Distributed Generation in Electric Power Systems: An Overview and Important Issues

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Abstract: - This paper discusses distributed generation (DG) in electric power systems. Various popular DG technologies that are currently used are also described, along with brief explanations of their working principles. It has been acknowledged that the integration of DG with renewable energy sources in power systems is increasing and will grow further. The main reason for this growth is the rising cost and environmental concerns of non-renewable energy sources (fossil fuels). Furthermore, DG offers some advantages, such as reducing power losses in transmission and distribution lines and improving power supply security. However, the increasing DG penetration brings technical implications for the power system to which the DG is connected. These critical issues are also highlighted in the present paper.

Key-Words: - distributed generation, electric power system, distributed generation technologies, renewable energy sources, distributed generation effects

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1 Introduction

The typical structure of an electric power system is given in Figure 1. Conventional power generating stations (for example, steam, hydro, and nuclear power plants) are generally large and can have a power rating of up to 1000 MW. These power generation stations are usually located far from load centres. Thus, the generated electrical power must be delivered through some long transmission lines. Because the generator voltage is typically low (6 to 24 kV), the generator voltage is increased using a power transformer to a higher voltage level (transmission voltage level). The higher voltage level is intended to increase the transmission line capacity and reduce power losses in the transmission line. The voltage reduction from the transmission voltage level is first carried out at the transmission substation, where the voltage is reduced to a lower voltage (sub-transmission voltage level). Then, a second reduction is carried out at the distribution substation, where the voltage is further reduced to a distribution voltage level.

Generators in conventional electric power systems generally use energy from fossil fuels (non-renewable energy). It has been well acknowledged that the extensive use of fossil fuels will significantly affect global climate conditions due to environmental pollution. Furthermore, because the electrical power must be delivered through long transmission and distribution lines, there will be significant power losses in these lines. These power losses are estimated at around 4 – 5% in transmission lines and 10 – 15% in distribution lines, [1].

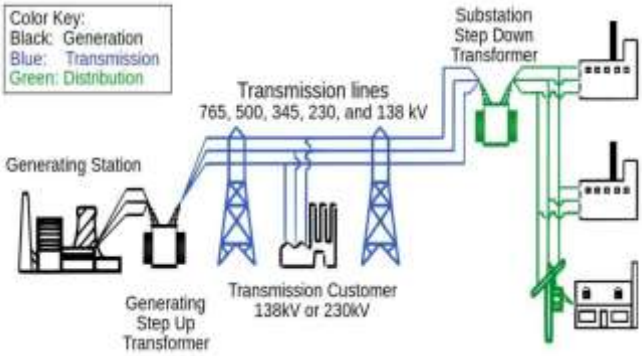


Fig. 1: Electric power system structure

Another disadvantage of the conventional electric power system is that the electric power flowing in the transmission line will also increase with the growth of the system load. If the power flow exceeds the line capacity, it needs to be improved by replacing or adding a new transmission line. This improvement will require quite significant investment costs.

The disadvantages of conventional power systems described above are the main reason for the increasing installation of distributed generation (DG) in electric power systems. DGs are power generation plants located close to load centres (in the distribution or sub-transmission systems). DG has a smaller capacity compared to conventional generators (Table 1), [1], [2]. Some of the DG technologies that are currently popular include wind power, solar photovoltaic, fuel cells, gas turbines, and microturbines, [1], [2].

Table 1. DG capacity

No	DG	Capacity
1	Micro	< 5 kW
2	Small	5 kW – 5 MW
3	Medium	5 MW – 50 MW
4	Large	> 50 MW

In Figure 2, DGs of the form wind power plants are installed in the distribution systems (primary and secondary distribution systems). Because it is close to the load centre, no power is lost in the transmission line (or the total power loss in the transmission line can be reduced). Furthermore, with the presence of DG, power flow in the transmission line can also be reduced, and the line capacity may not need to be improved if there is an increase in system load.

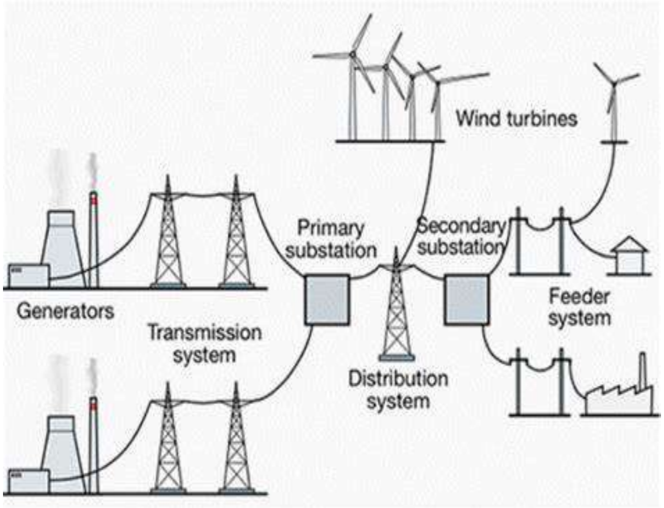


Fig. 2: DG in electric power system

Energy sources in DG generally come from renewable energy sources (for example, wind or solar) and, therefore, will not affect global climate conditions. This paper discusses DG in electric power systems. Various popular DG technologies that are currently used are also described and briefly explained. Important issues related to DG penetration in power systems are also given in the present paper.

2 DG Technologies

As mentioned before, some of the DG technologies that are currently popular include wind power, solar photovoltaics, fuel cells, gas turbines, and microturbines. Table 2, Table 3 and Table 4 show comparisons of these DG technologies, [1]. It can be seen from Table 2 that fuel cells, gas turbines, and microturbines have higher efficiencies than wind powers and solar photovoltaics. Meanwhile, Table 3 shows that the installation and maintenance costs of solar photovoltaics are higher than other DG technologies. However, these DG technologies (and also wind power) are relatively clean as they do not produce pollutant emissions (Table 4).

Table 2. Comparison of DG technologies (power output and efficiency)

Technology	Power Output	Efficiency (%)
Wind Power	300 kW – 5 MW	20 – 40
Solar Photovoltaic	300 kW – 2 MW	5 – 15
Fuel Cell	1 kW – 20 MW	80 – 90
Gas Turbine	15 kW – 50 MW	80 – 90
Microturbine	25 kW – 500 kW	80 – 85

Table 3. Comparison of DG technologies (installation and maintenance costs)

Technology	Installation Cost ($/kW)	Maintenance Cost ($/MWh)
Wind Power	1,000 – 5,000	1 – 4
Solar Photovoltaic	6,000 – 10,000	10
Fuel Cell	1,000 – 5,000	5 – 10
Gas Turbine	400 – 1,200	3 – 8
Microturbine	5 – 10	5 – 10

Table 4. Comparison of DG technologies (pollutant emissions)

Technology	CO_2 (kg/MWh)	NO_x (kg/MWh)
Wind Power	0	0
Solar Photovoltaic	0	0
Fuel Cell	430 – 490	0.005 – 0.01
Gas Turbine	580 – 680	0.3 – 0.5
Microturbine	720	0.1

2.1 Wind Power

The basic principle of a WPP (Wind Power Plant) system is based on the following two processes: conversion of kinetic energy from moving air (wind) into mechanical energy and conversion of mechanical energy into electrical energy. The conversion of kinetic energy into mechanical energy is carried out by a wind turbine, while the conversion of mechanical energy into electrical energy is carried out by an electric generator.

Figure 3 briefly explains the process of electric power generation by the WTG (Wind Turbine Generator) unit in the WPP system. The turbine blades will start to spin when exposed to wind, and it will, in turn, rotate the generator rotor. The turbine rotor is usually coupled to a gearbox, and the gearbox shaft is connected to the generator rotor. The gearbox is needed to convert the turbine rotor's low speed to the higher speed required by the generator to generate electrical power. A WPP usually contains a group of WTG units. A collection of WTG units located in one area to produce electrical power is referred to as a wind farm or wind park (Figure 4).

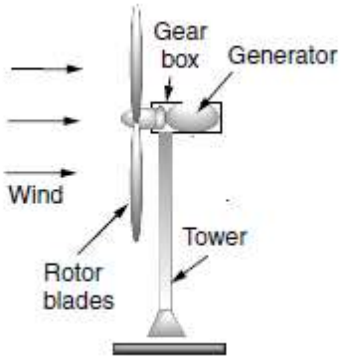


Fig. 3: WTG unit

Fig. 4: A wind farm

Based on the rotational speed, WPPs can be divided into two groups, namely: (i) fixed or near fixed-speed WPPs, and (ii) variable-speed WPPs. In fixed-speed WPP, the system frequency to which the WPP is connected will determine the rotational speed of the WPP generator. Therefore, the generator speed of this type of WPP is only allowed to vary at very narrow intervals (typically around 1 – 2% above synchronous speed). Fixed speed WPP generally utilizes a SCIG (Squirrel Cage Induction Generator) to convert wind energy to electrical power. Since fixed-speed WPP only operates at 1 – 2% above synchronous speed, the conversion of wind energy to electric energy will not be optimal. This disadvantage has recently resulted in the increasing use of variable-speed WPPs, [3], [4].

In variable-speed WPPs, wind energy conversion to electrical power is usually carried out using a DFIG (Doubly Fed Induction Generator) or PMSG (Permanent Magnet Synchronous Generator). However, DFIG is currently more popular because the price is cheaper. Compared to fixed speed WPP, DFIG-based variable speed WPP can operate at a much wider rotation speed range. The generator speed of this type of WPP can vary between 40% below synchronous speed and 30% above synchronous speed. This wider speed range operation is the reason why DFIG-based variable speed WPP can extract more wind energy than fixed speed WPP, [4].

2.2 Solar Photovoltaic

PV (Photovoltaic) cells in an SPV generator utilize semiconductor material (usually in the form of silicon cells) for directly converting solar radiation to electrical energy. These PV cells are generally connected in series and referred to as a PV module. This series connection is made so that the PV module can produce voltage with a desired magnitude. An SPV generator typically consists of several PV modules connected in a series-parallel combination, as shown in Figure 5. This series-parallel combination of PV modules is known as a PV array and is intended so that the SPV generator can generate the required voltage and power. Figure 6 presents a basic configuration of an SPV generator. Figure 6 shows that the main components of an SPV generator include the PV array, VSC (Voltage Source Converter), and filter.

2.3 Fuel Cells

Fuel cell (FC) directly converts the chemical energy contained in fuel (for example, hydrogen, natural gas, methanol, gasoline, etc.) into electrical energy. Figure 7 shows the basic configuration of a single-cell FC. As shown in Figure 7, a single cell FC contains two electrodes, namely a negative electrode (anode) and a positive electrode (cathode). An electrolyte separates the two electrodes. The fuel (e.g., hydrogen) is supplied at the anode, and the oxidant (usually air or oxygen) is supplied at the cathode. Oxidation and reduction processes will occur on the two electrodes and will produce an electric current. The process that occurs at these electrodes can be accelerated by using a catalyst.

Fig. 5: PV array

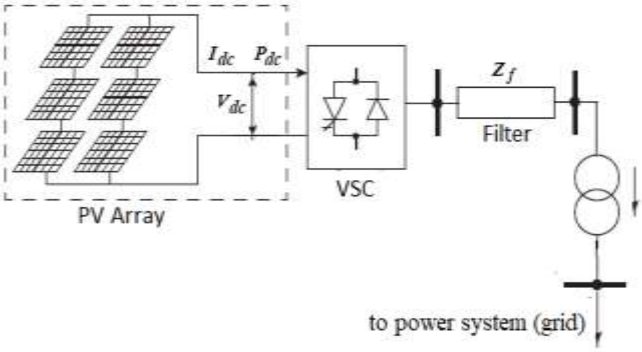


Fig. 6: SPV generator

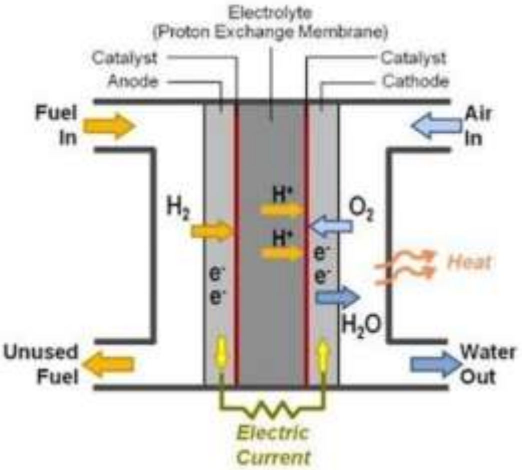


Fig. 7: Single-cell FC

A single-cell FC can only produce an electric voltage of less than 1 Volt. Higher voltage can be obtained by arranging several single-cell FCs in series, as shown in Figure 8. In multi-cell FCs, each cell is usually separated via a bipolar separator plate. The number of cells arranged depends on the desired power output and performance of each cell. Because FC does not have a hydrocarbon combustion process, it does not produce pollutant emissions such as CO_x and NO_x, so it can be considered clean from an environmental point of view. Based on the electrolyte material used, FC can be classified into PEMFC (Proton Exchange Membrane Fuel Cell), DMFC (Direct Methanol Fuel Cell), PAFC (Phosphoric Acid Fuel Cell), AFC (Alkaline Fuel Cell), MCFC (Molten-Carbonate Fuel Cell), and SOFC (Solid Oxide Fuel Cell).

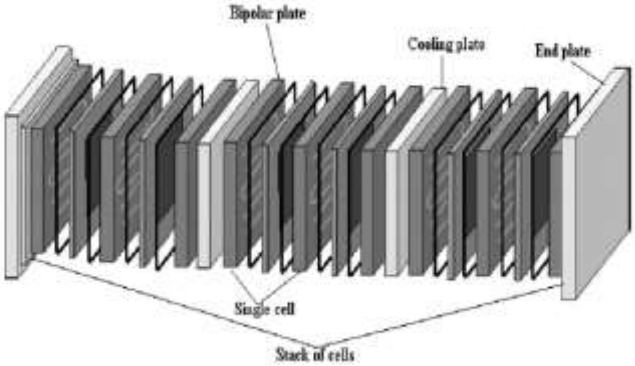


Fig. 8: Multi-cell FC

2.4 Gas Turbine and Microturbine

The basic configuration of a gas turbine that drives an electric generator is shown in Figure 9. It can be seen that the gas turbine system consists of three main components, namely: compressor, combustion chamber, and turbine. The incoming air is compressed in the compressor to increase its temperature and pressure. This hot, high-pressure air is mixed with fuel (usually natural gas) and burned in a combustion chamber. This combustion causes the gas volume to increase and be expanded into the turbine so that the turbine produces mechanical power to rotate the electric generator. In Figure 9, it can be seen that the turbine is also used to rotate the compressor. The power required to rotate the compressor is usually around 40% - 80% of the turbine power output. A microturbine is a smaller-scale gas turbine. The microturbine components are often made from the same materials as the gas turbine.

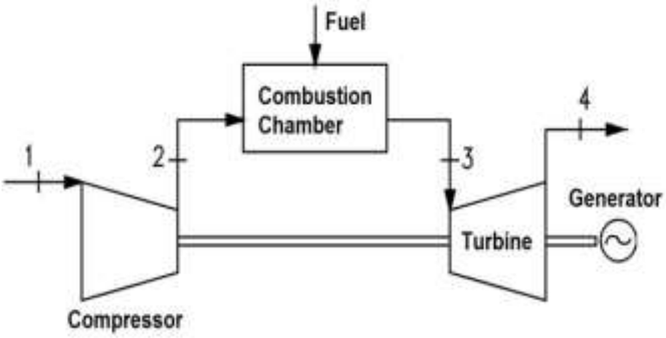
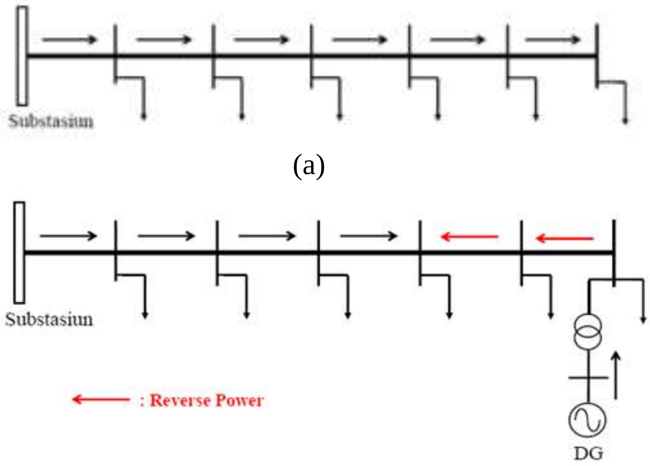


Fig. 9: Gas turbine and generator configuration

3 Impacts of DG on Power Systems

3.1 Load Flow and Voltage Profile

Traditional distribution systems are designed to receive electrical power from the transmission system and distribute it to customers (loads). Thus, electrical power will flow from a higher to a lower voltage level. However, with the presence of DG in the distribution system, the power flow direction can be reversed, as shown in Figure 10. In this case, the distribution network will no longer be a passive circuit that supplies loads, but it will be an active system where the DG will also determine the power flows and system voltage profile. Changes in power flow due to the DG will have technical and economic implications for the power system to which the DG is connected, [1], [2], [5].



(a)

(b)

Fig. 10: (a) Passive network, (b) Reverse power

It is also to be noted that with the presence of DG, the power flow in a distribution system component can increase beyond the component's thermal limit (or current carrying capacity). Furthermore, the presence of DG can increase the system voltage. This voltage rise can be a problem because the voltage in distribution networks is usually specified at ±5% of the nominal or working voltage, [2].

3.2 Short-Circuit Fault Level

In a traditional distribution system, the short circuit current will only flow from the transmission system to the fault point. DG installation will cause the fault current to increase due to the additional contribution of fault current from the DG (Figure 11). This increase in fault current can cause the fault level (or short circuit rating) designed for distribution system protection devices to be exceeded. If this happens, the short circuit rating of the protection devices must be increased, which, of course, requires quite a considerable cost, [2], [5].

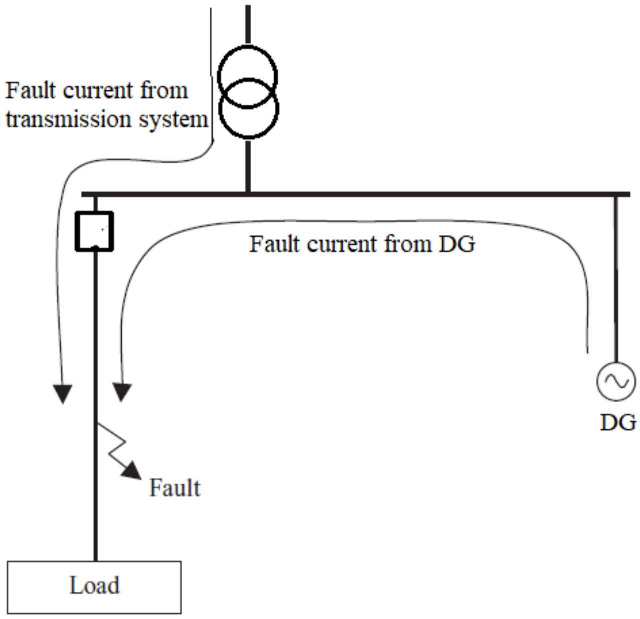


Fig. 11: DG effect on fault level

3.3 Harmonic Distortion

Harmonics can cause the voltage wave to no longer be sinusoidal. DG equipped with power electronic equipment (VSC) can generate harmonics in the electric power system. These harmonics can become problematic if the voltage wave distortion is outside the allowable tolerance, [2], [5].

3.4 Protection System

DG can have an impact on the protection system of the electric power distribution network. Protection problems arising from DG's presence in the distribution system include blinding of protection, false tripping, islanding, and auto-reclosing issues, [2], [5], [6].

3.4.1 Blinding of Protection

The blinding of protection problem can be explained by looking at Figure 12. Figure 12 shows that if there is no DG, relay R detects a fault current equal to the current drawn from the transmission system (I_G). However, in the presence of DG, relay R cannot detect the contribution of fault current from DG (I_{DG}). In other words, relay R is blind to the contribution of the fault current from DG, while the magnitude of the fault current is $I_G + I_{DG}$.

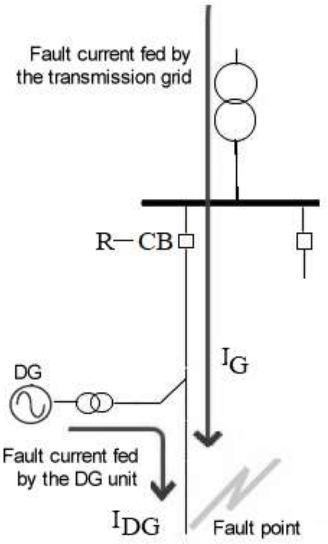


Fig. 12: Blinding protection

3.4.2 False Tripping

Figure 13 shows two feeders (Feeder 1 and 2) of a distribution network wherein one of the feeders (Feeder 1) has a DG. Both feeders are protected by overcurrent relays R1 and R2. If, for example, a fault occurs at Feeder 2. The fault current supplied by DG (I_{DG}) can cause R1 to trip or operate before R2. In turn, this unnecessary trip operation will cause the healthy feeder (Feeder 1) to be disconnected. False or sympathetic tripping is likely if the relay is a non-directional overcurrent. This type of relay cannot detect the direction of the fault current, so it cannot distinguish whether the fault is in the forward or reverse direction.

3.4.3 Islanding

An 'islanding' condition occurs when the power flow from the transmission system is disconnected, causing the DG and local loads to be separated from the system. This condition can be explained by looking at Figure 14. If there is a fault at the feeder, the feeder CB will open to isolate the fault. Opening the CB results in disconnecting the power supply from the transmission system, and the DG (along with local loads) will be separated from the system. This condition is undesirable and can be dangerous. To anticipate this, the DG must be designed to disconnect from the system (or shut down) if the power supply from the transmission system is lost. The exception is for feeders that supply essential local loads (e.g., hospitals). In this case, DG can be designed to operate both in on-grid and standalone conditions. In VSC-based DG, islanding can be detected using a harmonic distortion-based technique.

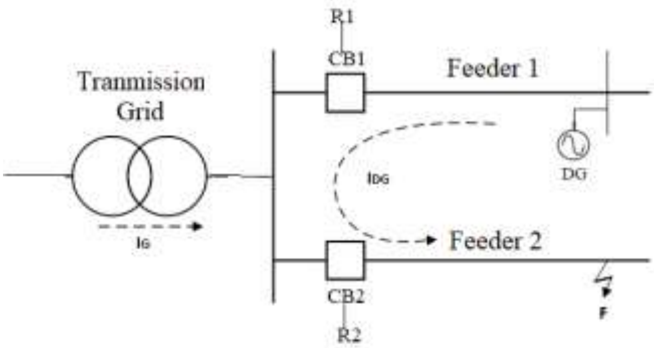


Fig. 13: False tripping

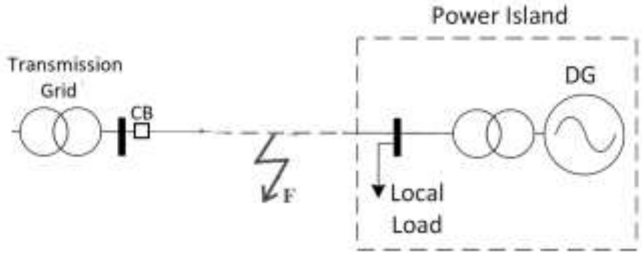
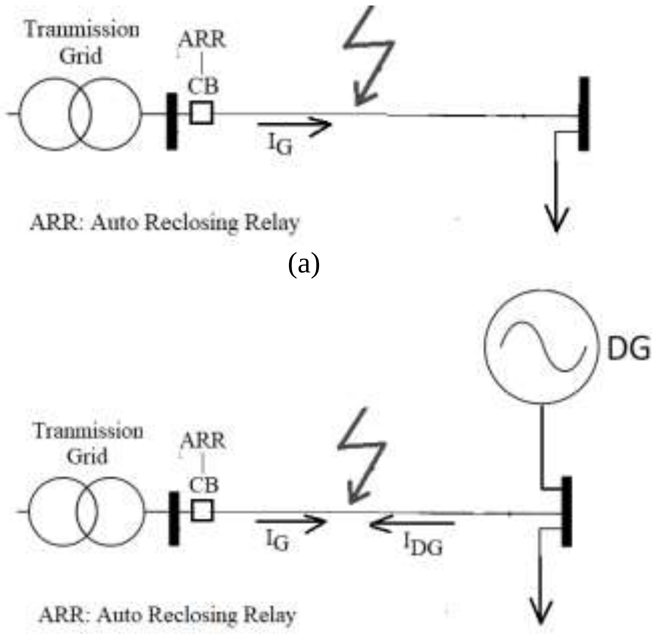


Fig. 14: Islanding

3.4.4 Auto-Reclosing Problems

ARR is commonly used in medium voltage distribution networks to anticipate temporary (transient) faults. However, the presence of DG in the distribution network can disrupt the operation of ARR, which can be explained by looking at Figure 15. Figure 15(a) shows the network without DG. When a fault occurs, ARR will send a signal to CB to open its contacts to isolate the fault. After some time delays, ARR will send a signal to CB to close its contacts. When the fault has disappeared (temporary fault), the CB will remain closed, and the system will return to normal operation. However, if the fault still exists (permanent fault), ARR will again send a signal to CB to open its contacts. If the ARR is single-shot reclosing, the CB will remain open. However, if the ARR is multi-shot reclosing, the CB reclosing process can occur more than once.

With DG installation in the distribution network, as shown in Figure 15(b), there will be two problems. The first problem is the presence of DG fault current (I_{DG}), even though the CB operation has cut off the fault current from the transmission system (I_G). This DG fault current causes the fault arc to persist, and in turn, it will convert the fault into a permanent fault (ARR detects that the fault is not temporary). The second problem is that if the ARR closes the CB after a fault, the DG may not be in sync with the transmission system, and loss of synchronism may occur.



(a)

(b)

Fig. 15: Auto-reclosing problem

4 Conclusion

In this paper, DG in electric power systems has been discussed and presented. Various popular DG technologies that are currently used (i.e., wind power, solar photovoltaic, fuel cells, gas turbines, and microturbines) have also been described and briefly explained. Critical issues related to DG penetration in power systems are also given in the present paper. These issues include system voltage profile, fault level, and harmonic distortion. DG can also impact the protection system of the electric power distribution system to which the DG is connected. Protection problems arising from DG's presence in the distribution system include blinding of protection, false tripping, islanding, and auto-reclosing issues. These issues have also been highlighted in this paper.

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