The Effect of Resistive-type Superconducting Fault Current Limiters on the Test Feeder with Wind-turbine Generation System

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ABSTRACT

This paper describes the study to analyze the effect of the resistive-type superconducting fault current limiters (RSFCLs) on the test feeder with the wind-turbine generation, which is a representative renewable energy source. The presented test case is the IEEE 34-bus test feeder augmented with two induction machines that would be typical of wind generation. It is worthy to mention that wind-turbines which are only squirrel-cage induction generator have been considered. The connection of wind-turbines to existing distribution networks may lead to the increasing fault levels beyond the capacity of existing switchgear. This can aggravate the reliability of the overall power system. The short-circuit currents are expected to be controlled by RSFCL. The analysis investigates the effectiveness of using RSFCL as remedial measures for fault level management in a wind power system. As a result, the highly efficient operation of the wind power system becomes more possible by introducing the RSFCL. All models are developed in the time-domain PSCAD/EMTDC dynamic simulation.

Keywords:
Distributed generation, Short-circuit current, Superconducting fault current limiter, Wind-turbine generation system.

1. INTRODUCTION

Due to the increase of electricity demand and the change of concerning environments, the penetration of renewable sources on power systems is increasing, which are mainly connected to a distribution system [1]. The wind-turbine generation system (WTGS) is one of the representative renewable energy systems. Wind energy is one way of electrical generation from renewable sources that uses wind-turbine to convert the energy contained in flowing air into electrical energy. The current technology with the majority of land-based wind farms is stall-regulated wind-turbines with conventional fixed-speed induction generators (FSWTs) which are connected directly to the power system. FSWTs are often used for wind power generation because of their simple construction and low maintenance cost [2]. As the penetration of wind-turbine in electrical power system increase, the level of associated short-circuit current during a fault will be increased in the distribution system. This increased short-circuit current leads to the increasing fault levels beyond the capacity of existing switchgear, especially in distribution network and it can have a negative effect on the entire power grid including WTGS with respect to stability [3]. Another issue in FSWT is their operation during grid faults. Faults cause voltage dip at the point of interconnection of wind-turbine in a power system. This results in an increase of the current in the stator winding of generator. Most induction generators are disconnected from grid when such fault occurs.

Thus, it is desired that the wind-turbines remain connected and are actively contributed to the system stability during and after faults and disturbances [4].

The ability of wind-turbine to stay connected to the grid during faults and voltage dips is stated as low-voltage ride-through (LVRT) capability. Several countries have proposed LVRT requirement for interconnection of wind generation. The proposed voltage requirement is described by Figure 1. It shows that only when the grid voltage goes below the curve, the turbine is allowed to disconnect [5]. The resistive-type superconducting fault current limiter (RSFCL) can be a solution to reduce the level of the short-circuit current during a fault, which is increased by the WTGS. Also, it mitigates the voltage dip in the machine terminal during the faulted condition. The RSFCL causes no power loss in steady state condition and improves the transient stability of power system by suppressing the level of the fault current with the quick operation and auto recovery capability [6,7]. Essentially, in order to improve system stability and to avoid replacement of the existing protection instruments, RSFCL devices should be installed near of wind turbines.

This paper is organized into the following sections: section 2 briefly describes the modeling of the FSWT used as WTGS, which operates in IEEE 34-bus test feeder. In section 3, a model of RSFCL is developed that is used to manage excessive fault current levels. Section 4 explains the simulation states and section 5 present the results obtained from the simulation. Finally, the conclusions are established in section 6.

2. MODELING OF THE WIND TURBINE

One of the most widely used wind-turbine is FSWT. In FSWTs, the rotor speed is fixed regardless of the wind speed. This speed is determined by the grid frequency, the gearbox ratio, and the number of poles in the generator [8]. FSWTs are equipped with a squirrel cage induction generator that is directly connected to the grid with a soft-stator through a connecting transformer. Induction machines consume reactive power, so it is conventional to provide power factor correction capacitors at each wind-turbine. These are typically rated at around 30% of the wind-turbine MW capacity and are used to compensate the induction machine magnetizing current. A typical configuration of FSWT-based wind turbines is shown schematically in Figure 2.

The proposed FSWT model for the generation system includes modules of wind speed, turbine, drive train, and generation system.

2.1 Wind Speed Model

The wind speed is set to a constant 20 (m/s) which is a wind speed that allows turbine to produce rated power. Then, there are no variations in its output power according to wind speed. A rated power operating point is chosen as the most burdening for the power system [9].

2.2 Wind Turbine Model

Wind energy is captured by the blades and is transformed to a higher speed at the generator shaft by the gearbox. Then, electrical energy is produced by the generator. The turbine model must take into account the behavior of the blades, the shaft, and both sides of the gearbox and the gearbox itself. The mechanical power extraction from the turbine is given by (1) [10].

$$p_{wt} = \frac{1}{2}\rho A V_w^{\ 3} C_p \tag{1}$$

Where, p_{wt} is the mechanical power extracted by wind turbine rotor, ρ is the air density (Kg/m^3), A is the sweep area of the blades (m^2), $V_w^{\ 3}$ the wind speed (m/s), and C_p the power coefficient that represents the rotor efficiency of the turbine. The power coefficient depends on the tip speed ratio (λ) and the blade angle (β). In the case of

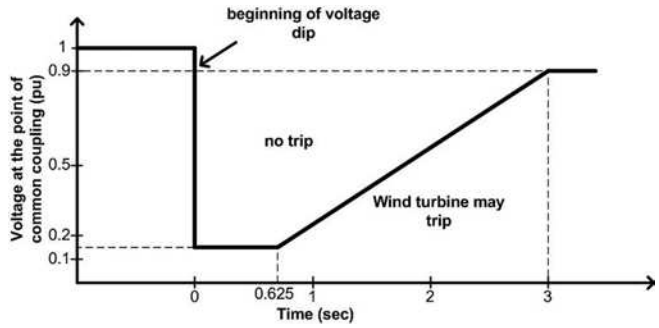

Figure 1: Voltage dip ride-through requirement.

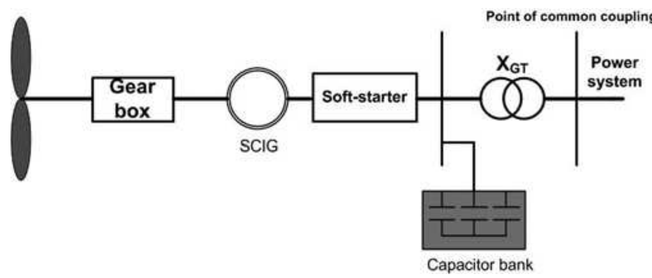

Figure 2: Basic configuration of FSWT.

turbines without pitch control, the blade angle is constant and depends only on λ. The tip speed ratio is expressed as

$$\lambda = \frac{\omega_T R}{V_W} \tag{2}$$

Where, ω_T is the turbine angular speed (rad/s) and R is the wind rotor radius (m).

2.3 Drive Train System

In wind-turbine applications, the lower shaft stiffness includes the fact that generator is much lighter than the turbine, causes that the drive train does not behave as a single equivalent mass. As a result, a multi-mass drive train must be used for dynamic/transient studies of wind-turbines with FSWT. In general, the wind turbine drive train is modeled as a two-mass model for dynamic applications [11]. The two-mass model is given by (3)-(5)

$$\frac{d\omega_r}{dt} = \frac{T_e + K_s\theta + D(\omega_t - \omega_r)}{2H_r} \tag{3}$$

$$\frac{d\omega_t}{dt} = \frac{T_m - K_s\theta - D(\omega_t - \omega_r)}{2H_t} \tag{4}$$

$$\frac{d\theta}{dt} = \omega_b(\omega_t - \omega_r) \tag{5}$$

Where, ω_r and ω_t are the turbine and generator speeds in (pu), θ is the shaft twist angle in (rad). H_r and H_t are the are the inertia constant of turbine and the generator in (sec), respectively. K_s is the shaft stiffness coefficient in (pu/elec.rad), D is the damping coefficient in (pu), T_e and T_m are the generator electrical torque and turbine mechanical torque, respectively, in (pu).

2.4 Generation System

The generalized machine model is developed based on the following assumptions:

a) Positive direction for the stator and rotor currents is assumed into the generator.
b) The equations are derived in synchronous reference frame using direct (d) and quadrature (q) axes representation.
c) All System parameters and variables are in per unit and referred to the stator side of FSWT.

Electrical model of the FSWT comprises the following base equations: The stator and rotor voltages and fluxes, and electromechanical torque [12,13].

$$v_{sd} = R_s i_{sd} - \omega_s \psi_{sq} + \frac{1}{\omega_b}\frac{d\psi_{sd}}{dt} \tag{6}$$

$$v_{sq} = R_s i_{sq} + \omega_s \psi_{sq} + \frac{1}{\omega_b}\frac{d\psi_{sq}}{dt} \tag{7}$$

$$v_{rd} = R_r i_{rd} - \omega_2 \psi_{rd} + \frac{1}{\omega_b}\frac{d\psi_{rd}}{dt} \tag{8}$$

$$v_{rq} = R_r i_{rq} + \omega_2 \psi_{rd} + \frac{1}{\omega_b}\frac{d\psi_{rq}}{dt} \tag{9}$$

$$\psi_s = L_s i_s + L_m i_r \tag{10}$$

$$\psi_r = L_m i_s + L_r i_r \tag{11}$$

$$T_e = \frac{L_m}{L_s}(\psi_{sq} i_{rd} - \psi_{sd} i_{rq}) \tag{12}$$

Where, ψ_s and ψ_r are stator and rotor flux, respectively, ω_b is the base of angular frequency, ω_s and ω_2 are synchronous angular frequency and rotor slip frequency, respectively. The subscripts d and q represent the direct and quadrature axes, respectively.

3. MODELING OF RESISTIVE-TYPE SUPERCONDUCTING FAULT CURRENT LIMITERS

The influence of RSFCL on the transient stability depends on its installation location and some parameters such as fault current amplitude, fault duration, and RSFCL impedance within the limitation regime. The RSFCL is designed to react very shortly after the instance of the fault to limit the first peak of the fault current when the fault current exceeds the threshold value. When the limiter operates during fault, a nonlinear resistance will be developed within the path of the fault. This resistance limits the available short-circuit current by its transition from the superconducting state to the normal state, the so-called quench. The quench characteristic of superconducting coil uses the following dependence:

$$R_{SFCL} = R_m\left(1 - \exp\left(\frac{t}{T_{sc}}\right)\right) \tag{13}$$

Where, R_m is the maximum resistance of superconducting coil in the normal state when the RSFCL is connected to the power system. T_{sc} is the time constant of transition from the superconducting state to the normal state, which is assumed to be 1ms [14].

The simple structure of this RSFCL unit is shown in Figure 3. This unit consists of the stabilizer resistance, R_2, and the superconducting resistance, R_1 which is connected with R_2 in parallel. The value of L_n is determined by the wound coils. It should be as small as possible because the inductance causes AC loss under the normal condition. In practice, the coil is wound to have very small inductivity. Therefore, the value of L_n is so small that its effect can be ignored.

4. SIMULATION STUDIES

Grid integration of wind-turbines in this paper was simulated by Electromagnetic transient PSCASD/EMTDC software. The wind-turbines are interconnected to a network via a RSFCL that is used to manage excessive fault current levels. The radial test feeder used for the simulation studies is shown as a single line diagram in Figure 4 with two identical wind turbines, $FSWT_1$ and $FSWT_2$. The test feeder is based on the IEEE 34-bus test feeder [15]. This is a rather lengthy 24.9 KV feeder with a small 4.16 KV section. $FSWT_1$ is assumed to be connected at the end of one of the 24.9 KV laterals and $FSWT_2$ is connected to the end of the 4.16 KV system.

The network was modeled by the standard components in PSCAD/EMTDC. Two wind turbines have been added to the feeder through two transformers for the purpose of simulation. Compensating capacitors are

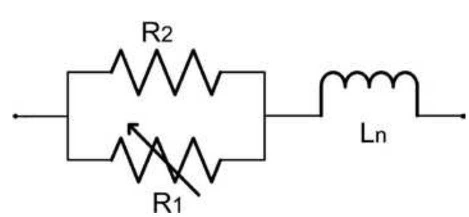

Figure 3: Resistive-type superconducting fault current limiter model.

connected at the low-voltage side of the transformers, so the power factor is 0.9 (lagging) at the wind-turbines connection bus. Meanwhile, the RSFCL(s) is installed on the main road of the wind turbines. In addition, the 4 and 6 Ω RSFCL in the normal stage of RSFCL after quenching occurred in a fault contingency that is used in this study. The generators are modeled by 6-pole asynchronous machine driven by a wind turbine to deliver 660 KVA output power with mechanical speed equal to 1 200 rpm.

The parameters of the 660 KV induction machine, shown in Table 1, are given referred to the stator winding. An active-stall controller is implemented which finds the right pitch angle during normal state and fault-free operation. It optimizes the active power production at the wind speeds below the rated wind speed. Initially, the whole system operates at a steady-state condition and the wind turbines are assumed to have the same capacity and the identical incoming wind speed distribution. The wind turbines operate normally when a three-phase to ground fault is assumed to be applied to the feeder as shown in Figure 4. The fault is applied at time t = 4 (s) with fault duration equal to 50 (ms). For simplicity, the permissible temperature rise of the elements is not considered and assumed to be constant, since this paper does not consider RSFCL technical design issues.

Table 1: Parameters of induction machine

Parameter (unit)	Value
Rated power (KVA)	660
Rated voltage (KV)	0.69
Pole numbers	6
Stator resistance (pu)	0.0053
Rotor resistance (pu)	0.007
Stator leakage inductance (pu)	0.106
Rotor leakage inductance (pu)	0.12
Magnetizing inductance (pu)	4

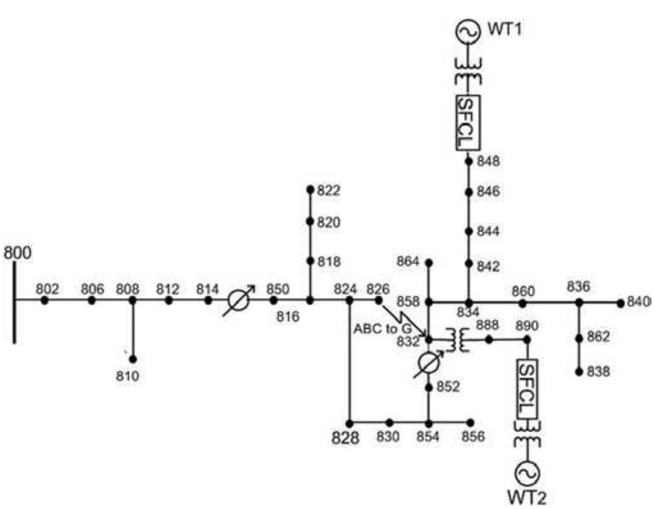

Figure 4: One-line diagram of 34-bus test feeder system with two-fixed-speed wind turbines.

5. SIMULATION RESULTS

5.1 Resistive-type Superconducting Fault Current Limiters Operation and Effect on FSWT2

A 50-ms three-phase short-circuit is applied to the feeder adjacent where the FSWT2 is connected, as shown in Figure 4 at 4 s. The response of terminal voltage, the rotor speed, and output active power of FSWT2 are shown in Figure 5. When the test feeder operates without the RSFCL, the rotor speed is increased by the fault. Also, the terminal voltage drops from 1 pu to below 0.5 pu during the fault. On the contrary, the speed and voltage responses are almost stable by the RSFCL operation. Likewise, the output active power response shows large oscillation in the range of 0.55 pu to 1.36 pu when the system has no RSFCL.

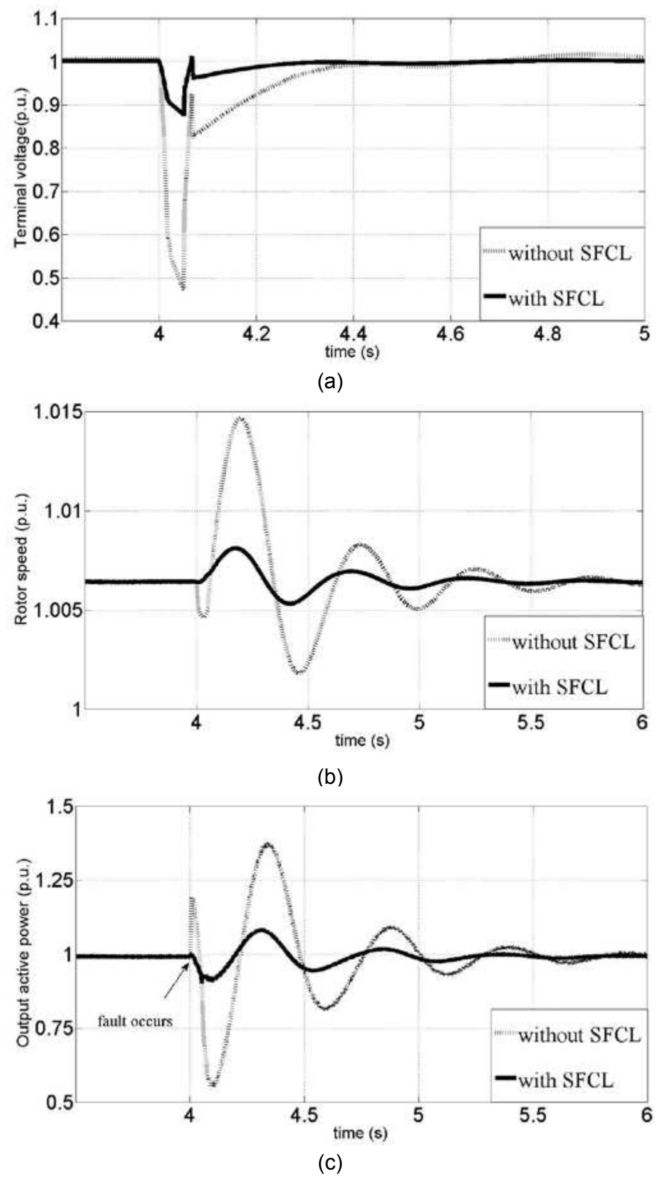

Figure 5: (a) Response of terminal voltage; (b) Response of rotor speed; (c) Response of output active power.

However, the variations of output power are dramatically reduced with RSFCL. Also, Figure 6 shows results of the *a*-phase current of the FSWT2 with and without adding RSFCL at the faulted feeder of the distribution network. The peak value of the transient current of the FSWT2 reaches 2.3 pu within first cycle without adding RSFCL.

However, the corresponding value is almost the same as the value of steady state operation with RSFCL usage.

5.2 Resistive-type Superconducting Fault Current Limiters Operation and Effect on FSWT1

As mentioned before, the 50-ms three-phase short-circuit is now applied to node 832 in Figure 4 at 4 s. The responses of rotor speed, terminal voltage, and output active power of FSWT1 are shown in Figure 7. Also, the *a*-phase current of the FSWT1 is shown in Figure 8. When the system operates without the RSFCL, the rotor speed increases up to the 1.02 pu at its maximum. However, the results improve that the speed is stable by the operation of RSFCL.

For the terminal voltage, Figure 7 shows the mitigation of the voltage dip in during the faulted condition by using RSFCL. It can be seen that fluctuations of output active power damps by using of RSFCL and wind turbine gradually stabilize back to the normal operation as the fault is cleared. Also, it can be understood from the result of Figure 8 that the *a*-phase current of the FSWT1 increase to 3.06 pu at its maximum during the fault without the RSFCL. On the contrary, when the SFCL is used, its corresponding peak value is 0.89 pu, which is not very different from the steady-state value. The short circuit reduction ratio in the first cycle is about 70%.

Once the RSFCL is adopted in wind system, the peak value of short-circuit current could be limited to a level within the switchgear rating, allowing deploying of light circuit breakers and transformers

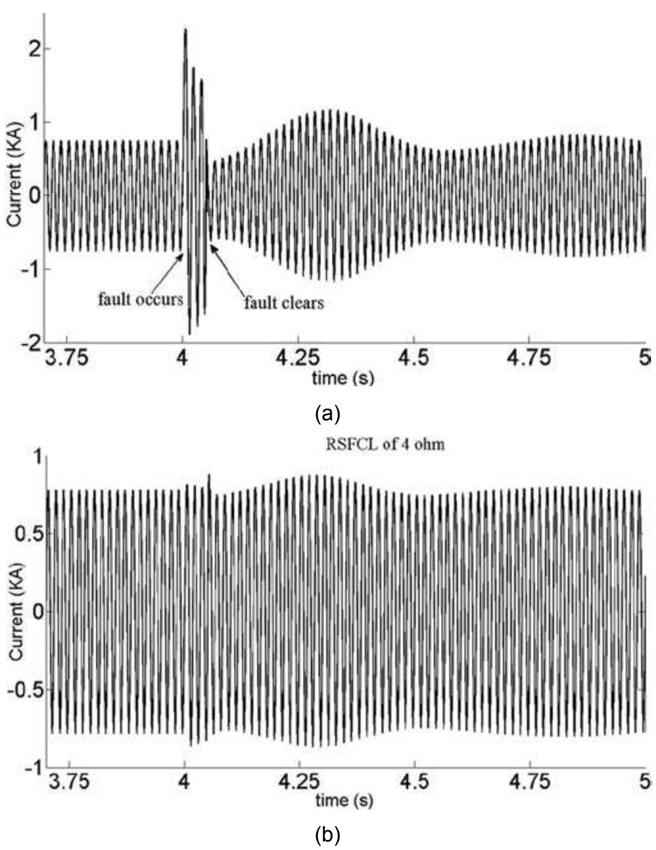

Figure 6: Response of *a*-phase current of the FSWT2 (a) Without SFCL; (b) With SFCL.

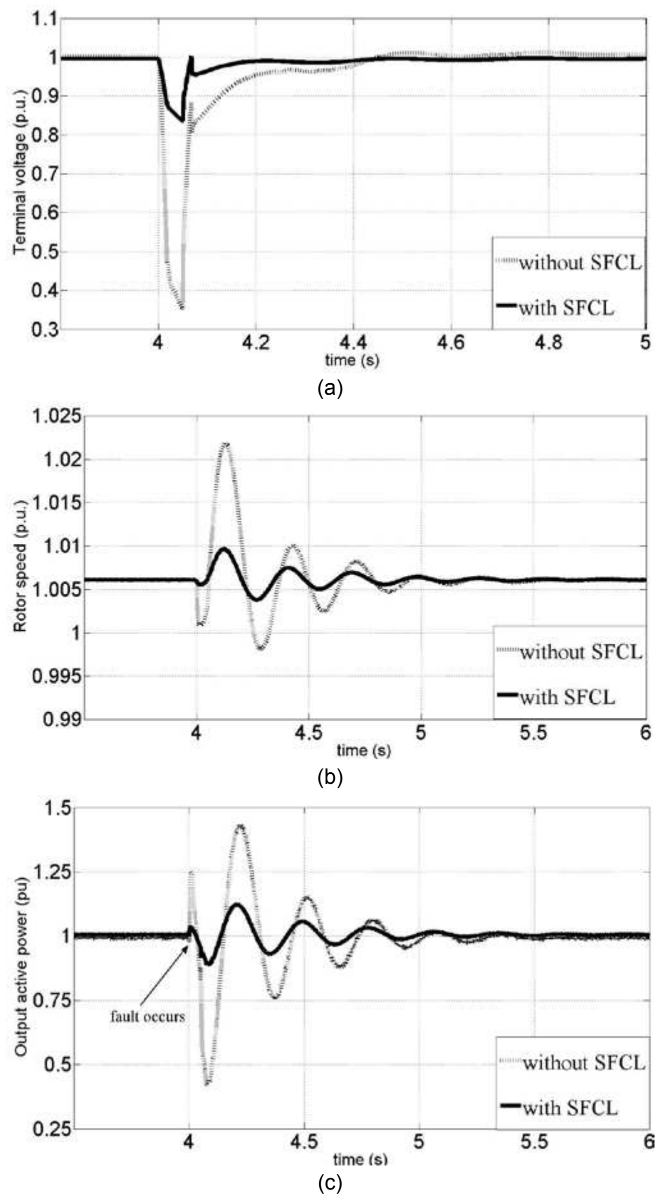

Figure 7: (a) Response of terminal voltage, (b) Response of rotor speed, (c) Response of output active power.

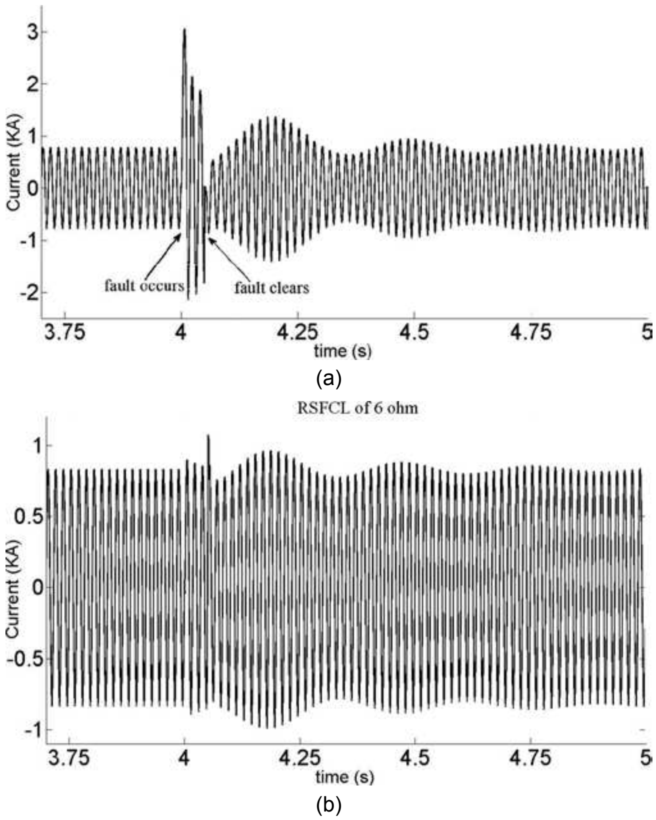

Figure 8: Response of *a*-phase current of the FSWT1 (a) without SFCL; (b) with SFCL.

by limiting fault currents during contingency periods.

6. CONCLUSION

This paper analyzes the effect of resistive RSFCL on the electric power grid with the WTGS. The behavior of the fixed-speed wind turbine (FSWT) in a three-phase to ground fault has been simulated in PSCAD and the results obtained. Then, these results are merged and plotted in MATLAB software. The simulation results on the case study showed that the RSFCL can not only reduce the level of short-circuit current, which might be increased by the WTGS, but also it dramatically improve the voltage dip, rotor speed, and output active power fluctuations. Thus, the reliability of grid-integrated wind-turbine system enhanced.

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