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Impact Assessment of Extreme Weather Events on Power Distribution Networks: a UK Case Study on Reliability and Protection

Possible topics	
Topic	**#**
System analysis	3
The Future of Electricity – PAC challenges of today and tomorrow	1
Protection operation analysis and lessons learned	28
. Any other protection, automation, control and communications related topic	32

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1 INTRODUCTION

Pledges made to have 95% of the United Kingdom's electricity set to low carbon by 2030 and recent power outages caused by extreme weather events raise questions on how reliable low carbon energy systems are [1]. The increasing penetration of variable renewable energy sources increases the weather dependent nature of power systems and may affect the ability of the grid to withstand severe weather operating conditions. Such conditions may affect power system reliability and protection and must be investigated thoroughly in order to prevent weather-induced power outages [2].

The effects of weather on power systems may include changes in the availability of power supply (for the increasing penetration of variable renewable energy sources), changes in load demand profiles (influenced by weather conditions), and power outages caused by severe weather conditions [3]. As power systems are increasingly influenced by weather in different ways, it is necessary to reduce negative effects on power system reliability and protection to ensure a satisfactory level of quality of service.

To ensure that the most appropriate strategies are adopted for reducing the vulnerability of power systems to extreme weather, this paper proposes to examine the impacts of extreme weather events on the reliability and protection of power distribution networks. Thus, it considers the correlation between different types of extreme weather events, renewable generation outputs, load demand profiles, and power outages caused by physical damage of components and/or violation of operating constraints. Ultimately, the analysis is aimed at identifying which parts of the grid are more vulnerable to different extreme weather conditions and which events have the most severe effects on the entire grid.

2 METHODOLOGY

The impact assessment methodology is based on analysis of power flows, contingencies, and violation of operating constraints under extreme weather conditions. The next paragraphs provide an overview of power flow simulations and describe the impact of extreme weather events on operating conditions.

2.1. Power flows

This article takes advantage of OpenDSS to conduct power flow analysis over a range of scenarios representing extreme weather conditions. For more information about OpenDSS, see [4]. For each simulated scenario, power flow and voltage measurements are checked against operating limits given by grid codes.

Power flow calculations on OpenDSS make use of iterative solutions. In the default mode, the elements in the network model are treated as a current injection source and used to solve a nonlinear system admittance equation matrix given by:

$$I_{inj}(V) = Y_{sytem}\, V$$

where I_{inj} is the vector of phasor current injections, Y_{sytem} is the system admittance matrix and V the vector of nodal phasor voltage. This equation matrix is solved iteratively until convergence. The next step iteration is defined as a function of the current step as:

$$V_{n+1} = \left(Y_{sytem}\right)^{-1} I_{inj}(V_n)$$

To ensure convergence of the power flow equations, the maximum number of iterations defined by the user should be a sufficiently large number..

In addition, voltage magnitudes at the network buses and power flows through branch elements are limited by their lower and upper limits given by operating constraints:

$$V_{min} \leq V \leq V_{max}$$
$$S \leq S_{max}$$

2.2. Extreme weather events

In this analysis, the impact of extreme weather events on a power distribution network is represented by changes in operating conditions and by physical damage to network components. As a consequence, extreme weather conditions may cause changes in the current injections I_{inj} and/or in the system admittance Y_{sytem} which ultimately affect the bus voltage V and the power flows S.

To represent different extreme weather conditions, the analysis considers a power distribution network put into operation using different generation and load settings, including variations in power generation outputs and load demand profiles. Physical damage to network components is represented by disabling parts of the network, as in N-1, N-1-1, and N-k contingency analysis. In addition, the analysis investigates the impact of extreme weather events on a highly renewable-based power distribution network with different penetration levels of wind turbines and solar photovoltaic (PV) panels.

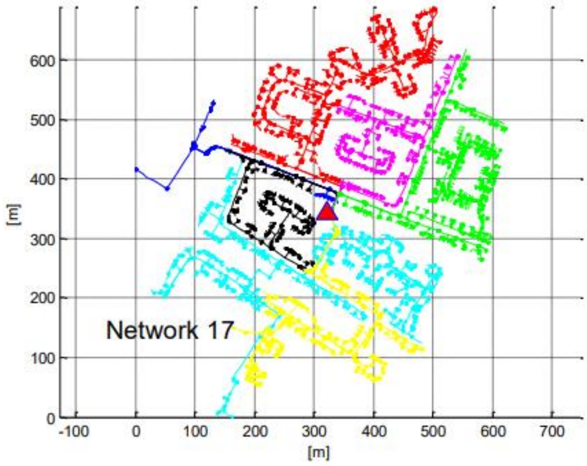


Figure 1: Diagram of a typical low voltage distribution network in the UK, showing the distribution substation (red triangle) and secondary feeders (coloured lines) [5]

Table 1: Number of lines and loads in each main feeder of the network.

	Feeder	Lines	Loads
NETWORK 17	**1**	376	118
	2	17	8
	3	115	78
	4	213	106
	5	314	159
	6	436	223
	7	219	121
	Total	**1690**	**883**

3 CASE STUDY

In this section, the impact of extreme weather conditions is evaluated on a typical low voltage (LV) power distribution grid in the United Kingdom, schematized in Figure 1, with information provided by [5], [6]. This LV network is an optimized version of one of the Electricity Northwest (ENWL) Low Voltage Network Solutions (LVNS) model number 17. The number of nodes has been reduced and the feeders with greater than 5% zero sequence unbalance have been removed, as in [6].

The network has 7 main feeders, as described in Table 1 and shown in Figure 1 in different colors. Its distribution substation transformer is a 11 kV to 0.416 kV transformer rated at 800 kVA and 0.01+ j0.05 per unit (p.u.) impedance. In normal operation, it adequately supplies power to all customers within the lower and upper voltage limits, typically set between 0.94 p.u. and 1.10 p.u. in the UK. The number of lines and loads in the model are listed in Table 1, whereas the load profiles for all the loads in the network are obtained from [5].

To demonstrate the effect of severe weather events on different renewable energy technologies, wind turbines and solar PV panels are introduced in the network in separate analyses. The profile models for the generator are obtained from Renewables Ninja, which has real data of historical wind power outputs, solar PV power outputs, and weather conditions [7]. The wind generator model is based on an existing community wind farm that has been in operation since March 2019 [8], with its generating capacity set to 2 MW. The distribution of PV generator power sizes is dependent on the actual data of domestic installations in the UK [9], with a 4 kW model being the highest and a 1 kW model being the lowest. Table 2 provides more information on the specifications of the renewable energy sources in use.

Table 2: Low Carbon Energy Resources Specifications

Element	**Power Rating (kW)**	**Total Number**	**Prototype**	**Point of connection**	**Specifications**
PV Generators	1 to 4	Up to 883	None	Loads	Tilt: 35° Azimuth: 180° Installed capacity: 1% 1kW, 8% 1.5kW, 13% 2kW, 14% 2.5kW, 14% 3kW, 12% 3.5kW, 37% 4kW
Wind Generators	200	Up to 4	Vestas V90 2000	Substation	Height: 125m for each

The grid performance is evaluated under different severe weather conditions, selected from the UK Met Office's past weather event data of the year 2019 [10]. In particular, two different extreme weather events have been selected for analysis: (1) the heat wave of July, in which the highest temperatures were observed on the 25th of July 2019 in Cambridge botanical gardens, and (2) the strong winds of November, in which high gust speeds were measured in the Needles old battery on the 2nd of November 2019.

Notably, the situations that will be investigated with each renewable energy technology (i.e., wind turbines and solar PV panels in separate) are:

1) **Scenario 1A:** Heat waves, characterized by high solar energy production and slightly heavy load demand due to air conditioners.
2) **Scenario 1B:** Heat waves, characterized by out-of-service lines and poles, due to fires, and slightly heavy load demand due to air conditioners.
3) **Scenario 2A:** Strong winds, characterized by high wind energy production and heavy load demand.
4) **Scenario 2B:** Strong winds, characterized by out-of-service lines and poles, pulled down, and heavy load demand, due to electric heating.

Table 3: Cases of penetration of PV panels in the grid

Case	***Penetration Percentage***	***Number of Panels***
A	0%	-
B	20%	177
C	40%	353
D	60%	529
E	80%	706
F	100%	883

3.1. Scenario 1A and 2A - PV and Wind

Scenarios 1A and 2A consider both PV and wind generators with an increase in penetration. In scenario 1A, light load demands are modeled by a 0-15% increase in the rated active power load (1 kW) to represent air conditioners. In scenario 2A, heavy load demands are modeled by a 0-25% increase in the rated active power load (1 kW) to represent electric heating.

As shown in Table 3, variations in the percentage of PV panels connected to the grid are introduced to check the effect of different amounts of solar power during the summer heat wave. Case A and case F represent two extreme cases: the former has no presence of PV panels and the latter represents an example of when every customer on the grid has a PV panel. The PV panels are allocated randomly in the model in terms of location and peak power. The PV output profiles for each panel are obtained from [7] and adjusted according to the specifications provided in Table 2.

The wind turbines also use the specification provided in Table 2 and the generation output profiles obtained from [7]. Variations in the number of wind turbines connected to the grid are introduced to check the effect of different amounts of wind power during the summer heat wave, as defined in Table 4. In this case, the wind farm is connected to the substation and power is transferred through the main distribution feeders to the customer loads.

Table 4: Cases of penetration of wind turbines in the grid

Case	*Penetration Percentage*	*Number of Wind Turbines*
A	0%	-
B	25%	1
C	50%	2
D	75%	3
E	100%	4

3.2. Scenario 1B and 2B - PV and Wind

Scenarios 1B and 2B consider out-of-service lines and poles due physical damage caused by severe weather events. Notably, scenario 1B considers electric fires in residential premises during a heat wave, whereas scenario 2B considers overhead lines and poles pulled down by strong winds.

These scenarios use contingency analysis to check for power flow and voltage constraints within the network model in different situations. In scenario 1B, N-1 corresponds to a single house on fire, N-1-1 corresponds to two houses on fire, and N-k corresponds to many houses on fire. In scenario 2B, N-1 corresponds to a single line segment down, N-1-1 corresponds to two-line segments down, and N-k corresponds to a situation in which many line segments are down and leave a network area out of service. These scenarios are illustrated in Figure 2, where the pink coated areas correspond to the inoperative sections of the circuit. For more information, Table 5 and Table 6 show the number of isolated components.

Table 5: Contingency scenarios and the type and number of isolated components for PV model

TYPE	ISOLATED COMPONENTS	NUMBER
N-1	Lines	1
	Loads & Generators	1 each
N-1-1	Lines	2
	Loads & Generators	2 each
N-k	Lines	128
	Loads & Generators	68 each

Table 6: Contingency scenarios and the type and number of isolated components for wind model

TYPE	ISOLATED COMPONENTS	NUMBER
N-1	Lines	1
	Loads	1
N-1-1	Lines	2
	Loads	2
N-k	Lines	128
	Loads	68

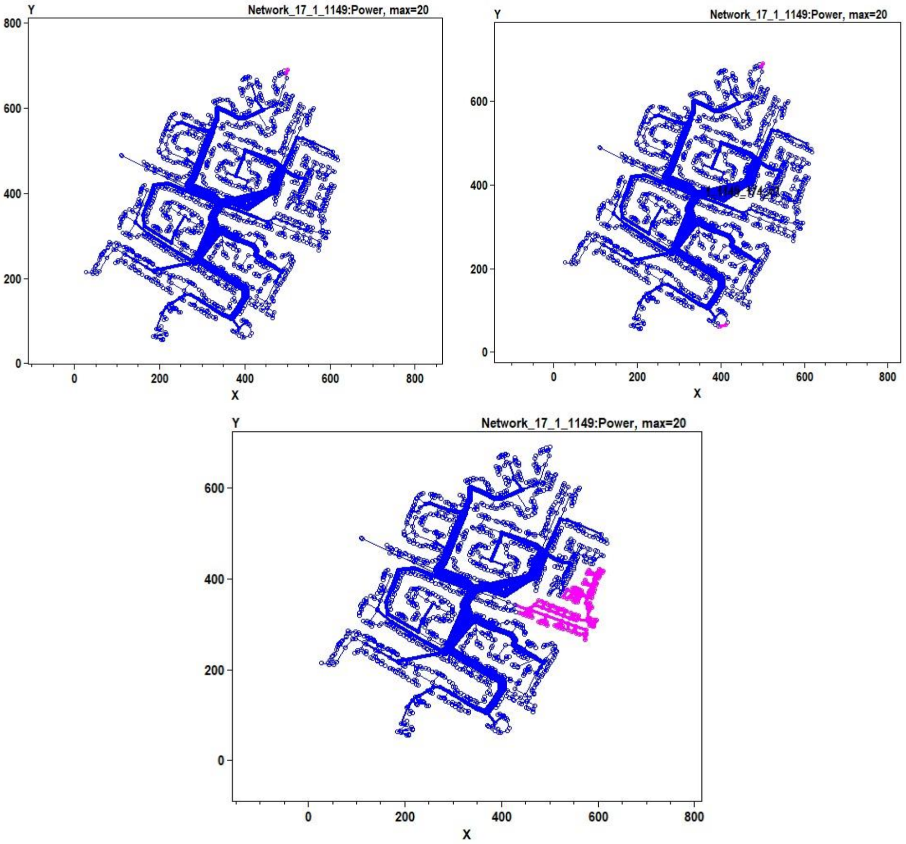


Figure 2: Contingency scenarios for the network model (isolated components in pink): N-1 (top left), N-1-1 (top right), N-k (bottom)

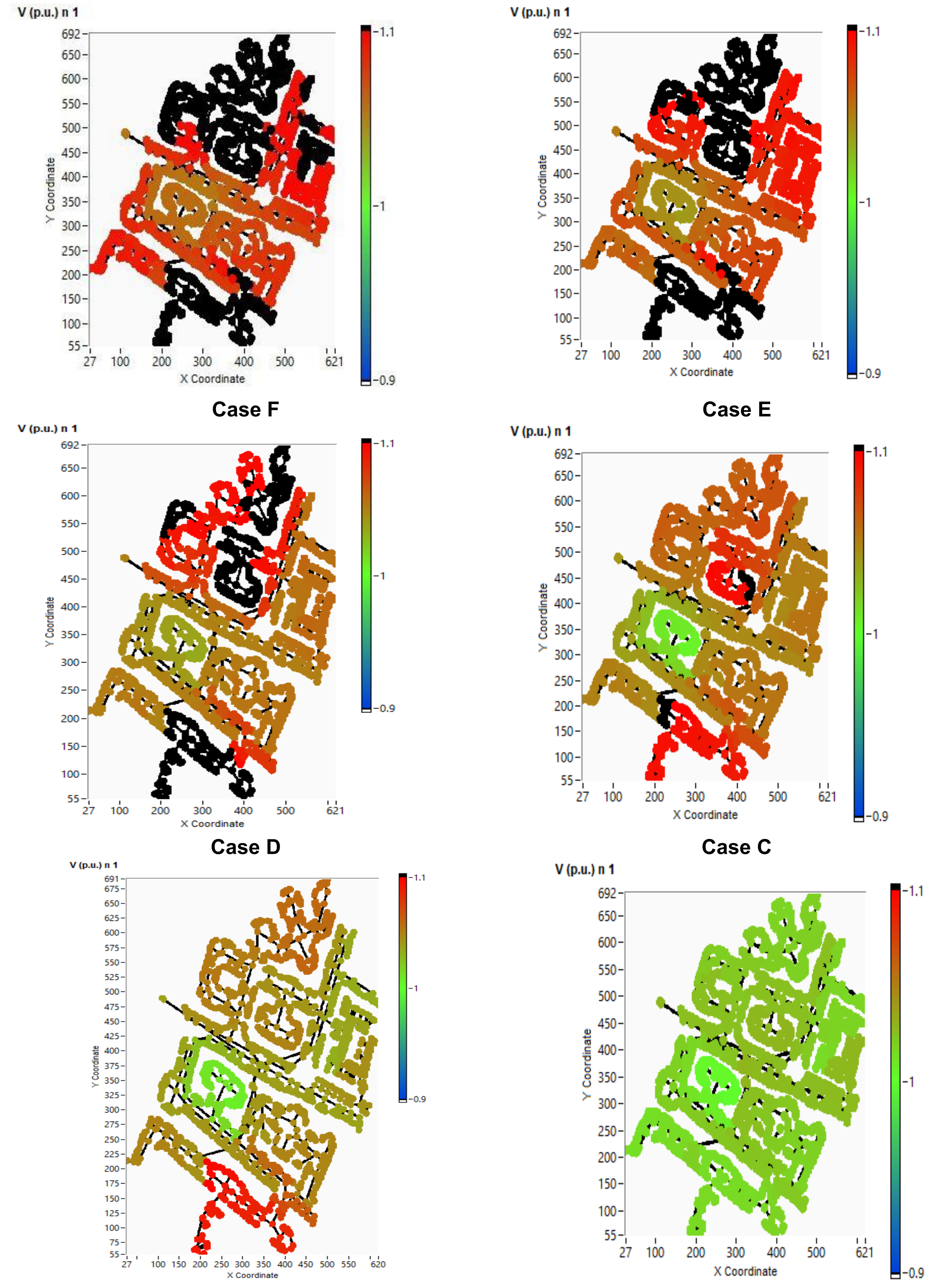
4 RESULTS AND DISCUSSIONS

4.1. Scenario 1A

4.1.1. Scenario 1A - PV

Overall, the results obtained in scenario 1A show that, during a heat wave, an increase in the penetration level of solar PV panels in the grid leads to an increase in the overvoltage. In case F, overvoltage (i.e., voltage magnitude above 1.1 p.u.) occurs in 54% of the network buses. Figure 3 displays the network voltage profiles from cases A to F. It can be noticed that all cases except for A and B are outside the acceptable per-unit voltage limits (0.94 p.u to 1.1 p.u). In particular, the regions with installed solar PV capacity greater than 2 kW tend to experience higher voltage magnitudes. In case F, the maximum voltage magnitude peaks at 1.21 p.u..

In addition, overloading is verified in cases D to F due to an increase in the penetration level of solar PV panels. Notably, the transformer experiences an overload in cases D, E, and F, while 10 out of 1690 branches are overloaded in case E and 18 out of 1690 branches are overloaded in case F. This is explained by the fact that the total power generated by the PV panels is up to four times the distribution substation transformer.



Case F

Case E

Case D

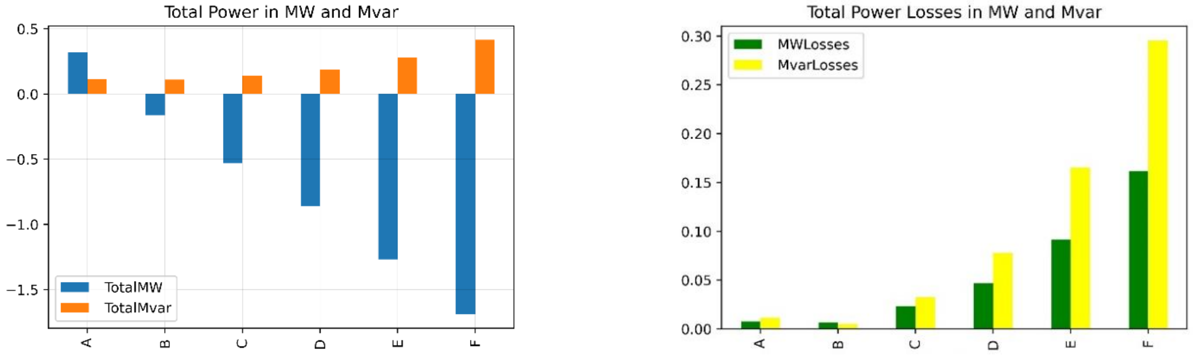
Case C

Case B

Case A

Figure 3: Network voltage profile in p.u for different cases of PV penetration.

It is noteworthy that the net active power becomes increasingly negative as the solar PV power output increases, as shown in Figure 4(a). The PV panels supply more power into the system, which explain the transformer and line overloading in cases D to F. In Figure 4(b) it can be noticed that the total power losses are proportional to the net power, decreasing slightly when there are relatively few solar PV panels in the network (e.g., case B in comparison with case A and case C). The losses attributed to PV panels become more predominant in the network in cases B to F.

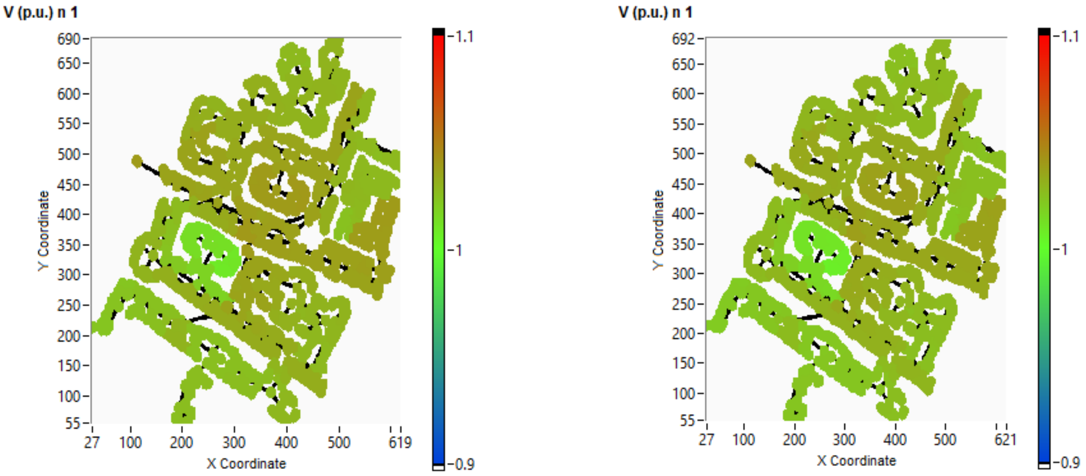


(a) **(b)**

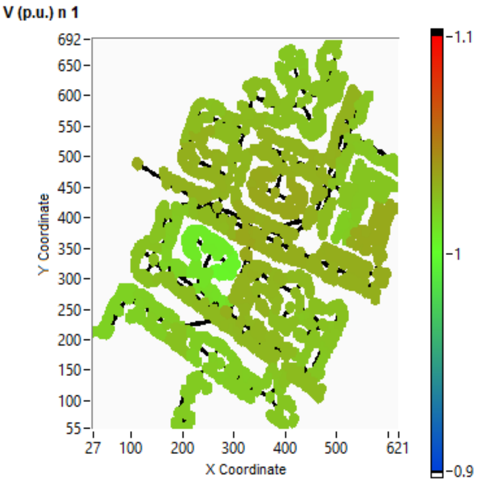
*Figure **4**: Net power and power losses in the network for each case of PV penetration.*

4.1.2. Scenario 1A - Wind

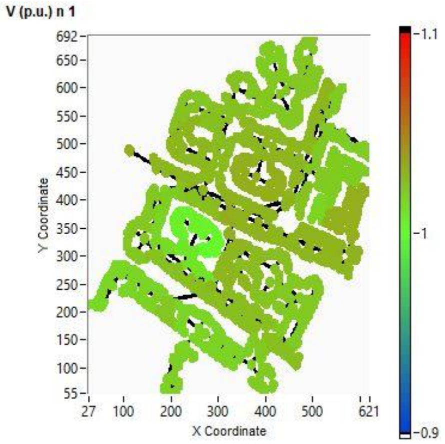
In this analysis, the results obtained in scenario 1A show that, during a heat wave, an increase in the penetration level of wind turbines in the grid does not lead to any undervoltage or overvoltage event. The voltage profiles shown in Figure 5 have an even distribution in almost all cases. This is explained by the low wind power production during the summer heat wave, which is enough to supply approximately the same power to network as with the distribution substation transformer. In addition, the increase in load demand due to fans and air conditioners is not high enough to produce undervoltage. Therefore, a comparison between the results obtained in scenario 1A with solar PV and wind turbines suggests that the network operation is more reliable with wind turbines than with solar PV panels added to the grid.



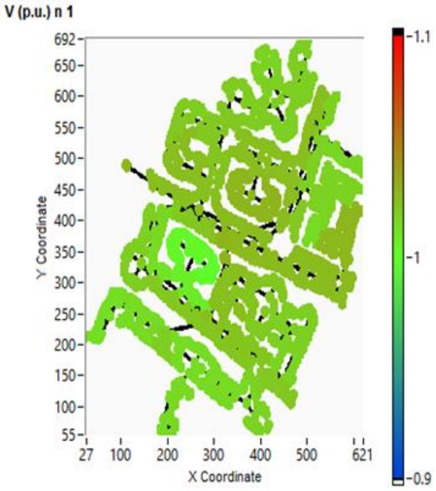
Case E **Case D**



Case C



Case B



Case A

Figure 5: Network voltage profile in p.u for different cases of wind penetration.

The net power and total power losses obtained in cases A to E are shown in Figure 6. The system shows a significant decrease in the net power and power losses in comparison with the same scenario using solar PV panels. Conversely, the introduction of wind turbines changes the symmetry between net power and power losses, as it increases the reactive power in the network while decreasing the active power and not changing significantly the power losses.

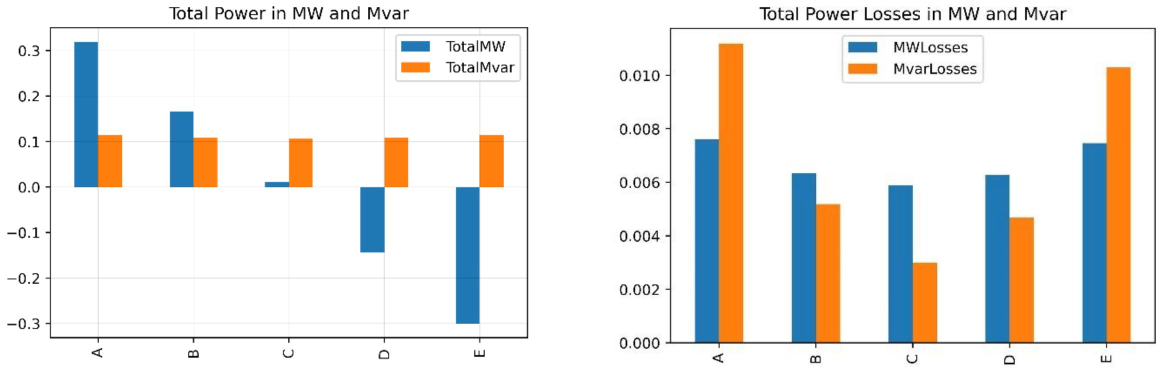


Figure 6: Net power and power losses in the network for each case of wind penetration.

4.2. Scenario 1B

4.2.1 Scenario 1B - PV

The results in this section show the effects of fire outbreaks on the network operation with the presence of solar PV panels. Figure 7 compares the voltage profiles when a single load is isolated (N-1) and when a subnetwork is isolated (N-k). Notably, 15 out of the 1562 lines in Case C are overloaded in the N-k analysis, whereas the N-1 analysis results in the same number of overloads as in scenario 1A with solar PV panels. In a situation of fire outbreaks, network overloading can further increase the risk of electric fires, if not properly managed.

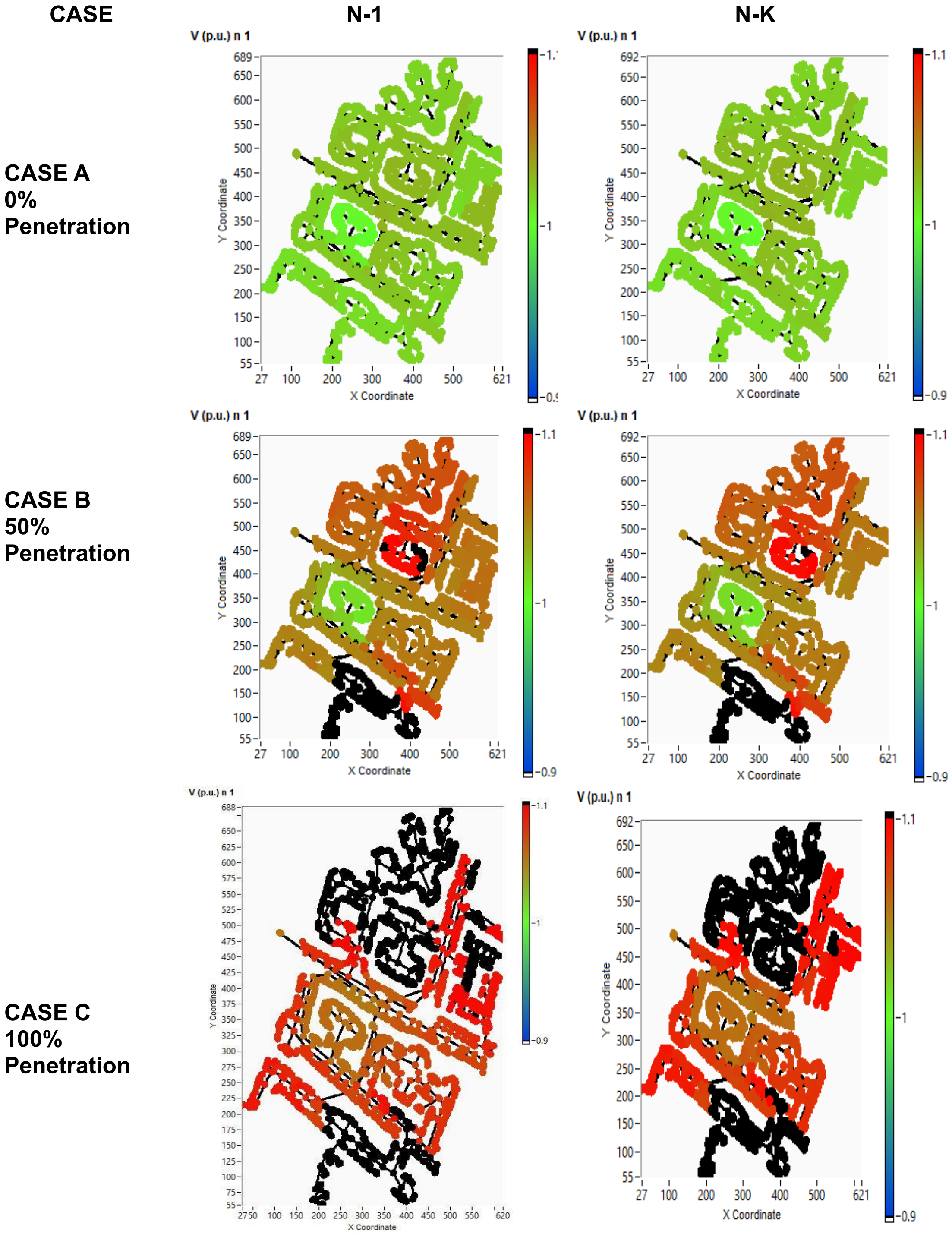


Figure 7: Network voltage profile in p.u for different contingency scenarios and PV penetration.

The total power and power losses plotted in Figure 8 show similar properties in all cases for all contingency analyses stated in Table 6. There is a slight decrease in the losses in the N-k analyses due to the reduction of components in the network model. In the N-k analyses, the net power becomes less negative when the PV penetration is greater than zero because the number of PV panels is reduced more significantly than the load demand.

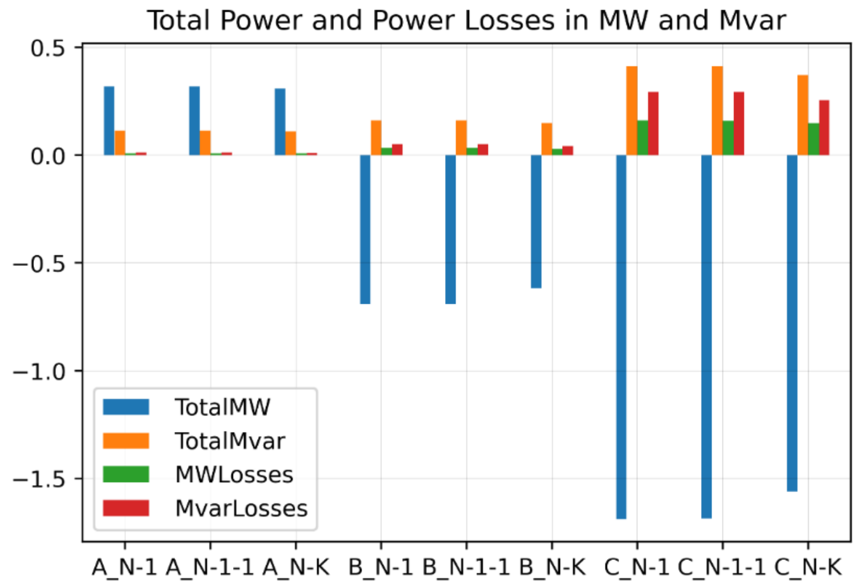
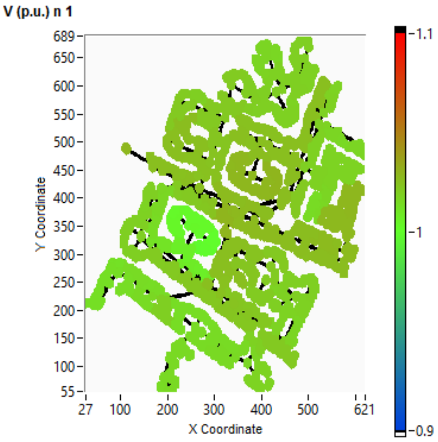
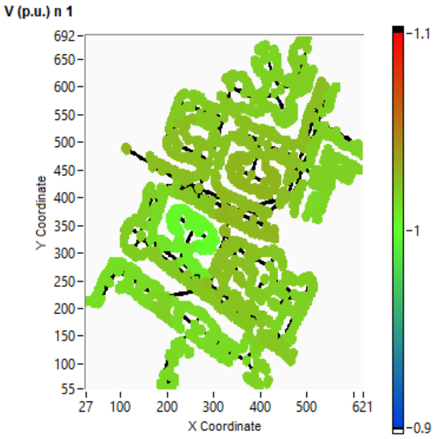


Figure 8: Net power and power losses in the network (in MW and MVAr) for different contingency scenarios and PV penetration.

4.2.2 Scenario 1B - Wind

During the heat wave, wind generation output profiles are relatively low. As the installed wind power capacity is enough to supply approximately the same power to network as the distribution substation transformer, the effect will not lead to any constraint violations in the network model. There is an increase in the per-unit voltage magnitudes on components of the circuit as the penetration increases, as illustrated in Figure 9.

CASE	**N-1**	**N-K**
CASE A **0%** **Penetration**		
CASE B		

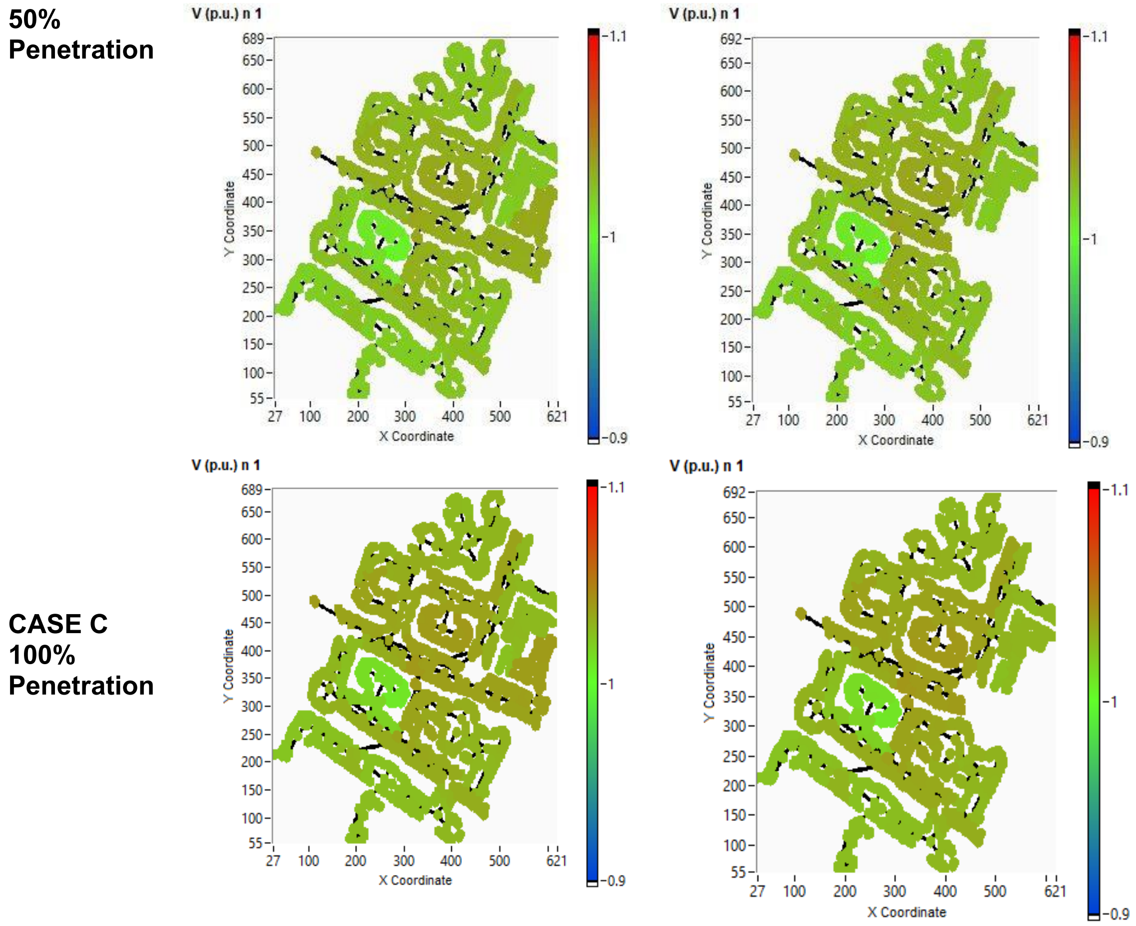


Figure 9: Network voltage profile in p.u. for different contingency scenarios and wind penetration.

Figure 9 shows the voltage profiles of the network for different contingencies and penetration levels of wind energy. It can be noticed that the voltage magnitudes increase slightly within acceptable limits as the wind energy penetration increases and that the isolated components do not negatively affect operation of the remaining functioning part of the grid.

Figure 10 shows the net power and power losses. As in the scenario with PV panels, they show similar properties for all cases and contingency analyses. There is a slight decrease in the net power in the N-k analyses due to the reduction of loads in the network model. As a result, the net power becomes more negative in all cases.

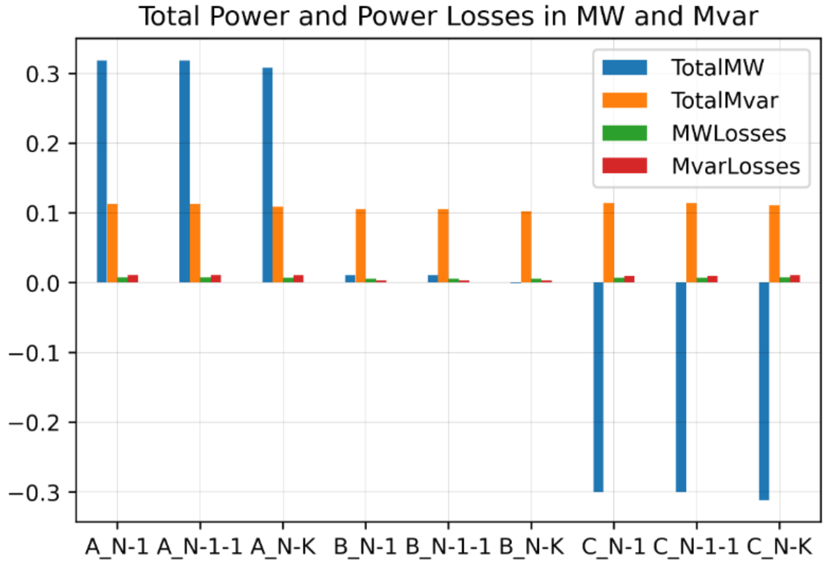


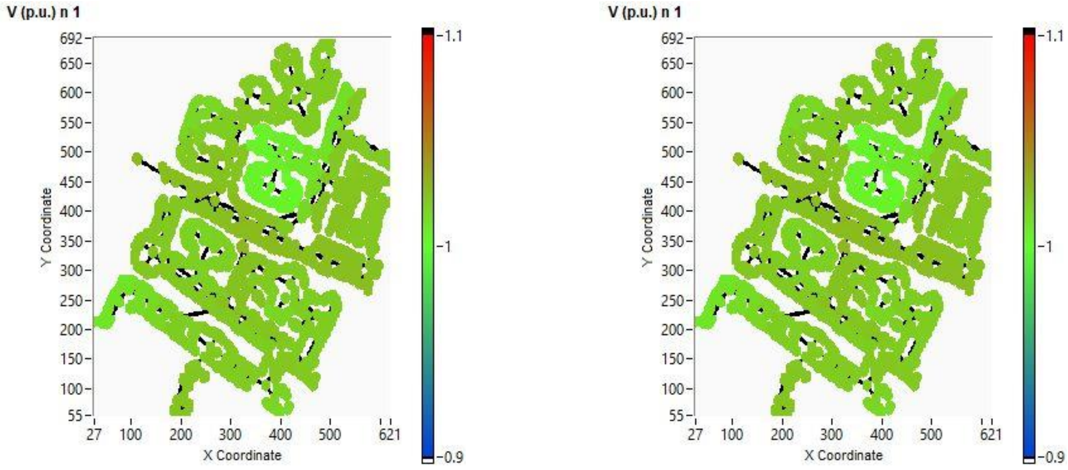
Figure 10: Net power and power losses in the network (in MW and MVAr) for different contingency scenarios and wind penetration.

4.3. Scenario 2A

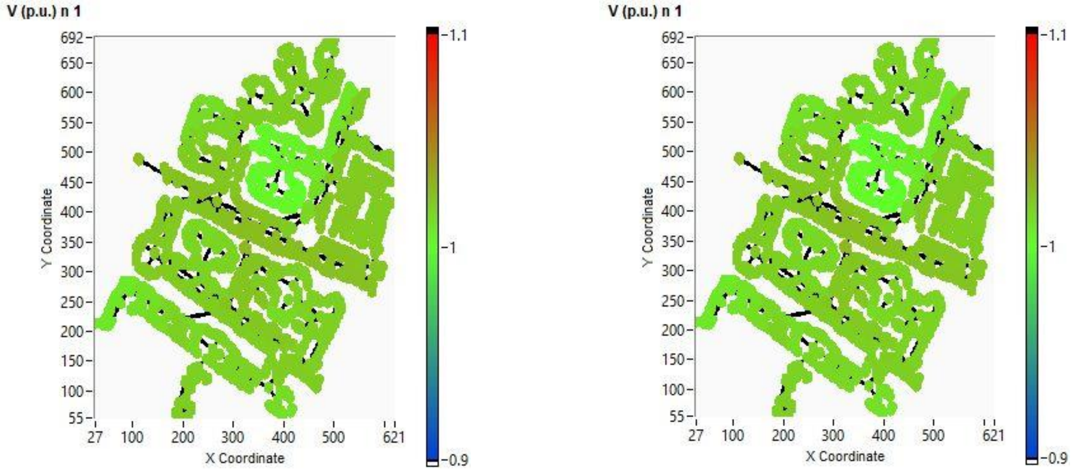
4.3.1 Scenario 2A - PV

In scenario 2A, there is a significant reduction in solar energy production, caused by cloudy weather and less sunlight hour, and increase in load demand due to uptake of electric heating. Nevertheless, the results show no overloading or undervoltage.

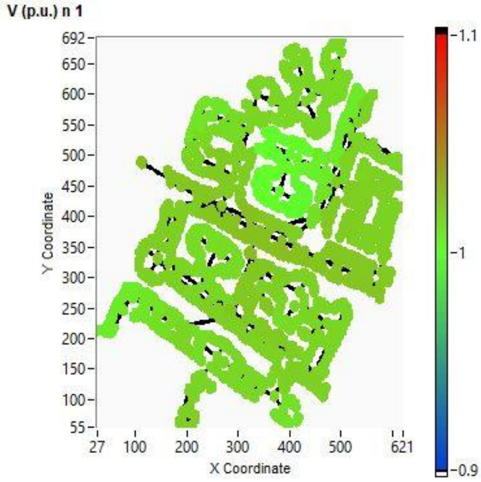
The per-unit voltage profiles shown in Figure 11 do not indicate any significant changes in operating conditions over all tested cases of PV penetration. The voltage magnitudes are in the same range (colour scale) at each grid location, regardless of the PV penetration level.



Case F **Case E**



Case D **Case C**



Case B **Case A**

Figure 11: Network voltage profile in p.u for different cases of PV penetration.

In Figure 12, the net power remains positive in all tested cases of PV penetration, which indicates that the PV panels supply enough power to meet part of the demand without supplying power into the grid. Unlike Scenario 1A, the net power in scenario 2A is not bidirectional (see Figure 4), as the solar energy output is not enough to achieve negative net power. In Figure 12, it can also be noticed that the net power and power losses are slightly reduced as the PV penetration increases.

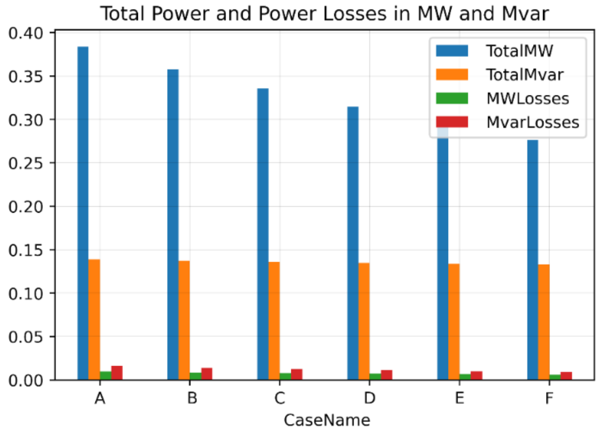
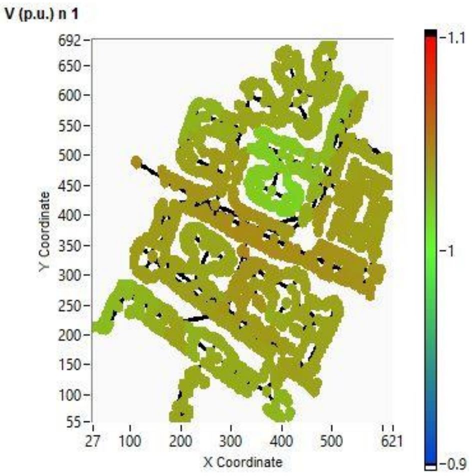


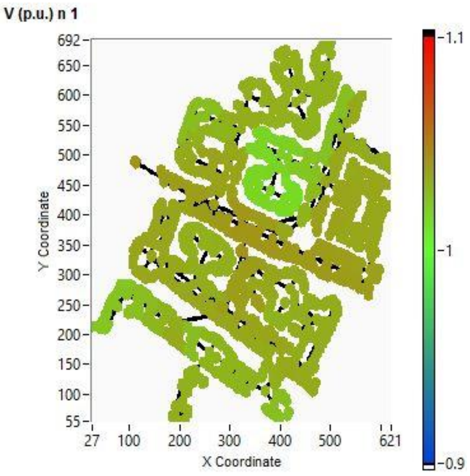
Figure 12: Net power and power losses in the network for each case of PV penetration.

4.3.2 Scenario 2A – Wind

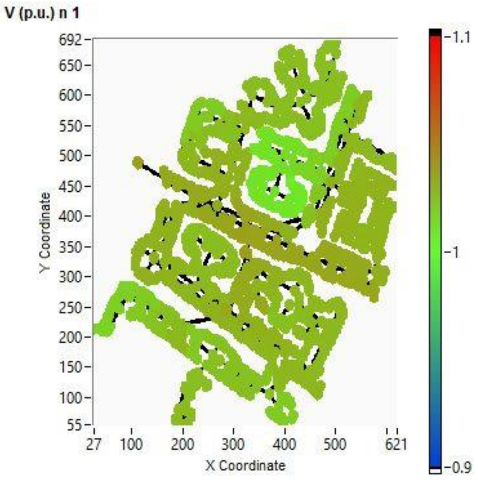
In this scenario, the strong winds lead to a considerable increase in the wind energy production in comparison with the heat wave in scenario 1A. The network voltage profile change with different cases of wind penetration, as shown in Figure 13. Although there are no occurrences of overvoltage and overloading, there is a significant increase in the net power and power losses in the model, as can be seen in Figure 13. Note that the net power becomes negative in cases C to E and that the power losses in case E are significantly higher than those obtained in case A.



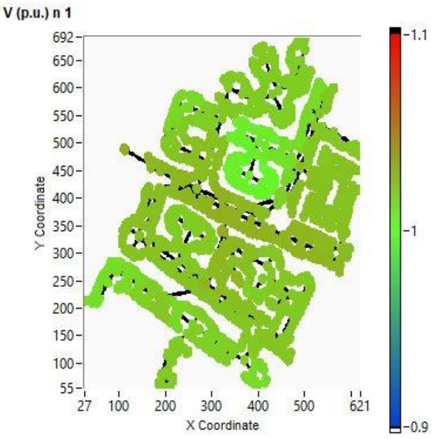
Case E



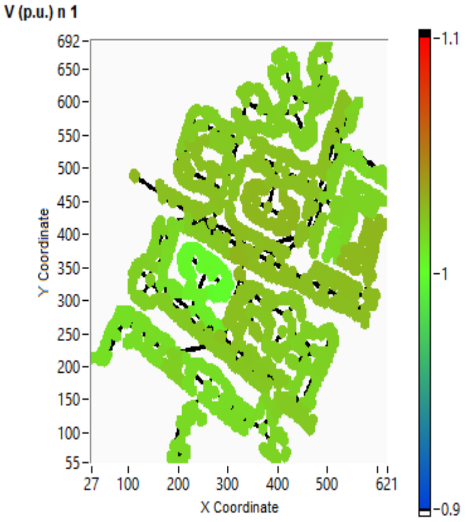
Case D



Case C



Case B



CASE A

Figure 13: Network voltage profile in p.u for different cases of wind penetration.

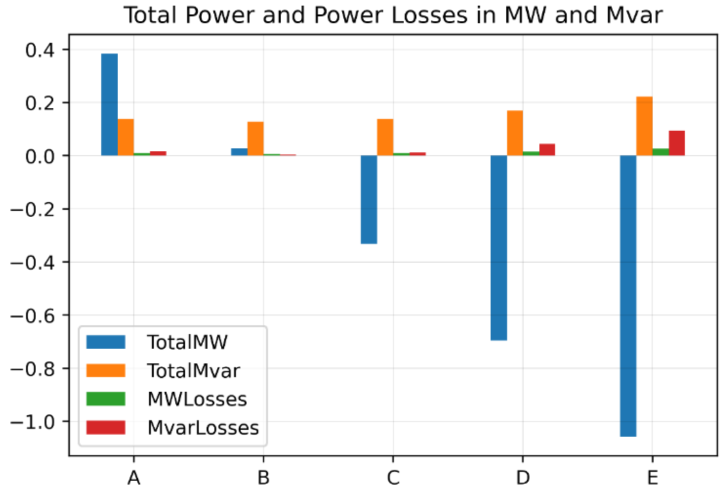


Figure 14: Net power and power losses in the network for each case of wind penetration.

Comparing minimum and maximum per-unit voltage of Scenarios 1A and 2A

The lower and upper limits of voltage magnitudes are set to 0.94 p.u. and 1.10 p.u. in the UK. In scenario 1A (summer heat wave), the network operation exceeds the maximum voltage constraints when solar PV panels are installed, with a mean per-unit voltage of 1.125, considering all tested cases. All the other scenarios lie between the voltage constraints, as shown in Figure 15.

In Figure 15, it can also be noticed that the network models with wind turbines have lower values of p.u voltage magnitudes in comparison to those with PV panels. This is explained by the fact that solar PV panels were connected to load buses, whereas the wind turbines were connected to the substation bus. Note that the winter scenarios correspond to the strong wind condition, which has lower per-unit voltage magnitudes in comparison to the summer heat wave scenarios for their operating conditions previously described.

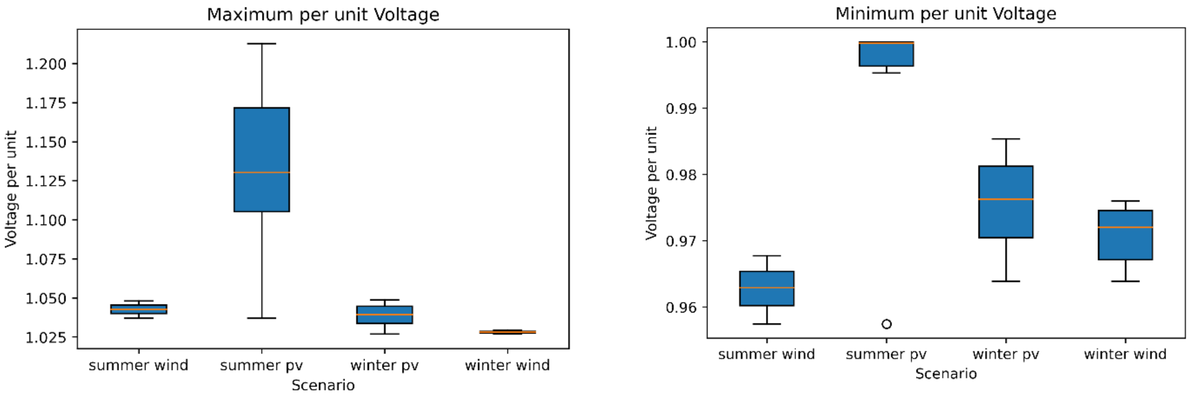


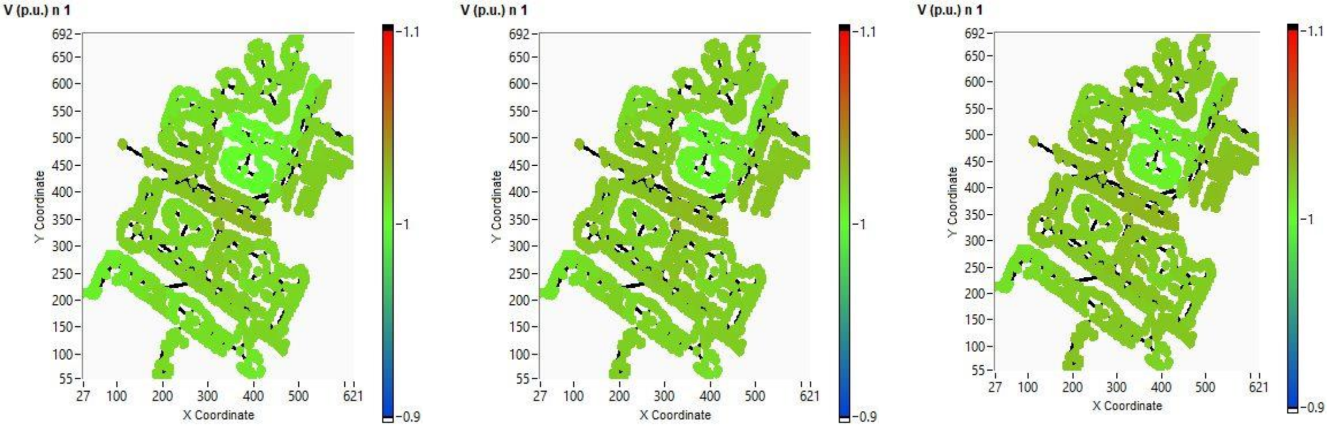
Figure 15: Distribution of per-unit voltage magnitudes for scenarios 1A (left) and 2A (right)

4.4. Scenario 2B

4.4.1 Scenario 2B - PV

In this scenario, there are no significant changes in per-unit voltage magnitudes in the N-1 and N-1-1 analyses, whereas the N-K contingency scenario shows a small increase in the p.u. values as the PV penetration increases.

The results obtained for the N-k contingency scenario are displayed in Figure 16 and Figure 17. In case C, the per-unit voltage magnitudes increase slightly, whereas the net power and power losses decrease more visibly, but not enough for the network to achieve a negative net power. It is noteworthy that all N-k cases have a reduction in the net power because of the reduction in the number of network components, especially loads.



Case A: 0% PV Penetration **Case B: 50% PV Penetration** **Case C: 100% PV Penetration**

Figure 16: Network voltage profile in p.u in the N-k contingency scenario and PV penetration.

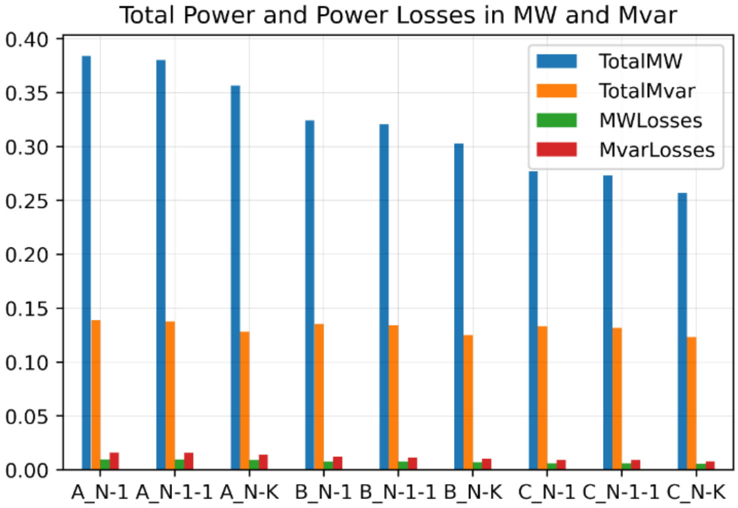
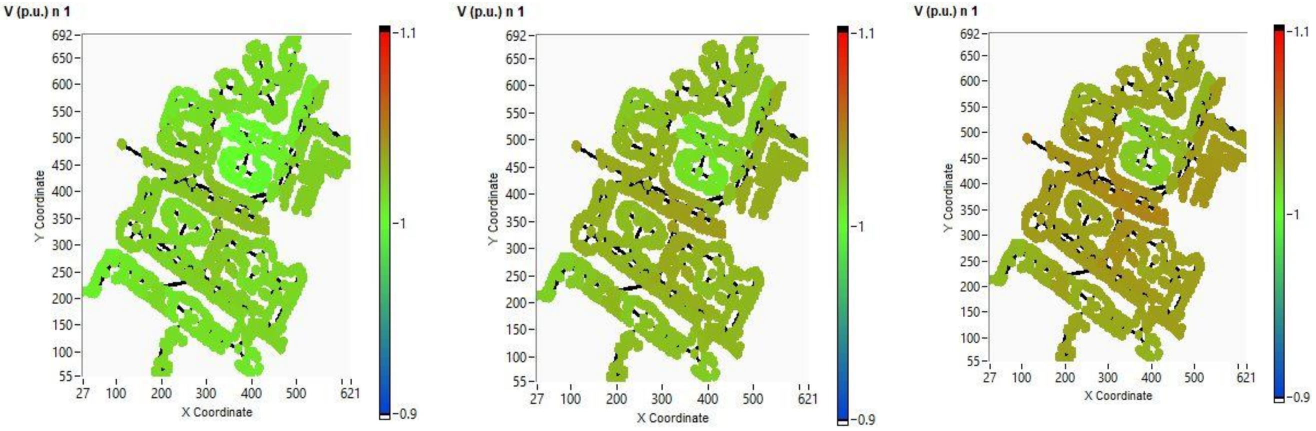


Figure 17: Net power and power losses in the network (in MW and MVAr) for each contingency scenario and PV penetration.

4.4.2 Scenario 2B - Wind

In this scenario, the variations in the network voltage profiles with wind turbines connected to the grid under strong winds are more evident than those obtained in the same scenario with PV panels. Figure 18 shows that the voltage magnitudes increase within the acceptable limits as the wind energy penetration increases. Figure 19 shows the net power and power losses for different contingency scenarios and wind energy penetration levels. It can be noticed that in cases B and C, the active power flows bidirectionally and the net power is negative. The net power becomes less positive in cases A and B and more negative in case C as the number of isolated components increase, since more loads are disconnected from the grid. Note that the power losses in the network model increase as the absolute net power increases.



Case A: 0% Penetration **Case B: 50% Penetration** **Case C: 100% Penetration**

Figure 18: Network voltage profile in p.u in the N-k contingency scenario and wind penetration.

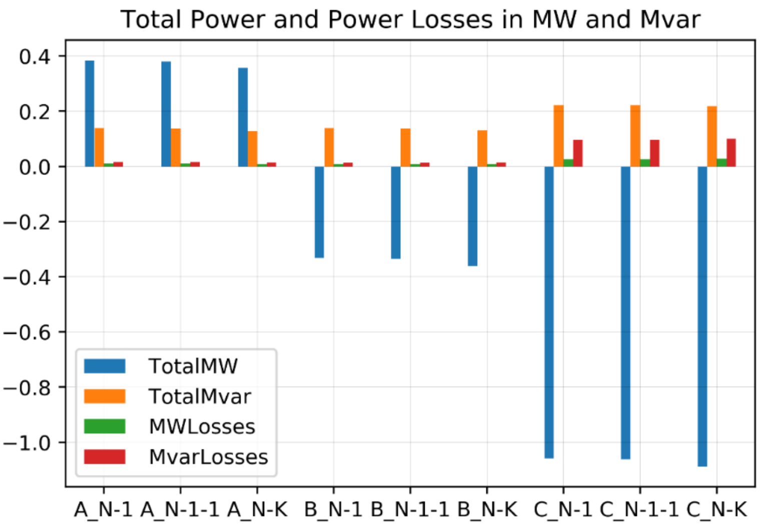


Figure 19: Net power and power losses in the network (in MW and MVAr) for each contingency scenario and wind penetration.

Comparing minimum and maximum per-unit voltage of Scenarios 1B and 2B
In scenarios 1B and 2B, the least and the highest per-unit voltage magnitudes are plotted in Figure 20 for the N-k contingency scenario. It can be seen that the values obtained for scenario 1B with PV generation are the highest, with more locations exceeding the upper limits in the network. It can also be noticed that the maximum p.u voltages in the network are lower in scenario 2B than in scenario 1B for wind and solar. In scenario 2B with wind generation, the lower voltage magnitudes are explained by the increase in the load demand in winter, which reduces the voltage in the network and compensates for an increase in the generation within acceptable operating limits.

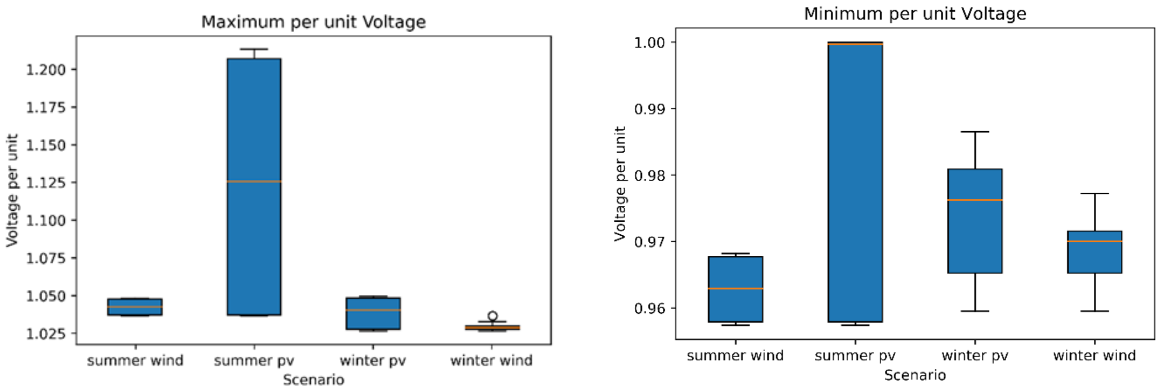


Figure 20: Distribution of per-unit voltage magnitudes for scenarios 1B (left) and 2B (right)

CONCLUSION

This paper has investigated the effect of extreme weather conditions on power distribution networks taking the UK as a case study. The methodology considered that extreme weather events affect power system operation in different ways, through physical damage and changes in operating conditions, and assessed the impact of these changes on power flows and violation of operating constraints. Notably, two severe weather events which occurred in 2019 in the UK were evaluated: a heat wave and strong winds. During both events, wind and solar generation showed predictable effects, with an increase in solar power output in summer and wind power output in winter. A slight increase in the penetration level of renewable energy was enough to supply power to the grid within acceptable operating limits, as well as reduce power losses and the loading of the substation transformer. However, as the penetration of solar PV panel increased in the summer heat wave scenario, overvoltage and overloading became more pronounced, as the amount of generation exceeded the demand. In the scenarios with damaged components, represented by N-1, N-

1-1, and N-k contingencies, constraint violations occurred because of changes in power flows plus operating conditions out of acceptable limits.

Overall, the results indicate that the impact of extreme weather events on the grid is conditioned to the type and amount of renewable generation connected to the grid, as well as the load demand and network components in service. These aspects must be properly understood, as well as the role of different energy technologies not included in this article, so that power system operation can remain reliable, safe, and resilient in a low-carbon energy future.

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