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Impact of Photovoltaic Generation Integration on Protection of Distribution Systems

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Abstract—Photovoltaic (PV) distributed generation (PVDG) has grown significantly in the recent years due to the rapid development of power electronic technologies. The PVDG is usually integrated to distribution systems. The integration of PVDG can alleviate energy demand effectively while reduce air pollution and greenhouse gas emissions. However, with the increasing integration, the PVDG systems inevitably lead to significant challenges on operation of power systems, including protection of distribution systems. In the existing literature, only a few papers discussed the impact of the integration of PVDG on the protection of distribution systems, and the corresponding technical challenges are not fully clarified. To fill the gap, this paper develops a generic distribution system with the integration of a PVDG system to analyze the impact of integration of PVDG on the overcurrent protection of the distribution system. It is found that the control of PV inverters can limit the fault current significantly during a short-circuit (SC) fault. This makes the SC current of the faulted feeder too low to trigger the circuit breaker, leading to a protection failure (should operate but does not). To verify this conclusion, a comparison case with the connection of a traditional synchronous generator is provided in this paper.

Keywords—PV generation, protection of distribution systems, current control, PV inverter, SC fault.

I. Introduction

During the last decade, renewable energy generation has increased significantly due to vast energy demand and climate impacts. The European Union (EU) points out that the increasing energy consumption from renewable resources will be up to 20% by 2020 to achieve an 80-95% reduction on greenhouse gas emissions by 2050 [1][2]. Among these renewable resources, solar resource has been widely applied due to its characteristics of green and endless. A main application is to convert solar energy into power generation by PVDG systems. According to the prediction of International Energy Agency (IEA), the global installation capacity of PVDG will be up to 1721 GW by 2030 [3].

The PVDG is integrated to distribution systems via an inverter to form a grid-connected PV system. The high-level penetration of the PVDG can alleviate overloads and reduce capacity of feeders and substation transformers effectively [4]. However, it also causes some undesired issues, including protection mis-coordination, power quality (e.g., voltage fluctuation and harmonics) and grid stability [5]. The study in [6] provided an in-depth review of methods and strategies to prevent over-voltages in distribution systems with integration of PVDG. In [7], the authors clarified the role of inverters and they added reactive power control, frequency regulation and storage systems to the functions of inverters, which are also called “smart inverters”.

The grid-connected PVDG system can impact the performance of protection of distribution systems when a SC fault occurs on a feeder. So far, only a few studies discussed this issue. The study in [8] introduced the impact of a PVDG system on the protection system of a distribution system by simulating the PVDG system on different feeders with a variable fault impedance in case of a fault. It concluded that the SC current generated by a PVDG system is insignificant, compared with that supplied by the upstream grid. However, the insignificant fault current can cause a serious problem as it may not be able to trigger overcurrent protection. In [9], the authors studied the negative influence of a PVDG system on the protection system of a distribution system. It provided a control algorithm to alleviate the negative impact on the distribution system. However, the applied case comparison with and without a PVDG system did not have an identical power flow. It is hard to show the difference of a PVDG system from a traditional synchronous generator.

Traditional radial distribution systems are protected by circuit breakers (CBs) controlled with overcurrent relays. Overcurrent relays are required to detect SC faults and send tripping signals to CBs to isolate the fault. Historically, to ensure the uninterrupted power supply (UPS) for some crucial loads, the distributed generators are usually equipped. The traditional distributed generators are usually synchronous machines, such as diesel generators. Due to the small subtransient impedance of synchronous generators, the fault current of a feeder fed by a synchronous generator is generally very high. It can activate the overcurrent relay of the faulted feeder to trigger the corresponding CB. For a distribution system with PVDG systems, the PV inverter is usually equipped with a control function of current limitation to protect the semiconductor switches of the inverter, as they are sensitive to a high current. When a SC fault occurs, the SC current generated by a PVDG system is limited by the current control to the limit value. As a result, the SC current flowing through a feeder can be too low to trigger the CB, leading to a protection failure (should trip but does not). In this case, the fault in the distribution system lasts for a long time. This can damage power system devices, resulting in huge economical losses of power systems. In order to avoid the situation, the protection schemes of distribution systems must be redesigned.

To guide the protection design of the future distribution systems with high-level penetration of PVDG, this paper presents a quantitative analysis of the SC fault characteristics of a PVDG system, which is compared with a synchronous generator. A distribution system benchmark is developed in this paper to study the operation of the overcurrent relay during a SC fault on a feeder. The same fault is performed in the distribution system with a PVDG system and a synchronous generator, respectively. Both of the simulation systems are with identical power flows. Comparing these two cases, this paper identifies the impact of the PVDG on the protection of distribution systems quantitatively.

The organization of this paper is as follows. Section II outlines a model of a grid-connected PVDG system and discusses the structure and control strategy of the PV inverter. Section III introduces the overcurrent protection of distribution systems and analyzes the impact of PVDG integration on the protection system. Section IV develops the simulation cases to compare the impacts of a PVDG system with that of a synchronous generator on the overcurrent protection of a distribution system. Section V is the conclusion.

II. System Configuration

A. The Mathematical Model of a PV Cell

Fig. 1 illustrates the equivalent circuit of a PV cell. The current source I_L is the cell photocurrent. The symbols I_{pv} and U_{pv} are the SC current and open-circuit voltage of a PV cell respectively. The symbols R_{sh} and R_s are the intrinsic shunt and series resistances of the cell respectively.

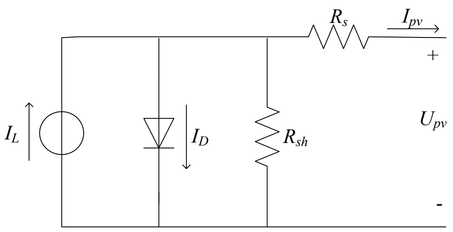

Fig. 1 Equivalent circuit of a PV cell

The SC current of a PV cell is given by the (1).

$$I_{PV} = I_L - I_0\left\{e^{q(U_{PV}+I_{PV}R_S)/AKT} - 1\right\} - \frac{U_{PV}+I_{PV}R_S}{R_{sh}} \tag{1}$$

where the symbol I_0 is the diode reverse saturation current. The symbol q is the elementary charge. The symbol A is the coefficient connected with the diode. The symbol K is the Boltzmann constant, and the symbol T is the temperature.

The symbols R_{sh} and R_s are usually neglected to simplify the analysis since the value of R_{sh} is very large and that of R_s is very small. As a result, the simplest equivalent circuit of a solar cell is a current source in parallel with a diode [10]. Due to the low output voltage of a PV cell, a plurality of PV cell modules is connected in series or parallel to create PV arrays to generate electricity in PVDG systems.

B. Grid-connected PVDG System

The simplified configuration of a grid-connected PVDG system as shown in Fig.2. The function of the PV array is to convert solar energy into DC power. The output voltage and power of PV array is affected by the weather conditions, mainly including temperature and illumination. Quantitative analysis of the effect is discussed in the [11]. In order to reduce this effect, a control strategy is carried to ensure that the output of PV array can maintain the maximum output power, which is called maximum power point tracking (MPPT). This function is achieved by the DC/DC boost circuit. The other function of the inverter is to transform the output of DC power into the AC power injected into the grid. Due to the two important functions of the inverter, this is the core component of the grid-connected PV system. The filter is used to reduce the current harmonics around the switching frequency of power devices. The structure of L-filter is simple, but it becomes quite expensive to realize high harmonic reactors. Moreover, the system dynamic response may become poorer. The LC-filter is the same as the L-filter when the PVDG system is connected with the gird. Therefore, the LCL filter with small values of inductors and capacitors is an attractive industrial solution [12].

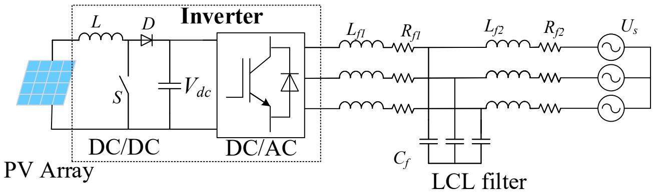

Fig. 2 Grid-connected PV system

C. The Control Strategy of a PV Inverter

The two-stage structure of an inverter is shown in Fig. 3, which is applied widely at present. The main structure consists of two types of circuits: a soft switch DC/DC boost converter and a DC/AC inverter. The DC/DC converter can make PV array maintain the maximum output power by using the MPPT strategy. The other function of the converter is to step up inverter output voltage to be more than $\sqrt{2}$ of the grid voltage to ensure the power generation from the PV arrays to flow into the grid [13]. The function of the DC/AC inverter is to convert the DC into the AC matched with the power grid.

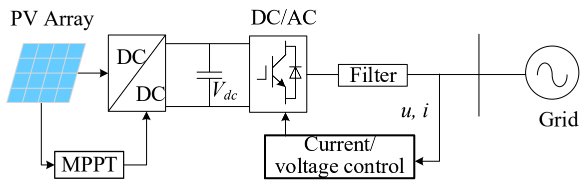

Fig. 3 Two-stage structure of an inverter

The inverter works as a current controlled voltages source. The grid-connected inverter generally applies a decoupled current control scheme. The current control of the inverter can limit the current during a SC fault, which is to avoid breakdown of the semiconductor devices in the inverter [14]. Fig. 4 shows the voltage and current control of the PV inverter. The subscript "_ref" is used to indicate the reference value [15]. Grid-connected PV inverter adopts a dual closed-loop control structure combining a dc voltage outer loop with a current inner loop.

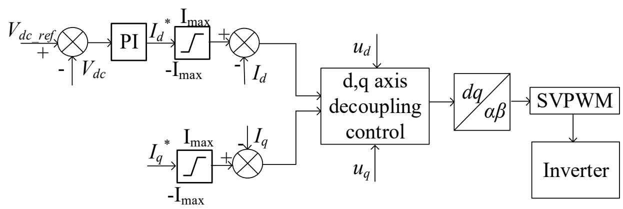

Fig. 4 Simplified control configuration of an PV inverter

The actual active power P and reactive power Q can be obtained by (2) and (3).

$$P = u_d i_d + u_q i_q \quad (2)$$

$$Q = u_q i_d - u_d i_q \quad (3)$$

The symbols I_d and I_q are the grid current in the d-q coordinate system and the symbols u_d and u_q are the grid voltage in the d-q coordinate system. The active power and reactive power can be controlled separately via decoupling the current under the d-q axis. With the inner loop of the current, the dc voltage can be controlled by regulating the current. When the output power of the inverter doesn't match with the input power of the inverter from the PV array, the dc voltage V_{dc} will fluctuate. This will trigger the regulating of the inner current loop to change the output power and make it match with the input power of the inverter. As a result, the voltage remains stable.

Specifically, the three-phase grid voltage and current are converted into the d-axis and the q-axis components in the d-q coordinate system by the Park transformation. The symbol V_{dc_ref} is the output of the MPPT and the symbol V_{dc} is the voltage of the dc-link capacitor. Since the dc voltage is controlled by regulating the current, the output of the voltage outer loop PI regulator is the current given value reference value I_d^* of the current inner loop. The symbol V_{dc} is subtracted from the reference value and the result is sent to the PI regulator. The output is the of the d-q axis current. The symbol I_q^* is determined by the reactive power delivered to the grid. Since PV inverters in distribution systems are usually required to operate at the unity power factor, I_q^* is usually set as 0 [16]. After passing through the current limiter device, the reference current values are subtracted with the actual I_d and I_q, and the result is through the d-q axis decoupling control to get a signal in the d-q coordinate system. The control signal could be obtained after the signal in the d-q coordinate system being converted into the α-β coordinate system. The signal controls the semiconductor switching devices in the inverter by SVPWM. In order to reduce the impact of disturbance of voltage on the current control, the feedforward control of u_q and u_d is added. This could also improve the dynamic response speed of the inverter.

D. *The Protection of Traditional Distribution Systems*

A typical distribution system from [17] is shown in Fig.5. Distribution substation has one or more feeders, which are mostly radial distributed. It means that there is only one way for power flowing from the substation to loads. The distribution substations are usually equipped with CBs to avoid overcurrent faults. A voltage regulator is designed to automatically maintain voltages at a constant level.

A part of traditional distribution system is shown in Fig.6. Each CB is equipped with an overcurrent relay. Power flows only from the substation to loads and there are no energy generations along the feeder. It is a single-source in-feed and radial current flow network. Based on this condition, distribution system is protected from overcurrent by using circuit breakers and fuses. In overhead lines, reclosers are usually required since most of faults are temporary fault. Generally, the protective device is non-directional [18-19].

For the distribution system in Fig.6, when a fault occurs at point F, the SC current from the substation I_f is detected by the overcurrent relay R1 and CB1 is tripped to isolate the fault from the rest of the distribution network. As a result, loads 2 and 3 are out of electricity until the fault is cleared and the CB1 is closed again. For some important loads, i.e. hospitals and factories, this situation can cause serious consequences. Therefore, distributed generators are usually equipped to provide uninterrupted power supply (UPS).

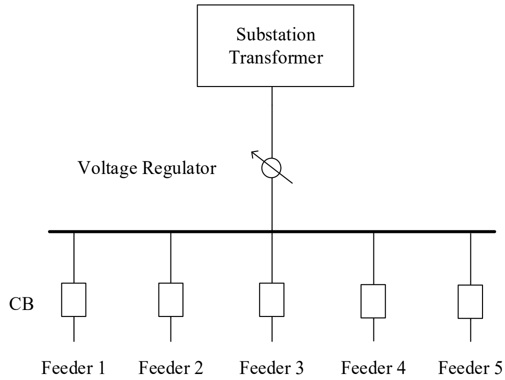

Fig. 5 Distribution system

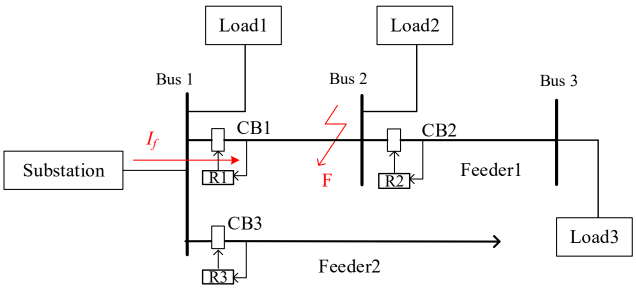

Fig. 6 Part of traditional distribution system

Generally, the traditional distributed power supply are usually diesel generators, which are synchronous generators. With the development of solar PV technologies, the distributed power supplies can be replaced by the PVDG systems. To study the impact of the PVDG system on the protection of the distribution systems, a benchmark system is developed with the connection of the synchronous generator as shown in Fig.7.

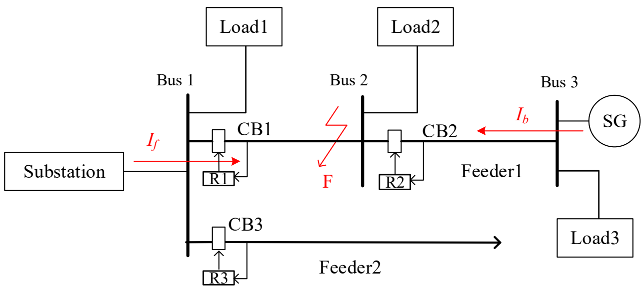

Fig. 7 Benchmark system with SG

Assuming the load 3 is an important load. To provide the UPS, a synchronous generator SG is equipped on the same bus of load 3. In this case, even though load 3 is disconnected from the substation after CB1 is opened, it still can be supplied by the SG. The SC current I_b can be large enough to trigger CB2 when a SC fault occurs at point F. Therefore, the SC fault located at F can be isolated from the distribution system successfully by the tripping of CB1 and CB2.

E. The Distribution System with PV Generaiton

Fig. 8 shows a part of distribution system with a PVDG system. It is assumed that this system has the identical power flow with the system in Fig. 7. The power generated by synchronous generators is taken place by the PVDG system.

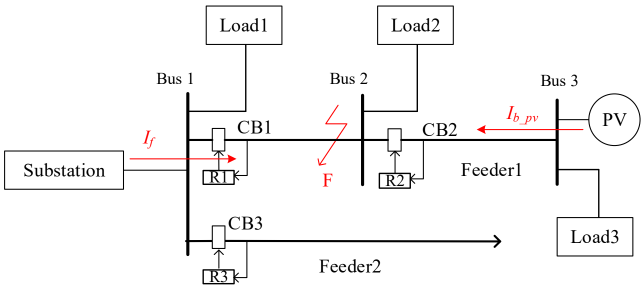

Fig. 8 Distribution system with PVDG system

It is assumed that the same SC fault occurs at point F. As the SC process only lasts a short time, it could be assumed that the external conditions (mainly including illumination and temperature) are constant, which means the maximum output power of the PV array remains constant.

The current control of the inverter can limit the current to a limit value I_{max} during a SC fault. The resulting SC current generated by PV is much smaller than the SC current I_b. The SC current I_{b_PV} can be too low to trigger CB2 in case of a fault, which reduces the stability and reliability of the distribution system and causes huge losses in power systems.

III. CASE STUDY

For the benchmark system shown in Fig. 8, the voltage level of the feeder 1 is 10.48kV and the capacity of the load is 90kW. The SG generates 46kW for the load. For the distribution system with PVDG system shown in Fig. 9, it is assumed that this system has the identical power flow with the benchmark system. The 46kW power generated by synchronous generators is taken place by the PVDG system.

A. Fault Scenario Study

It is assumed that the SC fault occurs at 0.5s at point F. Fig. 9 and Fig. 10 show the simulation results of comparison of fault voltages and currents of distribution systems with a synchronous generator and a PVDG system, respectively.

The steady state voltage and current of two generations are identical, which ensure the flows of two generations are identical so that we can compare the response of two types of generations during a SC fault.

When a SC fault occurs at point F on the feeder, the current of the synchronous generator suddenly increases to approximate 5 times as many as the steady state current. Since the synchronous generator has the property of inertial to maintain the present statics, the output power is not going to change instantly. As a result, the initial SC current can be boosted to a high value while the voltage has a sharp dip when SC fault occurs at point F. The SC current can be large enough to trigger the CB2 to clear the SC fault. The current and the voltage are the 0 after the fluctuation.

For the system with PVDG system, the SC current is limited by the current control of the inverter to a limit value. The limit value depends on the current level of the semiconductor switch of the inverter in reality. IGBT manufacturers usually define the maximum overcurrent capability of the IGBTs to be 3 times of the rating current [20]. In this model, the limit value is twice as many as the steady state current. The operation of the current limiter of the current control makes the PVDG system equal to a constant current source. As a result, the SC current can be constant if the SC fault exists. The voltage is close to 0 because of the impedance of the feeder. Compared to the SC current of the synchronous generator, the SC current of the PVDG system is much smaller, which makes SC current on the feeder too low to trigger the CB2, the SC fault can exist for a long time and power system devices can be damaged, resulting in huge losses in power systems.

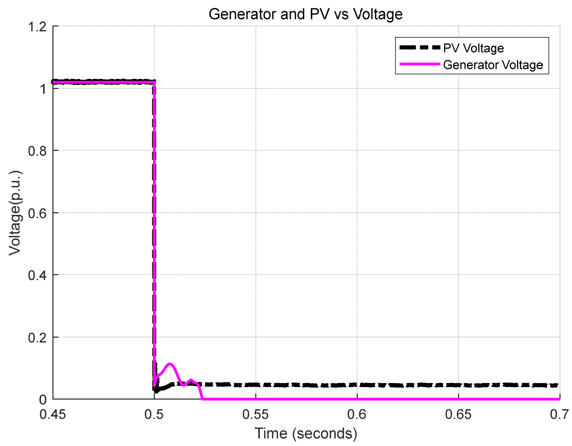

Fig. 9 Voltage on feeder 1

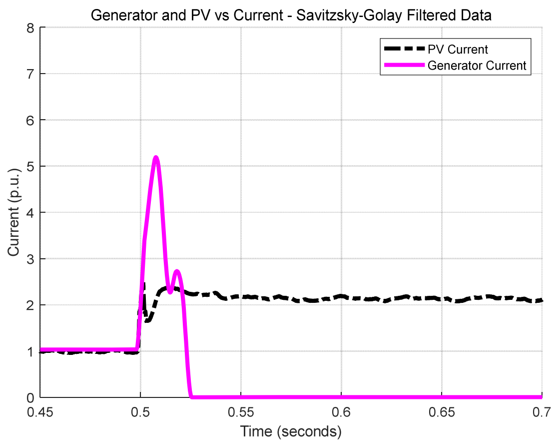

Fig. 10 Current generated by two generators

B. Discussion on Solutions

To avoid this situation, the control of the inverter or the protection schemes of distribution system should be redesigned. The direct solution is to improve current level of the semiconductor switch. However, designing inverters that can provide more fault current could be very costly. Another way is to set the overcurrent value of the relay near the PVDG system lower than the PV fault current. However, this would cause a failure of the discrimination of the fault current from the transient current and overload current. This may cause the maloperation of the relay (should not trip but does) responding to the transient current and overload current. A voltage-current protection scheme is proposed in [21]. It combines the feature of the voltage drop during the fault to recognize the fault and trip the CB. However, this method is also costly for installing the voltage measurement sensors in the large distribution system. More importantly, it cannot apply to the PV sources with capabilities of voltage regulation. The machine learning method provide a great opportunity for this issue. Applying the machine learning algorithm, the relay can detect the low fault current of the PVDG system after learning the features of the fault current.

IV. Conclusion

The impact of the increasing integration of PVDG on the protection of the distribution systems will lead to serious consequences. Since the characteristics of the inverter-based PVDG is very different with that of the synchronous generators in the traditional distribution systems, the protection system must be redesigned.

This paper discussed and identified the resulting impact on protection of distribution system during a SC fault on a feeder with a comprehensive study. When a SC fault occurs on a feeder of distribution system, a benchmark study shows that fault current of a distributed synchronous generator is 5 times the rating current which can trip the CB. However, the current control of the PV inverter can limit the current, which can lead the SC current on a feeder being too low to trip the CB. The protection failure can cause damage of power system devices, leading to huge economical losses to the power system. To avoid this situation, we are developing an intelligent protection scheme for current distribution systems with inverter-based distributed renewable energy integration based on machine learning. This protection scheme will adopt adaptive relays applied with the machine learning method to detect the limited fault current of the inverter-based distributed renewable energy. It will be verified by a real-time simulator OPAL-RT that can simulate the response characteristic of system state at a high speed and the simulation can be real-time.

References

[1] DECC, "The UK Low Carbon Transition Plan: National Strategy for Climate and Energy," 2009.

[2] "EU Energy Policy to 2050: Achieving 80-95% emissions reductions," European Wind Energy Association, pp. 68, March 2011.

[3] Technology roadmap: solar photovoltaic energy - 2014 edition, in, International Energy Agency (IEA) report, 2014.

[4] J.H.R. Enslin, "Network Impacts of High Penetration of Photovoltaic Solar Power Systems," *in Proc. IEEE PES GM*, July 2010.

[5] F. Katiraei and J. R. Aguero, "Solar PV integration challenges," ¨ *IEEE Power Energy Mag*., vol. 9, no. 3, pp. 62–71, May/Jun. 2011.

[6] S. Hashemi and J. Østergaard, "Methods and strategies for overvoltage prevention in low voltage distribution systems with PV," *IET Renewable Power Generation*, vol. 11, no. 2, pp. 205–214, 2017.

[7] M. Obi and R. Bass, "Trends and challenges of grid-connected photovoltaic systems–A review," *Renew. Sust. Energ. Rev*., vol. 58, pp. 1082–1094, Jan. 2016.

[8] H. Ravindra, M. O. Faruque, P. McLaren, K. Schoder, M. Steurer, and R. Meeker, "Impact of PV on distribution protection system," *in Proc. North American Power Symposium (NAPS)*, 2012, pp. 1-6.

[9] Morren, J. and de Haan, S.W.H., "Impact of Distributed Generation Units with Power Electronic Converters on Distribution Network Protection," *in Proc. Int. Conf. on Developments in Power Systems Protection*, UK, Mar. 2008, pp. 664-669.

[10] G. Walker, "Evaluating MPPT converter topologies using a MATLAB PV model," *J. electrical and electron. engineering,* vol. 21, no. 1, pp. 49–56, 2001.

[11] X. Nguyen and M. Nguyen, "Mathematical modeling of photovoltaic cell/module/arrays with tags in Matlab/Simulink", *Environmental Systems Research*., pp. 1-13, 2015.

[12] M. Liserre, F. Blaabjerg, and S. Hansen, "Design and control of an LCLfilter-based three-phase active rectifier," *IEEE Trans. Ind. Appl*., vol. 41, no. 5, pp. 1281–1291, Sep./Oct. 2005.

[13] J. Selvaraj and N. Rahim, "Multilevel inverter for grid-connected PV system employing digital PI controller," *IEEE Trans. Ind. Electron*., vol. 56, no. 1, pp. 149–158, Jan. 2009.

[14] R. Tonkoski, L. Lopes, and T. El-Fouly, "Coordinated active power curtailment of grid connected PV inverters for overvoltage prevention," *IEEE Trans. Sustain. Energy*, vol. 2, no. 2, pp. 139–147, Apr. 2011.

[15] L. He and C.-C. Liu, "Effects of HVDC connection for offshore wind turbines on AC grid protection," *in Proc. IEEE PES GM*, 2013, pp. 1–5.

[16] IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces, IEEE Std 1547, 2018.

[17] P. N. Vovos, A. E. Kiprakis, A. R. Wallace, and G. P. Harrison, "Centralized and distributed voltage control: Impact on distributed generation penetration," *IEEE Trans. Power Syst*., vol. 22, no. 1, pp. 476–483, Feb. 2007.

[18] Kersting, William H. *Distribution system modeling and analysis*. CRC press, 2006.

[19] L. He, C. C. Liu, A. Pitto, and D. Cirio, "Distance protection of AC grid with HVDC-connected offshore wind generators," *IEEE Trans. Power Del.*, vol. 29, no. 2, pp. 493–501, Apr. 2014

[20] R. S. Chokhawala, J. Catt, and L. Kiraly, "A discussion on IGBT shortcircuit behavior and fault protection schemes," *IEEE Trans. Ind. Appl.*, vol. 31, no. 2, pp. 256–263, Mar./Apr. 1995.

[21] A. Agrawal, M. Singh and M. V. Tejeswini, "Voltage current based time inverse relay coordination for PV feed distribution systems," *in Proc. National Power Systems Conference (NPSC)*, Bhubaneswar, 2016, pp. 1-6.

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