Improving Transient Stability in DFIG-Based Wind Turbines Using Bridge-Type SFCL

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***Abstract*—Nowadays, electrical energy is mainly produced by burning fossil fuels, which actually has negative effects on earth, namely global warming. In the electricity sector, measures that can be taken to reduce emissions include replacing conventional generators with renewable ones. Wind energy is one type of new renewable energies (NREs) with the potential to reduce emissions. Wind turbines widely used today are variable speed wind turbines, such as the doubly-fed induction generator (DFIG). DFIG has numerous advantages, like having more flexibility and being able to control both active and reactive powers. However, it often encounters instability problems in its system when experiencing transients. Therefore, a solution that can improve transient stability in DFIG is needed. The bridge-type superconducting fault current limiter (SFCL) was used in this research as a solution to improve the transient stability in DFIG, which consisted of two diodes and two inductors. This bridge-type SFCL operates by limiting the current in the event of faults, preventing the system from voltage drops or trips. The simulation results were analyzed under two circumstances. In the first circumstance, the 9 MW DFIG wind turbine system which was given faults using SFCL produced a voltage value of 219 V, with a more stable frequency value of 50 Hz, and an active power value of 9 MW. Meanwhile, when a system that did not use SFCL was given faults, the voltage dropped from the normal state of 219 V to 100 V. The frequency value was less stable, fluctuating between 49.75 Hz and 50.25 Hz, while the active power dropped from 9 MW to 6 MW. This result proves that the bridge-type SFCL method effectively increases the transient stability in DFIG.**

***Keywords*—Global Warming, EBT, DFIG, SFCL.**

I. INTRODUCTION

Electrical energy is mainly produced by combusting large-scale fossils, which brings negative effects to earth, namely global warming [1], [2]. Coal combustion has resulted in the production of carbon dioxide in enormous quantities, thereby destroying the ozone layer, causing the fluctuating temperature on earth, and triggering various diseases for living beings [3], [4]. Therefore, the world through the Paris Agreement has proclaimed a 25% reduction in emissions in the power sector by 2030 since this sector is considered easier to control than the transportation and other sectors [5]. In an effort to reduce fossil combustion to produce electrical energy, Indonesia has declared that by 2025, a minimum of 23% of its electrical energy supply must be generated from renewable energy sources [6].

In the electricity sector, measures that can be taken to reduce emissions is to replace conventional power plants with renewable energy ones [7], one of which is a power plant sourced from the wind [8]. In Europe, wind turbines are the fastest-growing generators among other renewable energy plants [9], [10]. In addition, taking into considerations the ongoing energy planning and development in several countries worldwide, wind energy is regarded as the most promising renewable energy source [11]-[13].

One of the most common types of wind turbines in use today is a variable speed generator, which is considered more flexible than other generators [14]. The doubly-fed induction generator (DFIG)-based wind turbine is also utilizing variable speed technology [15]. DFIG has numerous advantages, including the ability to control active and reactive power [16]. Besides that, DFIG is also superior in terms of its ability to capture large amounts of energy and its better controllability [17]. Despite its advantages, DFIG-based wind turbines frequently experience instability or tripping in the event of system faults, known as transient disturbance [18]. Transients occur due to sudden changes in the voltage value or current within a short time when in a steady state [19].

Therefore, cutting-edge technology capable of addressing the problem of decreasing transient stability is necessitated. One method that can be used to improve transient stability is the current limiter [20]. It is a method that can limit the current in the system so that when a fault occurs, the system will not experience voltage drops and trips. The most prevalent type of current limiter in use today is the superconducting fault current limiter (SFCL). SFCL can better increase transient stability and quickly respond to disturbances [21].

There has been much previous research that attempted to improve transient stability in power systems. Research has investigated ways to overcome DFIG in the event of voltage drops and random fluctuations. The method used in this research was a three-level NPC converter, which was compared to a conventional two-level system. The simulation results demonstrated that using three level method was better than using the two level since it could respond faster and had the control ability to respond during fault conditions and return to the initial voltage in a short time [22]. However, it is necessary to conduct research utilizing the bridge-type SFCL method for more optimal results.

Other research has tested methods for DFIG wind turbines to overcome faults or disturbances in compliance with the Swedish grid code. This research implemented SFCL using a high-temperature superconductor (HTS), allowing DFIG to ride through the faults connected to the grid. The results

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showed that DFIG without ride-through capability could disrupt the transient stability margin. When ride-through capability was applied, DFIG with the application of SFCL using HTS could enhance the transient stability of the small power producer (SPP) [23]. For more optimal results, it is necessary to conduct research using the bridge-type SFCL method.

Research also has been conducted to improve the transient stability of DFIG. The method used in this research was a fault current limiter (FCL) with HTS. The results demonstrated that the proposed scheme, namely FCL with HTS, served as a good voltage amplifier with low cost [24]. The scheme employing HTS requires time for the resistor to cool down, so a faster method is needed to overcome transient stability.

Other research has been conducted with the aim of making DFIG-based wind turbines able to ride through faults in short durations. The method used in this research was a superconducting magnetic energy storage-fault current limiter (SMES-FCL). The results showed that the SMES-FCL method allowed DFIG-based wind turbines to pass through disturbances, so they did not trip. The method could also increase the transient stability [25]. Thus, it is necessary to conduct research employing the bridge-type SFCL method so that the system can rid through the fault current more quickly.

Based on previous reserch, the current limiter method on a large-scale DFIG-based wind turbines was developed and analyzed to see its effectiveness. Therefore, transient stability analysis and improvement were carried out using the bridge-type SFCL method in DFIG-based wind turbines. Using the bridge-type SFCL method, a system that experiences a major disturbance is able to return to its original state without tripping occurring in a fast time. Furthermore, it will not exceed the predetermined value limit regulated in the Indonesian grid code.

II. METHODOLOGY

This paper discusses the systems of DFIG-based wind turbines with a capacity of 9 MW modeled in Simulink MATLAB. The study consists of several stages: modeling a DFIG-based wind turbine, designing a bridge-type SFCL method on a DFIG-based wind turbine system, performance testing, analysis, and conclusion.

A. Design Flow of the Research Method

Fig. 1 depicts a flowchart of a DFIG-based wind turbine modeling research conducted with Simulink MATLAB, employing parameters in the Simulink. The purpose of designing the bridge-type SFCL method on a DFIG-based wind turbine system is to improve transient stability so that the system does not trip and can quickly returns to its original state upon passing major faults. The system in this research is a DFIG-based wind power plant paralleled with bridge-type SFCL technology. With the influence of SFCL technology on the system when it encounters major faults, the system can automatically ride through the faults so that no trips occur.

Simulation and testing of the SFCL method on a DFIG-based wind turbine system were carried out in two circumstances. The first circumstance is testing the DFIG-based wind turbine system without SFCL technology when experiencing major faults. The second condition is testing the DFIG-based wind turbine system using bridge-type SFCL technology when experiencing major faults. The analysis phase attempted to prove that the proposed method, namely the bridge-type SFCL method, was the best method to be used for increasing transient stability. The SFCL method was expected to be able to ride through faults quickly, hence there would be no trip occurring in the system.

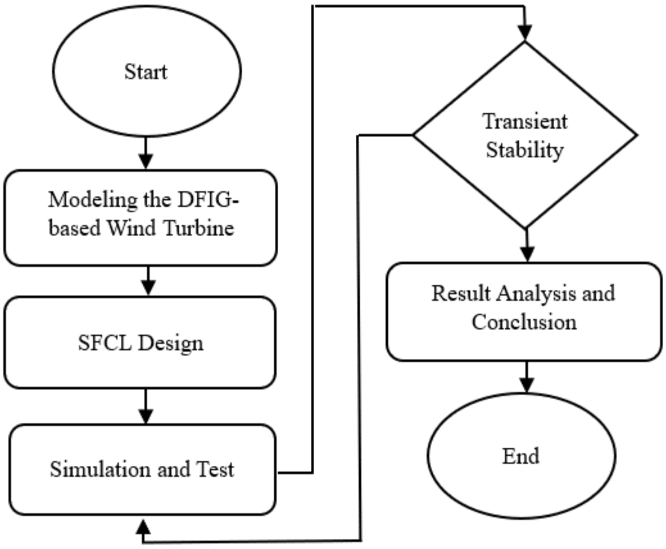

Fig. 1 Research flowchart.

B. Wind Turbines

Wind energy is one of the renewable energy sources that can be used to generate electricity [26], [27]. Renewable energies, including wind energy, are expected to be fast-growing energy sources [28]. Additionally, they are environmentally friendly energy alternatives that can reduce emissions. Emissions produced during the electrical energy generation from combusting fossil fuels are among the highest factors besides transportation. If efforts to reduce emissions are not made, the ozone layer will be damaged, resulting in temperature fluctuations and the emergence of several new diseases. This wind turbine operates with the help of many windmills installed in a place or field away from residential areas. This windmill will rotate the mechanical components of the wind turbine. Then, a generator will convert the motion energy into electrical energy using electromagnetic field theory. Ferromagnetic is permanently installed on the generator shaft, and coils of wire are formed around the shaft. As the shaft rotates due to the wind, a flux will eventually become a current and a voltage. Subsequently, the electrical power can be distributed to the public through the transmission grid and distribution system.

Wind turbine components include a rotor, propeller, gearbox, generator, low-speed shaft, high-speed shaft, and tower. The rotor functions to receive kinetic energy from wind gusts, which are then converted into motion energy to rotate. The propeller or blade usually consists of three blades; it catches the incoming winds or winds that hit its part and converts them into rotational energy to be passed on to the generator. Meanwhile,

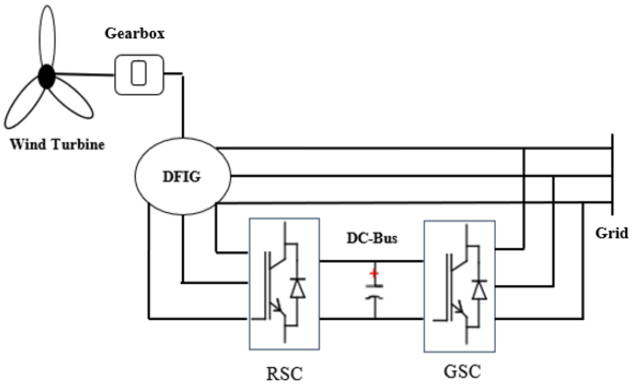

Fig. 2 DFIG-based wind turbines.

the gearbox functions as a wind turbine's speed regulator so that it moves constantly. The generator has an essential function, namely converting the incoming rotational energy into electrical energy. The low-speed shaft serves as the shaft connecting the gearbox with the rotor, while the high-speed shaft functions to rotate the generator to generate electrical energy. The tower serves as the wind turbine's support to support the load on the wind turbine unit above.

The value of the power generated from the wind turbine is influenced by the obtained kinetic energy. The equation for kinetic energy in a wind turbine is expressed in (1).

$$Ek = \frac{1}{2}mv^2 \tag{1}$$

with Ek denoting kinetic energy, m denoting mass, and v denoting wind speed in m/s. Equation (2) is used to determine the mass.

$$m = \rho A \mathrm{v} \tag{2}$$

with m being the mass value, ρ being the air density value in kg/m^3, and v being the air density value in m/s.

Equations (1) and (2) are utilized to generate an equation to find the value of the power in the wind turbine, which is shown in (3).

$$P = \frac{1}{2}\rho A v^3 \tag{3}$$

with P being the wind power value, ρ being the air density value in kg/m^3, A being the swept area of the wind turbine in m^2, and v being the wind speed m/s. Furthermore, wind turbine power is obtained from wind power using (4) and (5), involving the power coefficient parameter or Cp.

$$Cp = \frac{P\ wind\ turbine}{P\ wind} \tag{4}$$

$$P\ wind\ turbine = Cp\frac{1}{2}\rho A v^3. \tag{5}$$

C. Doubly-Fed Induction Generator (DFIG)

The most prevalently used wind turbine today is the variable speed wind turbine, one of which is the DFIG. DFIG is a dual distribution generator connected to the power generation grid. The DFIG performance is designed in an environmentally friendly scheme to control active and reactive power while also serving as a voltage measurement tool for wind turbines in the wind power generation system. DFIG has many advantages over other types, viz., being able to work more flexibly according to load requirements and to supply large amounts of energy. This DFIG-based wind turbine system incorporates a rotor induction engine operated as a generator by applying the negative torque method to the main shaft. The stator is connected to the grid by a transformer, while the rotor section is connected to a back-to-back converter [29].

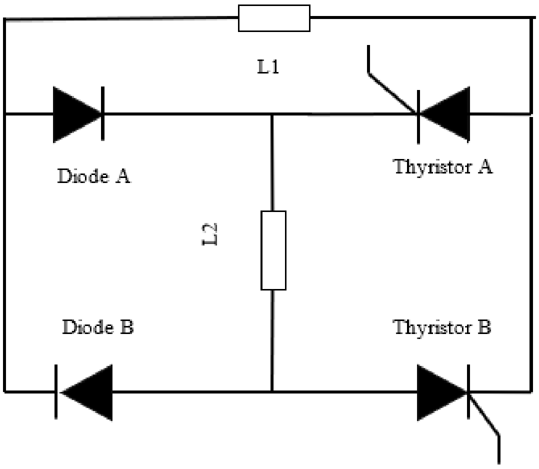

Fig. 3 Bridge-type SFCL.

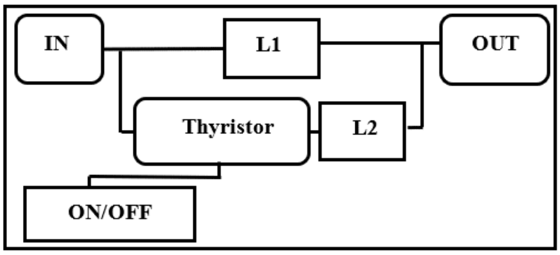

Fig. 4 Bridge-type SFCL control.

The DFIG-based wind turbine, shown in Fig. 2, consists of a gearbox, a rotor side converter (RSC), a grid side converter (GSC), and a DC bus. The gearbox serves to increase the rotational speed to be constant. DFIG is a generator that utilizes a converter to control the active and reactive power. As a results, the RSC is used to regulate the active and reactive power, i.e., the incoming current flow through the RSC is controlled to match the load. Next, the GSC functions to stabilize the DC voltage, while the DC bus serves to store temporary energy to facilitate the power flow. The equation for the wind turbine's input power is written in (6).

$$Pwt = \frac{1}{2}\pi R^2 \rho V w^3 \tag{6}$$

with Pwt denoting the input power to the wind turbine in the form of mechanical power (W); R denoting the turbine diameter (m), ρ denoting the air density (kg/m^2), and Vw denoting the air velocity (m/s). The wind turbine power generated in this system is determined by the wind's speed that rotates the wind turbine blades. These blades then spin the generator to produce electricity. The converter receives the current produced by the generator and regulates it to match the generated power to the load.

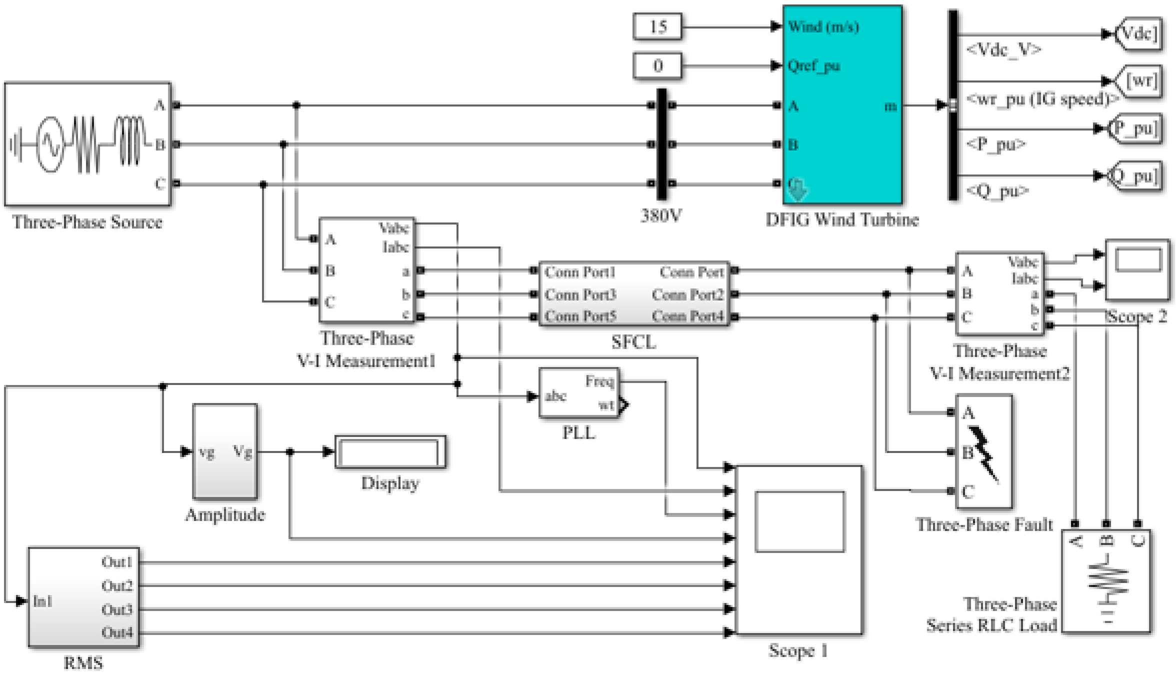

Fig. 5 System of DFIG-based wind turbines.

In the DFIG, the electrical energy is generated from the stator and rotor. The electric power generated by the stator can be calculated using (7).

$$Ps = T_{em}\ \omega_s \tag{7}$$

with Ps being power generated by the stator (W), Tem being the electromagnetic torque (N.m), and ωs being the speed of the stator rotating field (rad/s).

The total electrical power generated by the generator is equal to the mechanical power generated by the turbine. As a result, the electric power generated by the rotor Pr can be calculated based on (8).

$$Pr = Pm - Ps \tag{8}$$

with Pr expressing the rotor power, Pm expressing mechanical power, and Ps expressing the stator power.

D. *Superconducting Fault Current Limiter (SFCL)*

A current limiter is a current limiting technology used to limit the current when the system is experiencing faults. One kind of current limiter is the bridge-type SFCL, which is a combination of diode and thyristor in parallel. The bridge-type SFCL in the DFIG-based wind turbine functions as a current limiter. Using SFCL, a system will not experience a voltage drop and peak current when a transient occurs. The thyristor in the SFCL functions as a controller of the electric current, while the diode functions as a voltage limiter. For this reason, SFCL is used to improve transient stability in power systems [30]. The bridge-type SFCL block diagram is depicted in Fig. 3, while the way the control works is depicted in Fig. 4. Under normal circumstances, thyristor A and thyristor B will be off so that the current can pass through L1 only. When a fault occurs, diode B and thyristor A will be on, allowing the current to pass through two parts, namely through L1 400 mH and L2 600 mH. The thyristor will be on or off according to the time determined by the sequence following the fault time. When the system is disturbed at 0.5-0.7 seconds, the sequence will be adjusted at those seconds. This event is called limiting the current during a fault by dividing the current flow in half so that no peak current causes a voltage drop.

TABLE I
SYSTEM PARAMETER

Parameter	Value
Gen 1 active power	3 MW
DFIG active power	9 MW
DFIG vs_nom	380 V
DFIG vr_nom	380 V
DFIG frequency	50 Hz
L1 SFCL	400 mH
L2 SFCL	600 mH

E. *Transient Stability*

Transient stability is transitional stability or the ability of a power system to reach its equilibrium point to return to its normal state or steady state after experiencing major faults. Examples of these faults are the sudden release of the load or the occurrence of a short circuit which results in rapid changes in current and voltage. This rapid change in current and voltage can cause the power system to lose its stability and cause the system to experience a voltage drop and trip. This type of major faults can occur in the event of a sudden increase or decrease in the load’s power, which can lead to transmission line cuts and short circuit faults, such as three-phase, two-phase, and single-phase faults.

III. SYSTEM SIMULATION

A. *Parameter*

The system used in this research was a synchronous generator with a capacity of 3 MW in parallel with a DFIG with a capacity of 9 MW. The stator voltage had a nominal value of 380 V, and the rotor voltage had a nominal value of 380 V, with a frequency of 50 Hz. Then, a load capacity of 11 MW with a frequency of 50 Hz was added. The bridge-type SFCL which was used had L1 and L2 values of 400 mH and 600 mH, respectively. The system parameter is summarized in Table I.

B. *Simulink MATLAB Test*

This research tested the system by adding faults at 0.5-0.7 seconds under two circumstances. In the first circumstance, the system was tested using a bridge-type SFCL; in the second, no bridge-type SFCL was used to test the system.

IV. METHODOLOGY

In this research, a 9 MW DFIG-based wind turbine system was used. Simulink MATLAB was used to design the system. Fig. 5 shows the model results in Simulink. This research was carried out in two different circumstances. The first circumstance is the system state when given faults within a few seconds using a bridge-type SFCL. The second circumstance is the system state when given faults for a few seconds without using a bridge-type SFCL. This SFCL technology was also designed in Simulink, with the primary components being diodes and thyristors. A diode is a passive component, while a thyristor is an active component. The bridge-type SFCL was used to improve the transient stability in the system. When the system experienced faults, it would not trip because the system was configured with a bridge-type SFCL by dividing the current through two lines to control the occurrence of peak currents that cause a sudden voltage drop.

Fig. 6 depicts the simulation results of a 9 MW DFIG-based wind turbine with a fault at 0.5-0.7 seconds, using a bridge-type SFCL to minimize trips. The results showed that when the system was in normal condition, the resulting voltage was 219 V; the system did not experience a voltage drop when it was given faults. It demonstrates that the system with bridge-type SFCL can ride through the faults without any voltage drop or trip. It occurs since a system that uses a bridge-type SFCL allows current to pass through two inductors (two inductors limit current), which does not cause the peak current and makes the voltage value stable. Following the 2007 grid code, this condition is also considered normal as it is stated that 220 V ranges between +5% and -10%. Hence, a 219 V system is likewise regarded as normal if it has a voltage value in the range of 198-231 V.

Fig. 7 shows the voltage when the DFIG-based wind turbine system is given faults at 0.5-0.7 seconds without using the bridge-type SFCL technology model. The result demonstrated that the voltage value dropped to 120 V or the system entered a dead state with a normal voltage value of 219 V when the system was given faults at 0.5-0.7 seconds. When faults were applied without using SFCL, the voltage dropped drastically and abruptly since the peak current occurred as a result of the interference and absence of technology to limit the current. The difference between the nominal voltage and transient state without using SFCL was 100 V. In accordance with the quality standards of system operation in Indonesia, this condition is categorized as a fault condition because the voltage is below the normal voltage range, which is 198-231 V.

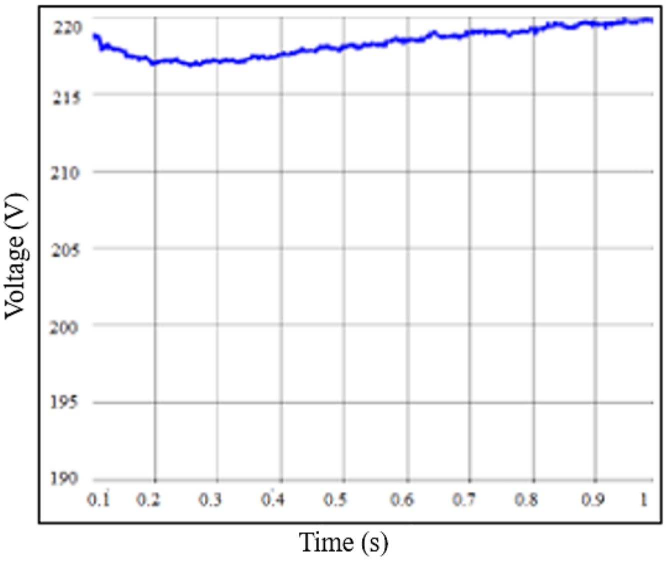

Fig. 6 Voltage value with bridge-type SFCL.

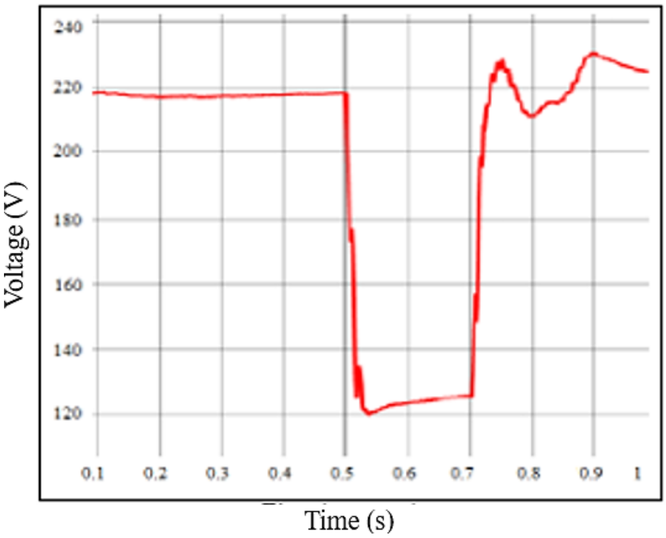

Fig. 7 Voltage value without bridge-type SFCL.

Fig. 8 exhibits the frequency value obtained by the DFIG-based wind turbine system using a bridge-type SFCL. The simulation results showed good results when SFCL was used. It happened because when a bridge-type SFCL was used in the event of faults, the system could maintain the rotor rotation stability, allowing the frequency value to remain at the nominal value. It was proven when the system was given faults at 0.5-0.7 seconds, i.e., the frequency value was still stable at 50 Hz. Based on the operating quality standard of the Indonesian grid code system, this condition is regarded as normal, as it is remains within the range of 49.00 Hz ≤ f ≤ 51.00 Hz.

TABLE II
TRANSIENT STABILITY IMPROVEMENT FROM THREE SCENARIOS

No.	Scenario		Volt	TSI	Frequency (Hz)	TSI	Active Power (MW)	TSI
1.	3-phase fault	With SFCL	219	1.84	50.00	1.005	9	1.8
		Without SFCL	117		49.75		5	
2.	2-phase fault	With SFCL	219	1.22	50.00	1.003	9	1.3
		Without SFCL	180		49.85		7	
3.	1-phase fault	With SFCL	219	1.03	50.00	1.003	9	1.0
		Without SFCL	212		49.85		9	

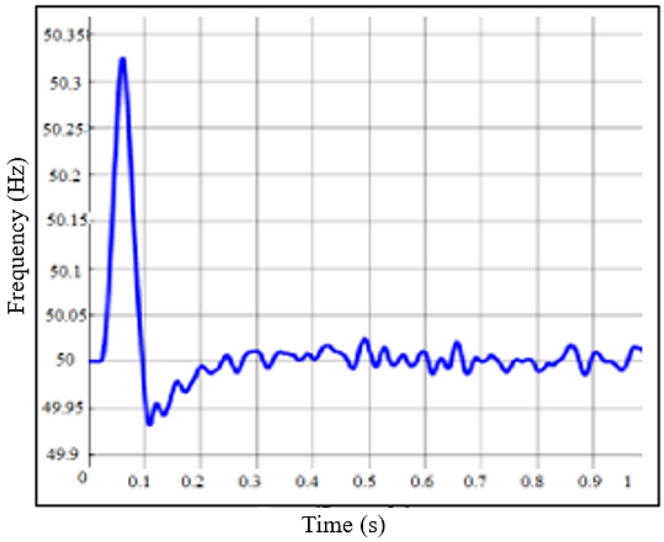

Fig. 8 Frequency value with bridge-type SFCL.

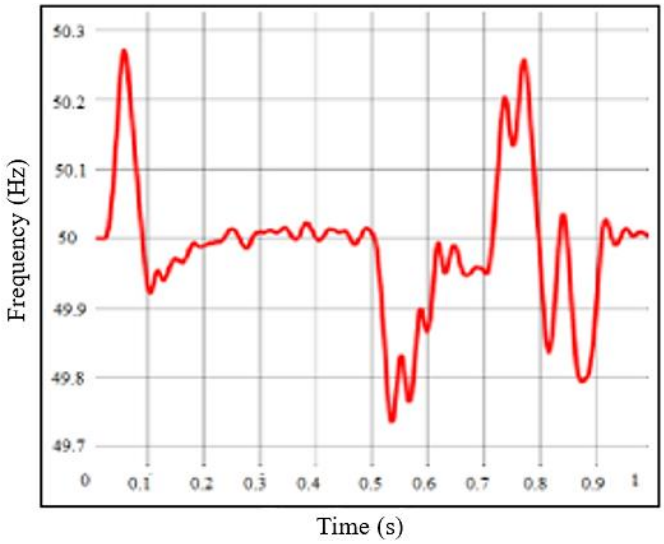

Fig. 9 Frequency value without bridge-type SFCL.

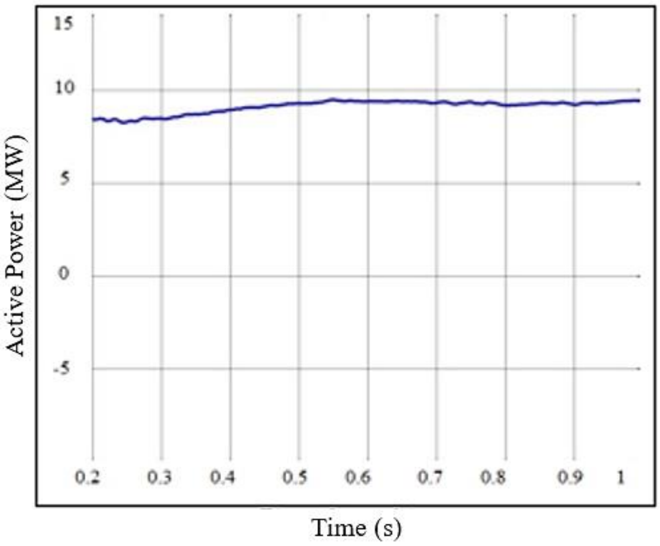

Fig. 10 Active power value with bridge-type SFCL.

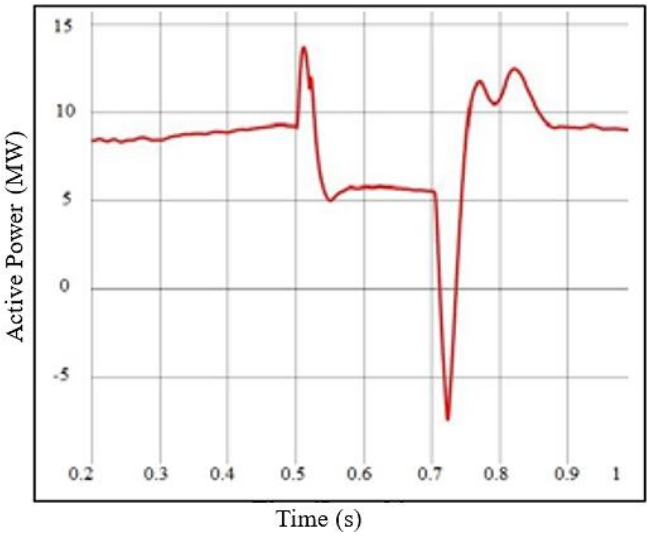

Fig. 11 Active power value without bridge-type SFCL.

Fig. 9 shows the frequency value in the DFIG-based wind turbine system without using a bridge-type SFCL. When the system was given faults, i.e., at 0.5-0.7 seconds, the simulation results were not more stable than those using SFCL. The frequency value was between 49.75-50.25 Hz. It occurred because, in the absence of the system with a bridge-type SFCL, the system was unable to properly maintain the rotor rotation's stability when there were faults, resulting in the frequency value which does not meet the standard. However, these conditions remain considered normal according to the Indonesian grid code, although the results are not much better than the system using SFCL when given faults.

Fig. 10 shows the value of active power in a DFIG-based wind turbine system with faults at 0.5-0.7 seconds using a bridge-type SFCL. The simulation results showed that the value of the active power disturbed using SFCL was 9 MW. This value corresponds to the system capacity, which is 9 MW. It was found that the system that was given faults at 0.5-0.7 seconds using SFCL did not experience a change in the active power capacity generated before the fault occurrences. In other words, the bridge-type SFCL could ride through the faults well since it prevented the system from experiencing peak currents, allowing the active power value remained at the system capacity value. Additionally, it was in accordance with the value of the voltage generated when there was a disturbance by a system that uses SFCL. Since the voltage value remains at the initial or normal value condition, the active power value is still at its capacity-appropriate value.

Fig. 11 shows the value of the active power on the system with faults at 0.5-0.7 seconds and without using a bridge-type SFCL. The simulation results demonstrated that the active power value was 6 MW, with the system capacity value before the fault occurrences being 9 MW. When compared to the system using SFCL, it was found that there was a significant decrease in the active power capacity generated before and after the faults were given. It happened because the absence of bridge-type SFCL caused the system to experience peak current when faults occurred, then experience voltage drops. As a result, the active power value dropped below that of the system capacity.

Table II presents the results of calculating the transient stability improvement (TSI) ratio, which was done by comparing the transient improvement with the transient without SFCL. It also displays voltage, frequency, and active power values tested with three scenarios: three-phase, two-phase, and single-phase faults. Furthermore, the table shows that the system with bridge-type SFCL gives better results than the system without SFCL.

V. CONCLUSION

A DFIG-based wind power system with a capacity of 9 MW has been tested. This system was given faults that led to system instability, resulting in a decrease in transient stability. A bridge-type SFCL was subsequently used to overcome this decrease in transient stability.

The system experienced faults at 0.5-0.7 seconds. The faults were tested under two circumstances. The first circumstance is when the system used a bridge-type SFCL, while the second one is when the system does not use a bridge-type SFCL. These tests found that the system with a bridge-type SFCL could ride thorugh faults since the current was limited by the SFCL, preventing the decrease in transient stability from occurring.

In the test using the bridge-type SFCL, the voltage and frequency values obtained are in accordance with Indonesian grid code stability standard. On the other hand, the absence of a bridge-type SFCL has resulted in a voltage value that does not meet the Indonesian grid code standard. However, the frequency value still adheres to the Indonesian grid code standard, although fluctuations occur. Thus, it is concluded that the system can control the transient stability well when a bridge-type SFCL is employed.

CONFLICT OF INTEREST

The authors declare no conflict interest in the arrangement of research entitled “Improving Transient Stability in DFIG-Based Wind Turbines Using Bridge-Type SFCL”.

AUTHOR CONTRIBUTION

Research topic, Doane Puri Mustika and Sasongko Pramono Hadi; software, Doane Puri Mustika; formal anlysis, Doane Puri Mustika, Sasongko Pramono Hadi, and Mokhammad Isnaeni B.; preparation and parameter, Doane Puri Mustika and Mohd. Brado Frasetyo; original draft preparation, Doane Puri Mustika; writing—review and editing, Doane Puri Mustika, Sasongko Pramono Hadi, and Tumiran; programming, Doane Puri Mustika, Sasongko Pramono Hadi, and Mohd. Brado Frasetyo; supervision, Doane Puri Mustika, Sasongko Pramono Hadi, Mokhammad Isnaeni B., and Tumiran.

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