Dynamic Investigations of Grid Connected Fixed-Speed Wind Turbine During Grid Faults

Ferchichi Noureddine, Ben Aribia Houssem, Abid Slim

Abstract: Especially during grid faults, grid code requirements for wind power integration have become a key element in improving grid efficiency and reliability. Under severe problems for network operation, wind turbines are expected to continue operating and supporting the grid during frequency restoration. This paper presents simulation results of a fixed-speed grid-connected wind turbine under various short-circuit current contributions. Fault analysis is carried out by studying the grid side line to ground fault, double line fault, double line to ground fault, and three phase fault involving ground and without ground. The obtained current waveforms are analyzed to explain the behavior, such as the rate of decay and peak values. Variations of active and reactive power during post-fault conditions and faulty conditions are investigated. Moreover, recommendations for switchgear and protection equipment are performed.

Keywords: Grid Fault, Voltage Support, Short-Circuit Current, Active and Reactive Power Strategies, Stability Improvement.

I. INTRODUCTION

The evolution of electrical networks has been marked, in recent years, by new design, operation and control strategies. Indeed, the solution adopted by most countries to deal with the problem of rapid growth in the demand for electrical energy can be essentially summed up in the following points: The commissioning of new, more powerful power plants, the mesh of more and more transmission and distribution networks, the exchange of energy between countries through international and even intercontinental interconnections and mainly the integration of renewable energies [1].

This structural complexity is essentially the basis of current problems encountered in online behavior especially the weakening ability of networks to maintain stability following a disturbance likely to alter the smooth running of equipment and industrial processes [2]. Among these disturbances, there are those of short duration such as voltage sags, short cuts and over voltages, which are generally caused by the presence of short circuits [3].

They are characterized by important variations in voltage amplitude and can have costly and harmful issues on electrical equipment. The most extreme grid code requirements, taking into account the voltage range level at which the frequency range is required were combined to dress a frequency-voltage profile as well as an active reactive power profile [4].

In modern grids, wind installations must be able to participate in the full dynamic support of the grid in case of failure [5,6]: remain connected to the grid and provide voltage support by injecting a reactive current. Dynamic grid support allows power plants to be able to stay connected in case of fault, support voltage by supplying reactive power during the fault, and consume the same reactive power or less after the fault is cleared.

Essentially, short circuit and open circuit faults represent the majority of electrical faults in three-phase networks. Also, these faults can be symmetrical or asymmetrical. They are due to the break of one or more conductors [7][21][22], or open circuit faults where an unbalanced current flows through the system, thus heating the rotating machines [8]. We can define a short circuit fault as being an abnormal very low impedance connection, whether it is established accidentally or intentionally between at least two points of different potential. It is the most severe and common type of fault, leading to abnormally high currents flowing through transmission lines or equipment. Even for a short time, if these faults are allowed to persist, this leads to important damage to the grid or equipment [9]. The different possible short circuit conditions are: three-phase to ground (L-L-L-G), three phase above ground (L-L-L), phase to phase (L-L), single phase to ground (L-G) and two-phase to ground (L-L-G) [10]. However, the study of these faults is necessary to select the circuit breakers breaking capacity, to choose the phase relay setting and other protective devices and finally to manage the transit of reactive and active powers [11].

In few past years, numerous research works have investigated fault classification schemes and estimation for power systems based on signal measurement, decomposition and analysis, feature extraction and classification, fault classification and location [12, 13, 14, 18, 19, 20]. Fault location is another important aspect to consider when designing a protection scheme because it gives an indicative sign of where the fault has occurred along the power distribution line, resulting in a much quicker restoration time. Also, it gives the effect of AC voltages, AC currents and especially the flow and waveforms at the grid side of AC active and reactive powers [15].

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II. PROPOSED POWER SYSTEM CONFIGURATION

The proposed and simulated wind energy conversion system architecture is presented in Figure 1. The device consists of a wind rotor connected to a rotor shaft of a squirrel cage induction generator (SCIG) through a gearbox converting kinetic energy captured by the wind turbine blades to mechanical energy. For this fixed-speed turbine, the highest efficiency is obtained at a particular speed only. Regardless of the wind speed, the rotor speed is fixed and is determined by the ratio of the gearbox, grid supply frequency and induction generator design. The SCIG is connected directly to the grid through a step-up transformer. According to grid code requirements, wind turbines must have the ability to absorb or generate reactive power to adjust the voltage level at the point of common coupling (PCC). A fixed power factor is maintained, so that the generator is not allowed to take reactive power from the grid and capacitors are sized to provide the suitable reactive power for improving the power factor and for induction generator magnetization needs. This wind turbine is equipped with a pitch angle controller to regulate the active power output to a defined level and also to increase the ability to control transient stability during faults.

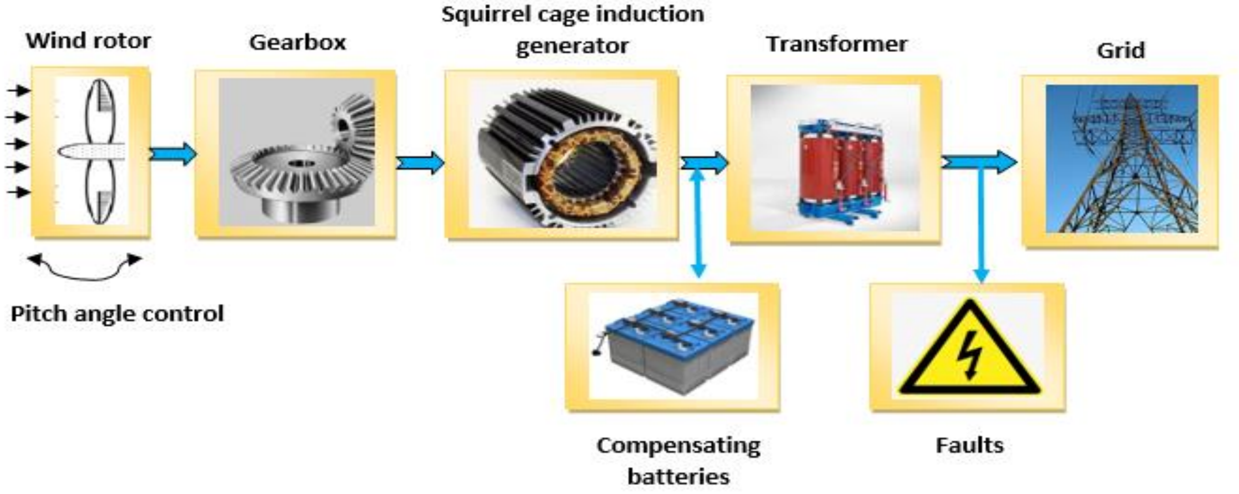

Figure 1. Fixed-Speed Wind Turbine Configuration

The mechanical power extracted from the wind is given by [12]:

$$P_m = C_p(\lambda\,,\beta)\frac{\rho\,A}{2}V_w^3 \qquad (1)$$

With:

C_p- Power coefficient

ρ- Air density (kg/m^3)

A- Turbine swept area (m^2)

V_w- Wind speed (m/s)

λ- Tip speed ratio

β- Blade pitch angle

For the studied SCIG, all parameters are referred to the stator side, and all stator and rotor quantities are in the arbitrary two-axis reference frame (d.q) [16]. The mathematical model of the SCIG is as presented in equation (2):

$$\begin{cases} V_{qs} = R_s i_{qs} + \frac{d\varphi_{qs}}{dt} + \omega\varphi_{ds} \\ V_{ds} = R_s i_{ds} + \frac{d\varphi_{ds}}{dt} - \omega\varphi_{qs} \\ V'_{qr} = R'_r i'_{qr} + \frac{d\varphi'_{qr}}{dt} + (\omega - \omega_r)\varphi'_{dr} \\ V'_{dr} = R'_r i'_{dr} + \frac{d\varphi'_{dr}}{dt} + (\omega - \omega_r)\varphi'_{qr} \\ T_e = 3/2p\left(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}\right) \end{cases} \qquad (2)$$

with

$\varphi_{qs} = L_s i_{qs} + L_m i'_{qr}$

$\varphi_{ds} = L_s i_{ds} + L_m i'_{dr}$

$\varphi'_{qr} = L'_r i'_{qr} + L_m i_{qs}$

$\varphi'_{dr} = L'_r i'_{dr} + L_m i_{ds}$

$L_s = L_{ls} + L_m$

$L'_r = L'_{lr} + L_m$

The mechanical mathematical model is given by the equation (3):

$$\begin{cases} \frac{dw_m}{dt} = \frac{1}{2h}(T_e - Fw_m - T_m) \\ \frac{d\Theta_m}{dt} = w_m \end{cases} \qquad (3)$$

with:

w: Reference frame angular velocity
w_r: Electrical angular velocity
w_m: Rotor angular velocity
R_s, L_{ls}: Stator resistance and leakage inductance
R'_r, L'_{lr}: Rotor resistance and leakage inductance
V_{qs}, i_{qs}: q axis stator voltage and current
V_{ds}, i_{ds}: d axis stator voltage and current
V'_{qr}, i'_{qr}: q axis rotor voltage and current
V'_{dr}, i'_{dr}: d axis rotor voltage and current
$\varphi_{qs}, \varphi_{ds}$: Stator q and d axis fluxes
$\varphi'_{qr}, \varphi'_{dr}$: Rotor q and d axis fluxes
L_m: Magnetizing inductance
L_s: Stator inductance
L'_r: Rotor inductance
Θ_m: Rotor angular position
p: Number of pole pairs
T_e: Electromagnetic torque
T_m: Shaft torque
h: Inertia constant
F: Viscous friction coefficient

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The simplified grid model is a three-phase system containing three single-phase star-connected sources. The internal resistance R_g and inductance L_g are defined as [17]:

$$R_g = \frac{X}{(X/R)} \cdot \frac{2\pi f L_g}{(X/R)} \qquad (4)$$

$$L_g = \frac{\vartheta_{base}^2}{P_{sc}} \cdot \frac{1}{2\pi f} \qquad (5)$$

with:

ϑ_{base} : Base voltage
P_{sc} : Inductive three-phase short circuit power (VA).
f : Frequency (Hz).

Unsymmetrical sets of voltages and currents under grid faults are represented using their symmetric sequence sets. If Z denotes the impedance matrix, voltages and currents in abc system may be converted to the 012 system to obtain

$$V_{012} = Z_{012}\, I_{012} \qquad (6)$$

This makes it possible to analyze the unbalanced 3-phase current system by separately analyzing the symmetric sequence systems and then adding the results.

III. SIMULATION RESULTS AND DISCUSSION

A detailed model of the SCIG-based wind turbine system was performed in Matlab/Simulink to explore its dynamic performances in case of short circuit faults. For a wind speed of 9 m/s, different fault conditions are applied at the grid-side of the transformer at time t = 6 s and cleared after 83 ms based on 60 Hz frequency. SCIG generates power when supplied by a negative torque on its shaft, this power is positive when consumed by the SCIG and negative when generated by the SCIG. A snapshot of simulation results is shown in Figures 2 and 3. From these figures, it can be seen that after approximately 4s, the turbine model parameters reach an optimum operating point. The transients of grid current, active and reactive power are plotted respectively in Figures (4) to (13) for each of the short-circuit faults.

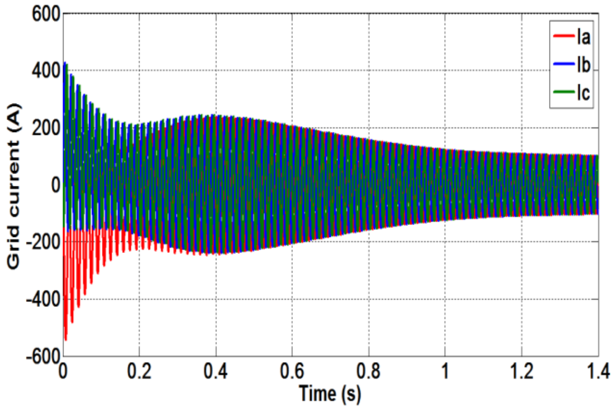

Figure 2. Grid Current

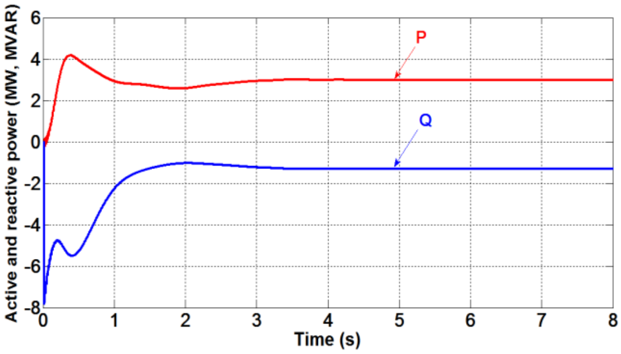

Figure 3. Injected Active and Reactive Power to the Grid

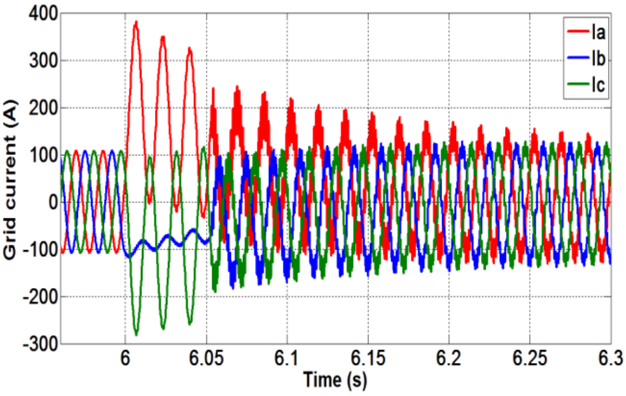

Figure 4. Grid Current with LG Fault

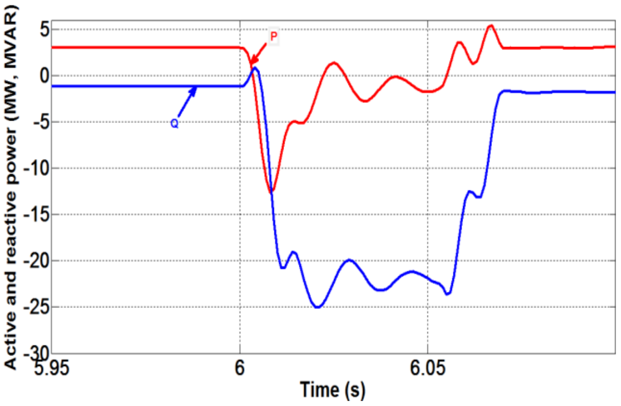

Figure 5. Active and Reactive Power with LG Fault

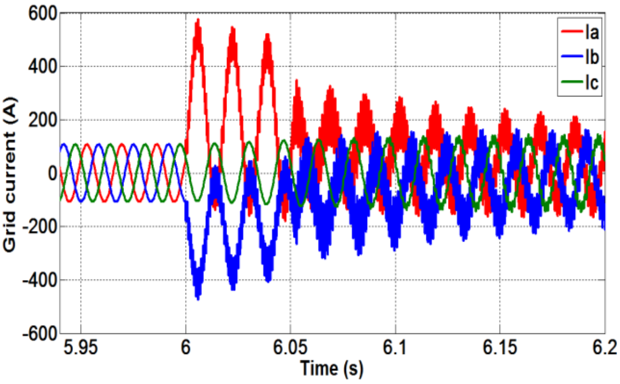

Figure 6. Grid Current with LL Fault

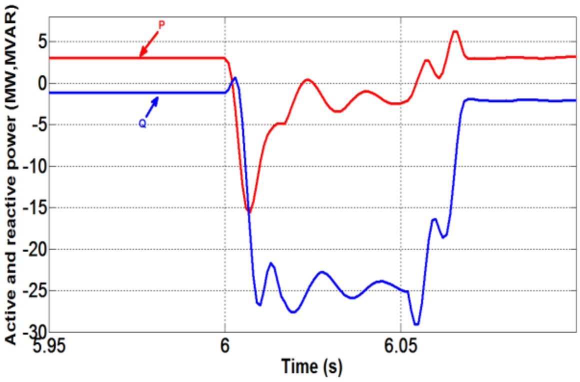

Figure 7. Active and Reactive Power with LL Fault

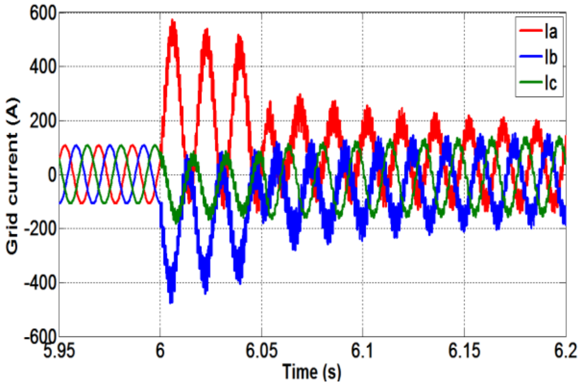

Figure 8. Grid Current with LLG Fault

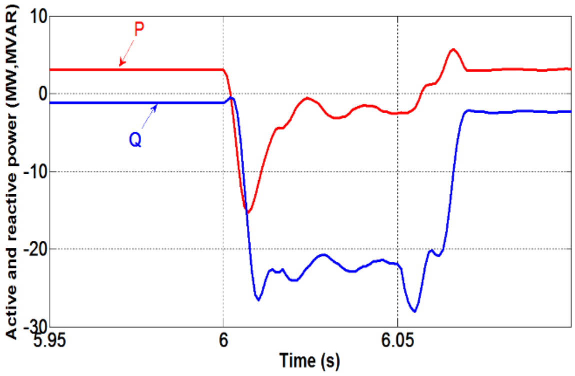

Figure 9. Active and Reactive Power with LLG Fault

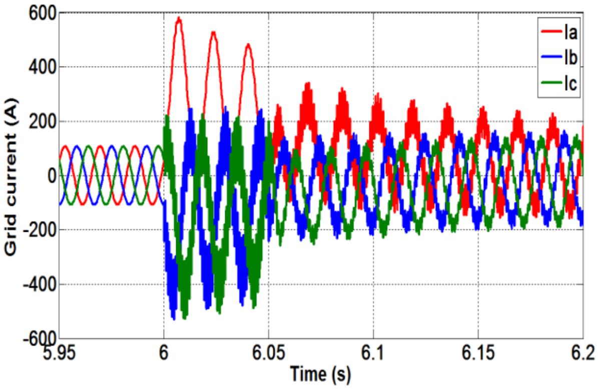

Figure 10. Grid Current with LLL Fault

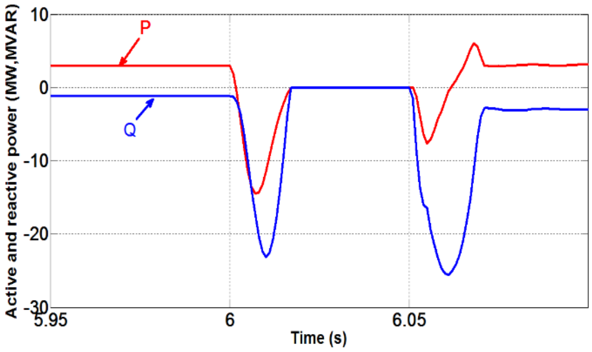

Figure 11. Active and Reactive Power with LLL Fault

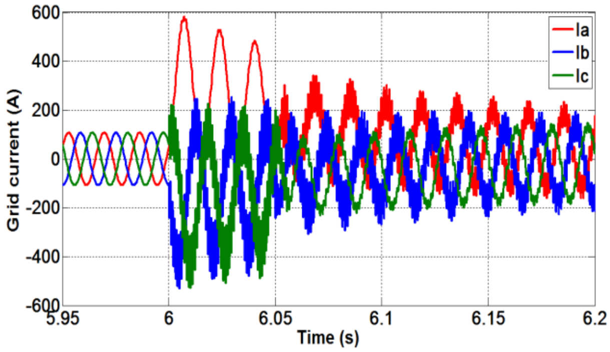

Figure 12. Grid Current with LLLG Fault

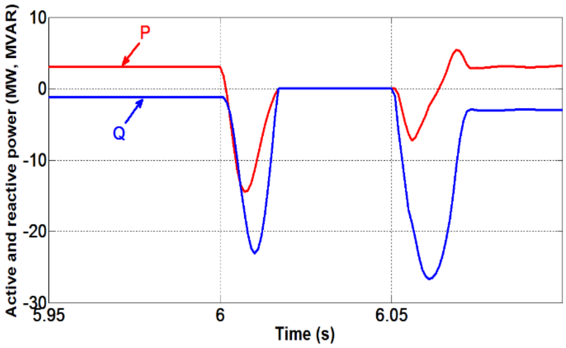

Figure 13. Active and Reactive Power with LLLG Fault

Phase currents, active and reactive powers variations during different faults are presented in the Table 1.

Table 1. Phase Currents, Active and Reactive Power Decays During Different Fault Conditions

FAULT	Rated current peak value for phase a	Rated current peak value for phase b	Rated current peak value for phase c	Rated active power peak value	Rated reactive power peak value
LG	355.88 %	53.87 %	262.35 %	137%	90.98%
LL	537.27 %	440.1 %	103.143 %	139.76 %	151.6 %
LLG	535.08 %	442.06 %	80.5 %	131.9 %	159.27 %
LLL	542.27 %	229.38 %	205.14 %	117.42 %	153 %
LLLG	542.27 %	235.03 %	211.02 %	117.42 %	153 %

The modeling and simulation results show the net current surge with a magnitude higher than the normal rated current. Notice that type 1 wind turbine generators can generate significant fault currents. Depending on the time of short-circuit, and including the dc component, the contribution during the initial cycle of the fault (asymmetrical current) can be as high as six times the rated current or more as given in Table 1. These high transient currents shown in Figures 4, 6, 8, 10 and 12 create an imbalance between system phases. We clearly distinguish as presented in Table 1 that LLLG, LLL, LLG and LL faults are respectively the most severe and present the largest short-circuit current. The three-phase fault is the least likely to occur, however, the duration of this type of fault must be the shortest because the air-gap flux of the induction generator collapses without sufficient line voltage support. The single line to ground fault is the most likely to occur. The terminal voltage and currents are sustained longer because the line voltages, except from one phase, can sustain air-gap flux. Although the short-circuit current contribution from this type of fault is the lowest among other different faults, that's why when sizing the relay setting and breaker capacity, this data must be very useful to overcome by safety equipment. If the fault remains, the magnitude of the contribution decreases. When the short-circuit is cleared, the supply voltage returns to its normal waveform but the system will still draw an unbalanced and higher-than-normal rated current. Wind turbines must have the ability to control their active/reactive power for transient stability, this is done by limitations on the rate of change of active/reactive power to suppress large frequency fluctuations, remagnetize the generator and solve the problem of generation/consumption imbalance of power. As presented in Figures 5, 7, 9, 11 and 13, a wind turbine can regulate its active power output to a defined ramp and level directly after fault clearance. A fast return to the normal active power supply is recorded. This is of a great importance for power system operation. The subject of these requirements is to ensure a stable system frequency, to minimize the dynamic operation effect on the grid, to prevent overloading of transmission lines and for transient stability during faults. Within a very narrow interval, the voltage level in the grid is maintained constant. Wind turbines can supply or absorb reactive power to maintain the voltage level at the PCC. To help the reestablishment of grid voltage, the reactive power as presented in figures 5, 7, 9, 11 and 13 needed for remagnetization of the induction generator is less after the fault is cleared.

IV. CONCLUSION

Fixed-speed wind turbine generators can contribute significant fault currents, this contribution can be as high as six times the rated current or more. These high transient currents create an imbalance between system phases. LLLG, LLL, LLG and LL faults are respectively the most severe and present the largest short-circuit current.

The single line to ground fault is the most likely to occur. The terminal voltage and currents are sustained longer because the line voltages, except from one phase, can sustain air-gap flux. Although the short-circuit current contribution from this type of fault is the lowest among other different faults.

As the fault remains, the contribution decreases in magnitude. When the short-circuit is cleared, the supply voltage returns to its normal waveform but the system will still draw an unbalanced and higher-than-normal rated current.

A wind turbine can regulate its active power output to a defined ramp and level directly after fault clearance. A fast return to the normal active power supply is recorded. This is of great importance for power system operation because it ensures a stable system frequency, minimizes the dynamic operation effect on the grid, prevents overloading of transmission lines and allows transient stability during faults. Within a very narrow interval, the voltage level in the grid is maintained constant. Wind turbines can supply or absorb reactive power to maintain the voltage level at the PCC. To help the reestablishment of grid voltage, the reactive power needed for the remagnetization of the induction generator is less after the fault is cleared.

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval and consent to participate with evidence.
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Authors Contributions	All authors have equal participation in this article.

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