Local Peer-to-Peer Energy Transaction Framework Based on Time of Using Pricing Scheme

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Abstract–The integration of Renewable Energy Sources (RESs) and Plug-in Electric Vehicles (PEVs) into existing Low Voltage (LV) distribution networks may cause bi-directional power flow, thermal, voltage and other technical issues. In this paper, real-time intelligent PEV charging management and distributed Battery Energy Storage (BES) Systems are implemented to mitigate these technical impacts on the distribution grids. Based on the concept of future Smart Grid, a novel local Peer-to-Peer (P2P) energy transaction framework based on Time of Using (ToU) pricing scheme is proposed to make profits for domestic customers by utilising the available BES and RESs' generation capacity. This P2P real-time energy transaction framework revolutes the traditional electricity market, providing a platform for Microgrid operation in islanding mode during utility grid disturbance.

Keywords–Plug-in Electric Vehicle (PEV), Smart Grid, Distributed Energy Storage (ES), Local Energy Trading, Time of Using (ToU) Pricing

I. Introduction

The worldwide concern on greenhouse gas emission and fossil fuel shortage force the installation of renewable energy generation and transport electrification. The existing LV distribution network is design based on radial and passive consumption and rated at After Diversity Maximum Demand (ADMD). However, the integration of small-scale renewable Distributed Energy Resources (DERs) and Plug-in Electric Vehicles (PEVs) into existing Low Voltage (LV) distribution networks may cause several technical issues, including bi-directional power flow, thermal, voltage and etc., due to the additional PEV charging load and intermit nature of renewable energy generation. To compensate for the increasing penetration of DER generation and PEV charging load within LV distribution networks, Smart Grid technologies are being proposed and applied. The future power system is expected to have intelligent active network management, energy transaction system and flexible operation modes to utilise the renewable energy generation and energy storage capacity by implantation advanced monitoring and communication technologies.

To mitigate the impact of PEV charging, PEV charging management algorithms are proposed in the literature. As an indirectly PEV charging control method, Time-of-Use (ToU) Pricing scheme is discussed in [1] to motivates PEV owners to recharge during off-peak times by offering time-varying rates depends on energy demand. The positive response from PEV owners about ToU Pricing scheme is investigated and indicates another load peak may appear, which is even higher than the indirectly controlled load peak, due to the aggregated PEV start charging at the same time when the electricity rate is lower [2]. Intelligent PEV charging management, directly controlled by Network Operator to maintain network assets constrains is addressed and simulated in [3]. Results suggested the method can flatten the overall load demand and release voltage drop issue. Obviously, the implementation of this type of real-time PEV charging control system requires extensive PEV data and power system information collection, communication and processing infrastructures. The comfort of PEV owners is also required to be evaluated, since the State-of-Charge (SOC) of PEV battery may lower than expected due to direct PEV charging management.

To encourage the installation of small-scale renewable DERs, the UK government deployed feed-in tariff [4] for electricity energy exported to the grid according to the record at smart meter. However, compared with the market price, this reward is still low. Battery Energy Storages (BES) are favourable for its flexible charging/discharging capability. Sizing, locating and control of Distributed BES has been extensively discussed among researchers [5, 6]. Nonetheless, the expense of equipment and wiring is a critical issue which makes it difficult to be widely implemented. The domestic BES store exceeded electricity generated from renewable DER, instead of feeding into the grid, and consume during peak-time. Meanwhile, high penetration of distributed BESs can partly mitigate the aforementioned technical impacts by releasing the dependency of the distribution network and the utility grid.

Peer-to-Peer (P2P) energy trading is addressed under future Smart Grid scenario, to utilise the available ES and RESs' generation capacity and create an opportunities to achieve a win-win situation for both domestic customers and the Distribution Network Operator (DNOs). Some P2P energy trading strategies are suggested and in trial in Europe and North America [7], with varying size of system and transaction algorithm.

A novel local P2P energy trading framework is proposed in this research that once the ES used out or electricity consumption over the power ratio of ES, an energy request will be broadcasted to all other houses and DNO. A bidding process will allocate the best energy sources to this customer and then start severing until the appearance of a more suitable energy provider or the end of energy requirement. The unit price of electricity is determined by the ToU pricing scheme. The proposed network diagram is shown in Figure 1. Two technical impacts mitigation solutions, PEV charging management and distributed ES, are engaged in the simulation to maintain constraints of thermal, voltage and other limits of the network assets. Microgrid operating in islanding mode for a short period, during utility grid disturbance, is enabled based on the proposed energy transaction framework. This P2P real-time energy transaction framework revolutes the traditional electricity market and enhances the role of DNOs as network or infrastructure providers. ES and RESs' generation capacity are utilised to make profits for assets owners.

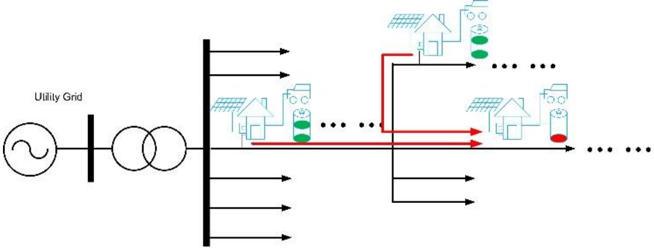

Figure 1 Illustrative diagram of network integrated with P2P energy transaction framework

In this paper, a representative practical 400V (line to line) distribution network is modelled. High-resolution domestic load, PEV charging behaviour and small-scale distributed RES generation profiles are created and validated in Section II. In Section III, the technical impact of DERs and PEV integration is quantified at a fixed penetration level for illustration. Then, a real-time PEV charging management system, based on the P control algorithm and minimising PEV customer inconvenience, is applied and simulated to mitigate the negative aforementioned technical impacts. Charging and discharging algorithms and benefit for both customers and network are presented, with the implementation of PEV charging management system, in Sections IV. In Section V, The proposed local P2P energy trading framework is addressed in detail and simulated for validation. Economic benefit for domestic BES is analysed according to the ToU pricing scheme. Microgrid islanding operation capability is also discussed and simulated in this section. Conclusions are drawn in Section VI.

II. MODELLING

1. Network

A practical LV distribution network serving 292 houses is modelled in OpenDSS. Geographical topologies of the physical LV distribution network is shown in Figure 2. The network is supplied by a 500kVA 11kV/0.4kV step down transformer.

2. Domestic Load

Due to the confidential agreement between DNO and customers, the load data of each dwelling is unavailable for this study. A domestic electricity usage model introduced in [8] is adopted in this study. 292 independent domestic customers' load profiles in the 1-min resolution are created. The accumulated synthetic load profile is compared with measured data at the substation in Figure 3. The correlation coefficient of these two variables is 0.9433, which indicates that the synthetic load profile is highly similar to the load profile measured at the substation. However, it is clear that at the first 40 min of a day, the accumulated synthetic load is underestimated, which is due to the basic domestic electricity usage model.

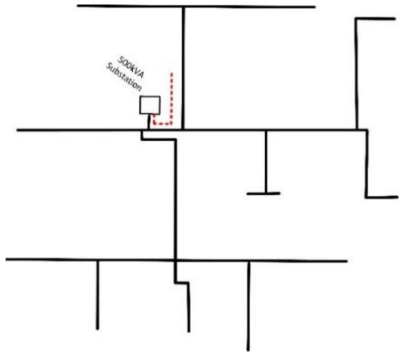

Figure 2 Geographical topologies of the objective LV distribution network.

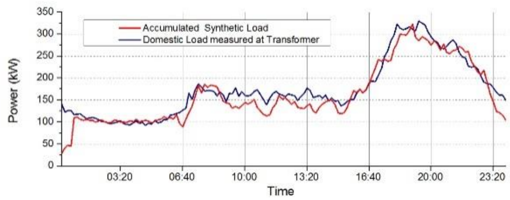

Figure 3 Comparison of accumulated synthetic load profile and measured data at the substation

3. PEV Charging Load

In this study, all the PEV are simulated as Nissan LEAF, which is the best seller of Battery Electric Vehicle (BEV) all over the world. The PEV is equipped with 24 kWh battery capacity and single-phase 3.6 kW charging rating. PEV charging behaviour is investigated in [9] based on a trail of measuring a fleet of PEV charging activates during a long period. Thus, 292 individual PEV charging profiles is created by using this model. The accumulated 292 charging profile is presented in Figure 4.

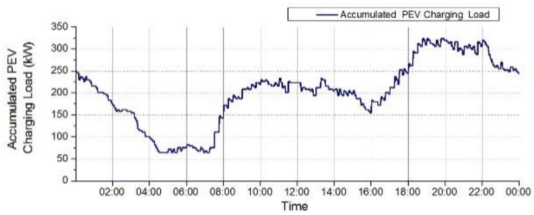

Figure 4 Accumulated PEV charging profile

4. Small-scale Photovoltaics

The small-scale DERs installed in this network are simulated as Photovoltaics (PV), 4 kW rooftop solar panel. A typical PV generation profiles [10] during a day, in 1-min resolution, is shown in Figure 5.

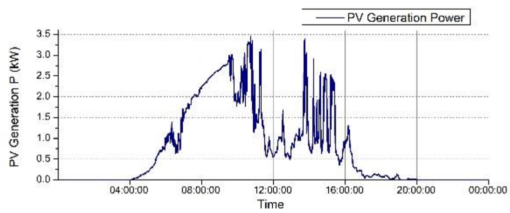

Figure 5 A Typical PV generation profile during a day (1-min resolution)

5. Technical impact quantification at certain 90% PEV and 60% DER penetration combination

In this subsection, power flow simulation is carried out to identify the transformer/ cable overload issue and voltage rise/dip issue at a certain PEV and DER penetration, i.e. 90% PEV and 60% DER penetration combination.

5.1. Transformer and cable overload issue

Power flow calculation results suggest that the overload issue appears for both transformer and cables. If the demand over the rated capacity of the 11kV/0.4kV step-down transformer, which is 500kVA, thermal issues emerge causing equipment deteriorated ageing. In Figure 6, the power at the transformer is presented. From the figure, some crucial result can be obtained that, transformer overload issue appear during peak time (16:00-22:30) with a maximum value of 639.9 kVA (128% of nameplate rated value) and reverse power to the utility grid accrue during daytime (6:00-15:30).

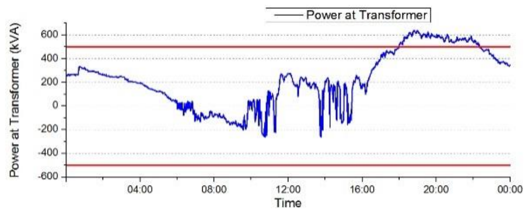

Figure 6 Time-series Power at transformer @. 90% PEV and 60% DER penetration combination

Cable thermal issue is also investigated and those time network suffering cable thermal issue is presented in Figure 7. Statistics show that with those cables with thermal issue, the current go through is 1.13 times of the rated current, with max 1.52 times the rating.

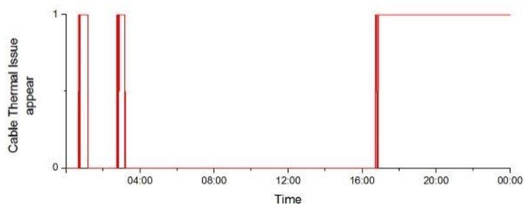

Figure 7 Cable Thermal Issue appear at these time slots

5.2. Voltage rise and dip issue

The Power flow calculation results also indicate that there are certain voltage dip issue in this network if 90% of the customers have one PEV and 60% of the customer installed a 4kW Photovoltaics. The maximum and minimum voltage at 292 domestic customers are recorded every minute during the simulation and shown in Figure 8. From the diagram, there is a slight voltage drop issue occur, which is still within the regulation.

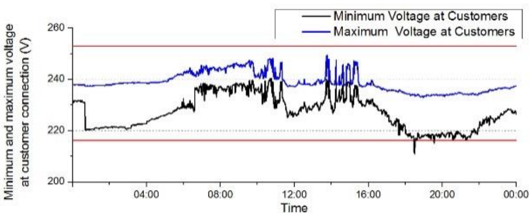

Figure 8 Minimum and maximum voltage at customer connection

Three-phase unbalance issue is also investigated during the simulation. However, there is not any bus with unbalance issue according to the Engineering Recommendation (2% over 15min). This may be due to the stochastically geographical connection of both PEVs and DERs. According to the thermal and voltage issues found in this section, the objective LV distributed network is unable to manage that amount of PEVs and DERs without an advanced energy management system.

III. Real-time PEV Charging Management Algorithm

In this section, a real-time PEV charging management system based on the P control algorithm is introduced. The control cycle and gain are optimised during simulation.

1. Introduction of the Charging Management Algorithm

Uncontrolled PEV charging can cause transformer and cable thermal issues as discussed in the previous section. The aim of this real-time PEV charging management system is to flat the peak load demand, reduce the disconnection times and inconvenience caused by postponed PEV charging. The control interface requires extensive sensor at the substation, data collection at each EV about charging time and SOC, a communication system and a control centre. The sensor monitoring the real-time power at the substation in 1-min resolution and send to the control centre. Each PEV charging activity information is sent to the control centre, including charging start time, initial SOC, charging finish time and final SOC via a communication interface. The charging control diagram is presented in Figure 9.

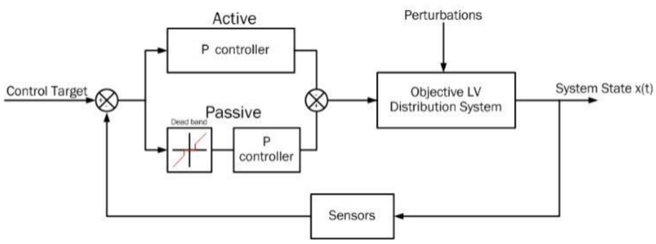

Figure 9 Close-loop control system diagram

At each control cycle, the error of power (kVA) at the transformer and control target, 450 kVA in this simulation is calculated and recorded. If this error is positive, it means that the power demand is over the transformer thermal limit and proper PEV charging management is required. Then, the amount of PEV should be disconnected from charging can be determined from this error multiplied by a control gain. The SOC of each PEV is always calculated and arranged in descending sort. Since there are 23 battery units in s Nissan Leaf (24kWh), those PEVs with more than 11 units charged will not participate in the charging management for reduce disconnection times and improving the usage convenience of PEV owners. According to this logic, the selected PEVs will be disconnected from charging and standby for reconnection. On the other hand, once the error between demand and control target is negative, and larger than the dead band, it suggests that the network can allocate more PEV charging. The dead band is designed for missed reconnection for the situation when demand is still in high level. Those PEVs with lower SOC will be reconnected to the grid for charging until all the PEVs are charged or reconnected to the grid. The control command will be sent to each charging point for disconnection or reconnection. More important, the tuning of control gain and the dead band is crucial which may reduce the PEVs impacted by this directly controlled charging management system. Moreover, the corresponding parking profiles of each PEV and comfort index is suggested to evaluate the inconvenience caused to PEV owners due to controlled PEV charging in a related paper, PID control algorithm is also tested and compared.

2. Simulation Result

Based on the developed model in Section II, the proposed PEV charging management system is simulated. Different control cycle, gain and reconnection dead band is tested. The simulation results indicate that when K equals to 1.3, reconnection dead band equals to 20kW, and the control system is selected as 10 min, the power at the transformer is shown in Figure 10.

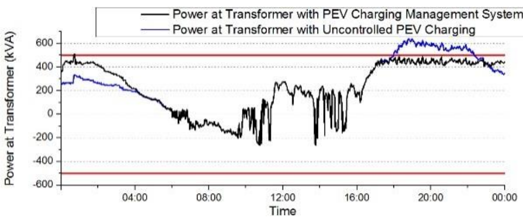

Figure 10 Comparison of transformer power before/after PEV charging management

This result well explained that the thermal issue at transformer is solved. However, a peak value at 0:40 shoots over the transformer thermal limit appear which is due to the sudden increase of domestic load. At this control cycle, 13 PEVs are disconnected to release network stress and congestion.

IV. IMPLEMENTATION OF DISTRIBUTED ES

In section III, a real-time PEV charging management based on the P control algorithm is introduced to stress thermal issue at transformer and cables. However, form the simulation result in Figure 10, there is still reverse power flow feeding to the utility grid, which makes less benefit to the DER owners. In his section, distributed ESs are introduced and simulated to estimate the potential benefit for both customer and network operators. Simplified distributed ES models are used to simulate the basic performances of ES systems. For each customer with a Photovoltaics, a 3kW/4.8 kWh lead-acid battery is equipped, assuming battery charging/ discharging efficiency is 90%. Idling consumption and reserve is not considered in this paper. The initial SOC of each battery is 0kWh at 8:00.

The distributed energy storage store electricity when the PV generation can supply the domestic load and PEV charging. On the other hand, the energy storage discharge while PV generation is idling or lower than the energy demand.

1. Distributed ES only

The distributed energy storage is implemented with those customers installing PV. The simulation result presented in Figure 11 suggested that the thermal issue is partly solved. Since all the energy storages are operated without coordination, nearly half of the energy stored is consumed before the peak-time when the overall demand is over the transformer thermal limit.

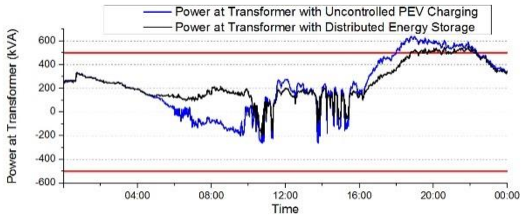

Figure 11 Comparison of transformer power before/after installing distributed energy storage

An example of distributed energy storage charging and discharging profile and corresponding SOC varying history is recorded and presented in Figure 12. The results suggest that the energy storage store some of the energy generated from PV system, but not the peak time, compared with the network overall energy consumption or generation profile simulated at the transformer, as presented in Figure 6, due to the uncoordinated charging strategy. During the peak time, the energy storage can only supply the PEV charging and domestic load for less than 2 hours and then PEV will continue charging by energy supplied from the utility grid.

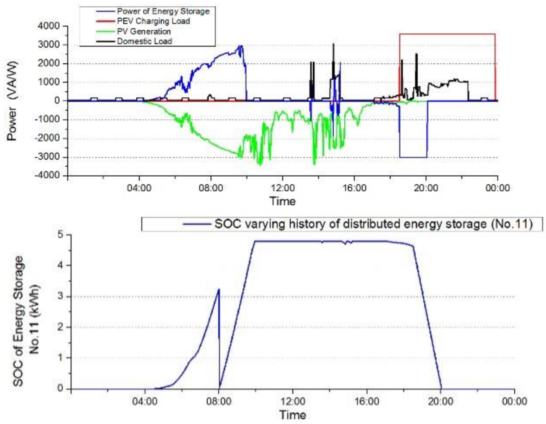

Figure 12 Charging/discharging profile (a) and historical SOC varying (b) of the energy storage installed at customer No.11

2. Distributed ES with PEV charging management

From the simulation results obtained in Figure 11, the uncoordinated distributed energy storage and uncontrolled PEV charging can still cause transformer over thermal issues. The PEV charging management algorithm is applied in this subsection with the same gain setting and control cycle as addressed in section 3.2. The only difference is that those PEVs are charging by using, or partly using energy stored in domestic battery energy storage will be skipped, i.e. not be disconnected from charging. Simulation result is presented and compared with all the simulation results obtained in previous sections in Figure 13.

This result showed benefits of implementation of PEV charging management and distributed energy storage together. The reverse power flow is eased and the transformer thermal issue is mitigated. Also, no further sensor or communication infrastructure is required in the combined optimisation approach. However, a larger size energy storage is proposed for the customers with PV installed for collecting the electricity generated from PV after 10:30. A better energy storage sizing process including cost-benefit analysis is required to balance the usage of distributed energy storage in different season and weather conditions.

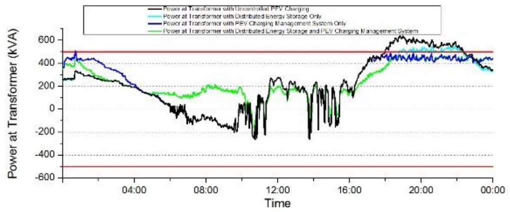

Figure 13 Comparison of transformer power before/after PEV charging management only, distributed energy storage only, PEV charging management and distributed energy storage together

V. PROPOSED P2P ENERGY TRANSACTION FRAMEWORK AND MICROGRID ISLANDING OPERATION

1. Proposed P2P energy transaction

To utilise the capacity of energy storages, a P2P energy transaction framework is proposed in this section. Once the domestic ES used out or electricity consumption over the power ratio of the customer's ES, an energy request will be broadcasted to all other houses and DNO. A searching process will allocate the best energy sources (one or more than one) to this customer and then start severing until the appearance of a more suitable energy provider or the end of external energy requirement. The unit price of electricity is determined by the ToU pricing scheme, the Economy-7 which is widely applied in the UK is implemented as an economic analysis basis of P2P energy trading. If the customer installed an energy storage with stored electricity energy, the PEV is not charging, and willing to put the energy stored into the community, the P2P energy trading is enabled during the peak time of a day. The proposed P2P real-time energy transaction framework revolutes the traditional electricity market and enhance the role of DNOs as network or infrastructure providers. ES and RESs' generation capacity are utilised to make profits for assets owners.

2. Simulation result

Based on the previous PEV charging management algorithm and distributed ES system, in this subsection, the proposed P2P energy transaction is simulated. Different sizes of distributed ES is tested, 4.8kWh and 9.6kWh storage capacity.

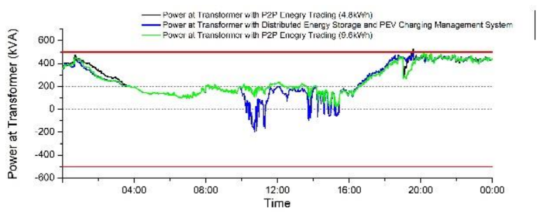

Figure 14 Comparison of transformer power before/after P2P energy transaction, 4.8kWh and 9.6kWh storage capacity with PEV charging management

In Figure 14, the power at the transformer with P2P energy trading enabled is presented and compared with the result obtained in section IV.2, in which only implemented PEV charging management and distributed ES system. The simulation results suggest that the energy trading is only available for a short period due to the accumulated energy demand of domestic load and high penetration of PEV charging, also the relevant low PV and distributed ES installation penetration. The figure below shows the power of energy traded during the peak period and accumulated ES capacity through the day.

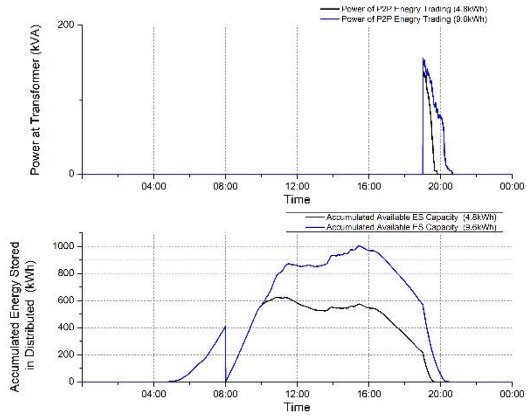

Figure 15 Power of energy traded during the peak period and accumulated available ES capacity through the day

3. Economic Analysis

The electricity price per unit in the cheapest Economy 7 and cheapest normal electricity-only is listed in Table 1.

Tariff	Peak Rate	Off-Peak Rate
Cheapest Economy 7	15.2p/kWh	7.1p/kWh
Cheapest normal electricity-only	12.6p/kWh	12.6p/kWh

Table 1 Cheapest Economy 7 vs cheapest electricity-only

According to Feed-in tariff, the government will reward the licensed Distributed Generator for the energy feed into the utility grid. The current price for energy fed in per unit is 3.93 p/kWh. Thus, the net benefit of a customer with P2P energy trading and Economy 7 is analysed, present in the table below.

Size of Energy storage	Average Energy Traded	Max Energy Traded	Average Benefit
4.8kWh	0.59 kWh	1.96 kWh	£ 0.065
9.6kWh	1.23 kWh	3.63 kWh	£ 0.139

Table 2 Net benefit of a customer with P2P energy trading based on Feed-in tariff and ToU pricing scheme

4. Potential of Microgrid Operation in islanding mode

In this study, the energy storage installation is related to the availability of PV in each customer. Thus, the higher PV penetration in this system will lead to a higher distributed energy storage installation. Assume the PV penetration is 100%, i.e. every customer installed PV generation and distributed ES in this network. Thus, the power and capacity of ESs may support the LV distribution network as an independent sub-system for a short period during utility grid disturbance, known as Microgrid. The proposed energy transaction framework provide a link between all the available distributed ES and their available power and capacity.

Simulation is carried out to identify the potential of this LV distribution network operating in islanding mode. Due to the domestic load is defined as having a power factor as 0.98, and the ES and PV cannot supply reactive power, the simulation is still grid connected for reactive power supply. The utility grid disturbance is set at 19:00. According to the simulation results, when all the distributed ESs have4.8kWh capacity, the network can operate in islanding mode for 26min, while 49min for 9.6kWh capacity ESs, presented in In Figure 16. However, reactive power is demanded, about 35kVar, from the utility grid or other reactive power support devices, such as capacitors or distributed synchronous generators.

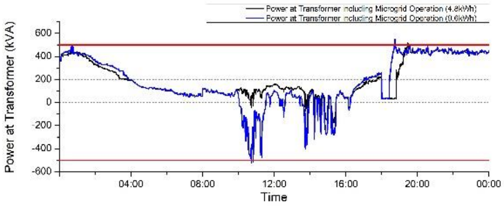

Figure 16 Potential of islanding operation estimation for 4.8kWh capacity ESs and 9.6 capacity ESs, respectively.

5. DC Microgrid discussion

The steady state power flow simulation in this study is based on a practical AC LV distribution network. To connect increasing penetration of PV generators, ESs and PEV charging to the existing LV distribution network in the near future, a DC distribution network has its own advantages in integration these devices, such as reduced cost of converters and their energy losses. The proposed EV charging management algorithm and P2P energy trading framework are also applicable in a DC grid, meanwhile, reactive power support issue is avoided or can be solved by converters at the rotating household appliances. However, control, communication, energy balance and protection technologies are essential to guarantee a safe and economic operation of DC Microgrids.

VI. CONCLUSIONS

In this paper, a practical LV distribution network and related profiles are modelled to quantify technical issues caused by high penetration of PEV charging and DER generation. Real-time intelligent PEV charging algorithm and distributed Battery Energy Storage (BES) Systems are proposed and simulated based on the developed model. Simulation results suggest that these approaches are able to mitigate the technical impacts due to the integration of PEVs and DERs in high penetration. Then, a novel local Peer-to-Peer (P2P) energy transaction framework based on Time of Using (ToU) pricing scheme is proposed to make profits for domestic customers by utilising the available BES and RESs' generation capacity. Economic analysis of P2P trading is presented based on Economy 7 ToU pricing scheme. The potential of Microgrid operating in islanding mode during utility grid disturbance is estimated. Finally, the implementation of the proposed approaches in DC Microgrid is discussed.

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