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Decomposition control system to suppress the fluctuating voltage of a weak grid connected with a mega wind farm

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Abstract

Clean energy such as wind power has rapidly grown over decades. However, unstable output of wind farm (WF) causes the fluctuating voltage and reactive power shortage problem that directly affects security and stability of the grid when a mega WF is connected to a weak grid. The goal of this research is to suppress voltage fluctuation and reactive power shortage of a weak grid. MATLAB/Simulink is implemented as a simulation platform. In addition, the penetration limits of WF to power grid (IEEE 30 Bus Test System) was investigated. As a result, 9 out of 30 buses are available for Mega WF. Furthermore, in this paper, the decomposition method using time delay to send 54 MW of WF to a weak grid was carried out. PQ inverter and STATCOM were also implemented into the control system to compensate the reactive power and enhance the stability of a weak power system. As a consequence, 54 MW of WF was successfully able to transmit to a weak grid by implementing the approach mentioned above.

Keywords: Decomposition approach, STATCOM, mega wind farm, weak grid, IEEE 30 Bus Test System

1. Introduction

Over decades, sustainable energy has grown rapidly worldwide due to higher energy demand, the depletion of limited fossil fuel, and the awareness of global warning. Increasing renewable energy such as solar and wind power can reduce the emission of carbon dioxide (CO_2), which is the main factor causing global warming and climate change. In addition, renewable energy can help conserve the world's natural resources and provide reliable power supplies and fuel diversification, which enhances energy security, lowers the risk of fuel spills, and reduces the need for fossil fuel [1]. According to [2], global renewable capacities increased from 38% (2008) to 63% (176GW, 2018) to total power additions in 2018. A major example of this clean energy is wind power (hereafter, WP), which has been increasing rapidly since the 1990s, from 4.84GW of its installation in 1995 [3] to 197 GW in late 2010. Additionally, in 2019, 60.4 GW of WPs were installed (19% growth compared to 2018), bringing total installations to 650 GW in more than 90 countries [4]. However, the output of WF is unstable and fluctuates unexpectedly due to changes in wind speed, when this WF is connected to a power system (especially a weak grid). In addition, the voltage of the linked bus of the system rises above the specified value, and the reactive power (Q) is consumed, which may lead the power system to unstable state and affect the security of the power system. In this case, the FACTS devices such as Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM) are essential [5]. As stated by [6], the results of simulation have shown that STATCOM performs better than SVC. Currently, the installation capacity and influence on the power system of WP is small, so it can be neglected. However, as the WP capacity increases in the future, the impact of the fluctuating output of WF on the grid can no longer be ignored. Hence, the investigation of the limitations of WF according to

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the connected grid needs to be considered carefully in the future. Some conventional studies have been carried out to suppress the fluctuation of output by inserting a Dynamic Voltage Restorer (DVR) between an independent or small-scale WT and a grid, introducing phase control by the DVR, or by inserting energy storage system [7], [8]. In their results, they claimed that voltage fluctuation is suppressed; however, little investigation on the suppression of voltage fluctuation when linking mega WF to a weak power system has been reported. Thus, this research is built on previous research [9] to solve the problem of reactive power shortage due to voltage fluctuation when a mega WF is connected to a weak power system. The results describe the investigation of penetration limits of WF to the power grid (IEEE 30 Bus Test System) and reveal how the control system implementing decomposition approach successfully transmitted 54 MW of a mega WF to a weak grid.

2. Penetration Limits of WF to IEEE 30 Bus Test System

2.1. IEEE 30 Bus Test System

The IEEE 30 Bus Test System represents a portion of the American Electric Power System in the Midwestern US. This model has officially been recognized as a benchmark since 1961 by the IEEE. Moreover, it was recommended to the power system researchers to use this model as a standard model system; thus, the obtained results of similar simulation could be compared together. In this study, the IEEE 30 Bus Test System developed by Nagasaka Laboratory in MATLAB/Simulink was also used for the first time [10], [11]. The IEEE 30 Bus Test System model has 30 buses and 6 generators linked to Bus1, Bus2, Bus13, Bus22, Bus23 and Bus27. Additionally, the original total installed capacity of 6 generators is about 189.2MW (Fig. 1.). Nevertheless, in general, only basic data of the IEEE 30 Bus Test System has been provided, but the penetration limits of each bus have not yet been reported. Hence, it is vital to investigate the penetration limits of each bus while linking the WF to each one for future research. As stated by [9], [11], Bus8, Bus7, Bus2, Bus21, Bus12 and Bus30 are the highest demand buses.

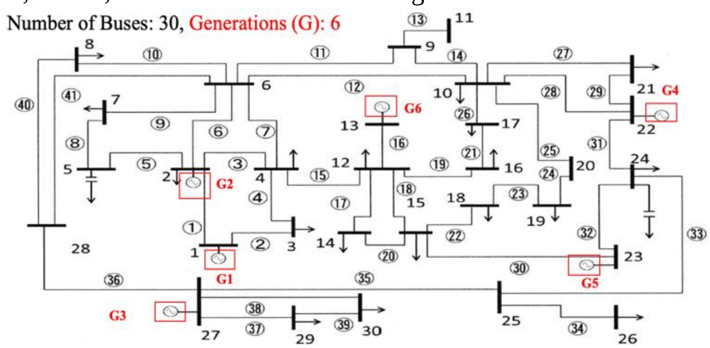

Fig. 1. IEEE 30 Bus Test System diagram

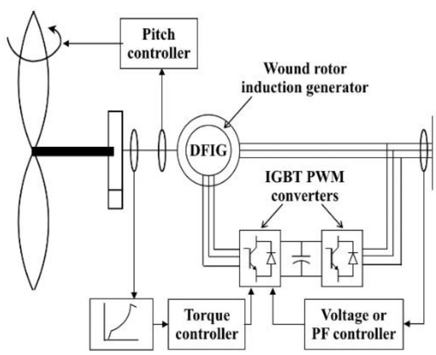

Fig. 2. Circuit diagram of DFIG wind turbine

2.2. DFIG wind turbine

A doubly fed induction generator (DFIG) is a variable speed wind turbine. Regarding results reported in a previous paper [9], the optimal wind turbine for this study was Vestas V 100: 1.8 MW, which is DFIG type. As such, DFIG, the most common variable speed WT, was implemented. It controls the rotor current to obtain the maximum output efficiency of the motor against variable wind speed. Fig. 2. shows a DFIG circuit diagram in which an IGBT converter is connected to the winding. A typical DFIG WT has three control loops: the pitch control maintains rotor speed by controlling the pitch angle of the blade parallel to wind direction and stopping at high wind speed, the torque control moves a WT's driving point according to the maximum power curve, and the power factor/voltage control maintains the power factor generator level value requested by the grid system manager [9].

2.3. System study model

The system study was modeled and simulated under the MATLAB/Simulink platform. The simulation system for this study is shown in Fig. 3., where a WF is connected to the 135kV Bus. The electricity generated by turbine was 690V, which was then transformed to 33kV by a transformer and sent through the distribution lines. Afterwards, the voltage was raised again from 33kV to 135kV by the transformer in order to transmit it to the 135kV grid. However, when a WF is linked to the grid, it becomes necessary to investigate how the reverse power flow affects the grid. At first, the WF was connected with the main grid in the 3 cases: buses studied in advanced, buses with high demand, and generator buses which are nearest the high demand buses. In total, 11 buses were investigated and the results have been reported in [9]. In this paper, the remaining 19 buses of the system were investigated. Those buses are Bus1, Bus3, Bus4, Bus5, Bus9, Bus11, Bus14 to Bus20, Bus23 to Bus26, Bus28, and Bus29. Afterwards, by increasing the rated output of the WF gradually from 0MW, the voltage and reactive power are measured in various simulations to investigate the influence of the WF and the penetration limits of WF to the IEEE 30 Bus Test System. Moreover, in this study, an operation when the rated output of WF's 0MW was considered as a reference, and if voltage and reactive power are within $\pm 5\%$, the system is operating normally.

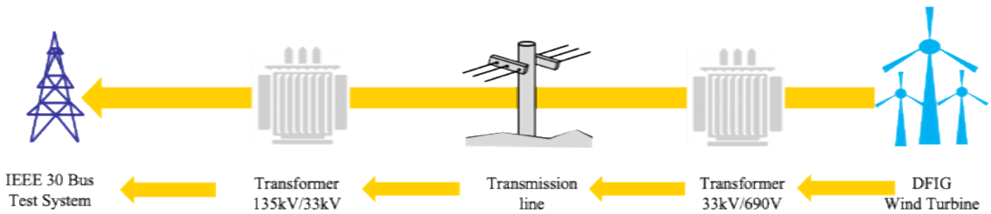

Fig. 3. Simulation study system of WF penetration limits to IEEE 30 Bus Test System

2.4. Results of the simulations

Table 1. Results of penetration limits of buses available for a mega WF

Bus No.	Penetration limits (MW)	P (MW)	Q (MVar)	V (kV)
1	41.5	11.27	4.84	133
2	5.57	54.41	92.92	135
3	16.20	2.20	1.10	130
4	25.20	65.08	107.77	128
5	4.19	4.90e-10	3.54e-10	134
6	4.63	22.89	21.29	131
7	18.00	19.14	9.77	129
8	17.00	25.82	25.51	127
28	2.54	0.36	1.65	133

Table 1. shows the results of the simulation. The simulation results have revealed that 9 out of 30 buses were able to introduce mega WF. Regarding to Table 1., it's clearly obvious that Bus1 was the strongest bus, which had 41.5 MW of its penetration limit. Meanwhile, Bus28, Bus5, Bus6, Bus2 were the weak buses which had its penetration limits of 2.54 MW, 4.19 MW, 4.63 MW, 5.57 MW respectively.

3. Decomposition Approach of Control System to Transit 54 MW of a Mega WF to a Weak Grid

3.1. Operating principle of static synchronous compensator (STATCOM)

The STATCOM is a shunt device implementing power electronics to control power flow and improve transient stability on power grids. It can compensate for both inductive and capacitive current linearly and continuously [12]. Also, it regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from the power grid. In general, active power (P) and reactive power (Q) are given by the equations below [12]:

$$P = \left(\frac{V_{bus}V_s}{X}\right)\sin\delta \tag{1}$$

$$Q = \frac{V_{bus}}{X}(V_{bus} - V_s\cos\delta) \tag{2}$$

Where X is reactance of interconnection transformer and filters, δ represents phase angle of V_{bus} with respect to V_s, and $\delta = \delta_1 - \delta_2$ as shown in Fig. 4. In steady state operation, V_{bus} is in phase with V_s which means $\delta = 0$, and only Q is flowing. Hence, from equation (2), the reactive power is given as below:

$$Q = \frac{V_{bus}}{X}(V_{bus} - V_s) \tag{3}$$

In addition, as shown in Fig. 4.:

- If $V_{bus} > V_s$, Q is flowing from V_s to V_{bus} which means STATCOM generates Q to the power system.
- Whereas if, $V_{bus} < V_s$, Q is flowing from V_{bus} to V_s, and STATCOM absorbs Q from the grid.
- If $V_{bus} = V_s$, no power will be exchanged, and STATCOM will operate in floating mode [12].

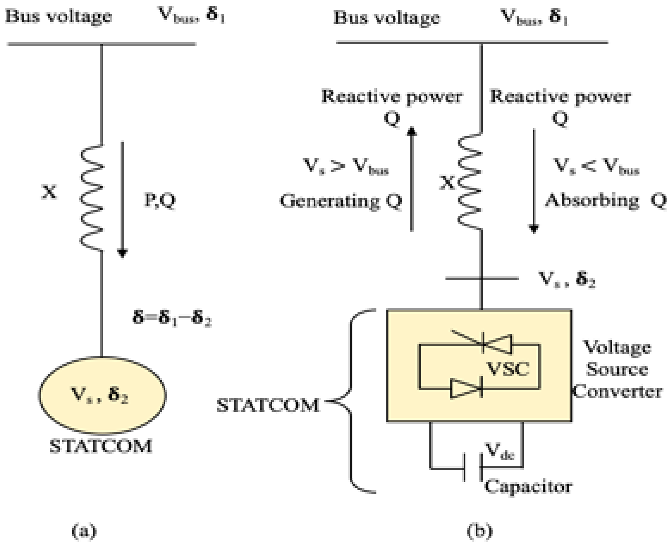

Fig. 4. Operating principle of the STATCOM: (a) an equivalent circuit; (b) Operating principle

3.2. Decomposition approach

In [9], the WF was designed under the condition of a 5 km × 5 km flat area considering three main factors: annual output, initial investment cost, and capacity factor. As a result, 54MW (1.8 MW, WT (DFIG type): 30 Turbines) of the WF was the optimal under the condition provided. So, the goal of this study is to send a mega WF of 54MW to a weak power grid.

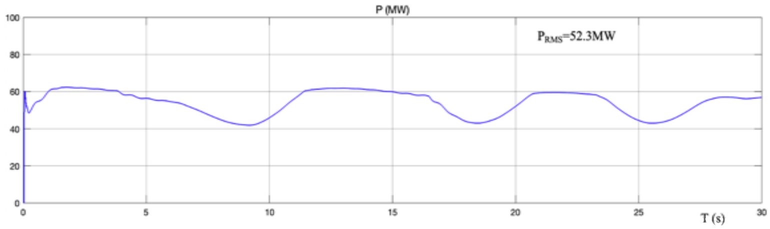

Fig. 5. Imaginary diagram of fluctuating output of a mega WF wanted to transmit to a weak grid

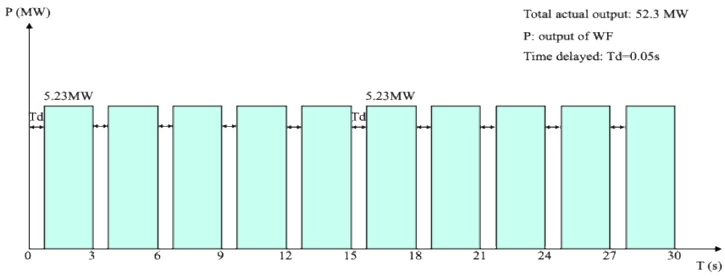

Fig. 6. Diagram of implemented decomposition approach

Based on the results of the penetration limit investigation, Bus2 has been found as one of the most potential buses to investigate as it is a weak bus with high demand and near the generator. Because Bus2 has 5.57 MW of its penetration limit, it's precise that 54 MW of the WF will not be able to transmit directly in the same time to the power system. In order to transmit it, the idea of decomposition was implemented, imagining sending data as packages, and for this research, 54 MW have been divided to 10 groups of 5.4 MW for each (actual output is 52.3MW as Fig.5., 5.23 MW for each group) and then implemented 0.05s of time delay for each group as shown in the Fig. 6.

3.3. Control system based on decomposition approach

Fig. 7. represents the scheme of control system in this study, where:

- Pw denotes generated output of each group.
- Trans. is step-up transformer.
- Filter block includes the PQ inverter in order to regulate harmonics and reactive power to the set point.
- CB represents circuit breaker, which is controlled by external signal to switch on/off in the time provided. For instance, group 1 of WF is on at 0.05s and off at 3s by CB, after that group 2 of WF is on at 3.05s with 0.05s of time delay as shown in Fig. 6.
- TL denotes transmission line.
- PQ inverter block is a block used to control harmonics and reactive power before sending it to a grid.

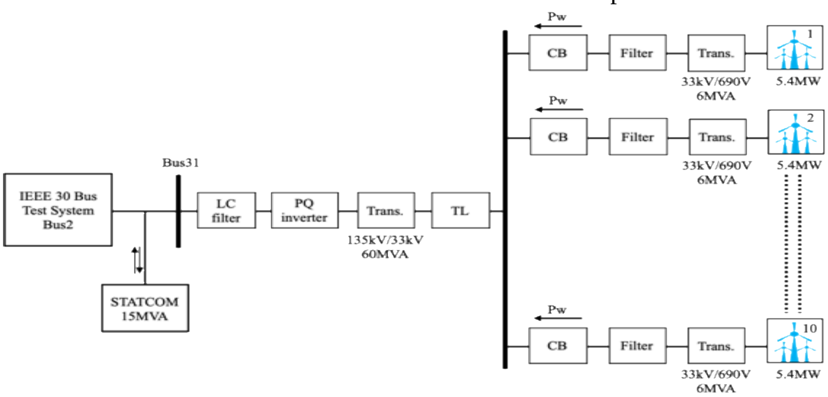

Fig. 7. Scheme of control system based on decomposition approach using time delayed

- LC filter is a low pass filter which is used to filter out unwanted reactive power that may be presented in a band above the wanted pass.
- STATCOM is a shunt device of FACTS (flexible AC transmission system) to control power flow and improve transient stability of power system (in this case is Bus2 of the grid) by both absorbing as well as generating reactive power to supply the power system. Moreover, in this study 15MVA of STATCOM is implemented.

As presented in Fig. 7., Fig. 8. and Fig. 9., the decomposition control system in this study has been modelled in order to transmit a mega WF, 54MW to a weak grid of Bus2 of IEEE 30 Bus Test System. 54 MW have been divided into 10 groups of 5.4 MW each. Then, circuit breakers with external control signals and 0.05s of time delay for each group were used. Additionally, a PQ inverter, LC filter, and STATCOM have also been implemented to control power flow and support the stability of the power grid.

3.4. Simulation results

Table 2. represents simulation results of Bus2 based on the decomposition approach using time delay as mentioned previously, and Figure. 10. has shown the voltage and current of Bus2. In [9], it was reported that Bus2 maintains its usual operation status (tolerance condition) when the reactive power and bus voltage are fluctuating within ±5% of its initial status, where reactive power is between 91.80 ~101.46 MVar, and bus voltage is between 126.36~139.65 kV.

Table 2. Simulation results of Bus2

Active power P (MW)	Reactive power Q (MVar)	Bus Voltage V (kV)
65.76	100.25	134

The results shown in Table 2. reveal that the bus voltage of Bus2 was 134kV, while the reactive power of Bus2 was 100.25 MVar. This means that both the bus voltage, and the reactive power of Bus2 were under tolerance condition. Consequently, the decomposition approach introduced above was successfully able to transmit 54 MW of a mega WF to a weak Bus2 of the IEEE 30 Bus Test System. In other words, the decomposition approach helps solve the problem of system stability of a weak power system caused by the fluctuating voltage and reactive power shortage while connecting a mega WF to a weak grid.

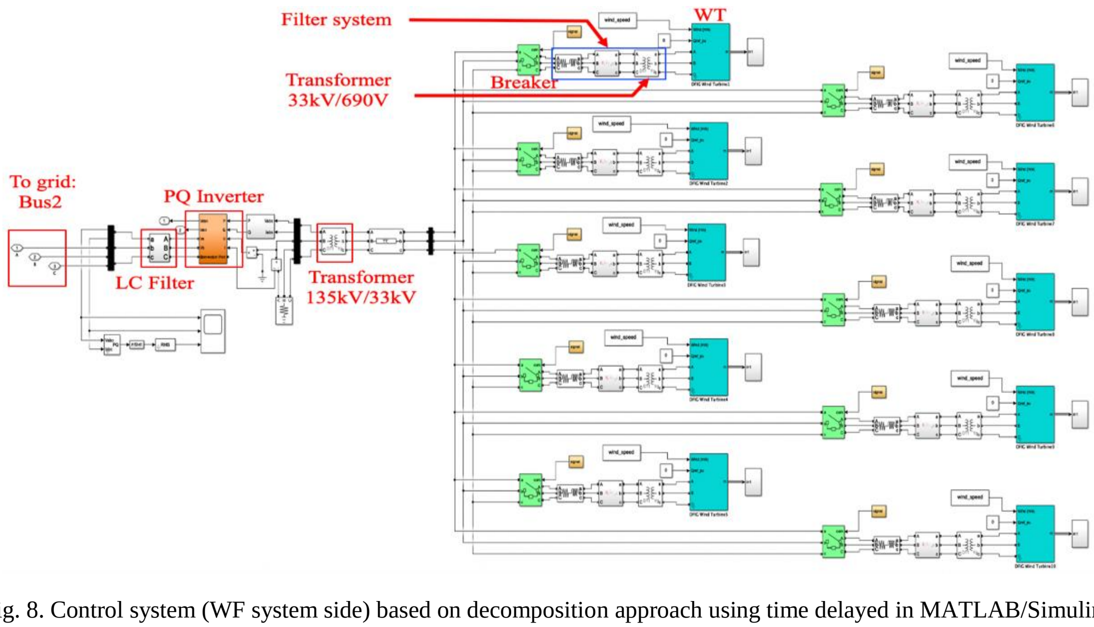

Fig. 8. Control system (WF system side) based on decomposition approach using time delayed in MATLAB/Simulink

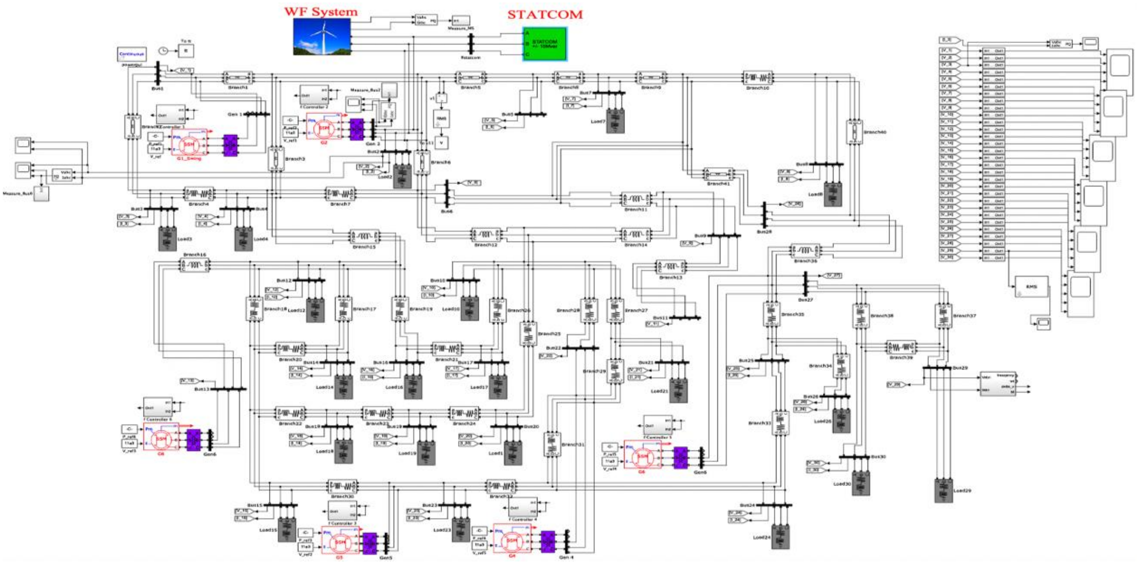

Fig. 9. Control system grid side (IEEE 30 Bus Test system on MATLAB/Simulink developed by Nagasaka laboratory)

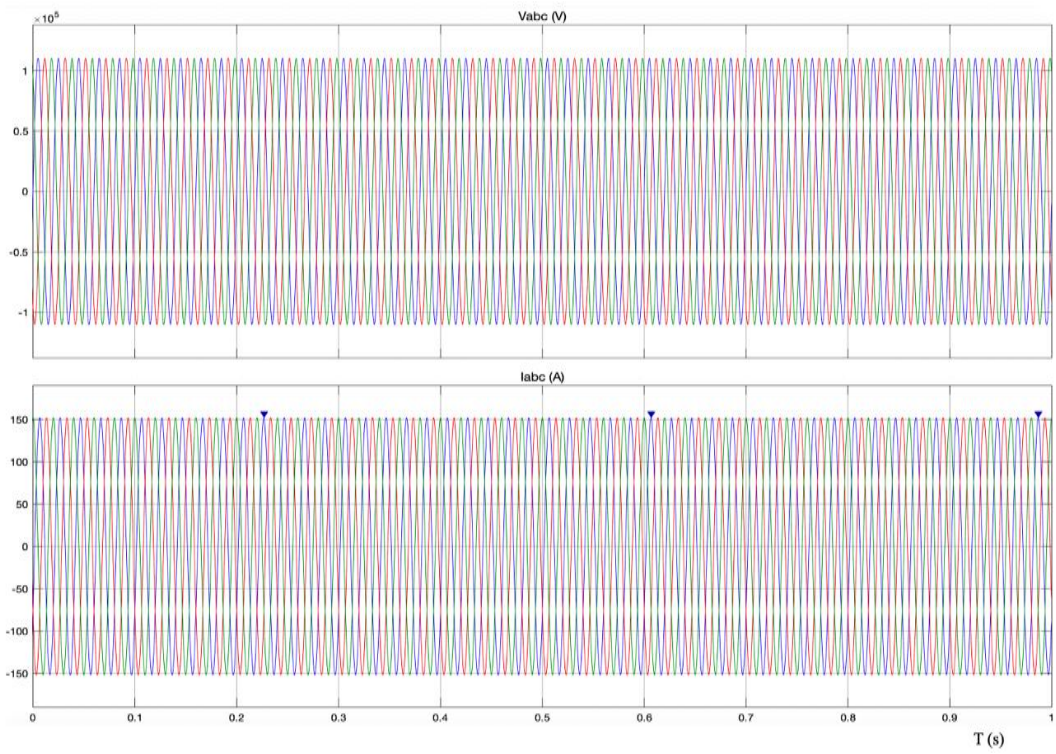

Fig. 10. Results of voltage and current of Bus2

4. Discussion and Conclusion

In this paper, an investigation of the penetration limits of a wind farm (WF) to the IEEE 30 Bus Test System has been carried out as a continuation from the previous paper [9] under the MATLAB/Simulink platform. Results revealed that 9 out of 30 buses were available to introduce mega WFs, where Bus1 was the strongest bus with its penetration limit at 41.5 MW, while Bus28, Bus5, Bus6, and Bus2 were the weak buses with its penetration limits of 2.54 MW, 4.19 MW, 4.63 MW, 5.57 MW respectively. Furthermore, the control system to send 54 MW of a mega WF to a weak grid by implementing the decomposition approach has been introduced and discussed. As a result, the reactive power; bus voltage of Bus2 were 100.25 MVar and 134 kV respectively, values which were within the tolerance condition. This finding indicates that the decomposition approach using 0.05s time delay was effective to send the power of a mega wind farm to a weak grid successfully under its tolerance condition. It guarantees that the system stability is under control, and the concern of the voltage fluctuation and reactive power shortage problems are suppressed and compensated by implementing STATCOM into control system. However, the work presented above considered the WF side to transmit power to the grid effectively. In the future, the grid side such as ancillary service also needs to be considered and researched.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Aroun Sanelath conducted the research work and wrote a paper under the guidance of professor Ken Nagasaka. All authors had approved the final version.

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