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Improved Fault Ride through Capability of SCIG-based Wind Turbine based on Photovoltaic System

Dinh Chung Phan*[1] and Dinh Truc Ha*

Abstract – *This paper investigates the operation of a hybrid system including a two-stage PV system and a SCIG based wind turbine. The wind turbine is connected directly to the AC side of the PV system's inverter and they are connected to the external grid through a step up transformer. With this configuration, the free land around the turbine tower can be utilized to install the PV system. A more important thing is that the inverter of the PV system can play the role of a STATCOM to support reactive power to the SCIG –wind turbine. This allows reactive power compensating equipments such as capacitor bank, SVC and so on to be absent at the wind turbine. The simulation results show that thank to the support of the PV system's inverter, the SCIG-turbine can be stable in steady state and it can ride through fault easily. In addition, this investigation demonstrates a locus of critical fault-clearing time among different PV capacities and the minimum capacity of the PV system helping the wind power to ride through fault is identified.*

Keywords – Control system, FRT, hybrid, PV system, SCIG wind turbine.

1. INTRODUCTION

Electricity demand is higher and higher in the word while conventional energy sources such as fuel, fossil coal and so on have been gradually exhausted. Moreover, the exploitation of these resources is one of dangerous culprits leading to environmental pollution phenomenon. From these reasons, finding alternative energy sources which are available, renewable and plentiful has been encouraged, and this is deeply interested by researchers.

Up to now, wind and solar are well-known renewable sources interested and exploited the most popularly in many countries in the word such as UK, Germany, USA and so on. According to the agreement of European Renewable Energy Council (EREC), up to 2020, at least 20% of energy demand in EU is supplied from renewable resources. However, each source has its advantage and disadvantage. The photovoltaic (PV) system often owns good control ability so it can maintain a stable connection after faults occurring on external grid. The main reason is that it is integrated into the external grid by means of an inverter [2]-[5]. This allows controlling not only the power exchange with utility grids but also the voltage at the point of common coupling (PCC). By contrast, the wind turbine employing a squirrel-cage induction generator (SCIG) cannot control the power output or the voltage at the terminal of generator [6]-[10] despite of its good features such as strong connection, simple in structure and economical price. This wind generator must receive a huge amount of reactive power from the external grid and this quantity is reliant on wind speed or its active power output. The PCC voltage is, consequently, hard to maintain a constant value. From these features, some ideas came up with a combination of a solar energy system and a wind one [11]-[19]. Some of them, the wind turbine is connected to the PV system via a DC link [11]-[13]. This configuration seems to be convenient for the case of permanent magnetic synchronous generator or conventional synchronous generator based wind turbine, in which a rectifier is normally equipped at the terminal of generator. Another configuration, a battery bank was suggested in the hybrid system to store energy [14]-[16] and it is installed at the DC link of the hybrid. This configuration is highly appreciated in the case of isolated operation. The main reason is that with the isolated grid, the surplus energy can be stored in or released from the battery bank to maintain active power balance. It, therefore, allows the isolated grid to utilize the energy capturing from the wind and solar system fully. Some authors also considered about the economic issue of a wind turbine/PV hybrid and its optimal operating schedule [17]-[18].

Concerning to a SCIG wind turbine/PV hybrid, transient performance was investigated [14], [15]. In these references, both the PV system and the wind turbine are, however, connected to a DC link. It cannot debate that with this configuration, the SCIG-wind turbine is separated from the utility grid so faults on the connected grid hardly affect the wind turbine's operation. The main disadvantage of this configuration is that a rectifier is required to install at the wind turbine's generator and the capacity of the inverter must be higher than that of the PV system standing alone. Therefore, with this configuration, it seems to be uneconomical. Another research studied on a PV system and SCIG wind based integration where they are put together at the AC side of the PV system's inverter. Unfortunately, this research only focused on the mathematical modeling of this hybrid [19]. The transient performance has not yet researched.

This paper will investigate further a combination of a solar and a SCIG wind turbine. In this hybrid-system,

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150kW PV system and 1.5MW wind turbine are connected at the AC side of inverter installed at the PV system. The inverter plays the role of a STATCOM to support reactive power to the wind turbine as the same time the exchange reactive power with the power system. In the dynamic condition, it must support reactive power to the connected grid to improve the poor fault-ride-through (FRT) ability of the SCIG-wind turbine. This idea is going to be tested under MATLAB/SIMULINK environment in two cases: normal condition and the external grid–faulted one. By simulation, a locus of critical fault-clearing time with different PV system's capacity will be built to evaluate the support of the PV system to the wind turbine. A minimum capacity of the PV system is defined so that the SCIG wind turbine becomes stable operation after a fault on the connected grid.

2. CONFIGURATION

In this paper, the investigated PV/Wind hybrid system is indicated in Figure 1 where the SCIG wind turbine is directly connected to the AC side of the PV system. The output of the solar arrays is connected to a boost converter in order to step up the DC voltage output to a higher level and then it is converted into AC voltage to connect to the utility AC grid. It is noted that the capacity of the inverter is calculated based on the rated power of the PV system. Comparing to the configuration in [14], [15], the capacity of the inverter is smaller and the capacitor bank at the wind turbine is absent. This allow saving the pre-investment on the inverter and the capacitor bank. The same as configurations of wind turbine using DFIG or PMSG, which own good reactive power control ability thank to their inverters, the proposed configuration also allows controlling reactive power via the inverter of PV system. This improves the drawback of SCIG-based wind farm in the term of reactive power adjustment. Moreover, with this configuration, investors can utilize the free land surrounding the wind turbine tower to install the PV system. It means that with the same an area of the wind farm using DFIG or PMSG, the planned system can generate a higher active power.

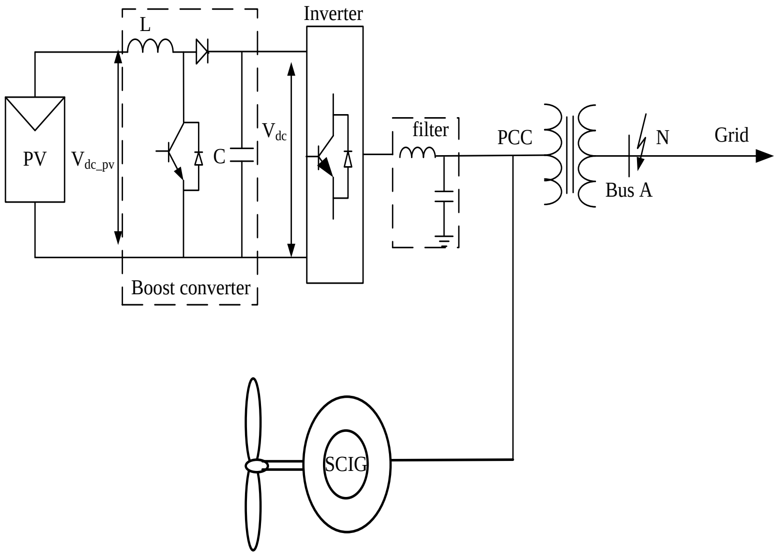

Fig. 1. Configuration a hybrid of PV and SCIG wind turbine.

2.1 PV System

The most fundamental component of a PV system is the solar cells, which is often composed of semi conducting materials such as silicon, germanium, and so on. The solar cell is to convert the energy of sunlight directly into electric energy by photovoltaic effect, which is the release of positive and negative charge when light strikes the semiconductor. As photons hit the solar cell, they may be reverberated or absorbed or they may pass right through. Only the absorbed photons supply energy to produce electricity and electrons get this energy to jump past the band gap n to conduct electricity. If electrical conductors link between the positive and negative terminals, they will become an electric circuit and the flow of electrons will, as a result, form an electric current. It is worth to note that each individual solar cell produces only 1 or 2 watt and its voltage is so small, its power is not enough for most of applications. To overcome this limitation, cells are electrically connected into a packaged weather tight module. Each module comprises of many solar cells in series connection. The main purpose of this connection is to form a high voltage of module. In practical, to reach to an expected voltage and current, several photovoltaic modules are connected in series and parallel to form a PV array. The equivalent circuit of a PV system is described in detail in [20].

2.2 SCIG- Wind Turbine

A wind turbine system consists of three basic parts, turbine or blade system, shaft-gearbox system and generator. The blade is to convert wind energy into mechanical energy rotating the shaft of turbine. Via the shaft-gearbox system, the rotor of generator rotates and it generates electricity at the output of generator. There are, practically, three well-known types of generator used in wind turbine system are SCIG, doubly fed induction generator and permanent magnetic synchronous generator. The most simple wind turbine system is SCIG-wind turbine due to no required power converter and simplicity in structure. However, its disadvantage is resulted from the poor control ability. During operation period, SCIG requires a huge amount of reactive power from the grid to excite the generator. Therefore, to reduce amount of reactive power transmitting on the utility grid, compensator equipments such as capacitor bank, STATCOM, SVC, and so on are often required [6], [7] at the terminal of SCIG. Otherwise, once a fault occurs on the external grid, it is hard to be stable operation. With the configuration offered in this research, thanks to the inverter of the PV system and its controller, reactive power compensating equipments fail to be required.

3. CONTROL SYSTEM

3.1 Wind Turbine's Control System

When wind speed hitting the wind turbine is higher than the rated value, the mechanical power output of the turbine is likely to become over the rated value. As a result, the rotor speed and its power output are too high and this can affect not only the mechanical stability but also generator-connected equipments' overload. Therefore, to reduce this impact, the blade system is able to rotate around itself to reduce the force attacking the blade and the mechanical power on the shaft system. A pitch control system, normally, undertakes to limit the mechanical power on the turbine's shaft in operating range by rotating the blade around itself. Figure 2 indicates a pitch control system where ω, P, and β are the rotor speed, the power output, and the optimal position of blade, respectively.

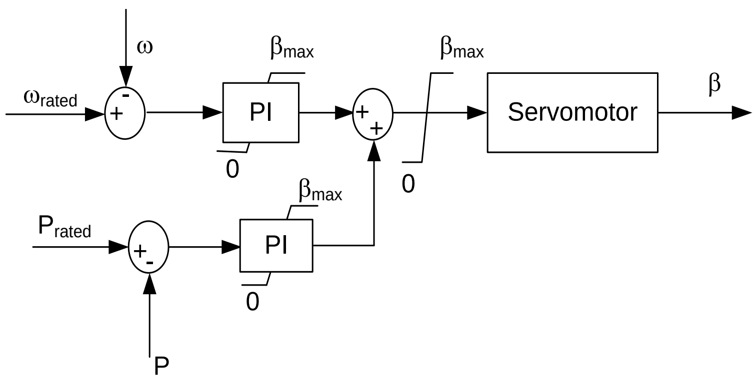

Fig. 2. Pitch control system of wind turbine.

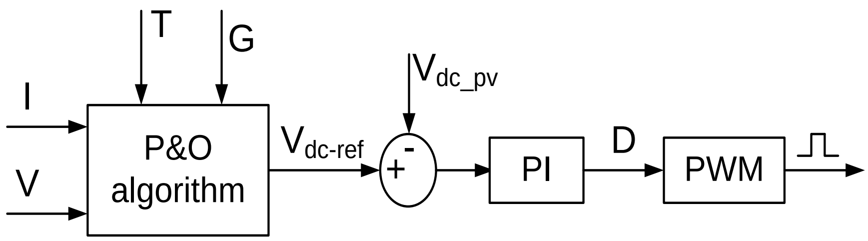

Fig. 3. Control diagram applying to the boost converter.

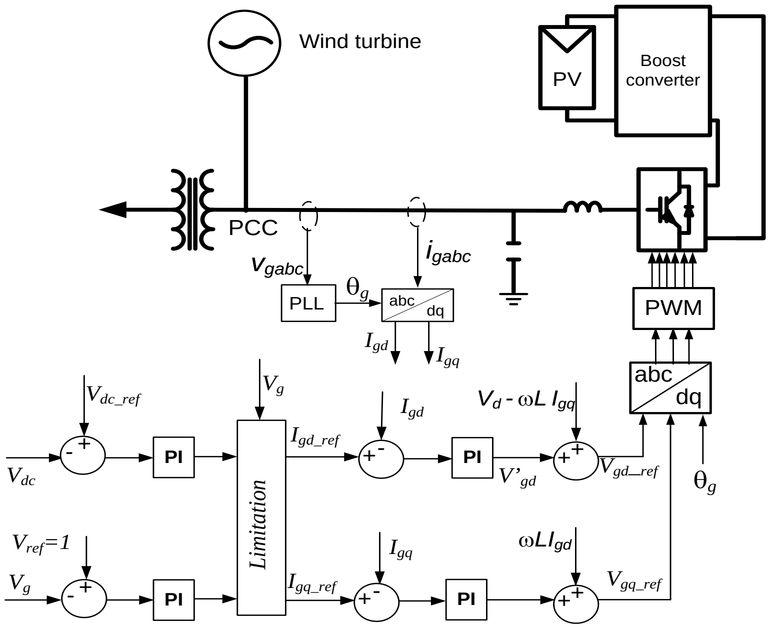

Fig. 4. Control diagram applying to the inverter.

3.2 Control System of PV

Because the voltage output of the PV system is quite small, only around 500V, a boost converter is employed to step up a higher value, suitable for the voltage output of the SCIG wind turbine. By adjusting the duty cycle of pulses applying to this converter, the terminal voltage of the PV system attains the optimal DC voltage value that is estimated based on P and O algorithms [21] and the power output of the PV system consequently reaches to the optimal power. The control diagram applying to the boost converter is indicated in Figure 3. In this diagram, temperature, irradiation, current, and voltage output of the PV system are input signals of P and O algorithm. This algorithm designates a reference DC voltage, $V_{dc\text{-}ref}$, and a PI controller is used to modify the duty cycle D of pulses, sending to the boost converter, based on the error between actual value V_{dc_pv} and V_{dc_ref} .

The first objective of the controller applying to the inverter is to maintain a constant DC voltage at the DC side of the inverter or the output of the boost converter. The aim of this job is to ensure that all power output of the PV system is transmitted to the connected grid. The second one is to maintain the rated voltage at PCC. It is means that the inverter always supports reactive power to the SCIG –wind turbine.

With dq frame chosen the same as that in [22], which d-axis is aligned with the vector voltage at PCC V_g while *d*-axis lags behind *q*-axis by 90^o, the control diagram applying to inverter is demonstrated in Figure 4. The d-axis and q-axis current components are used for the DC voltage and the PCC voltage control, respectively. In this figure, V, I, ω, θ, and L correspondingly represent voltage, current, angle speed, phase angle, and the inductance of filter installed in the AC side of the inverter. The subscripts *dc*, *g*, *ref*, *d*, and *q* stand for the dc side, PCC, reference value, *d*, and *q* components, respectively.

The duty of "Limitation" block allows I_{gd_ref} to reach to the maximum current of inverter I_{max} if V_g is over 85% of the rated value while the limitation of I_{gq_ref} is designated by the remainder of the inverter, as shown in equation 1. Otherwise, I_{gq_ref} can reach to the rated value I_{max} and I_{gd_ref} only takes the rest of the inverter as Equation 2. It means that at normal operation, the inverter is prioritized to transfer active power from the PV system to the utility grid and when fault occurs on the grid, the control of PCC voltage is prioritized.

$$I_{gq\_ref\_max} = \sqrt{I^2_{max} - I^2_{gd\_ref}} \quad \text{and} \quad I_{gq\_ref\_min} = -\sqrt{I^2_{max} - I^2_{gd\_ref}} \tag{1}$$

$$I_{gd\_ref\_max} = \sqrt{I^2_{max} - I^2_{gq\_ref}} \quad \text{and} \quad I_{gd\_ref\_min} = -\sqrt{I^2_{max} - I^2_{gq\_ref}} \tag{2}$$

4. SIMULATION RESULTS

To test the operation of the proposed configuration, the first component is a SCIG-wind turbine of 1.5MW with the rated wind speed of 12m/s and the rated voltage of 575V. The second one is a 150kW PV system which consists of 64 arrays in parallel. Each array comprises of 13 modules in series and one module includes 72 cells in series of 5A and 0,5V. A DC/DC boost converter is employed to increase voltage at the DC side of the inverter about 1150V. This wind turbine and the PV system are connected to the 22kV external grid through a step up transformer, as shown in Figure 1. It is worth to note that no capacitor bank is installed at the terminal of SCIG.

4.1 Normal Operation Condition

This section, the irradiation applying to the PV system is indicated in Figure 5a where the irradiation is $900W/m^2$ and then it increases to the normal value of

1000W/m^2. The irradiation drops to 0W/m^2 at 120s from 1000W/m^2 at 115s. This circumstance practically occurs at night when the sun sets. Wind speed at the wind turbine is shown in Figure 5b. Simulation results are depicted in Figure 6.

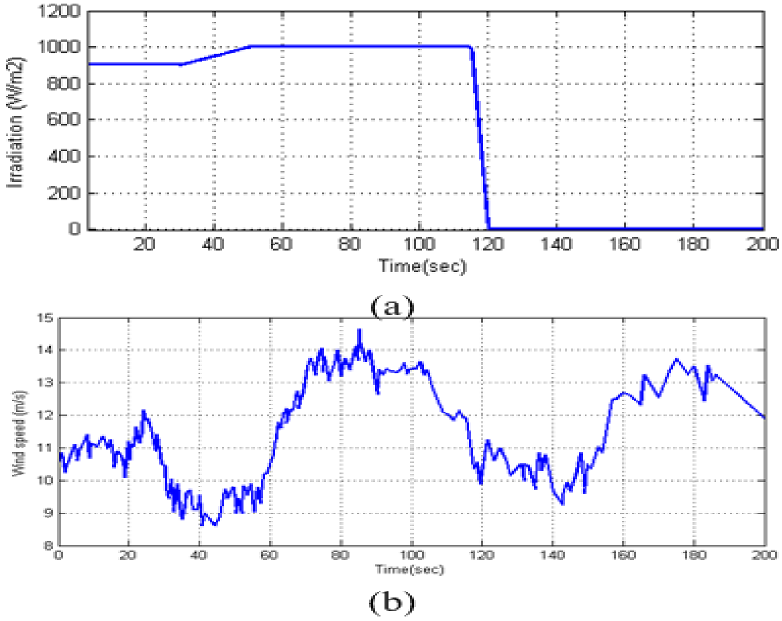

Fig. 5. Irradiation of shun (a) and wind speed (b).

As can be seen from Figure 6a, with the support of the PV system, the inverter remains the rated voltage at the terminal of SCIG, 575V, as shown in the continuous curve. By contrast, the case of no PV system represented the dotted curve in Figure 6a, the voltage at the terminal of SCIG fails to remain the rated value. This is resulted from capacitor bank of 175kVAr at SCIG-wind turbine. Its reactive power is almost constant so reactive power transmitting on the connection line varies among active power. As a result, voltage drop on the connection line and the PCC voltage varies among on active and reactive power. Obviously, it completely depends on the power output of SCIG, which are reliant on the wind speed, as indicated in Figure 6b.

The DC voltage output of the PV system is heavily reliant on the irradiation applying to the PV system. It is around 510V as the irradiation gets 1000W/m^2. In the case of no irradiation, the DC voltage drops to zero, as shown in Figure 6c. Therefore, the power output of the PV system reaches to the rated value of 150kW as the irradiation soars up to 1000W/m^2 and it declines to zero when the irradiation decreases to 0W/m^2, presented by the continuous line in Figure 6d. With regard to reactive power, when the power output of the PV system is equal to zero, the inverter can play a role as STATCOM to control reactive power, shown in the dotted line in Figure 6d, so that the voltage at SCIG can be constant at the rated value.

Because the inverter of the PV system injects active power to PCC, the active power output at Bus A in the case of the hybrid system is so difference from the case of no PV system. Certainly, from 120s to 200s, due to no irradiation the active power output from the PV system is zero. Consequently, the active power output in two cases is the same, Figure 6e.

Regarding to reactive power at Bus A, because a capacitor bank of 175kVAr is installed at the terminal of SCIG in the case of no PV system, the reactive power at Bus A, dotted curve in Figure 6f, is so different from the terminal voltage of SCIG in Figure 6b. In the case of hybrid system, the reactive power which the proposed system receives from the grid is higher than that in the case of no PV. The main reason is that the capacity of PV system is smaller than that of the capacitor bank in the case of no PV system.

It is clear that with the support of the PV system's inverter, whole system is stable operation and the voltage at the terminal of SCIG or PCC is maintained at the rated value without any compensation equipments. Moreover, with this configuration, the operation of this hybrid system is not depending on the irradiation of the PV system. It means that this hybrid system can properly operate at night when the irradiation is almost equal to zero.

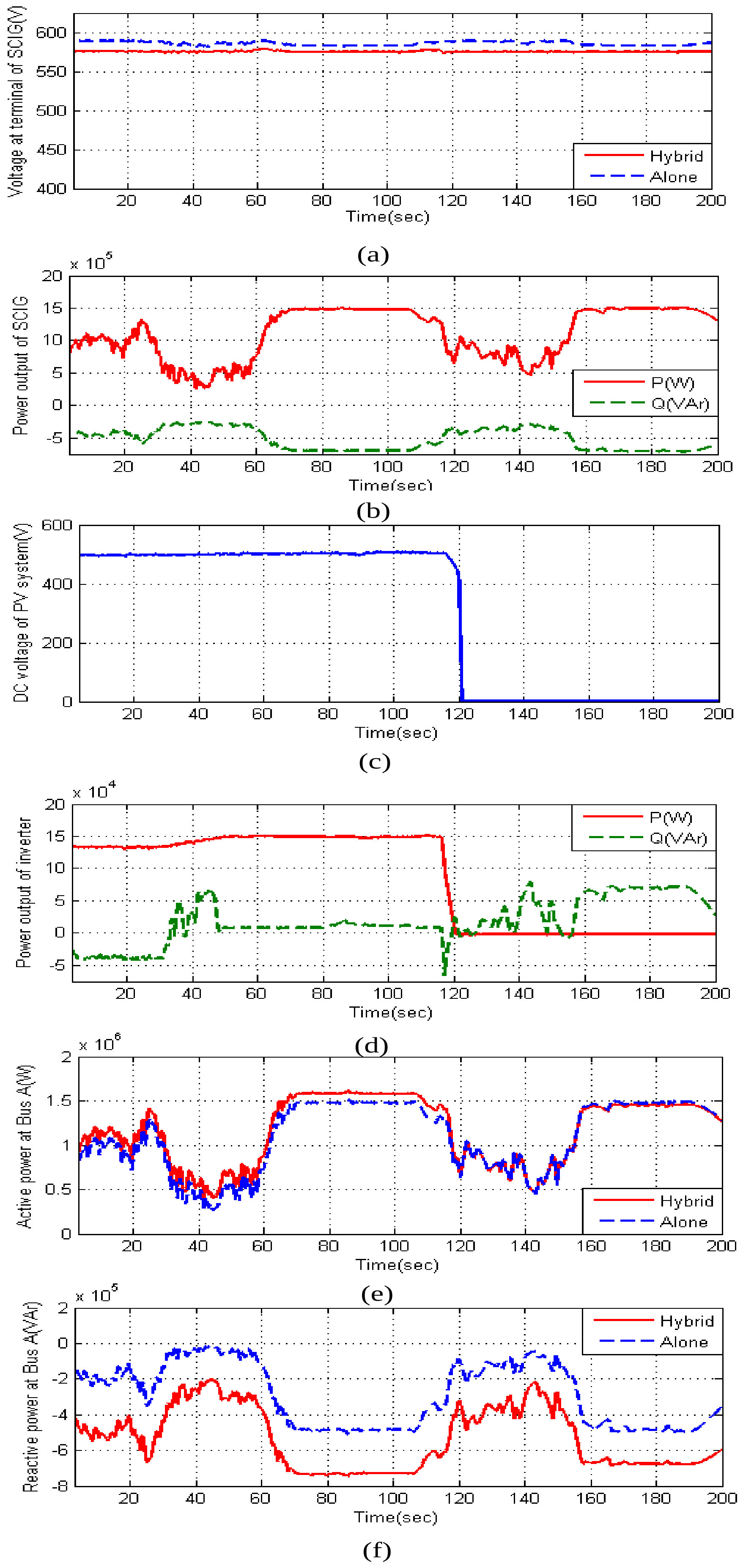

Fig. 6. Simulation results: voltage at terminal of SCIG (a), power output of SCIG (b), DC voltage of PV (c), power output of inverter (d), active power output at Bus A (e), reactive power at Bus A (f).

4.2 Dynamic Operation Condition

To test the proposed configuration under dynamic operation, two scenarios of fault, two-phase and three phases, are considered. Assuming that a 150ms-lasting fault occurring at point N at 10s. In this research, the terminal voltage of wind generator is always referred to Sweden's grid code requirement [23]. It is noted that the wind speed and the irradiation in these cases are the rated value. Simulation results are shown in Figure 7 and Figure 8.

As can be seen from Figure 7a, in the case of no support of the PV system, after three-phase fault clearance, the terminal voltage of SCIG fails to recover and following an unstable operation of whole system, as depicted the doted curves, is unavoidable. By contract, in the hybrid system, thanks to the reactive power support of the PV system's inverter, SCIG's terminal voltage fully restores and whole hybrid system can work properly, as shown in the continuous curves. Obviously, the voltage at the terminal of the wind generator has just satisfied the grid code requirement. Figure 7b indicates that after fault isolation, the inverter generates around 150kVAr to the grid until the voltage reaches to over 85% of the rated value. This depicts that in this period, the inverter only prioritizes to the PCC voltage adjustment.

Likely, the dotted curve in Figure 8a illustrates that without the PV system, after a two-phase fault, the voltage at the terminal of SCIG can restore to the rated value. Unfortunately, it takes long time to recover, about 4.5s after fault clearance, this violates the grid code requirement and the wind turbine is compelled to separate from the connected grid in order to ensure the utility grid's stable operation. By contrast, with the reactive power support of the inverter of the PV system Figure 8b, the voltage at the wind generator is reached to the normal value early and it entirely meets the grid code requirement. This can be seen evidently from the continuous curve in Figure 8a.

Another thing is to identify the limitation of the PV system capacity so that the hybrid system can become stable operation after a fault on the utility grid. From several simulations with different PV system capacities, the critical time to isolate a fault on the grid is plotted in Figure 9 Noted that the capacity of the wind turbine is still 1.5MW.

Figure 9 shows the critical time to isolate a fault among PV's capacities. For example, with PV's capacity of 150kW, 10% of wind power, the fault isolating time obliges to be below 150ms and 205ms for three-phase fault and two-phase one, respectively. Otherwise, the voltage at the terminal of SCIG will violate the grid code requirement and the hybrid system must be separated from the grid. Moreover, Figure 9 proves that a higher capacity of the PV system allows a longer fault clearing time. When the capacity of the PV system is 50% of the wind power, the fault-clearing time can be up to 360ms and 450ms for three-phase and two-phase fault, respectively while they are only 125ms and 185ms if PV's rating is 5% of the wind power. With normal relay protection system and circuit breakers existing in practice, the minimum time to isolate a fault is around from 130ms to 170ms, it depends on the mechanical acting system of circuit breaker. Therefore, to improve the FRT of SCIG wind turbine, the capacity of PV system at least must be over 7% of the wind power.

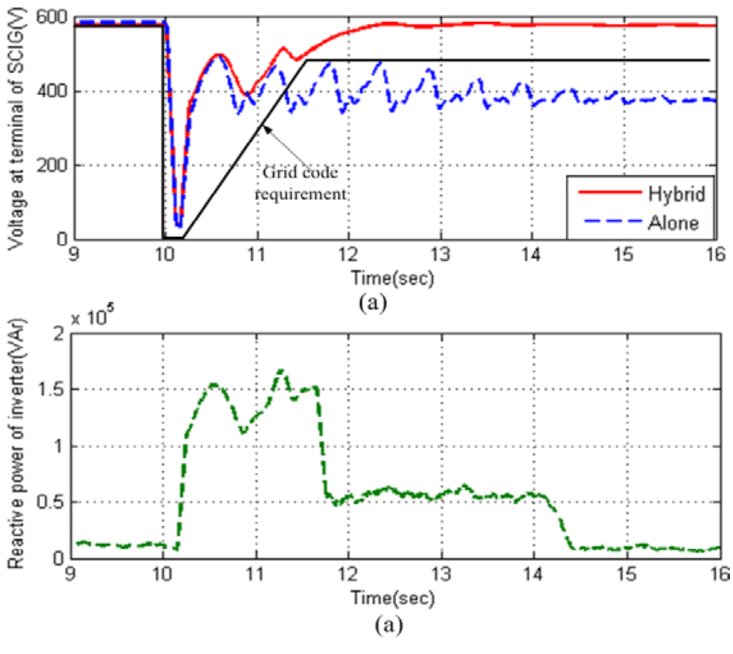

Fig. 7. Simulation results as three-phase fault: voltage at terminal of SCIG (a), inverter's reactive power (b).

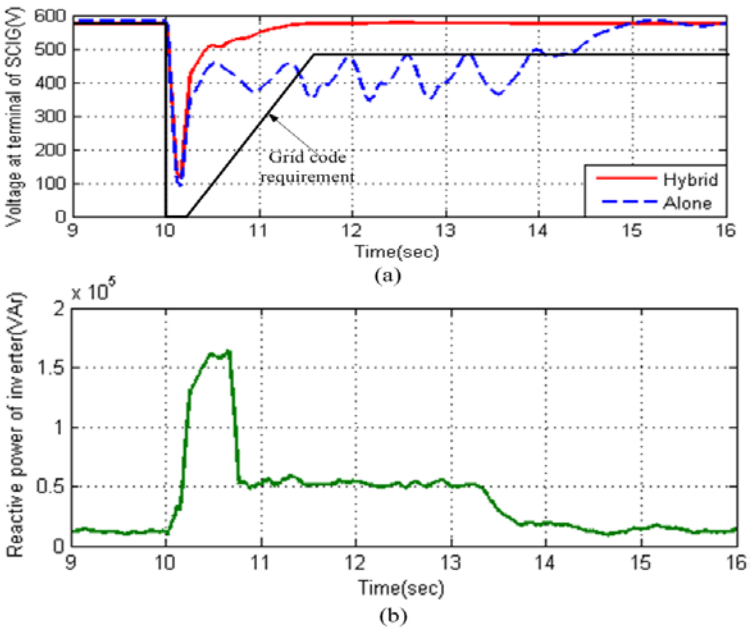

Fig. 8. Simulation results as two-phase fault: voltage at terminal of SCIG (a), PV system's reactive power (b)

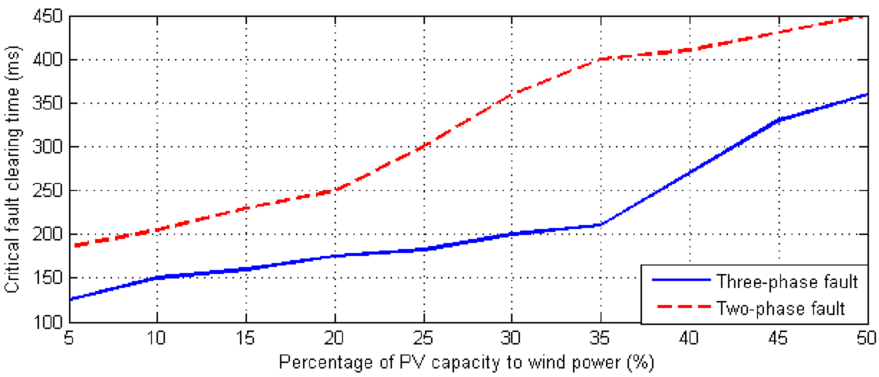

Fig. 9. Locus of critical fault isolating time with different PV capacity.

5. CONCLUSION

This paper investigated a hybrid system including a two-stage PV system and a SCIG based wind turbine. The PV system is installed nearby the wind turbine and both of them are connected to the low voltage side of a step up transformer connecting to the external 22kV grid. This configuration allows investor utilize the free land around the wind turbine tower to install the PV system. Furthermore, by controlling the inverter of the PV system, this inverter can support reactive power to the SCIG –wind turbine instead of conventional compensator equipment such as capacitor bank, STATCOM or SVC. Simulation results indicated that whole system can work properly in the normal operation and the SCIG-wind turbine can ride through fault easily. Another contribution is that this paper demonstrated a locus of critical fault-clearing time with different PV capacity. This locus shown that the higher capacity of PV system is the longer the critical fault clearing time is. A minimum capacity of PV system to improve the wind power's FRT ability is about 7% of the wind power capacity.

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