Improving the Operational Reliability of Wind Farms with Vehicle-to-Grid

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Abstract— **This paper investigates the integration of a wind farm with electric vehicles capable of Vehicle-to-Grid operation, and the impact of this integration on the reliability of the energy supply to the load. The operational reliability of wind farms was considered, in order to predict the outage probability. The operational reliability model was implemented on a small power system, and a case study analysis was undertaken of the influence of Vehicle-to-Grid in the event of an outage at the wind farm. Several reliability indices were calculated for the case study. Results show a significant improvement of the system's reliability by the presence of Vehicle-to-Grid functionality, since it is able to compensate for the power lost during a wind farm outage.**

Keywords—power system reliability, Vehicle-to-Grid, wind energy, outage probability, microgrid

I. INTRODUCTION

The automobile sector's dependency on fossil fuels plays a key role in the contribution towards severe environmental problems worldwide. Therefore, the use of electrical vehicles (EV) has been brought to attention as an alternative solution. The electricity that powers an electric car is stored in batteries before being used by the electric motors to drive the car wheels. However, despite the benefits of EV, there are constraints that must be overcome, mainly due to the charging loads imposed on the power system. Currently, charging stations can have considerable impacts on electrical grids such as voltage fluctuations and statutory limits violations [1].

The potential adverse effects of EV adoption are different during peak times, when energy demand is close to the power system's capacity limits. With limited storage available at grid level, at peak times EV-heavy power systems may require additional sources to generate sufficient power to match the level of demand. In contrast, during off-peak times, unused energy from non-controllable sources such as renewables will lead to curtailment and wasting energy, also leading to additional costs in energy regulation and operation [2]. Vehicle-to-Grid (V2G) is a concept proposed to settle these problems, by utilising the batteries in EVs as energy storage devices. Parked EVs provide energy storage and backup to a bidirectional V2G system, which is interconnected with the power system [3]. This stored energy can be fed back towards the main grid when the demand load is too high, or EVs can absorb the excess energy when the demand load is not sufficient to consume the available generation [2, 4]. V2G systems can also be used for investment deferral [5]. Such coordinated operation for V2G systems requires consideration of the sociotechnical complexities, like range anxiety [6].

There are two methods that stored energy can help the operation of a power system; V2G and Vehicle-to-Home (V2H). V2G is a parallel grid system which has the potential to be used to power a house by feeding its power back to the wider power system. V2H approaches have more limitations, as typically an individual car can only be used to supply a single house [7].

Furthermore, the reliability of the system, based on real-time operational parameters, should also be considered when developing reliable infrastructure for EV charging stations [8-9]. This includes the age-related failure of electrical components used in the power system, weather dependent failure rate and current dependent overload protection [10]. Ageing failure of components is dependent on the individual lifespan of the material used, especially when it comes to the effect of temperature on the component's material. Weather dependent failure rates also play a significant role in operational reliability. Nearly all transmission line equipment is exposed to varying and sometimes harsh weather conditions. Therefore, the weather-dependent failure rate should always be considered for outdoor equipment. Lastly, the current dependent overload protection is needed to estimate the probability of an outage due to overloading protection arrangements throughout the system.

Considering all the above factors, it can be seen that the integration of renewable energy and EV in the same power system is not straightforward, and requires careful planning and assessment of the reliability of such a combined system. For this study, the operational reliability of wind farms has been considered in order to predict the outage probability and the influence of V2G integrated within the same local power system as the wind farm.

Reliability assessment methods have been investigated for decades and they form an integral part of power system operation [8, 10]. They sometimes involve indicators / metrics that are used to measure the reliability of a real power system, in terms that are associated with the system or the customers [11]. This requires empirical data, which is how the power industry traditionally assesses reliability [12].

However, there are also probabilistic methodologies, which consider the nature of failures and outages, which is semi-random. A failure of a component is theoretically deterministic, but in practice it involves so many parameters, many of which are not measurable, such as the conditions of its materials, the environmental conditions, its ageing rate, and so on. Some of these parameters can be analysed in more detail, and used as predictive indicators of potential failures. Thus, a probability of failure of a component can be associated with the specific environmental conditions. This forms the basis of operational reliability assessment. The following section describes this in more detail, with a particular focus on wind farms.

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A. *Contribution to knowledge*

The overarching contribution of this paper is the reliability analysis of a local electricity network, fed by a wind farm, in the presence of a V2G system. The impact of the V2G system on reliability is investigated and results provide a measure of the change in reliability metrics for the customers, in light of interventions by the V2G system. The results show a significant improvement in system reliability, due to the presence of V2G functionality.

II. OPERATIONAL RELIABILITY OF WIND FARMS

It is important to assess the operational reliability of a wind farm, which is effectively about predicting the probability of failure. The probability of failure is directly influenced by the operational conditions. For this study, the outage probability of the wind farm is predicted by performing calculations based on the probabilities of time-dependent aging outage, wind speed-dependent outage and the weather-dependent outage probability model in [13].

A. *Time-dependent aging outage*

Time-dependent aging outage is modelled by a Weibull distribution where it exhibits the life basin curve, as shown below in Fig. 1. It is evident that the probability of component failure is higher during the commissioning period, which is due to possible installation failures. Similarly, during the effective life period the failure rate is constantly at a minimum. However, throughout the attenuation period the failure rate increases with time, due to the degradation of the wind turbine's components.

The function of the aging outage probability is represented as follows [13]:

$$P_{ga} = 1 - e^{(\frac{T}{\eta})^{\beta}} - (\frac{T+\Delta t}{\eta})^{\beta} \tag{1}$$

where T is the component's age, η is the characteristic lifetime, β is shape parameter and Δt is the operating time or time interval. η and β must be adjusted to fit the different area of the life basin shape.

For modelling the shape parameter of the early failure rate, a value between 0.4 and 0.9 is typically used. In the case of the attenuation period, the failure rate increases with the age of the components, hence β is greater than one [14]. For this study, assuming there is a declining failure rate, the shape parameter of 0.5 is used and the characteristic lifetime of 17,520 hours is applied to calculate the time-dependent failure rate for the first 2 years of installation.

B. *Wind speed-dependent outage*

The wind speed-dependent outage probability estimates the wind turbine failure rate due to wind speed based on previously measured data, which was collected through a statistical analysis on wind power. The function of the outage probability is represented as a cubic polynomial function [13]:

$$P_{gv} = av^3 + bv^2 + cv + d \tag{2}$$

where v is the wind speed, and a, b, c and d are the coefficients from a fitted cubic function. These were determined empirically as $a = 7 \times 10^{-5}$, $b = 0.001$, $c = 0.006$ and $d = 0.0016$.

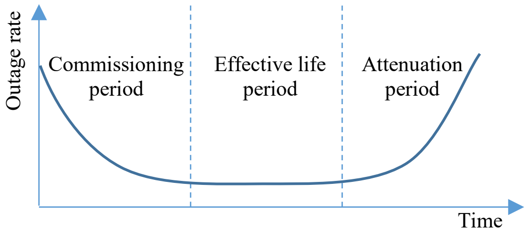

Fig. 1. Life basin curve of a wind farm, adapted from [9]

This outage function is only related to the normal wind speed, but there is also a function that is related to extreme weather conditions, which is related to the occasional outage probability, as described in section C below.

C. *Weather-dependent random outage*

The weather dependent random outage probability calculation is about determining the failure rate of a wind farm in the occurrence of extreme weather conditions, such as typhoons, snow and hurricanes [13]:

$$P_{gc} = 1 - e^{\lambda_{gc}\Delta t} \tag{3}$$

where λ_{gc} is the occasional outage probability, and is empirically assumed to be 10^{-6} in this study.

D. *Hybrid outage probability*

The short-term outage probability of the wind farm can be calculated as a combination of time-dependent (P_{ga}), wind speed-dependent (P_{gv}), weather dependent (P_{gc}) and the overload protection current dependent probability (P_r) model.

$$P_g = 1 - (1 - P_{ga})(1 - P_{gv})(1 - P_{gc})(1 - P_r) \tag{4}$$

This model only analyses the average day to day weather, and it is also assumed that power output from the wind farm is lower than its rated capacity, hence the overload protection outage probability P_r is ignored in this paper.

III. VEHICLE-TO-GRID SIMULATION

In this study, a system which can predict the failure of a wind farm is considered, to showcase the application of V2G which is able to act as a backup system in the event of failure. This has been investigated to an extent in [15], by deriving a new reliability index, and in [16]. However, this paper is looking at the existing widely used reliability indices. This is possible as EVs can be regarded as both a load and a generator when charging and discharging respectively. The simulation model is adapted from Simscape's "24-hour Simulation of a Vehicle-to-Grid (V2G) System" [17].

Fig. 2 represents a 24-hour simulation of a microgrid system which consists of a wind farm that is producing renewable energy, a Diesel generator acting as the main power supply, a V2G and residential load representing household power usage.

Several preliminary simulations were conducted prior to the final model, aiming to select an appropriate rated power for the Diesel generator, which would sit within a suitable

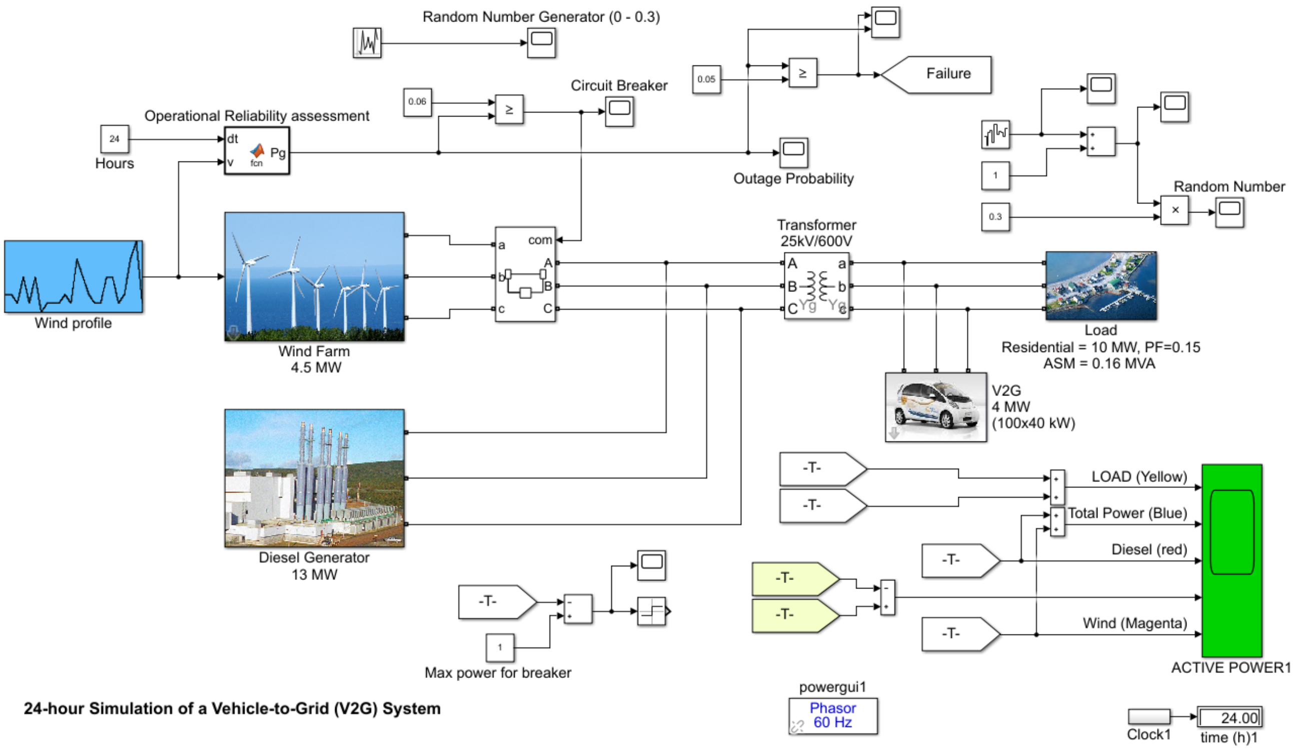

Fig. 2. Simulink model based on a pre-constructed example, modified to implement the operational reliability assessment block (top left)

threshold to both supply the residential load, and be able to adjust accordingly when power is cut from the wind farm. It was evident from the simulation results that the Diesel generator with a power rating of 13MW is the most suitable to supply the power to the residential load. Since the simulation was designed for proving the effectiveness of V2G systems in regulating local microgrids, the capacity of the Diesel generator was deliberately kept close to the peak load. Thus, a wind farm outage would bring the total load close to the Diesel generator limits. This is a risky scenario, but possibly representative of some modern power systems with very limited generation headroom.

Outages of the wind farm are determined by the operational outage probability, as described in section II. This is implemented in the model as a Simulink function block, containing MATLAB code. Whenever the outage probability

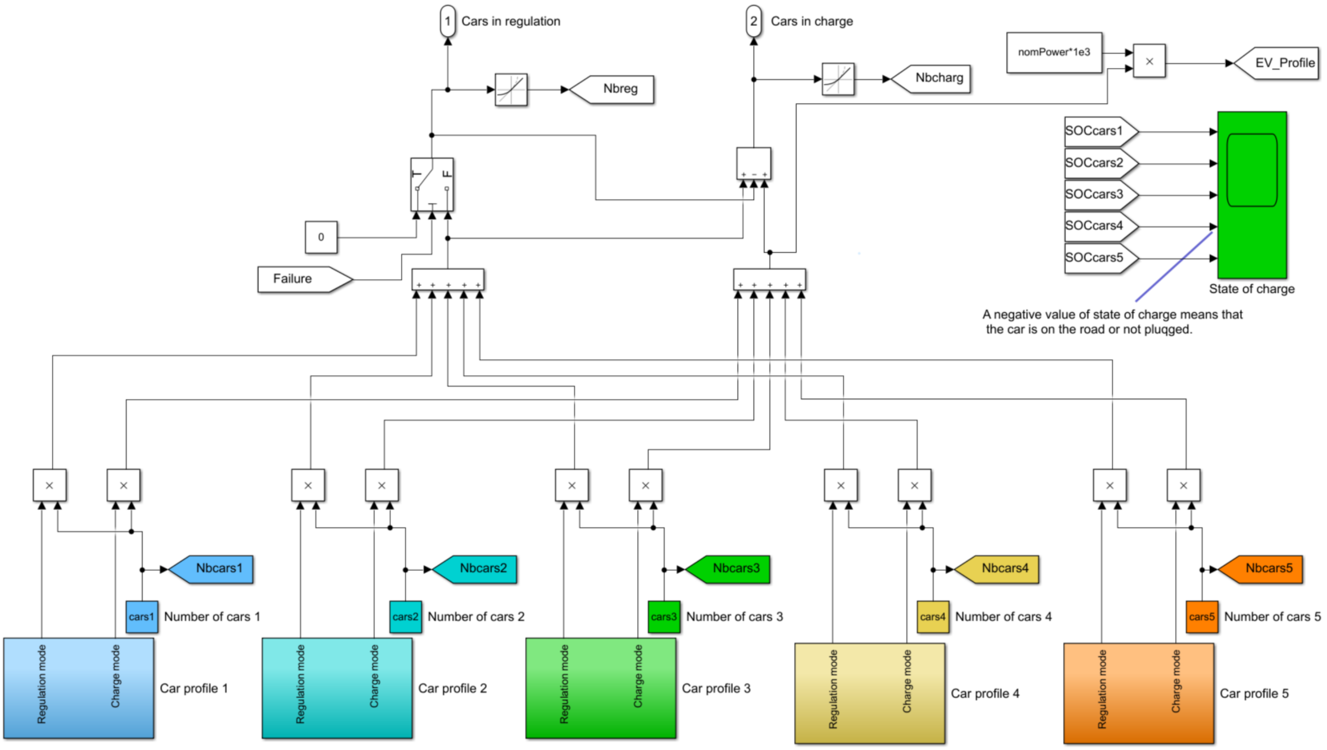

Fig. 3. Vehicle profile Simulink code, showing the modifications that allow the V2G system to respond to outage probabilities / faults

is greater than a predetermined probability, set at 0.06, the circuit breaker will cut off the wind farm from the microgrid to model a wind-speed dependent outage. The probability level of 0.06 was selected semi-arbitrarily after looking at the reliability trace, so that the simulation produces two failures in the 24-hour test period.

The V2G system is set up to have three main operating modes:

- **Regulation** mode, which is the Simulink model's default "smart charging" mode, where the EVs are being automatically regulated based on certain criteria.
- **Charging** mode, which is Simulink's default non-smart charging mode where EVs simply charge without any significant control.
- **Discharging** mode, which is a modification to the Charging mode, in order to override charging and allow discharging of EVs to the grid, again without much control. Essentially power flow is reversed.

Just like the circuit-breaker threshold, when the outage probability is greater than 0.05, the V2G system will switch from the Regulation mode to the Discharging mode. The Discharging mode occurs at a probability level 0.01 (1%) prior to cut off from the wind farm, as the response time of the V2G is slower than the wind farm's response time. This is intended as an early warning system to enable the V2G to take pre-emptive action. In a more complex model, this early warning system could be informed by a wind speed forecast instead. This gives the V2G system a head-start to take action before the outage actually occurs. The scenario of the outage not occurring is not investigated in this particular study, but this will need to be addressed in future work, to prevent inaccurate action on behalf of the EVs, for a predicted outage that never occurs.

This is achieved by producing logic blocks within the V2G profile, as shown in Fig. 3. When no failure is expected, vehicles remain in their current mode, either Charge or Regulation. However, when a failure is expected, any vehicle in Regulation mode will be rerouted to Charge mode, then all the vehicles now in Charge mode will have their power flows reversed and begin discharging to the network. This effectively transfers them to the Discharge mode.

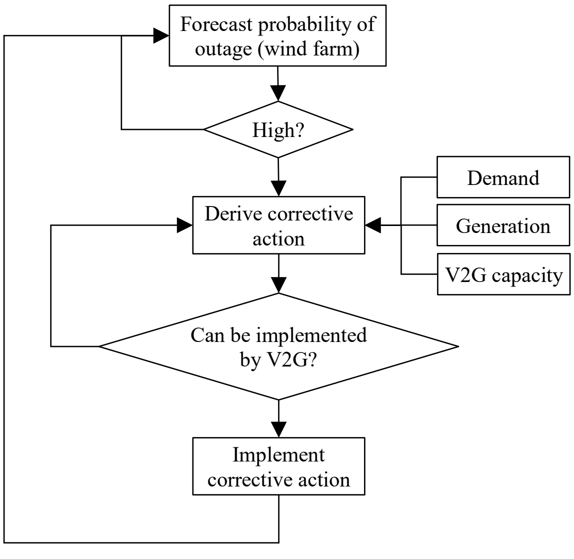

Fig. 4. Flowchart of V2G corrective actions procedure

The above control scheme is a simplistic one, and very limited forecasting is used. Forecasting is in the form of wind farm outage probability, which is then used to determine the V2G response in anticipation of an outage. With a more advanced forecasting capability, this setup has the potential to predict more complex upcoming situations that are very likely to lead to failures, and take corrective control actions to prevent an outage. Such corrective actions would be implemented by the V2G system, in accordance with the system load and generation parameters, as well as the availability of energy in the V2G car pool. A flowchart of this approach is shown in Fig. 4.

IV. RESULTS AND DISCUSSION

A. *Output of the 24h simulation*

From equations (1)-(4), and specifically (2), it can be derived that the probability of failure in such a wind-based system is directly proportional to the wind speed, with a polynomial relationship. Hence, the shape of the outage probability shown in the bottom curve of Fig. 5 resembles the wind profile of the day. The fact that a simplified outage criterion was selected, i.e. a set threshold, results in the top trace of Fig. 5. This diagram is binary, and shows the times when the EV system expects that an outage is occurring. At those times, the trace is at 1, otherwise when an outage is not taking place, the trace is at 0.

Fig. 6 demonstrates the results produced from simulation of the final model. It is evident that for every occurrence when the wind farm is cut off, due to high outage probability, V2G is being discharged. This is shown in Fig. 6, as the EV trace tends towards a negative value. This aims to compensate for the power that is inaccessible from the wind farm.

In the model, the threshold for the EV system detecting a failure has been lowered to 1% probability level below the actual threshold when an actual fault is supposed to occur at the wind farm. This is visible in the diagrams in Fig. 5 and 6, as the EV load starts to be reduced several seconds before the wind farm is cut off. This acts as a fail-safe mechanism, and even though it manages to reduce some transient effects, some still remain.

However, it is important to note that this is not a fully dynamic simulation, and the transients observed are simplified representations of the Phasor mode in Simulink. Hence, they cannot be taken as representative of a real system.

B. *Reliability indices*

The functionality of the V2G system in this simulation partially compensates for the outage of the wind farm. This means that, in practice, the power fed to the residential load is unaffected. The Diesel generator compensates for the rest. Hence, the customers will not experience any outage in their power supply, and the Diesel generator will not reach its generation limit, thus providing enough headroom for further unforeseen load spikes. In this sub-section, the reliability indices that would be affected by the outage are calculated [12, 18-19]. The indices that are used are:

- System Average Interruption Frequency Index (SAIFI)
- System Average Interruption Duration Index (SAIDI)

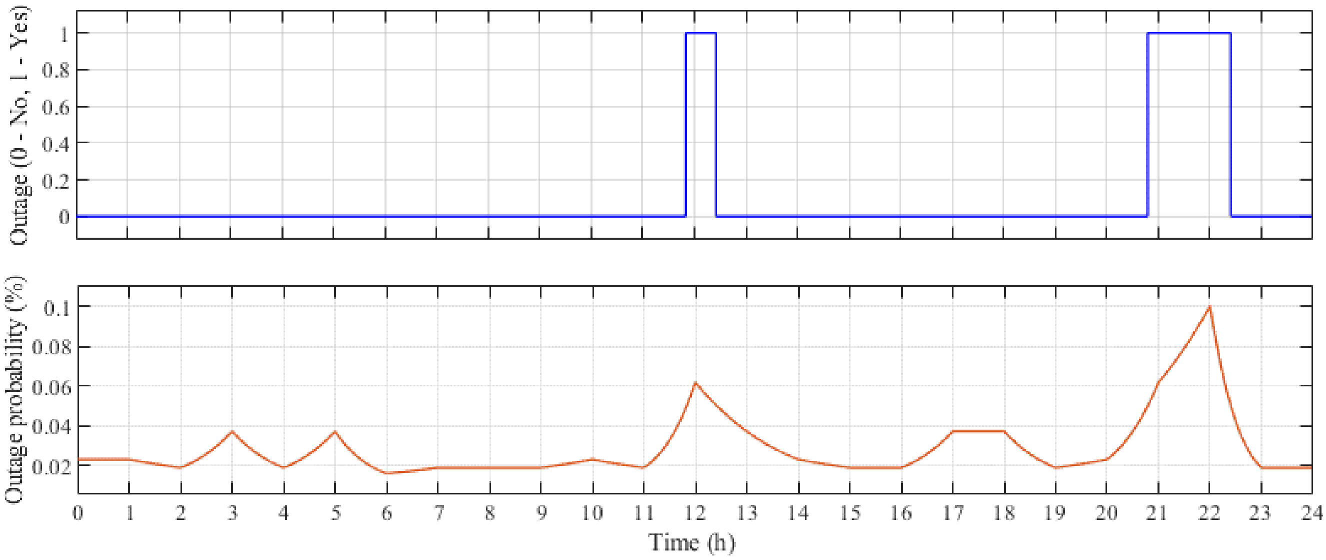

Fig. 5. Outage (top) and outage probability (bottom) during the simulation

- Customer Average Interruption Duration Index (SAIDI)
- Average Service Availability Index (ASAI)
- Average Service Unavailability Index (ASUI)
- Energy Not Supplied (ENS)
- Average Energy Not Supplied (AENS)

The above indices were calculated for the simulated scenario. The following assumptions were considered:

- After Diversity Maximum Demand (ADMD) of 1.3kW per customer [20].
- Hence, 10MW would be equal to 7,692 customers (total customers, N_T).
- Two failures occurred in the simulated day. This cannot be taken as a typical day, as it would be highly unlikely that two failures would occur daily. For that reason, it was assumed that one such day might occur every month of the year. This results in 24 interruptions annually (failure rate λ_i, per interruption i).
- The duration r_i of the first outage was recorded as 303 seconds (5.05 minutes / 0.08417 h), whereas the second outage lasted approximately 4,800 seconds (80 minutes / 1.33 h).

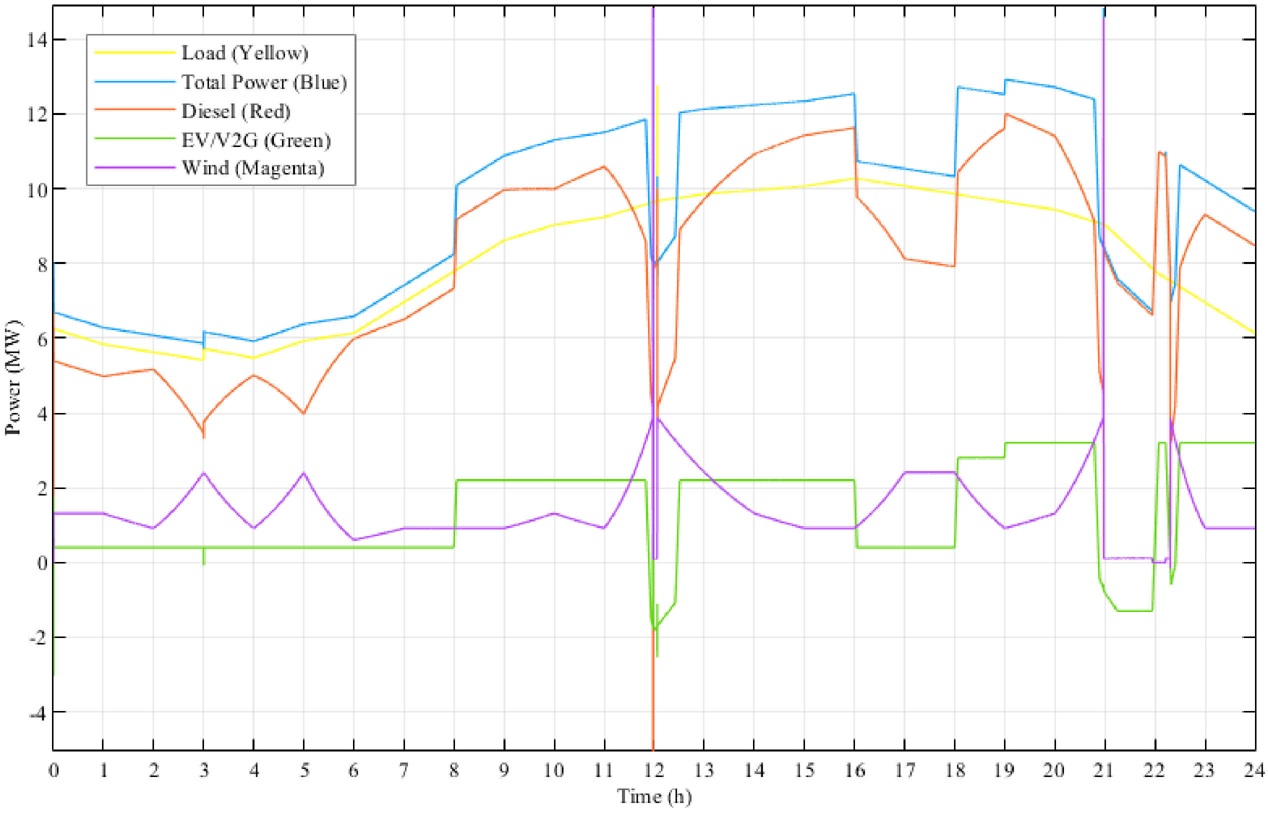

Fig. 6. Scope output of microgrid simulation, showing the power generation and demand

- The wind farm, at the time of the outage, was providing on average 3.87MW, which translates to 2,977 customers interrupted (N_i).

The contribution of the wind farm to the above reliability indices at the point of the residential load is as follows:

$$SAIFI = \frac{\sum \lambda_i N_i}{N_T} = 9.289$$

$$SAIDI = \frac{\sum r_i N_i}{N_T} = 0.5486\ h/year$$

$$CAIDI = \frac{\sum r_i N_i}{\sum N_i} = 1.4175\ h/year$$

$$ASAI = 1 - \frac{SAIDI}{8760} = 0.999937$$

$$ASUI = \frac{SAIDI}{8760} = 0.000063$$

$$ENS = 5.486\ MWh$$

$$AENS = \frac{ENS}{N_T} = 0.713\ kWh\ per\ customer$$

The above calculation illustrates that the improvement of reliability indices is significant, by combining the wind farm operation with a V2G system. In practice, outage probabilities would exist in all system components, including the V2G installation, but by combining these systems the overall system reliability is improved.

In the particular simulated system, a Diesel generator is also installed, which could mostly recover the load that might have been lost by the outages in the wind farm. However, in this simulation, it would have almost reached its capacity limits, leaving very little headroom. If the outage occurred closer to peak load, the Diesel generator would not have been able to supply the load. Hence, the results show the important role that V2G control of electric vehicles can play in the reliability of such small local power systems.

V. CONCLUSIONS

The operational reliability of wind farms was considered in order to predict and mitigate the outage probability. Modelling the failure base of the outage probability is essential in order to address problems that may be encountered in the microgrid during an outage, as well as to act for preventive maintenance to the wind turbines.

The proposed failure model that has been implemented looks at the influence of V2G in the event of an outage. It predicts the failure base on the outage probability and isolates the wind farm from the micro grid, in order to protect both the grid system and wind turbines. The concept of V2G integration within the microgrid has been shown to behave as either a load, or a distributed energy storage device, while the wind farm is cut off. This has been shown to improve the reliability performance of the microgrid at the point of the customer load, by preventing power cuts to the residential loads as well as reducing the risk of lost revenue.

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