \dfrac{\phi_{ds} - M.I_{dr}}{L_s} \\ I_{qs} = \dfrac{\phi_{qs} - M.I_{qr}}{L_s} \end{cases} \tag{12}$$

Then the torque is simplified as indicated below

$$\begin{cases} V_{dr} = R_r.I_{dr} + \sigma L_r \dfrac{dI_{dr}}{dt} - \omega_r \sigma L_r I_{qr} - \omega_r \dfrac{M}{L_s}\phi_{qs} + \dfrac{M}{L_s}\dfrac{d\phi_{ds}}{dt} \\ V_{qr} = R_r.I_{qr} + \sigma L_r \dfrac{dI_{qr}}{dt} + \omega_r \sigma L_r I_{dr} + \omega_r \dfrac{M}{L_s}\phi_{ds} + \dfrac{M}{L_s}\dfrac{d\phi_{qs}}{dt} \end{cases} \tag{13}$$

From these equations, the PI controller of rotor current can be designed for the modified vector controller. It must tale into account the quadrature stator flux ϕ_{qs} and the dynamics of the stator flux $(\dfrac{d\phi_{ds}}{dt}, \dfrac{d\phi_{qs}}{dt})$ in the case of grid voltage dips [13]

Fig. 4 shows the block diagram of the system with this new controller models with grid voltage dynamics considered

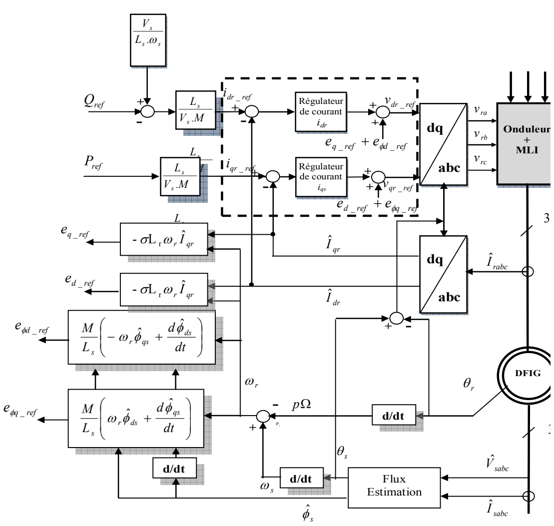

Fig. 4 The block diagram of the modified vector control strategy of the DFIG

VI. SIMULATION INVESTIGATION

In order to verify the capability of the proposed modified DFIG models and associated control strategies, simulations for DFIG generation were carried out using Matlab/Simulink. DFIG is rated at 1.5 MW and its parameters are given in Table 1. Rotor and grid side converters were represented using the average VSC

The results shown here were for conditions where the dip in the stator voltage was about 50 %

Table 1 Parameters of the simulated DFIG

parameters	values
Turbine	
diameter	60 m
number of blades	3
hub height	85 m
gearbox	90
DFIG	
Power	1.5MW
Voltage	380V (Y)
Frequency	50 Hz
Pole pairs	2
Speed	100 rad/s
Torque	50 N.m
Stator resistance	1.2 Ω
Rotor resistance	1.8 Ω
Stator inductance	0.1554 H
Rotor inductance	0.1568 H
Mutual inductance	0.15 H
(turbine+DFIG)	
J: inertia	50 kgm2
f: viscous coefficient	7.1e-2Nms/rd

In order to study the influence of the proposed control strategy against voltage dips, a three-phase fault, which causes a voltage dip of about 50 % depth and 2 s duration at the stator terminal of the DFIG will be considered. This value is common when voltage dip at thepoint of common coupling is about 85%. As the fault time is rather small compared to the wind speed fluctuation, the wind speed can be assumed to be constant in the grid fault simulations. Immediately after the fault occurs at 5 s, the voltage at the wind turbine terminal drops, as it is shown in Fig. 5. The voltage dip will lead to a decrease in the stator flux. Thus an oscillation of the flux both in direct and quadrature components occurs during the voltage dip and after the clearance of the fault. In addition, the q-axis stator flux can not maintain to be zero due to the voltage dip. That is why both the quadrature stator flux and the dynamics of the stator flux should be considered in the modified vector controller.

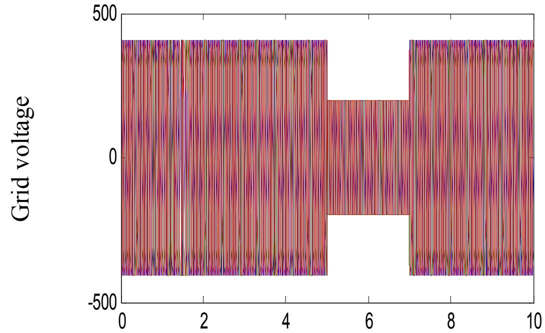

Fig. 5 Grid voltage during a common three-phase fault

The analysis was carried out in MATLAB/SIMULINK environment. A variable step solver is used with maximum step size of 1e-3 and minimum step size of 1e-4. Fig. 9 shows the response of stator power and rotor currents for average wind speed of 12 m/s. The 3-phase short circuit has been introduced at time instant

2s. The fault has been modeled by a stator voltage reduction down to zero for a time of 5 s. The stator power due to the occurrence of fault first decreases to zero, then after clearing the fault it rapidly rises in the positive direction and then starts to oscillate until it reaches its steady state value before fault.

A high transient rotor current due to the occurrence of fault, then after clearing the fault it increases negatively and then starts to decay until it reaches its steady state value before fault. The rotor current due to the occurrence of fault first increases, then after clearing the fault it increases negatively and then starts to decay until it reaches its steady state value before fault.

Fig. 6 shows the simulated results of the proposed vector control strategy compared to the conventional one in the synchronous frame in fig.7 . Fig. 6, shows the active power converter during the voltage dip. Although the active power drops converter, the control scheme can control it back to its reference value. Moreover, with considering the dynamics of the stator flux.

According to Fig. 6, the proposed control scheme results in much smaller rotor over current than the conventional one, which indicates that the modified vector control strategy can provide adequate control of the rotor current during voltage dips

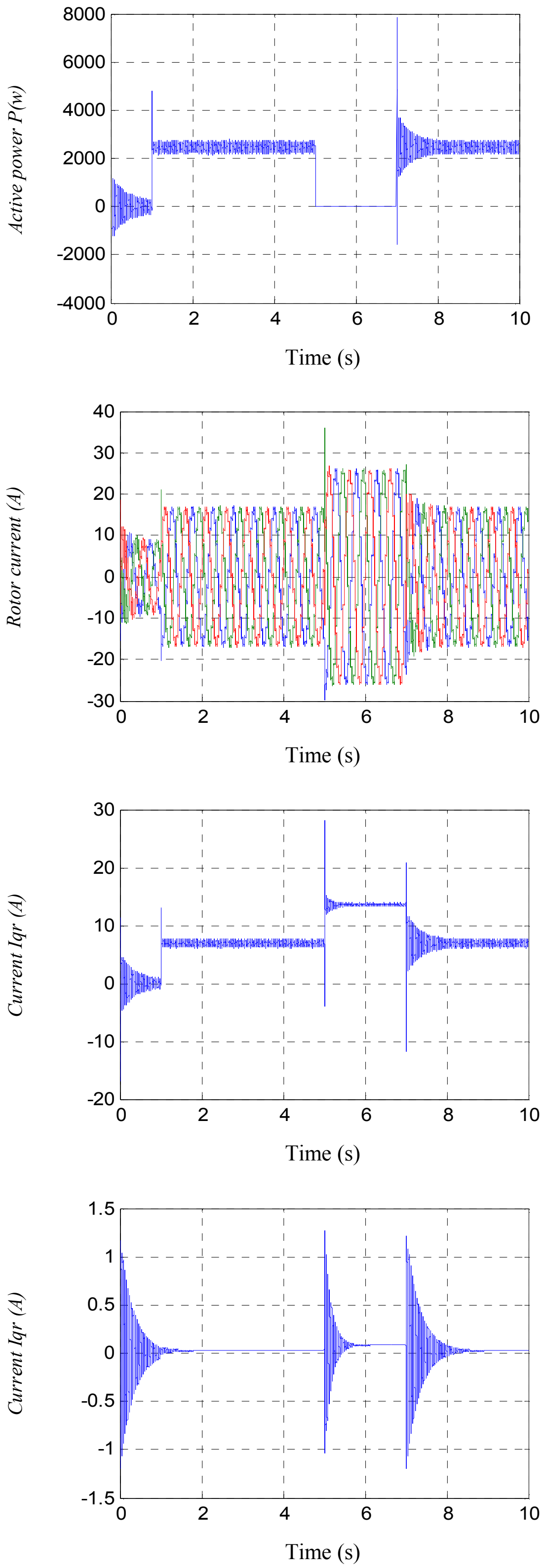

Fig 6 . dynamic behavior of the DFIG during the voltage dip with conventional vector control

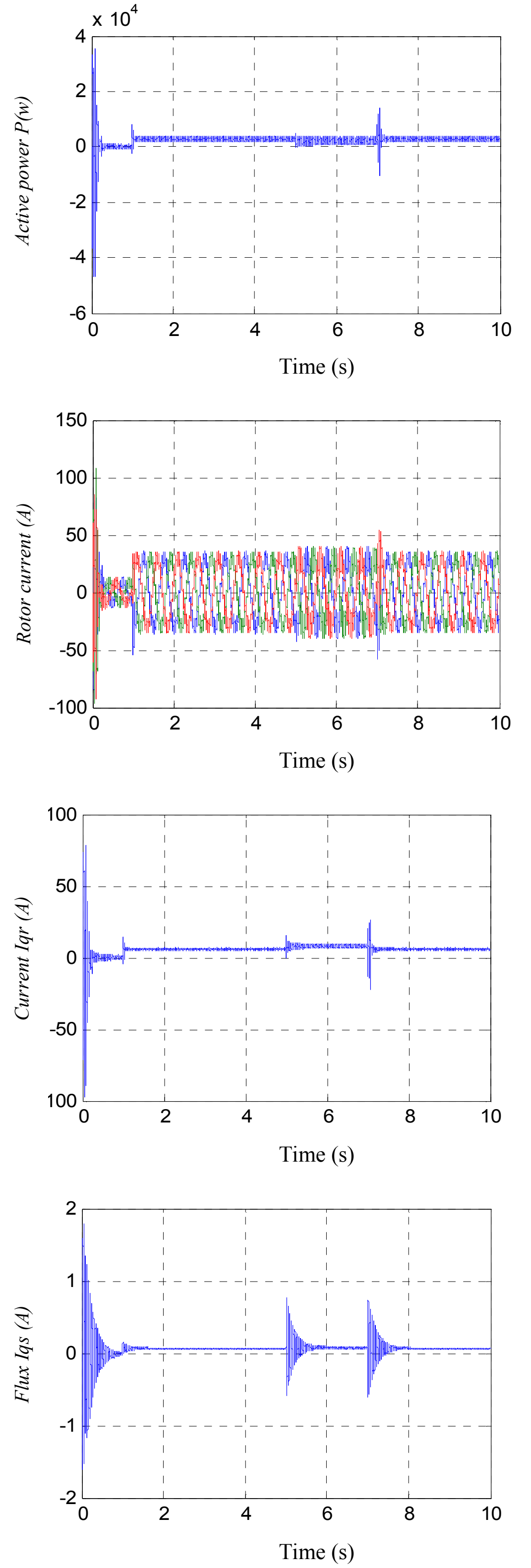

Fig 7. dynamic behavior of the DFIG during the voltage dip with modified vector control

CONCLUSION

Transient behavior of a DFIG variable speed wind turbine
connected to the network and controlled by vector control has been studied. The transient simulation results are for a 1.5 MW DFIG under a three-phase short circuit at the generator ncrease rapidly to value with amplitude more . So the rotor circuit converter must be protected against the increase in the rotor current. Simulation results also show that the amplitude of transient stator power is reduced when the fault occurs. On the other hand, the stator power oscillates after the fault is cleared until it reaches steady state value before fault

Comparison shows that when the crowbar is implemented, the stator and rotor transient current decay rapidly to value with amplitude and rotor circuit is properly protected. Simulation results also showthat the amplitude of transient stator power is reduced when the crowbar is activated.

Appendix:
System parameters

parameters	values
Turbine	
diameter	60 m
number of blades	3
hub height	85 m
gearbox	90
DFIG	
Power	1.5MW
Voltage	380V (Y)
Frequency	50 Hz
Pole pairs	2
Speed	100 rad/s
Torque	50 N.m
Stator resistance	1.2 Ω
Rotor resistance	1.8 Ω
Stator inductance	0.1554 H
Rotor inductance	0.1568 H
Mutual inductance	0.15 H
(turbine+DFIG)	
J: inertia	50 kgm2
f: viscous coefficient	7.1e-2Nms/rd

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