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CASE STUDIES

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The impacts of the transmission line length in an interconnected micro-grid on its performance and protection at different fault levels

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Abstract

Power systems, in recent years, have been experiencing a dynamic rise in the amount of power obtained from distributed renewable energy sources leading to the concept of microgrids to address the distributed power grid integration issues. Microgrids, a promising means of facilitating the green transformation of power systems, allow the union operation of distributed energy resources (DER) such as combined heat and power (CHP), renewables like photovoltaic (PV), wind and fuel cells (FC), energy storage systems, diesel generators, and controllable loads, either individually or in combination. The protection of DERs within microgrids can be considered as one of the main challenges associated with such phenomenon. Short and Long power transmission lines, in case of a fault, both have particular impacts on system parameters and may result into subsequent events threatening the microgrid and renewable generation units. On the other hand, The high penetration of microgrids not only can change the power flow within the power network, but it can also affect the fault current levels and may lead to their islanding in case of a fault. Before investing in microgrids, especially those in far places, this paper develops a tool to be used in investigating the influence of the interconnecting transmission line length as well as the type/severity of fault on the microgrid performance. The toolbox was developed using MATLAB/Simulink Toolbox. The developed tool was then validated on a case study microgrid and results show that the length of the interconnecting transmission line and the fault severity directly impact the microgrid performance (i.e. voltage and power deviations). In that case, interconnection or islanded mode is contingent upon the decision of the utility operator which also depends on the sensitivity of the equipment used in the microgrid.

Keywords Microgrid, Distributed generation, Transmission lines length, Wind farms, Power systems faults, Power systems stability

1 Introduction

Conventional power plants mainly depend on fossil fuels that inject high amounts of carbon dioxide emissions into the atmosphere. The increased concern about global warming effects has increased the interest in renewable energies [1–3]. In recent years, thermal and diesel power plants have been gradually replaced by renewable energies especially in industrialized communities. However, the decline of power system inertia, increased frequency excursion after a disturbance and more voltage and

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power fluctuations are the most important impacts associated with the replacement of thermal power plants by renewable energy resources [1, 4–6].

With the increased awareness to environmental protection, more microgrids are now used to enable the tremendous penetration of clean energy resources to the low or medium voltage distribution network through the Point of Common Coupling (PCC). Moving towards distributed generation (DG) has commonly positive effects on the transmission lines capability given that the renewable energy resources are generally near to consumers, less power is transferred from generation to consumption, less power losses are arose and also power mismatch is decreased [7–10]. While microgrids can be developed in areas without renewable energy resources, they are used in places with plenty of sun shine, wind power, hydrogen repositories or even geothermal energy [9, 11–13].

Microgrids can offer several benefits for both the consumer and utility. Overall, their capability to reduce congestion, decrease the urgent need for surplus generation, and increase the system ability to respond to rapid changes in loads are the most remarkable benefits [5, 14]. From the view point of consumer, the microgrid is capable of simultaneously supplying their heat and electricity demands, increasing reliability, decreasing greenhouse gas emissions, improving the power quality and also reducing their consumption costs. From the prospective of the main grid operator, microgrids have many advantages such as the drop in demand, reduction in transmission lines development expenses, and removal of peak consumption loads leading to reduced grid losses [7, 13, 15–19]. The most important contributions of islanding process are increasing the consumer reliability, facilitating the maintenance operation, and providing reliable power for critical loads [10, 16, 20–22]. Moreover, the loads and energy sources within microgrids could be disconnected and re-connected to grid, thereby leading to increased reliability in the provision of the microgrid loads [23].

The protection for a microgrid is different from that for the traditional power grid. When fault occurs in the microgrid, it will have an impact on the protection of the distribution network [10, 16, 23–29]. Although the protective apparatus of distribution systems are designed to accommodate large fault currents, they are not capable of the microgrid protection. The reason for this is that when a fault occurs in a microgrid that consists of decoupled DG units operating in islanded mode, the DG current contributions may not be capable of reaching the total fault current due to the usage of inverters with low capability of thermal overloading which limits their maximum output to 2–3 times more than the rated value [9, 25, 27, 30, 31]. Moreover, the power flow within

microgrids is bidirectional due to the different allocations of DG units. When a fault occurs in the microgrid, the desired response to the protective strategies is the isolation of microgrid from the rest of the system leading to the microgrid islanding mode. On the other hand, if the fault occurs in the microgrid, the associated protection system isolate the least possible faulty zones in order to clear it [16, 29].

Microgrids may integrally disconnect from the main grid at the PCC to operate in islanding mode whenever a grid disturbance occurs [32–34]. Therefore, an appropriate protection system must respond to the microgrid faults in both interconnected and islanded modes of operation. For allowing the maximum efficiency of distributed renewable energy systems, power electronic equipment are vital to be used [13, 16, 34–36]. Subsequently, sensitivity and performance of the over current relays might be influenced in the system [28, 37, 38].

Many protection schemes have been suggested to mitigate tremendous challenges associated with microgrid protection in both grid-connected and islanded modes. The authors in [39] have utilized distance and directional relays to identify the single-line-ground fault so that the fault detection can be implemented by the comparison of zero sequence current. In [40], the authors have proposed the connection of relay at the end of each microgrid line to ensure an exact protection. Mohd Asim Aftab et al. claimed a promising protection application and worked on protection settings and restricting fault current by traveling wave based fault location techniques [37].

The variation in the fault level is also based on the DG type, location and technologies [25, 27], and thereby the usage of distance relays that can measure the line impedance can be considered as a proper approach to operate for failures taking place between the relay and an available point. In [37] the ability of the protective strategies to clear faults in microgrids in both interconnected and islanding modes of operation has been investigated. Other protective strategies that are based on fuse re-closers, fault ride-through capability, adaptive and numeric protection and other problems and methods in both operating modes were presented in [23, 25, 37, 41–44].

Furthermore, DG units as wind generators and PV panels are intermittent power sources that can supply less than their rated power values during low wind or sun hours, resulting into an insufficient level of power supply for fault diagnosis, and voltage stability problems [7, 45]. Therefore, if a power system becomes unstable after a fault occurs, then DG units should be disconnected from the main grid to prevent their negative effects on it [27, 42].

The influence that DGs have on the distributed network is entirely proportional to their capacity and

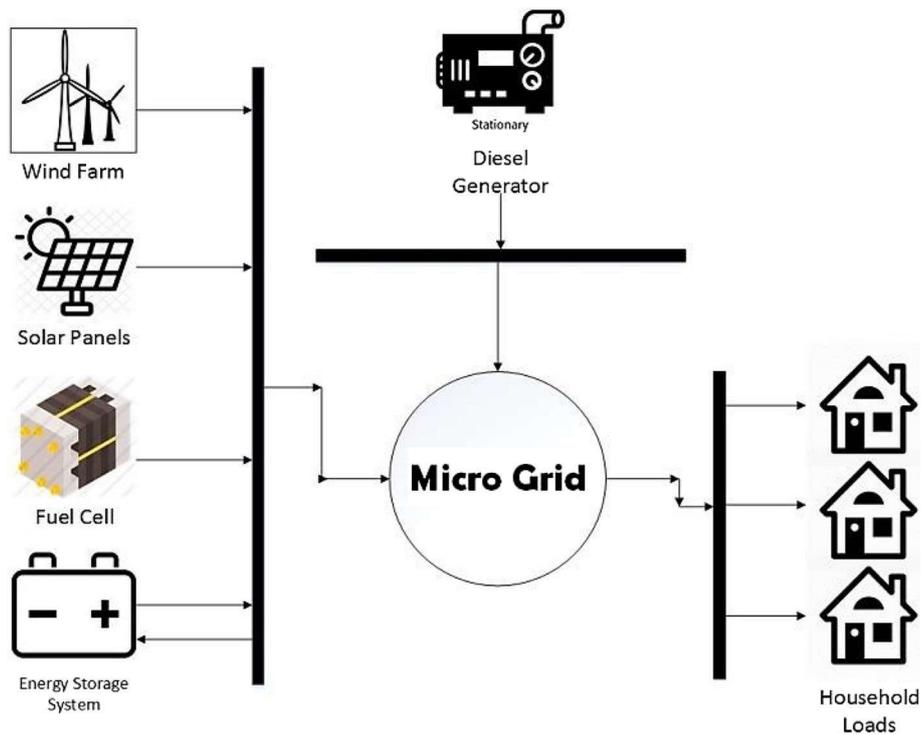


Fig. 1 A simplified structure of microgrid [16]

location which affects the operation of the over-current protection. Previous Studies have shown that the location and installed capacity of a DG have influences the short circuit current amplitude, voltage stability, voltage over of distribution network and other parameters. A well-designed architecture and appropriate DG location can effectively improve the microgrid voltage stability and power factor as well as reduce the active power losses [9, 17, 27, 46–48].

Most of the research studies have mainly focused on the protection and line relying schemes using fault detection and avoiding the problems arising from the microgrid interconnection and adaptive distance protection, thus resulting in high overall system cost due to the extra protective equipment [39, 49, 50]. Such extra protective equipment could be avoided if the correlation between the fault level and its distance from the DG units is considered. Regarding this matter, this paper investigates the impact of the fault current on the microgrid performance parameters through using a case study microgrid with high penetration of wind power generation. Despite the fact that the most papers are unanimous about the disconnection of microgrid in case of fault, it can still stay connected to the main grid and continue to operate. Owing to current constraints associated with islanded microgrids, it is better

to utilize the DERs in interconnected mode, especially in regions with abundant resources [51].

2 Microgrid fundamentals

Microgrid is a novel concept in modern energy distribution systems which enables the unification of the renewable energies. It is an innovative electrical power system which improves the cleanness, reliability, security, cooperation and effectiveness of the conventional power systems. Microgrids can be defined as small-scale power generation networks with low voltage that are designed to supply electrical loads for small communities like campuses, commercial areas and others [10, 16, 26, 29, 32, 52–55].

Microgrids can be defined as electrical networks involving the integration of renewable energies and are mainly based on DG units, Energy Storage Systems (ESSs) and loads that are connected to the grid via power converter interface which can be utilized in either interconnected or islanding modes [24, 36, 56]. DG units refer to small-scale generators or decentralized generation units that can be used in remote places either as a stand-alone system or in inter-connected mode [11, 20, 33, 54, 57, 58]. They offer several benefits including power flexibility, quality and stability improvement, distribution system optimization and the reduction of transmission and distribution costs [20, 36, 59]. Figure 1 depicts an islanding microgrid

including different DERs. Each DG unit is connected to the main grid via power electronic converters resulting in losses reduction, more simple design and low cost control [9, 18, 24].

Microgrids also have Uninterruptible Power Supply (UPS) units especially in places with critical loads like bank systems, semi-conductor industries, hospitals and data centers [10, 34, 60, 61]. Microgrids can supply heat and power simultaneously to meet load demand requirements and also improve the power quality by local voltage and frequency support [8, 14, 16, 62]. The larger and more complicated the microgrid is, the more backup units are needed to avoid any disasters and voltage fluctuations especially associated with critical loads [9, 24, 63].

Microgrids are configured in a way that allows connecting to AC or DC low or medium voltage distribution grids [25, 56]. Based on their infrastructure, they often connect to each other through distribution cables and transmission lines in order to form a unified power system for contribution to feeding the local loads. Figure 2 represents an interconnected microgrid

equipped by power converter interfaces and household consumers and prosumers.

In microgrid systems connected to the main grid, inverters enable a signal from the main grid as a reference for maintaining signal in a correct frequency domain in case of AC microgrid (ACMG) and correct voltage in case ACMG and DC microgrid (DCMG) which is necessary for power factor correction of the reference current. Each DG unit can generate its voltage and frequency domain adjusted relative to the amount of active and reactive power in order to meet a proper load demand [42].

3 Faults in microgrids

A microgrid may suffer from unbalanced behavior when being disconnected from the main grid leading to frequency variations due to low inertia and small time constants [32, 41, 50, 58, 65, 66]. Moreover, faults that can suddenly occur in the main grid due to multiple reasons such as failure in equipment, falling of trees on power lines, lightning strike and destructive attacks [10, 21, 56], leads to protection problems associated with both ACMGs and DCMGs. The main issues associated with

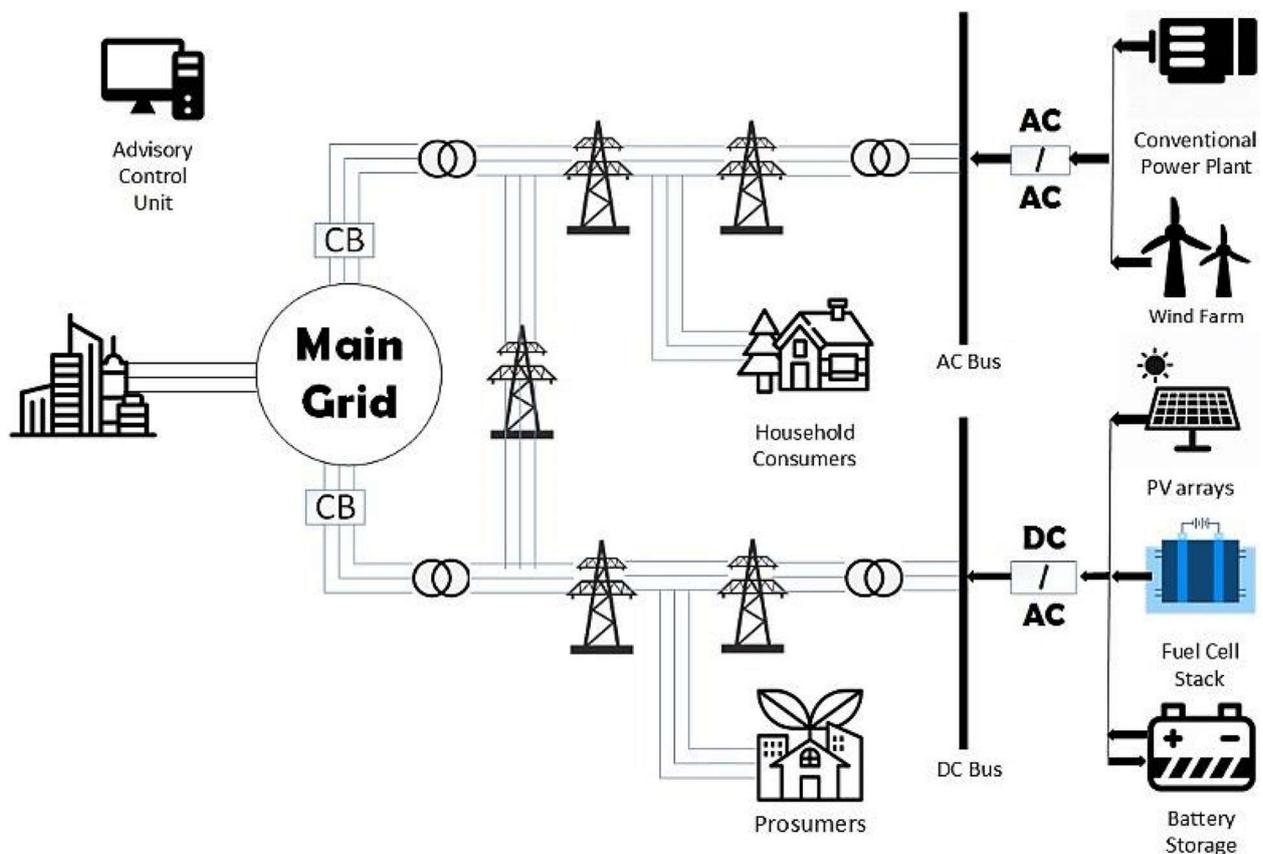


Fig. 2 Simultaneous operation of DC and AC units in a microgrid [64]

the protection of DCMGs are the detection and determination of fault [23, 24, 37]. Distance protection methods have been implemented for long transmission lines [23, 27]. For ACMGs, the high penetration of Wind energy is currently experiencing new challenges related to the inherent variations or unpredictable nature of wind [45].

These fluctuations which affect the electrical output power of wind energy conversion system (WECS), are detrimental for power system quality [13, 67]. Such consequences are more noticeable in islanded microgrids than in grid-connected WECS [52]. Therefore, the voltage and frequency control is such a vital process for microgrids especially in islanded mode [36, 52, 62, 68]. Variable Speed Wind Turbines (VSWT), DFIG and permanent magnet synchronous generator (PMSG) can be used to improve the ACMG performance during the islanding mode. By means of flexible control of DFIG, the dynamic and transient behaviors of ACMG during the both islanding and inter-connected modes have been seen improved [69–72]. In case of large fault in wind farms, only a minor failure can be changed to a cascade phenomenon which is propagated throughout the power system leading a disastrous fault for power grid and could have huge social and economic effects on society [42, 63, 66]. To tackle this phenomenon, intelligent microgrids are generally designed to disconnect the energy supply from the main grid and transfer this into the islanding mode in order to decrease the cascade faults impacts while maintaining the power supply from the clean technologies through using energy storage systems [16, 32, 36, 41, 42]. Microgrids are subject to faults even in islanding mode and in spite of the circuit breakers used especially for high impedance faults in microgrid, it is still necessary to use protection equipment to avoid serious problems for critical loads [7, 12, 23–25, 28, 63].

A typical power system is equipped with various sensing apparatus installed in different locations in order to detect sudden and gradual deviations in voltage and current from optimal condition. There are some examples of such equipment like Smart Meters, Wireless Sensor Networks (WSN), and Phasor Measurement Units (PMU) [7, 21, 23, 25, 32, 41, 56, 61].

Faults in inter-connected mode can be classified into balanced and unbalanced faults [56]. Failures including balanced and unbalanced voltage drops could take place in each phase causing tripping signals and leading to microgrids islanding modes of operation. If the breaker is tripped without any supportive measurements, the Inverters in micro grids might face some transients in voltage or current causing semi-conductor equipment faults. In order to detect the fault in the main grid, the voltage and current phasors are compared with their rated values at the PCC to generate an error signal enabling the

series inverters to protect the microgrid semi-conductor equipment [9, 73]. Some parameters such as frequency, voltage and impedance are compared to their nominal values in order to change the grid mode to islanding if it is necessary [56]. By monitoring the frequency variations and changes in load power, some methods are invented to detect the grid islanding process.

Mostly, the failures in micro grid electrical infrastructures are more severe in islanding mode as the sources, cables and transmission lines are more catastrophic in small scales due to lower inertia and even small disturbances can lead to sustainability problems [14, 19, 56]. Moreover, if the fault is not detected and solved quickly, the rest of the grid can get entangle and cause a system collapse [24, 35, 63].

Furthermore, underground cables are usually exposed to mechanical faults and lack of heat release due to soil nature as an insulator [21]. On the other hand, overhead transmission lines are exposed to natural disasters that can cause failures such as lightning, freezing, breakage owing to trees or animals interference, short circuit, overloading, frizzle, human activities or lack of maintenance [56, 74]. Major faults types include: Single Line-to-Ground Fault, Double Line-to-Ground Fault and Line-to-line Fault [25, 27, 29, 30, 49].

It is clear that, the more renewable energy systems utilized in a microgrid, the less inertia constant will be. From the view that the inertia is a significant factor for DG units, system frequency can be very dependent on this factor in case of disturbances and failures [42, 63, 75]. Conventional power plants like diesel generators work with desire level of inertia so the deficiency of whole inertia would be compensated by their contribution. However, conditions will become worse if high penetration of renewable energy resources is used [19, 44, 60, 62].

4 Transmission line principals

Transmission line models mainly consist of inductive and capacitive components which can be calculated due to the line length and its geometric shape. They can be classified into three categories based on their length [76]:

- Short-Line ($L < 80$ km)
- Medium-Line ($80 \text{ km} < L < 240$ km)
- Long-Line ($L > 240$ km)

Microgrids are mainly connected to the power system over short distances, or medium ones in some areas with high potential of renewable energy resources, to be able to deliver the generated power to the main grid. The following section will explain in details the modeling of short and medium transmission lines that are mostly employed for microgrid interconnection.

4.1 Short-Line model

In this model, line shunt capacitors could be ignored [76].

$$V_s = V_r + ZI_r \rightarrow V_s = V_r + (R + jX)I_r \tag{1}$$

$$I_s = I_r \tag{2}$$

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \tag{3}$$

where V_s and V_r are sending and receiving end voltages respectively, I_s and I_r are sending and receiving end currents respectively and Z is the whole line impedance. The equivalent circuit of the short transmission line is demonstrated in Fig. 3 which has only the total R and X is the transmission line parameters.

4.2 Medium-Line model

In this model, line capacitance is considered. There are two types of line for this model, T and π . The line capacitance is modeled in parallel between the line and the ground [76].

$$V_s = \left(1 + \frac{ZY}{2}\right)V_r + Z\left(\frac{ZY}{4} + 1\right)I_r \tag{4}$$

$$I_s = (Y)V_r + \left(\frac{ZY}{2} + 1\right)I_r \tag{5}$$

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 + \frac{ZY}{2} & Z\left(1 + \frac{ZY}{4}\right) \\ Y & \frac{ZY}{2} + 1 \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \tag{6}$$

$$V_s = \left(\frac{ZY}{2} + 1\right)V_r + ZI_r \tag{7}$$

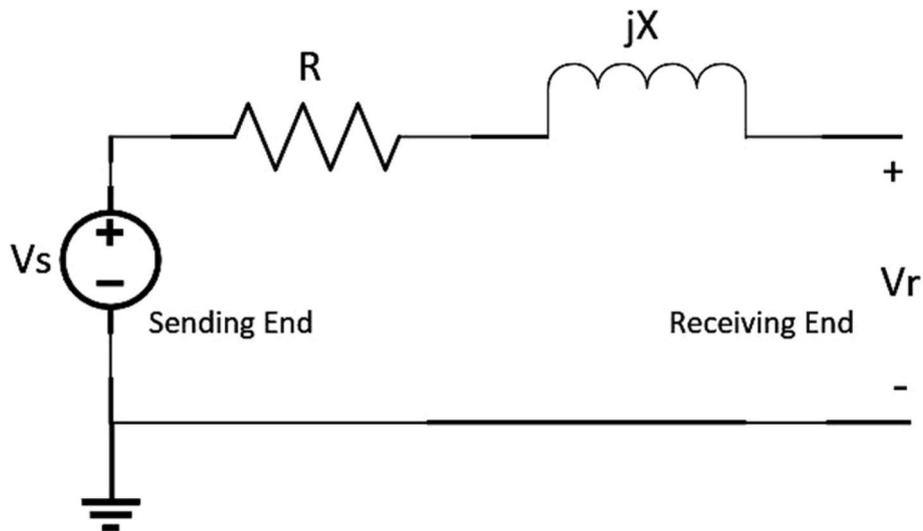


Fig. 3 Equivalent circuit of a short transmission line

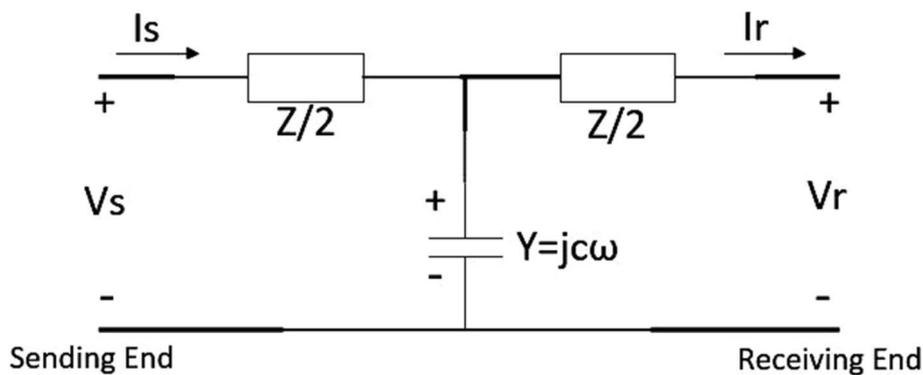


Fig. 4 Equivalent circuit of a medium transmission line – T model

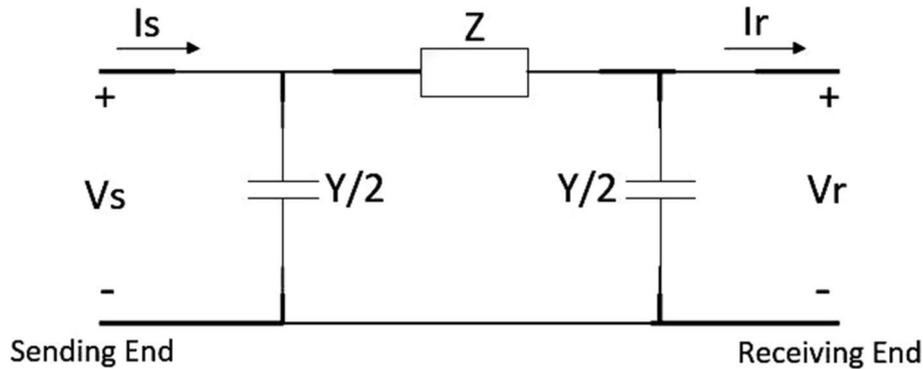


Fig. 5 Equivalent circuit of a medium transmission line – π model

$$I_s = Y \left(1 + \frac{ZY}{4} \right) V_r + \left(1 + \frac{ZY}{2} \right) I_r \tag{8}$$

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 + \frac{ZY}{2} & Z \\ Y \left(1 + \frac{ZY}{4} \right) & 1 + \frac{ZY}{2} \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix} \tag{9}$$

where Z and Y are the whole impedance and admittance respectively. The equivalent circuits of the medium transmission line are represented in Figs. 4 and 5 in which the impedance and admittance are structured as T and π models respectively.

Due to line length increase, line shunt capacitors are combined together and create larger admittances so the line capacitance is considered in medium and long transmission lines.

5 Case study microgrid

Single-Line diagram of the studied microgrid is displayed in Fig. 6. The analyzed micro grid comprises high penetration of renewable energy resources, a conventional power plant, Battery Energy Storage Systems (BESS), overhead transmission lines, consumption load demands and other network belongings as illustrated in Fig. 7. A 9 MW wind farm, including 6 DFIG, each with rated power of 1.5 MW provides the main load demands which works with Maximum Power Point Tracking (MPPT) [70, 71, 77]. Moreover, an asynchronous diesel unit with quick start characteristic supplies 1.8 MVA with power factor fixed to 0.93 for backup generation in order to generates the maximum value of 1.68 MW active power.

BESSs are utilized to make a balance between generation and load demands, compensate the intermittency of renewable energy resources, avoid power mismatch and works also as a backup in critical conditions [35, 78]. As

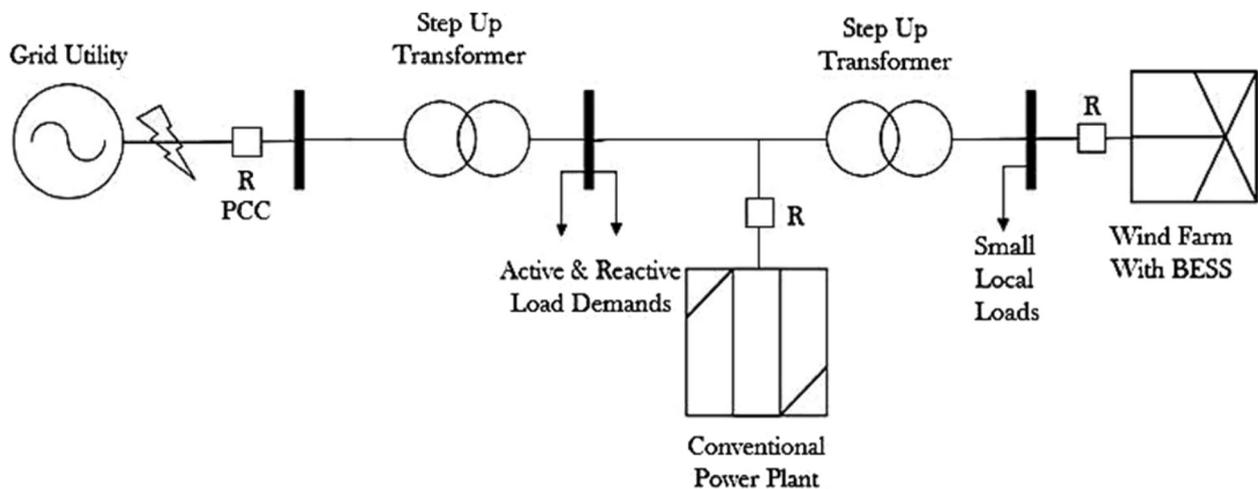


Fig. 6 Single-Line diagram of studied microgrid

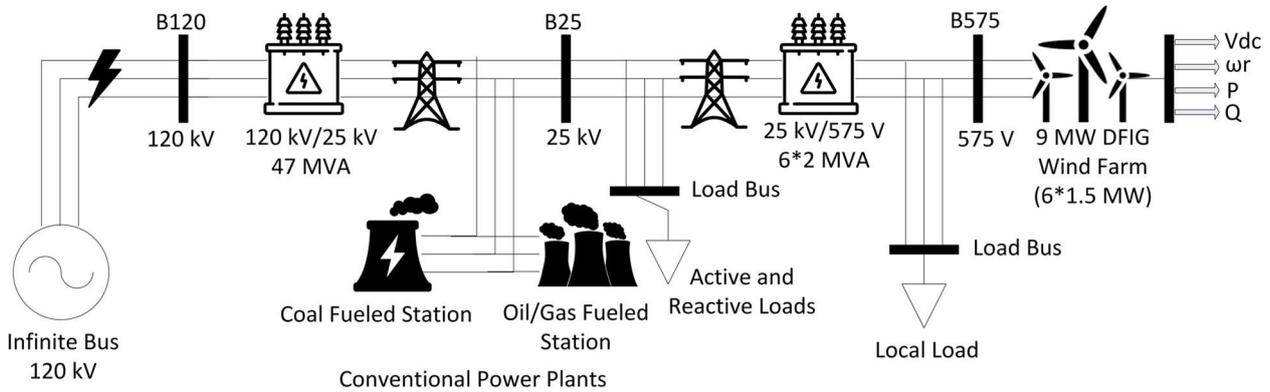


Fig. 7 Detailed configuration of the studied microgrid

wind power is intermittent, BESSs are connected to each wind turbine’s DC link to guarantee energy balancing. The Wind farm and conventional power plant are both equipped by protective devices to prevent probable outages and severe disturbances whereas the whole microgrid is equipped with circuit breakers to disconnect the microgrid from grid utility in case of severe faults. However, Preferably, to analyze the depth of the fault and examine the subsequent consequences, tripping methods and circuit breakers are considered off and have not been taken into account in this paper. The proposed system is modeled using MATLAB/Simulink toolbox to simulate the system operation and control.

The studied network consists of three buses and two distributed parameters transmission lines between them. The first one is connected to the wind farm, the second one is attached to the local load demands and the third one is connected to the PCC between microgrid and grid utility, through both transmission lines as a backup for DG units. Local load demands include 6 MW active and

2 Mvar reactive power, whereas the rest of the generated power is delivered to the main grid.

Two adjustable distributed transmission line were considered here to analyze the impacts of this factor on different parameters. Also two step-up transformers are embedded before and after transmission line to enhance the level of voltage in order to be matched with the main grid. In the middle of the transmission line, there are some household and industrial loads under the load bus. As the microgrids are subject to disconnection from the main grid in case of a fault [7, 15, 33, 41, 50, 79], an analysis must be carried out to specify the nature of the interconnected or islanded mode in microgrid.

6 Simulation results

The wind speed is considered in a constant value of 12 m/s until all the parameters can reach their reference value considering it is constantly changing indeed. As it shown in Fig. 8, in this wind speed, the wind turbine operates to extract the maximum power from the wind

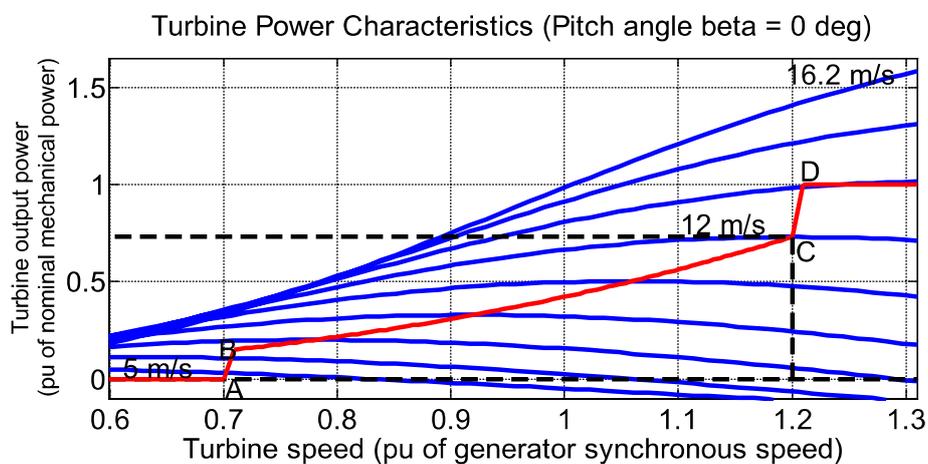


Fig. 8 Wind turbines power characteristic

energy and the MPPT methods are utilized. As the aiming of this study which is the fault and voltage drop as well as the power mismatch assessment of a microgrid over different distances, wind speed has a constant value in generator control zone to avoid pitch control or other tripping methods [16, 25, 27]. However, in some conditions, it might be essential to activate tripping methods to avoid any catastrophe for power system.

As the short circuit fault is one of the severe problems in power systems, it has been considered here to demonstrate more tangible results. Two scenarios have been investigated here, single-phase and three-phase short circuit faults to analyze the impact of interconnecting transmission line length on the microgrid parameters. In each scenario the length of the transmission line is enhanced until its impact on the results could be seen. Short and medium power transmission lines have been surveyed due to their potential capabilities. On the contrary, long transmission lines have not been studied here because they are not beneficial for this matter. Nonetheless, as in some areas there are plenty of renewable energy resources, long transmission in form of hydrogen pipelines has also been proposed [80–82].

The microgrid behavior is analyzed over a period of 60 s as a spot check. Contingent on the simulation results, in normal conditions and in the absence of external fault and disturbances, microgrid parameters are almost the same, so they can be overlooked. During the first 25 s, all the parameters reach their steady state then after 40 s, a 0.2 s short circuit fault is applied on the grid side bus to specify the continuity of the microgrid. If there is not any tripping in DG units and apparatus, fault impacts influence the microgrid parameters that rely on the depth of the fault as well as the length of the transmission line in this study. Based on the fault level, the common approach is to disconnect the microgrid from the main grid in PCC and trip the DG units to avoid any serious problem [7, 27, 34]. However, in this section circuit breakers and tripping equipment have been adjusted not to operate very soon and allow the system to work even under pressure.

6.1 First scenario: single-phase short circuit fault

According to simulation results, impacts of transmission line length on the wind farm side, grid side and conventional power plant were reviewed respectively. Several basic parameters connected to them were analyzed that shows the system stability over a few seconds. In normal condition, all the parameters are relatively the same and the slight difference is probably only due to transmission line losses. As the line length increases, some oscillations appear because the whole microgrid is driven to instability. In fact, the fault amplitude is shorter at longer distances. Nevertheless, the fault troubleshooting time is longer. In other words, These oscillations are not seen in shorter

lengths. However, a better performance can be seen in longer transmission lines in the moment of fault owing to farther distance between the fault location and apparatus. On the generator side, the active power is subjected to zero (see Fig. 9a) because of a short circuit fault as this power cannot be delivered to the main grid. In other words, the longer the transmission line, the more severe the fault is and vice versa. The wind farm capacity is almost negligible in comparison to the main grid so in case of fault, the entire generated power is lost. On the other hand, the reactive power is increased in order to keep the DC link voltage constant (see Fig. 9b). Considering the priority for power flow in wind turbines' converters is active power, after falling this parameter to zero, reactive power is permitted to pass through these power converters resulting a balance in voltage stability. In overall, conventional power plant and the main grid are responsible for reactive load demands while the wind farm is responsible for keeping DC link voltage fixed by generating reactive power in case of fault. In spite of preparations, however some deviations could be seen from set point in DC voltage. As mentioned earlier, the level of fluctuations has been risen in line with the line length increase.

The condition on the grid side is quite the opposite as after the fault, active and reactive powers both have different behaviors (see Fig. 10).

6.2 Second scenario: three-phase short circuit fault

A more severe fault i.e. a three phase short circuit fault applied to the surveyed microgrid and the simulation results were analyzed. Figure 11 illustrates the fault results on the generator side while Fig. 12 represents these results on the grid side. According to Fig. 11, active power decreases to zero in the moment of fault whereas the reactive power increases in order to keep the voltage fixed. More severe deviations could be seen for DC link voltage in three-phase fault in comparison with the single-phase. Results demonstrate an opposite behavior for grid side parameters as the active power is increased while the reactive power is decreased. The voltage drop is almost zero especially for shorter transmission lines as the impacts of fault are more tangible here (see Fig. 12c).

Two scenarios clearly represent the voltage excursion and reactive power increase as the backup solution for compensation. On the other hand, any power mismatch between generating units and load demands cause a change in DC link voltage because the power is generated but could not be delivered to the loads so as long as the reactive power reaches its appropriate value for compensation, DC link voltage meets some excursions. Considering simulation results, in case of fault the active power increases whereas the reactive power drops so as to compensate the power mismatch and

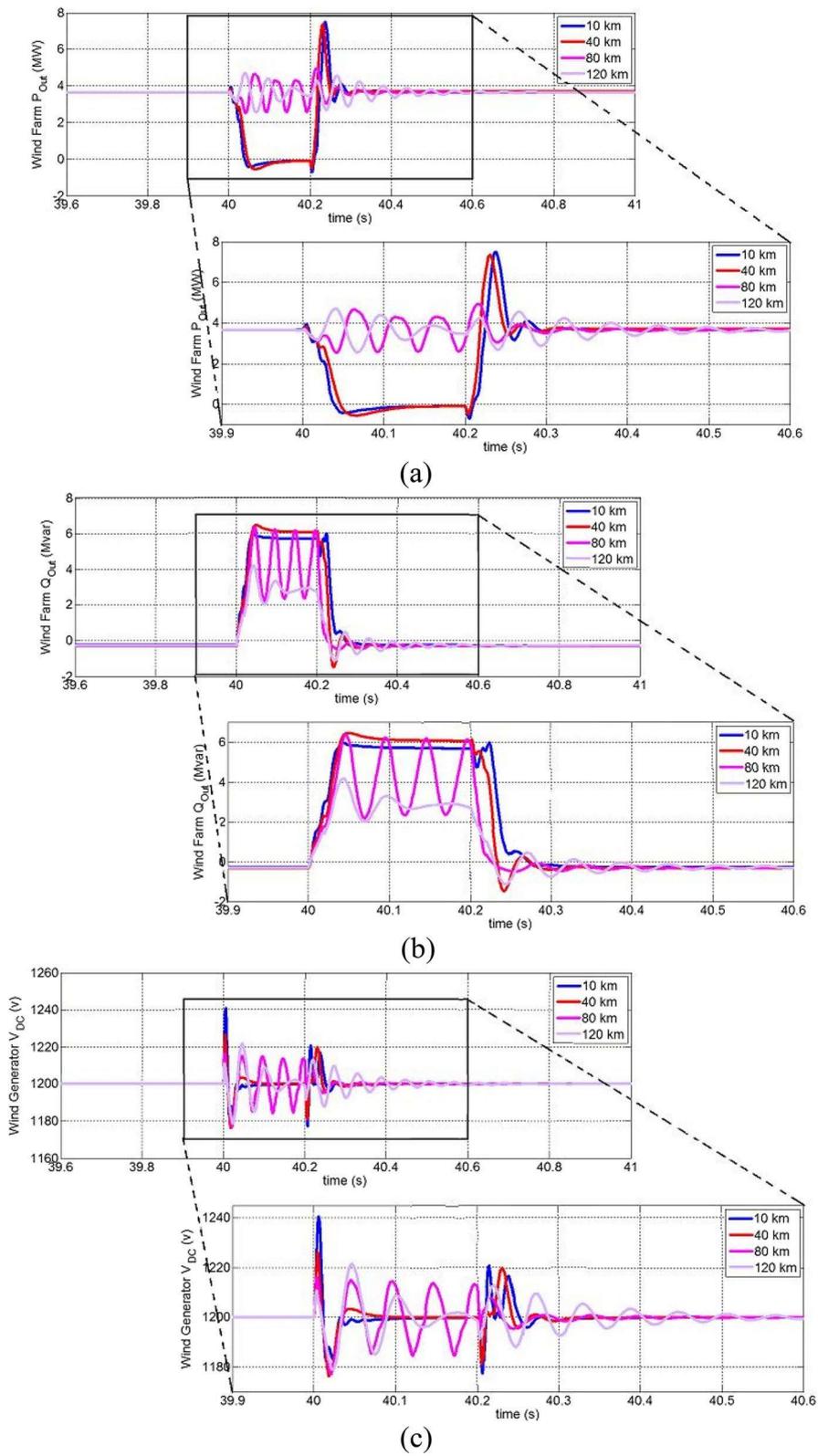


Fig. 9 Wind farm output parameters after single-phase short circuit fault. **a** Active power. **b** Reactive power. **c** DC link voltage

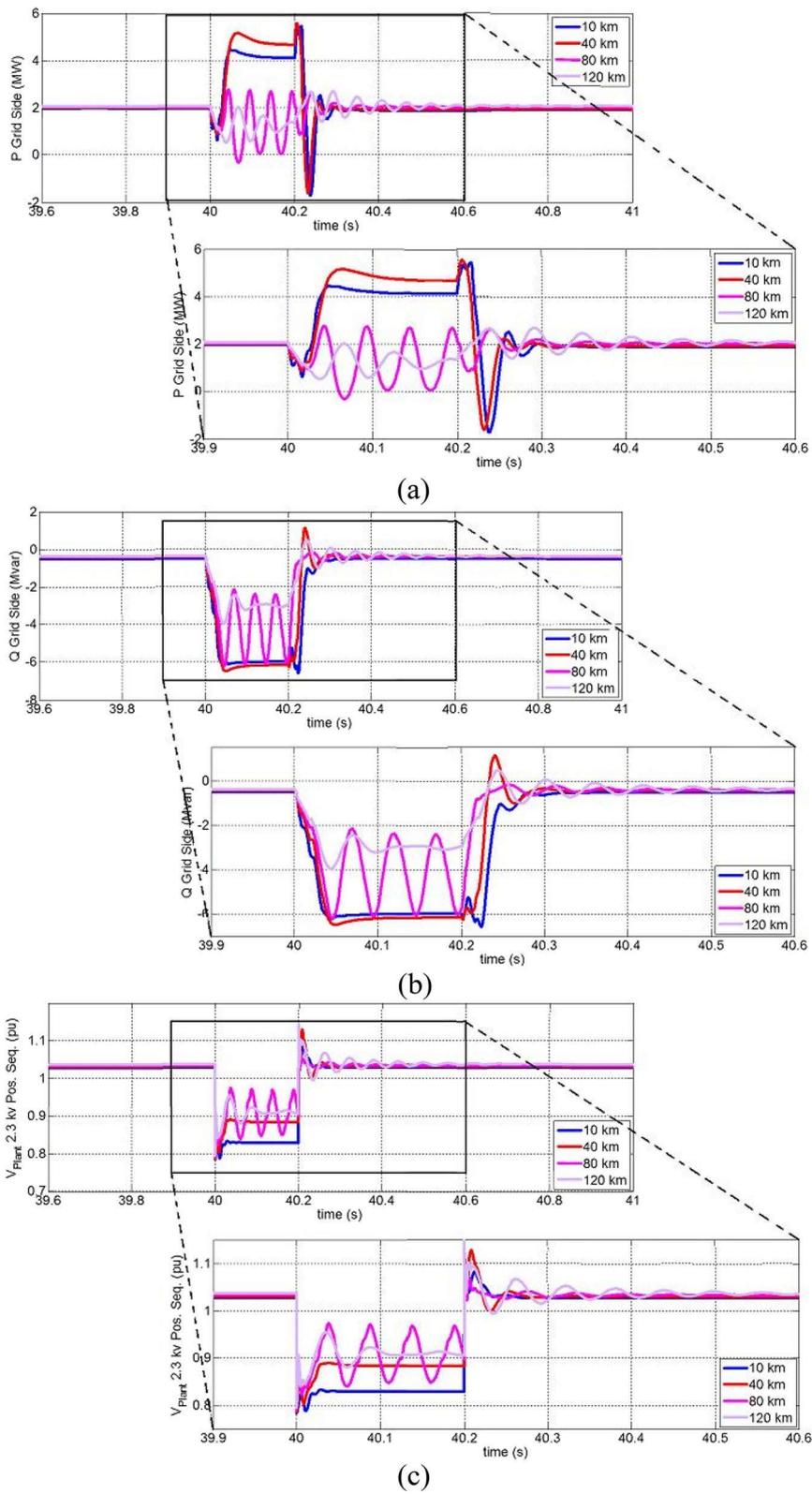


Fig. 10 25 kv Bus parameters after single-phase short circuit fault. **a** Active power. **b** Reactive power. **c** Conventional power plant output voltage

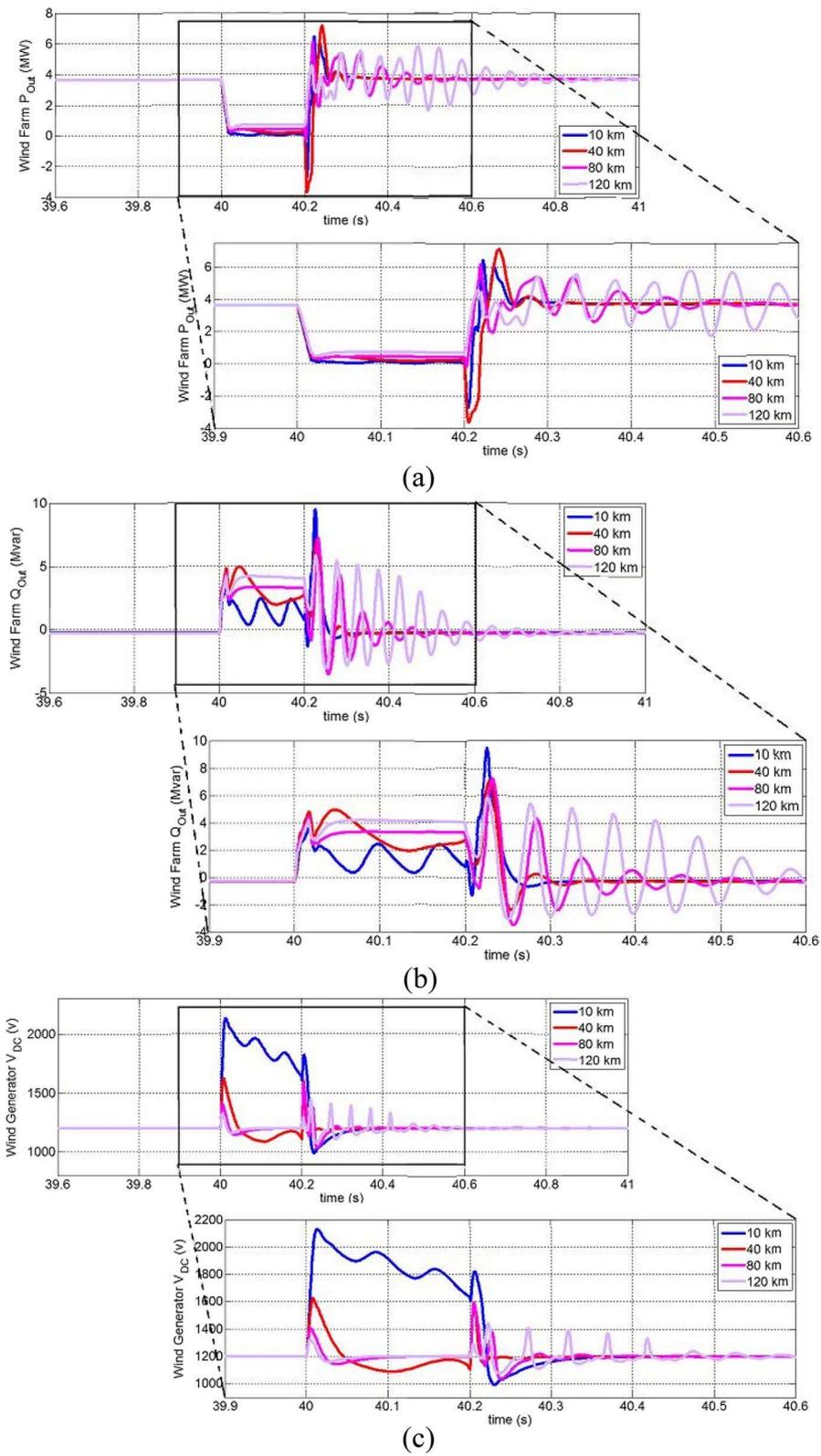


Fig. 11 Wind farm output parameters after three-phase short circuit fault. **a** Active power. **b** Reactive power. **c** DC link voltage

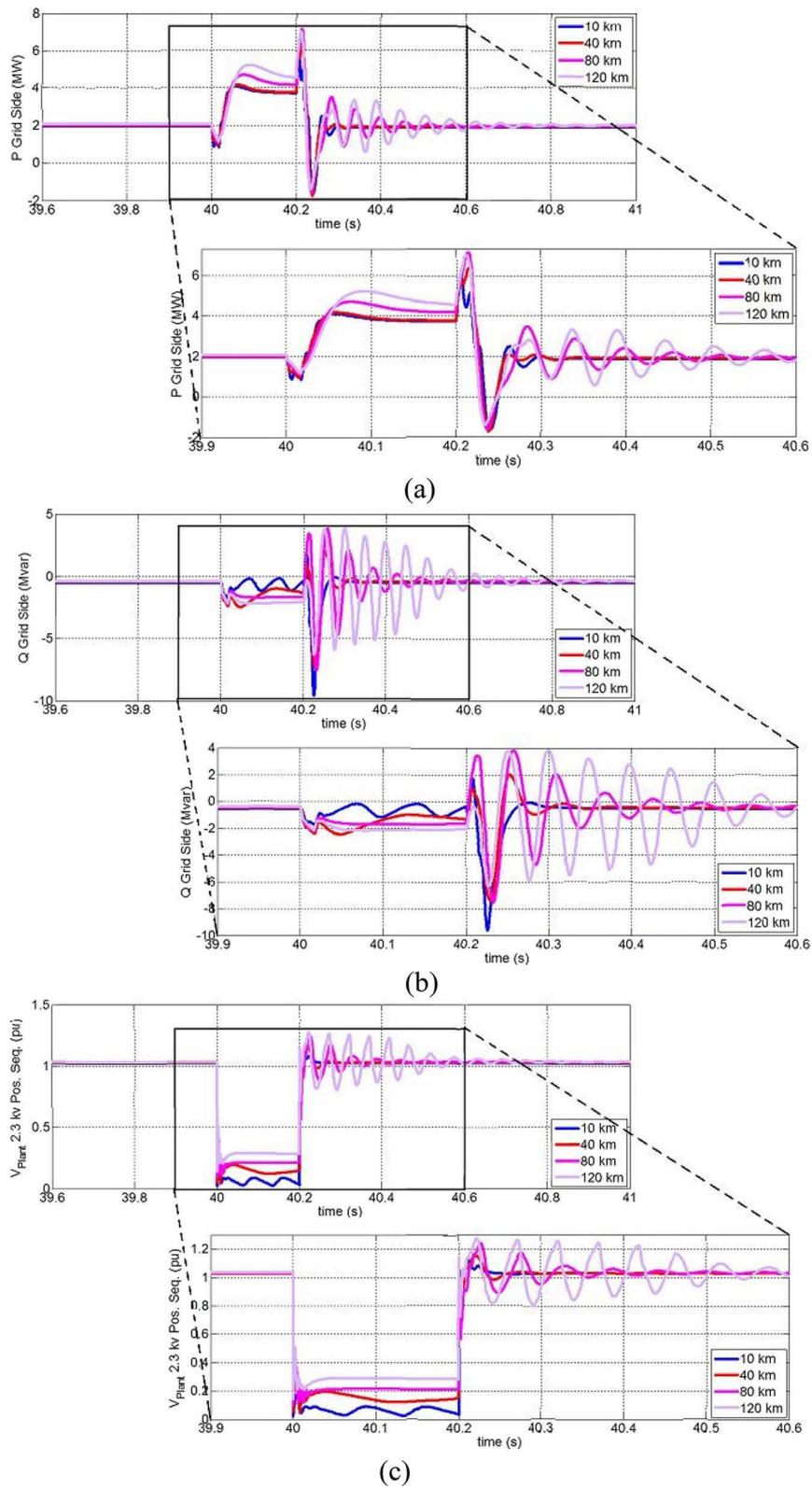


Fig. 12 25 kv Bus parameters after three-phase short circuit fault. **a** Active power. **b** Reactive power. **c** Conventional power plant output voltage

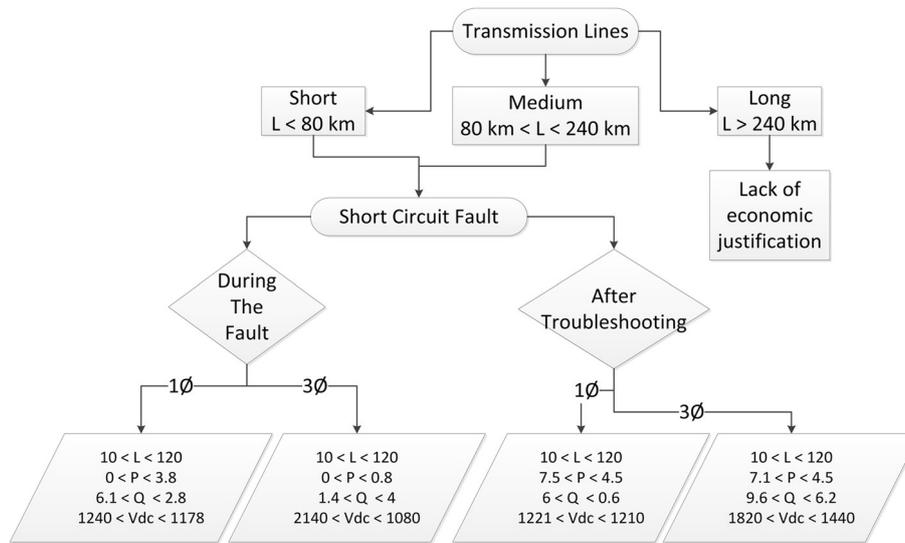


Fig. 13 A brief review of the studied system using a flowchart

make a balance between generation and consumption. Because the total complex power is considered constant [76], the opposite behavior of the grid side parameters is justified.

Figure 13 demonstrates a flowchart expressing a progressive trend for the essential parameters of the wind farm. By a comprehensive review on this flowchart, the impacts of transmission line length after a fault could be concluded. Based on results in the literature, it could be seen that as the length of transmission line becomes longer, the microgrid stability margin becomes less and may be taken to unstable zone especially for more severe failures. Here the adjustment of circuit breakers and tripping equipment is so important from the view point of protection strategies. What is noticeable is that although the longer transmission line has more fluctuations in few seconds after fault

troubleshooting, it has better stability margin at the time of fault. In both scenarios, while settling time is desired, other parameters such as overshoot, undershoot and initial fluctuations become more severe in 3-Phase scenario. Overall the results demonstrate that the shorter transmission line has better performance in steady state as the analyzed parameters reach their desired value very soon while the longer transmission line has more proper reaction at the time of fault as illustrated in Table 2.

While Table 1 represented a general overview of the studied microgrid, Table 2 demonstrated a detailed review of the wind generation as a representative of renewable energy resources. Short and medium transmission lines were thoroughly analyzed whereas the long transmission line was ignored because it does not have justifiable economy.

Table 1 Generalized overview of the results in both scenarios

	Short Transmission Line		Medium Transmission Line	
Fault Type	During the fault	After troubleshooting	During the fault	After troubleshooting
Single Phase	Rather severe	Reaching steady state soon – Short settling time Relatively high overshoot and undershoot	Fairly stable with fluctuations around the set point	Reaching steady state late – Relatively long settling time Negligible overshoot and undershoot
Three Phase	Severe	Reaching steady state soon – Short settling time Considerable overshoot and undershoot	Severe	Reaching steady state very late – Long settling time Little overshoot and undershoot

Table 2 Detailed overview of the main parameters in wind farm in both scenarios

Fault Mode	Transmission Line Length	During the fault				After troubleshooting			
		10	40	80	120	10	40	80	120
Single Phase	P (MW)	0	0	3.8	3.8	S.s ^a ≈3.8 O.s ^b ≈3.7 U.s ^c ≈0.6	S.s≈3.8 O.s≈3.5 U.s≈0.3	S.s≈3.8 O.s≈1.1 U.s≈0.8	S.s≈3.8 O.s≈0.4 U.s≈1
		Q (Mvar)	5.8	6	4.2	2.8	S.s≈-0.2 O.s≈0 U.s≈0	S.s≈-0.2 O.s≈1.4 U.s≈0.6	S.s≈-0.2 O.s≈0.2 U.s≈0.2
	V _{dc} (v)	S.s≈1200 O.s≈40 U.s≈17	S.s≈1200 O.s≈28 U.s≈22	S.s≈1200 O.s≈18 U.s≈22	S.s≈1200 O.s≈10 U.s≈21	S.s≈1200 O.s≈21 U.s≈22	S.s≈1200 O.s≈20 U.s≈19	S.s≈1200 O.s≈10 U.s≈8	S.s≈1200 O.s≈10 U.s≈8
Three Phase	P (MW)	0	0.2	0.5	0.8	S.s≈3.8 O.s≈2.4 U.s≈0.1	S.s≈3.8 O.s≈3.3 U.s≈0.2	S.s≈3.8 O.s≈2.2 U.s≈1.8	S.s≈3.8 O.s≈0.7 U.s≈1.3
		Q (Mvar)	1.4	2.6	3.2	4	S.s≈-0.2 O.s≈9.6 U.s≈0.4	S.s≈-0.2 O.s≈7.4 U.s≈2.2	S.s≈-0.2 O.s≈7.2 U.s≈3.3
	V _{dc} (v)	S.s≈1200 O.s≈940 U.s≈N.D ^d	S.s≈1200 O.s≈420 U.s≈100	S.s≈1200 O.s≈200 U.s≈50	S.s≈1200 O.s≈110 U.s≈30	S.s≈1200 O.s≈620 U.s≈210	S.s≈1200 O.s≈400 U.s≈50	S.s≈1200 O.s≈400 U.s≈160	S.s≈1200 O.s≈240 U.s≈120

^a S.s Steady state, ^b O.s Overshoot, ^c U.s Undershoot, ^d N.D Not definite

7 Conclusion

This paper analyzes the impact of fault current level on microgrid parameters including voltage, current, active and reactive power. Through this research, a microgrid with high penetration of wind power generation, BESS, and a conventional power plant has been studied and the influence of fault current level on its parameters have been tested and validated using MATLAB/Simulink Toolbox through multiple scenarios. Based on simulation results in both scenarios, as the transmission line length becomes longer, the stability margin and microgrid security gets involved with the sustainability issues and might be taken into instability. In normal condition, the only difference in simulation results is a slight difference in the parameters that is due to the transmission line losses. However, after a disturbance, Short circuit fault as one of the most challenging problems has been considered in this paper. While the short lines represent more severe deviations in the moment of fault, they show better performance after fault troubleshooting. The opposite results were illustrated for longer lines. Nonetheless, the utilization of renewable energy resources from very far distances to the main grid in interconnected mode may lead to risks and challenges for microgrid. Consequently, transmission line length and the fault location both depict a potential impact on microgrids. The obtained results show that the fault current level as well as the duration and type of fault are also effective factors that can be carried out in current studies. Using some ESSs with short

time constant of dynamic response like Super Capacitors (SC) and Superconducting Magnetic Energy Storages (SMES) are also promising technologies for future studies.

Authors' contributions

Arash Khoshkalam, the corresponding author supplied the material, did the research, wrote the main body of the paper, did simulations and drew figures. Dr Dalia Ali proofread the manuscript and mentioned some comments and corrections before submitting the paper.

Declarations

Competing interests

The authors declare that they have no competing interests.

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