Journal of Solar Energy Research Updates, 2018, 5, 25-38

Commercial Scale Solar Power Generation (5MW to 50 MW) and its Connection to Distribution Power Network in the United Kingdom

Jayanta Deb Mondol* and Gibu Jacob

Centre for Sustainable Technologies, Belfast School of Architecture and the Built Environment, University of Ulster, Newtownabbey, Northern Ireland, BT37 0QB, UK

Abstract: Over the years, the contribution of solar photovoltaic systems to the power generation is expected to grow through household small scale, and commercial scale solar installation. Researcher pronouncing that delivering such a determination require greater motivation and innovation and much more dynamic power grid network to manage solar generation connection. This research work identifies and recommends the possibilities of applying proven technical know how to get the maximum from the existing power network economically. The simulated case study examples of various capacity connection requests was carried out to provide key insights on the problems faced by the PV farm connections in their line of business. This research is also an effort to give many answers to solar PV developers and enthusiasts who are not very technical and confused about different money saving connection options and the electrical constraints of the power grid. This study data can be used to provide recommendations to further enhance the growth of commercial scale solar power generation in the UK.

Keywords: Photovoltaics, Power network, Electricity, Solar energy, Costs.

1. INTRODUCTION

The UK government has setup a target to reduce the carbon emissions by 35% in 2020,and by 80% in 2050. The UK power industry has contribution from the renewable energy sources which contributes 7% of the UK's electricity. However, EU set the target to be 30% which needs to be met by 2020 [1]. This ambitious goal can be achieved by increasing wider use of distributed renewable energy [2]. Hence, there is a potential for the renewable energy such as solar power to play a key role to reduce the CO_2 and contribute largely to the UK electricity transmission and distribution network.

The solar power would create around 60 GW of generation capacity by 2030 which is the equivalent demand for power required for over eighteen million homes in the UK [3]. The commercial scale solar PV system also have the potential to create over 50000 jobs across the solar supply chain [4]. The ground mounted solar farms can contribute 25.5 billion pounds to the UK economy by 2030, which will ensure savings for consumer of 425 million pounds [5]. This will exceed the energy generation capacity of offshore wind and nuclear and all this can be achieved only using 0.2% of the UK's land area. The cost reductions in the solar PV installations, solar components and availability of talent led to a dramatic growth of the commercial solar scale power generation coupled with high efficiencies in British operations. Studies reveal that strides in the solar PV power systems are the way ahead in reaching the ambitious target of 80% reduction in greenhouse gas emissions by 2050 [6]. In support of CO_2 reduction, the Solar Trade Association (STA) criticised the removal of solar subsidy on the commercial solar projects and warned the government to keep the British solar companies from losing their global competitiveness. The cost reductions in the solar installations should lead to gradual cuts in subsidy without effecting the industry growth [7]. Hence, it can be hypothesise that the UK power sector has lost a considerable amount of electricity production since the reduction in the subsidy which could have been added to the transmission network. However, the innovation have been promoted by the solar power developers through efficiencies in the operations, manufacturing of solar components and these fuelled the growth of solar PV systems on a commercial scale within the UK over the last few years [8]. Some industry experts also call for solar independence as there is no external support for solar power developers with uniform adoption across residential, commercial rooftops and ground-mounted. The growth in the commercial rooftops and ground mounted installations are closely contested in the UK [1, 9].

Common strategies introduced are the provision of Feed in Tariffs for the renewable generation and provision of loans to fund capital energy efficiency. In order for the technological innovation to thrive, bring economic and environmental benefits to the commercial premises, government has set out regulators to oversee the functions of key industry

---

*Address correspondence to this author at the Centre for Sustainable Technologies, Belfast School of Architecture and the Built Environment, University of Ulster, Newtownabbey, Northern Ireland, BT37 0QB, UK;
Tel: +44 (0) 2890 368037; E-mail: jd.mondol@ulster.ac.uk

E-ISSN: 2410-2199/18

players. For example, the electricity and gas markets in the UK are regulated by the Office of Gas and Electricity Markets (Ofgem) which plays a key role in protecting the interest of consumers. It also ensures sustainability and fairness by promoting competition within the marketplace which enables new product such as PV systems to enter into the Power and Energy market. As a regulator, it has the authority to issue licences to companies to carry out activities in the solar energy sectors. Ofgem works as a safety net for the solar energy sector which sets the level playing field in the UK power and energy market [10]. As a regulator, it sets the levels of return energy companies can make to eradicate monopoly and makes decision on the changes that energy companies are allowed to make in the market with regards to price and promotions.

The potential of commercial scale solar power generation is high with large contribution to the national electricity grid by 2020 with no government support. The transition to the low carbon society has already started in the UK, and the reduction in the hardware costs over the last decade has only made the solar panels affordable to the domestic market for commercialisation [11]. The commitment from the electricity power companies such as German EON suggest that the industry is moving toward the renewable sources of energy in the long term [12]. Activists on solar PV systems predict that this form of energy generation will be competitive in UK without any subsidy in the commercial rooftop market. The large scale adoption of schools and offices towards solar generation would be economic within the next ten years in UK. The excess electricity generated from the commercial scale solar projects erected on the rooftops of schools or offices will be stored in batteries and integration with the national grid through smooth inter connectors will promote this technology to survive.

There are certain barriers for the commercialization of solar PV systems [13]. These include access to capital, the transaction costs, suitability of building stock and split incentives, primarily landlord-tenant issues. These listed issues were uniform across the European Union and lack of a uniform solar PV commercialization policy is a void for the rapid growth of PV systems in near future. The commercial scale deployment would incur large capital investments from the landlord for the solar photovoltaic panels and take the feed-in tariff payments on a regular basis. However the tenants benefit from the commercial solar PV systems from reduced energy bills. In the UK, the government set up a solar PV strategy group to study the barriers in the adoption of solar PV systems and report on opportunities for reduction in solar installation costs in the region. The property issues in commercial projects in the UK are handled through long term lease contracts between landlords and tenants. The separate finance task force built to overlook the barriers proposed new development rights to spearhead the growth of commercial PV solar systems in the country [14]. The existing rules suggests that the rooftops with over 50 kW in capacity would require approval from planning commission for solar PV installation, and this process further lead to long deadlines & uncertainty. The solar developers association voiced this as a major concern in the deployment of large scale commercial solar projects, and proposed the approvals to be limited up to solarinstallations of one megawatt.

The aim of this research is to understand the role of solar power generation in the UK Energy and Power sector, and comprehend all aspects of successful implementation ofcommercial scale solar power generation. This study also highlighted the problems encountered in the implementation of the solar units from technical feasibility, profit viability, and other environmental perspective. The research study is also aim to look at the process followed in the installation of a commercial solar power generation unit and other external factors that plays a key role in such implementation. The main objective of the study were as follows

- To study the problems in the implementation phase of commercial scale solar power generation units within UK.
- To study the economic and technical issues related to the connection of solar generation to the distribution network.
- To propose new solutions in line with the policies and regulations that can assist in the growth of commercial scale solar power generation in UK.

Both qualitative and quantitative approaches were used for this study. The qualitative approach was applied for the analysis of present condition of power network and solar power connections and took the benefit of qualitative approach to analyse the data collected from different sources.

2. POWER NETWORK IN THE UK

The electrical power supply to the end customer is facilitated through transmission and distribution companies in the UK. The transmission system operates at normally 400,000 volts (400kV) or 275,000 volts or 275kV. In Scotland it includes 132,000 volts (132kV) as well. The distribution system operates at voltages from 132kV to the usual domestic voltage of 230V [15]. The power distribution industry is competitive in the UK with many companies operating through purchase of electricity from generators and sells it to the domestic residents or industries accordingly. Responsibility of providing a reliable and quality supply of electricity commodity to their connected customers relies on transmission and distribution companies which are regulated by Ofgem. They are also subject to other statutory requirements like the Electricity Act and Electricity Safety Quality and Continuity Regulations which are overseen by DECC and the HSE.

2.1. UK Transmission and Distribution Network

In the UK, the power network system consists of a mixture of overhead lines and underground cables. Then there are substations, where voltage are stepping up or stepping down for the transmission convenience. These substations are also used for controlling and switching of power transmission and distribution. Current network design takes account of steady growth of around 1.5% per year but various studies by different organisations indicate load growth is likely to be unchanged or may be decreased due to economic crunch and recently developed energy efficiency applications. Connecting more renewable generations to the low voltage network also in effect reduce the power flow in high voltage systems. Generally in the UK any voltage that is at 11,000 volt is called as High Voltage and voltage above and including 33kV is called as extra High Voltage. The network that is above and including 275kV is widely known as super grid network. The design of UK electricity network is, normally overhead lines of 33kV and above connect one big substation to another substation with no midway connections. From EHV substations 11kV overhead lines or cables go out to feed small distribution transformers or individual HV customers. The distribution transformers then reduce the high voltage to 230 volt single phase and 400V three phase for domestic use. In this radial feeders, the current flowing in at one end of the circuit gradually reduces along the line as current is consumed by individual customers.

2.2. PV Generation and Grid Connection

Distributed Generations like PV systems fundamentally provide some benefits to the distribution system. They may level the load curve, improve the voltage profile across the feeder, may reduce the loading level of branches and substation transformers, and provide environmental benefits by offsetting the pollutant emissions. Utility company's benefits also include loss reduction, generation capacity, distribution and transmission capacity investment deferral, lowering risk from fluctuating fuel prices, green pricing etc.

The integration of solar power grid to the existing power grids is a challenge for the power transmission companies. Increased integration of Renewable Energy Sources (RES) such as PVs introduce additional uncertainties in the power injections into the system due to their intermittent generation throughout the year [16]. The penetration of 10GW of power generated from the solar PV systems would not cause any major operational problems in regulation of power supply. The solar PV installations should comply with the relevant standards for frequency tolerance across the power grids. The solar PV tripping at the low frequencies should be managed for efficient power transfer from the solar grid at the commercial power generation facility to the adjacent power grid.

Since PV generation depends on sun light there is continual change in the voltage and frequency response of the system. The fundamental PV systems used for solar generation and consumption are basically designed on unity power factor where output power depend heavily on the efficiency of inverter. The inverter used have no fault detection and utilization plan neither they are designed in way to fulfil voltage requirements at low voltage times. As there is no inertia as such involves in photovoltaic system so to maintain frequency oscillations extra devices are used. The size of generation solar cell is small. PV system does not consume any reactive power. It was found that if PV system is installed centrally with maximum tolerable system level protection of 5% the limit will be imposed by transient following capabilities (ramp rates) of the main conventional generators [17]. Another research shows that the plant had a very stiff connection with the grid and it completely showed very low PV penetration level at Southern California Edison central-station PV plant at Hesperia, CA [18]. Distributed generation (DG) with high penetration of renewable energy sources as in (DISPOWER) is called by European consortium which include many institutes and universities along with manufacturers and many people from the utility community. Many different configuration and combinations of DG were examined in the report. The Power Quality Management System (PQMS) in which physical communication channel known as TCP/IP as its protocol and Ethernet cables is used. Some of the initial test concluded was found suitable, the problems which may rise at high penetration levels of DGs were discussed in one section of the report. Though harmonics were found a bit higher when the DGs were found present but they never reach to some dangerous level. The study has no report on the consequences which may occur in case of maximum penetration level. Study shows that in UK the series impedances were slightly higher than they were found in United States. It analysed the likelihood conveyances of voltages in a mimicked 11 kV dissemination framework with differing levels of PV entrance, utilizing a lopsided burden stream model. At 50% penetration level the voltage found higher than the mentioned examined limits [19]. So the authors suggested and concluded that the limit which was purposed as 33% is arbitrary. Voltage dips because of cloud drifters may be an issue at half infiltration, and the creators recommend further investigation of this issue.

2.3. Impact on the National Grid

UK used the Feed-in Tariffs (FiT) initiative to highlight the potential of solar power generation, and created a new age interest in the solar PV generation [11]. Ofgem stated that the reduced price of PV panels and coupled with reduction in Feed in Tariffs unit cost accelerated the contribution of the solar power to the total national electric grid. The present system does not have any integration with the commercial scale solar power generation units, and national grids couldn't track the capacity addition from the solar generation. However the standalone residential solar PV systems are sustainable for the internal use and excess electricity is stored in the batteries. The smart meters were one way to track the electricity flow from the commercial solar grids to the national grid to account their contribution. Studies conducted to identify the impact of solar power generation on the national grid resulted in few theories to understand the effect on the summer minimum demand and winter peak demand. According to National grid, almost 10GW of PV generation can be accommodated on the system without having any issues with the existing transmission network operation [20]. Anything beyond this will create issues with regulating down over summer minimum and will increase the amount of wind power constrained off.

The researcher also reviewed the data from the national grid UK experiment results on the electricity storage options that can mitigate transmission of electricity from solar grid to the national grid. The contribution from the solar grid is expected to have a smooth integration with the national grid through interconnectors, and frequency modulation to ensure transition accordingly. Cavalcanti [15] questioned the readiness of the national grid to hold the demand from the commercial scale solar projects that are currently underway in high solar radiation zones within the UK. The transmission network inefficiencies should be fixed to ensure zero loss in the electrical transmission from standalone solar grids to the nearby national grids in the region for commercial purposes. The unit cost of the power sourced from the commercial scale solar plants range from four to five pounds per watt.

2.4. System Analysis for Connection Design

There are varieties of modelling tools to perform system analysis. Engineers use these tools in the design, analysis, maintenance and operation of electrical power systems. Most common analysing softwares available in the market are Powerfactory, ETSP, PSSE, PSCAD etc. Any tools that needs data depends to the voltage level, size and location of the connection. These data's are normally supplied by the generator to DNOs when they are applying for the connection. After collecting the data's, DNOs undertake studies like embedded generation at 132kV or less, which is connected to the transmission system via super grid transformers.

This model includes equivalent source representing existing generating machine's fault level arising from asynchronous plant, interconnection impedances, loads, and possibly thegenerators proposal for reactive compensation plant. The parameters of these elements depends upon the selection of the boundary nodes between the equivalent and detailed networks in the model. Knowledge of the transformer tap changer limits voltage control set points is essential. It may be beneficial to model some of the 'active' elements in full detail. Figure **1** shows the power distribution model in the UK.

Super grid, grid, primary and other distribution transformers can be considered active for the purpose of determining voltage control limits. Fault contribution may also come from other rotating plant.

2.5. Security of Supply

Security and supply quality standards (SQSS) are meant at providing all resources and infrastructure to

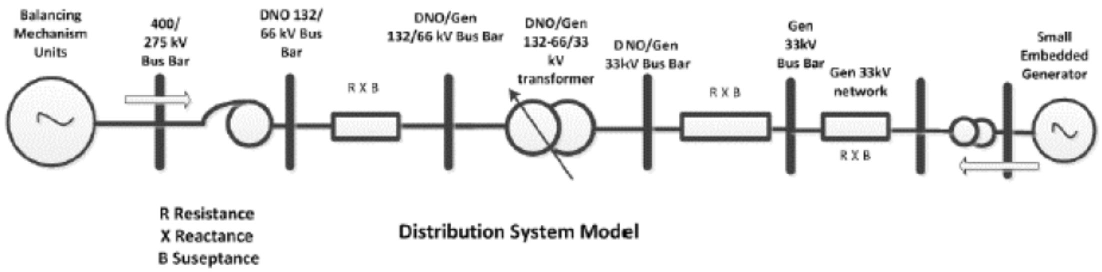

Figure 1: UK power distribution model.

provide reliable power supply to the customer. The connection of new generators to the distribution system should not generally increase the risk of interruption to existing customers. Isolation of the generator from the system should be possible by minimum interruption to the network. Most DNOs have some rules on this matter. For example a connected circuit should be able to isolate from the system by parting not more than seven circuit breakers and these circuit breakers shall not be located at not more than four different substation. The security for the connection of the generator is subject to economic consideration by the generators. A firm connection option should let the full capacity to be exported at all times of year even after one outage or fault of any one circuit of the distribution network. Most PV generators are opting for non-firm connection due to the cost implication as it required more circuit breakers and associated equipment.

All generators that need connection need to be assessed by the DNO, considering of maximum and minimum load and generation export scenarios during system intact conditions and for maintenance outages of both the distribution system and generator. Since the generation discussed here is solar, worst case scenario is summer, where less demand and maximum generation.The main factors that affect the network safety and reliability of power supply are:-

- Harmonic Distortion
- System Stability
- Fault Level
- Frequency of the electricity
- Voltage of the electricity

2.6. Protection Requirements

Parallel operation of embedded generation requires under/over voltage and under/over frequency protection. Loss of Mains protection relay is also required. G59/2 or G59/3 multifunction relays now have this function built in as standard. Additional requirements such as neutral voltage displacement, intertripping and reverse power are sometimes required. It is recommended that the generator unit's transformer star points or neutrals are permanently connected to earth to minimize the circulating currents and harmonics.

The main function of the protection systems is to prevent the generator feeding an islanded section of the distribution network which could pose a hazard to the distribution network or customers connected to it. The settings of these systems adopt two stage approaches that are to have long delay from smaller variations that may be experienced during normal operation of the network to avoid unnecessary tripping, but with a quicker approach for greater variation of parameters. The basic required protection for the generator is

- Under Voltage
- Over Voltage
- Under Frequency
- Over Frequency
- Loss of Mains

Following the DNO study for the new generation connection, the generator may require additional protection to be installed to detect below parameters.

- Neutral Voltage Displacement
- Over Current
- Earth Fault
- Reverse Power Flow.

Above protection will usually be connected on equipment owned by the distribution network operator. If intertripping is considered for any system outages or fault, the equipment would be installed by the distribution network operator.

2.7. Active Management of Power Flows

Active management is a procedure by which DNO and the generator monitor their respective plant with the purpose of responding to network or generation changes in order to make sure that the network and generation continue to operate within safe and approved parameters, where monitoring means manual, electronic or any other form of monitoring that is appropriate for the specific connection. Active management of power flow is necessary for distribution networks to overcome power flow limitations associated with the connection of a generating station. So basically, active management solutions are one of the techniques available to help enable the connection of more distributed generation in support of government targets for renewable generation. Even though these options are available to facilitate the connection of a generator, there could be circumstances where a DNO is unable to offer connection due to fault level or voltage control issues. Basically there are four solutions for increasing the use of the power flow capability of the distribution system, considering each solution as a separate choice as a substitute to killing power flow restrictions by traditional expensive asset reinforcement. In making a decision the DNO will be expected to consider the ratings of plant both in the forward and reverse direction and at the same time the network remains compliant with the requirements of the distribution code and regulations. And the study provides some information on situations where a particular solution is most likely to be suitable. The solutions described here is generally applicable to distributed generation connected to high voltage networks supplied by two or more circuits operating in parallel at 132kV or below.

When evaluating the rating of electrical equipment and circuits it is essential to look at all likely conditions of operation. This includes the ambient temperature, summer and winter rating, short term rating of the equipment. Moreover for ground mounted plants such as transformers, it will be crucial to consider if there is any restriction on rating for reverse power flows. When assessing a transformer rating, attention should be given to the rating without cooling fans and pumps (ONAN) and whether there are any ambient temperature limitations. Continues emergency rating of the transformer is based on the fans and pumps running all the time (OFAF). The transformer will not be operating outside of its cyclic rating in any circumstances.

Power flow management consider the capability and safety of the network for both an intact system and following circuit outages, transient or permanent faults. A first circuit outage (FCO) incident can be either a planned event or due to faults. A second circuit outage (SCO) incident normally refers to a fault happened on a network that has already hit a FCO.

2.8. Pre Outage / Pre Fault Constraints

Traditionally generators are allowed to connect to the distribution network to the capacity of the network that would be available under the first circuit outage conditions. That condition is often called as firm capacity of the network. So the generation needs to be limited to the post outage network capacity. If the network have two parallel circuits of equal rating, above said approach will allow the generation at full output for both an intact system and following the first circuit outage. For the networks where more than two parallel circuits, under the condition of first circuit outage, whether it is a fault or planned, the generator will be required to reduce the generation to a level or below the capacity of the second circuit outage of the power network or shut down completely.

2.9. Consideration of Demand

It is possible to connect the generator by taking into account the local demand on the substation. If the substation minimum demand is considered, allowed generation can be increased to 14MVA by adding minimum demand 2MVA to 12MVA. It is assumed that the substation plant can allow full reverse power flow. If that is not the case in reality generation capacity may need to be reduced according to the reverse power flow capabilities and protection settings. The connection capacity could be further increased by use of summer and winter minimum demands but due to the volatile nature of the demand DNO can’t guarantee that demand will always remain at certain level. The generation capacity that can be connected at a particular point on the network could be based on and intact system with summer minimum demand. Solar electricity generation is maximum in summer when demand is low respective to winter.

2.10. Active Management Solutions

Since it is risk allowing the generation in excess of the traditional limit of the firm capacity of the substation active and passive solutions need to be applied or considered for the connection. Below cases are based on the assumption transformers are rated for full reverse power flow and no protection issues that prevent reverse back feeding. The solutions proposed here is for reduced overall connection cost since network reinforcement may not be necessary.

3. CASE STUDY SIMULATION AND CONNECTION PROCESS

3.1. Case Study and DNO's usual Connection Process

Grid integration costs include the costs associated with integration of PV into bulk power and distribution and modeling the cost of each of these systems involves distinct challenges [21]. DNOs assesses the technical considerations required in making an economic PV generator power connection. The feasibility study of DNO identifies the cost effective options taking into attention network capacity, voltage rise, fault level rise, reverse power flow capability of grid transformers. Once DNO received a generation application to connect to their network, they offer a complete and comprehensive connection service, however if the generator wants they can ask an Independent Connections Provider (ICP) to carry out some of the work identified as the 'contestable' work. Regardless the connection option generator chooses, DNO sends the generator a formal quotation for the work they undertake. This is called a connection 'Offer'. Mainly two types of works are associated with DNO connection, Contestable works and Non Contestable works. Contestable works are works that can be done by an Independent Connection Provider rather than DNO. These include design, materials, site civil works, trenching, laying, construction and some elements of reinforcement and alteration to the existing network. Non Contestable works are works that must be done by a DNO. These include providing point of connection, design approval, consents and wayleaves, inspection and final testing and commissioning.

3.2. Study Simulation

In the following case study simulations examples of different capacity PV request to the DNOs used to do the technical assessment and check the most possible option of connecting the PV farm to the power network. The aim of the case study simulation is to understand how the connection requests are handled by a DNO's assessment engineer technically according to the size and location of the plant. The assumption is made for the total cost calculation and the price may vary according to manufacturers and contractors even though some information taken from Parsons Brinckerhoff [22] unit costs review for a DNO 'Western Power Distribution'. Figure **2** shows the Normal

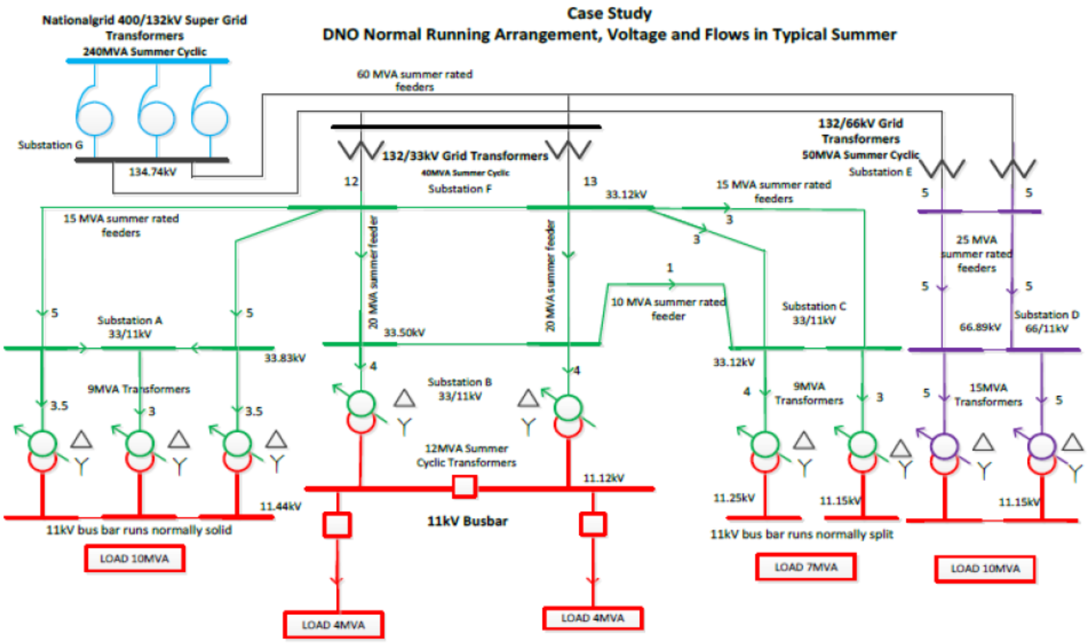

Figure 2: Normal Network Running Arrangement for Case Study Simulation.

Network Running Arrangement used for Case Study Simulation

3.2.1. Case Study on 5 MW PV Farm Connection

The first case study considered a 5 MW solar PV system installed on a farm land in the UK. The solar grid is connected from a farm which is 500 meter away to a 66kV/33kV primary substation. The farm is equipped with five 1000kVA inverters and single 5000kVA transformer. The analysis of the farm grid is based on the site assessment, feasibility assessment, and electrical assessment to build a case for integration of the solar grid with the national electric grid.

3.2.1.1. Site Assessment

The key characteristics of this PV system are follows:

- The full export capacity of the solar PV farm grid is 5.0 MW.
- Farm site is close to existing 11kV 50 sq. mm 180A summer rated ACSR OHL feeder and 500m away from nearest primary substation 'B'. Feeder maximum demand or flow is less than 1MVA.
- 33kV line access is more than 5 km away from the farm
- There is no 132kV access in the nearest vicinity of the farm.

3.2.1.2. Feasibility Assessment

- Farm site is close to the High Voltage OHL feeder. So less cable work is required.
- There is a 391A 33kV 100 sq. mm AAAC OHL goes 100meters away from the farm.

3.2.1.3. Electrical Assessment

- Tee off 11kV connection is the best but the rating of the existing OHL is not enough to carry 5MW generation. √3 × (11 × 11000) × 180= 3.42MVA. Reinforcement required to existing line that costs high and obtaining consents and way leaves may take long time to finish. So a connection at 11kV bars at Primary through a CB is the possible option.
- As the 11kV option is identified and connection point is not far from the farm, 66kV option ruled out due to its high connection cost. The more the voltage the more the expense due to equipment costs.
- Proposal is to connect the generation to 11kV bus bars at primary substation 'B' through a new circuit breaker.
- 12MVA rated transformers still feed the 3MVA demand at site and total flow will be equally shared by both transformers. No reverse power flow identified. Transformer tap changer is automatic and still one tap left before it reach maximum to control the voltage.
- (-1.16+1.59)=0.43. Max tap is 0.43%. 11kV at HV bus bar is slightly raised to 11.34 from 11.12 in the normal running arrangement.
- Flow through the EHV circuits is still within the limit and no overloading identified. N-1 studies indicate no issues. One transformer outage will leave the remaining on service and rated enough to supply the demand and no voltage issues.

Table 1: Costs of Grid Connection for a 5MW PV Project

SlNo	Items	No's	Unit cost (£)	Total cost (£)
1	185 mm^2 triplex EPR cable	500	17	8,500
2	Straight joint and installation	1	682	682
3	Excavation Roadway	500	83	41,500
4	Ring Main Unit	1	5,000	5,000
5	11 kV Enclosure	1	2,000	2,000
6	11kV CB	1	10,000	10,000
7	Miscellaneous	1	10,000	10,000
8	Telecontrol Facilities	1	10,000	10,000
	Total			£87,682

Rounded to: £90,000.

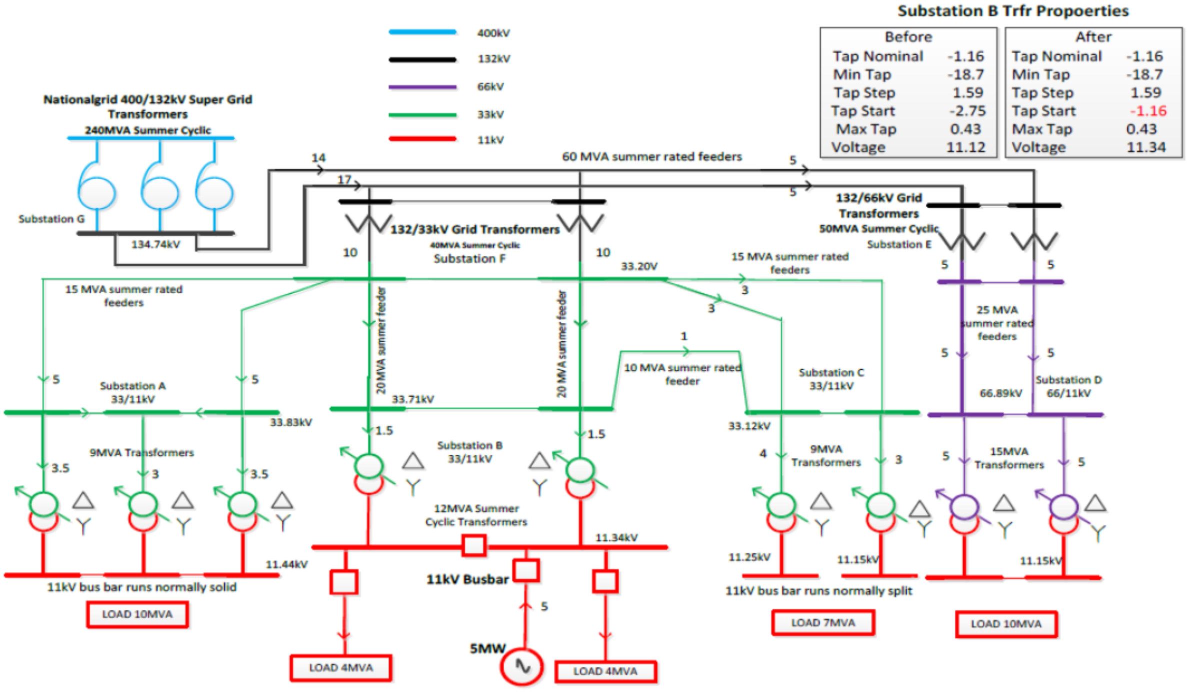

Figure 3: 5MW PV Connection to 11kV.

Any 33 kV circuit outages in the vicinity are not causing any overloading due to its good rating.

Table **1** summarises the various costs components of the costs of grid connection for a 5 MW PV project. Costs given below are indicative and for sample calculation purposes only. Actual costs may vary with manufacturers and contracts. The total project costs is estimated to be around £90,000. The analysed costs can be compared with the study reported by [21].

3.2.2. Case Study on 30MW PV Farm Connection

A 30 MW solar PV system installed on a farm land in the UK is considered for the case study. The solar PV farm is 700 meter away from the nearest 66kV/33kV primary substation. The farm is equipped with 30 1000kVA inverters and single 30000kVA transformer.

3.2.2.1. Feasibility Assessment

- 11kV option not considered due to the size of the PV generation.
- The full export capacity of the solar PV farm grid is 30 MW.
- Farm site is 700m close to existing 33/11kV substation.
- Two 200 sq. mm 638A summer rated AAAC OHL on steel tower is feeding the nearest substation.
- There is no 66kV or 132kV access in the nearest vicinity of the farm.
- 8Farm site is 100m away from the EHV OHL feeder. So less cable work will be required for a ‘tee off’ connection.
- 33kV connection located at more than 5 kms from the site.

3.2.2.2. Electrical Assessment

- Connection at 11kV bus bar is the cheap and best but the 12MVA transformers are not rated enough to export the full generation. Hence 11kV connection possibility is ruled out.
- Next option is to tee off the closest 33kV feeder as it got 35MVA summer rating. Since it is close to the PV farm, less cabling required. As the ends and addresses numbers are within the limits and the circuit is not unit protected, it is electrically possible to ‘tee off’.
- Tee off to steel tower need new tower with cable sealing end platform and any tower replacement costs a fortune. So tee off option need to be cancelled as the OHL is on steel tower. Steel

tower is only viable if the total capacity of the power station is high enough and cabling to next possible option is too long to justify the connection cost and there are no other options available.

- Since the 33kV primary substation is only 700m away from the PV farm and the substation compound got enough room to accommodate a new bay it is finally proposed to connect the generation to the 33kV bus bars at 33 kV substations.
- Voltage rise is within the statutory limit in connecting and neighbouring substations. Transformer tap changers are also in control. No further issues identified in studies.
- Flow through the EHV circuits is still within the limit and no overloading identified. N-1 studies indicate no thermal or voltage issues.

3.2.2.3. Cost Analysis for the 33kV project

Table **2** shows the costs of grid connection for a 30 MW PV project. The total project costs is estimated to be around £525,000.

3.2.3. Case Study on 40MW PV Farm Connection

The third case study is a 40 MW solar PV system installed on a farm land in England. The solar PV farm is 2 km away from the nearest primary substation and 200m away from the 200AAAC 66kV OHL so less cable work will be required for a ‘tee off’ connection. The farm is equipped with 40 1000kVA inverters and single 50000kVA transformer.

3.2.3.1. Feasibility Assessment

- 11kV option not considered due to the size of the PV generation.
- The full export capacity of the solar PV farm grid is 50 MW.
- Farm site is 2000m close to nearest primary substation.
- Two 200 mm^2 638A summer rated AAAC OHL on H Poles is going close to the farm site.
- There is no 33kV access in the nearest vicinity of the farm. 132kV connection option is in less than 500m away from the farm site.
- 33kV connection located at more than 5 km from the site.

3.2.3.2. Electrical Assessment

- Connection at 11kV circuit is cheap and best but the 40MVA cannot be connected to 11kV practically.
- Next option is to tee off the closest 663kV feeder as it got 73MVA summer rating. Since it is close to the PV farm, less cabling required. As the ends and addresses numbers are within the limits and the circuit is not unit protected, it is electrically possible to ‘tee off’.
- Connection to 132kV is ruled out as 66kV option is available and 132kV connections always cost more.
- Number of ends and addresses checked and they are in the limits. Protection also has no issues for tee connection.

Table 2: Costs of Grid Connection for a 30 MW PV Project

SlNo	Items	No’s	Unit cost (£)	Total cost (£)
1	185 mm^2 triplex 33 kV EPR cable	700	50	35,000
2	Straight joint and installation	2	682	1,364
3	Excavation Roadway	700	83	58,100
4	33 kV farm substation complete	1	300,000	300,000
5	Primary substation reinforcement	1	50,000	50,000
6	33 kV CB	1	50,000	50,000
7	Miscellaneous	1	10,000	10,000
8	Telecontrol Facilities	1	20,000	20,000
	Total			£524,464

Rounded to: £525,000.

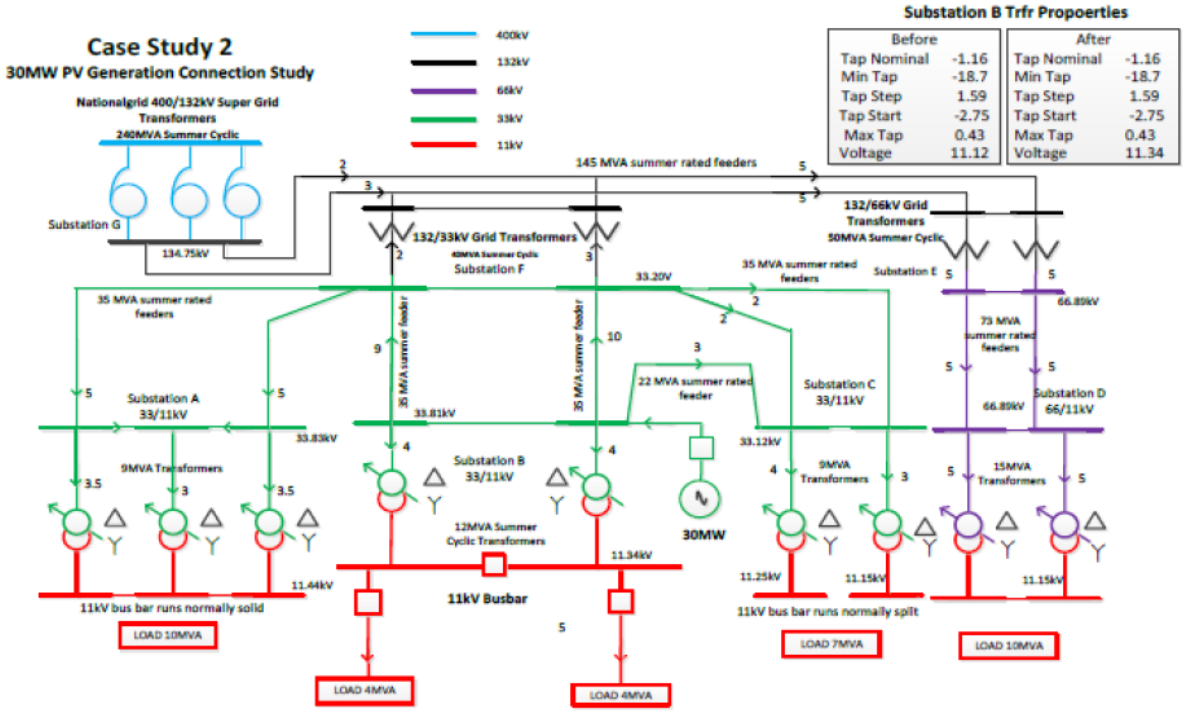

Figure 4: 30MW PV Connection to 33Kv.

- Tee off to 66kV H pole is the cheapest option identified and it is finally proposed to connect the generation to the 66kV OHL as a 'tee' connection.
- Voltage rise is within the statutory limit in connecting and neighboring substations. Transformer tap changers are also in control. No further issues identified in studies.
- Flow through the EHV circuits is still within the limit and no overloading identified. N-1 studies indicate no thermal or voltage issues.

3.2.3.3. Cost Analysis for the 66kV PV Project

Table **3** shows the costs of grid connection for a 40 MW PV project. The total project costs is estimated to be around £600,000.

3.2.4. Case Study on 50MW PV Farm Grid

Final case study considered in this study is a 50 MW solar PV system installed on a farm land in England. The solar PV farm is 2 km away from the nearest primary substation 'Substation F' and 100m away from the 300AAAC 132kV OHL circuit so less cable work will be required for a 'tee off' connection.

Table 3: Costs of Grid Connection for a 40 MW PV Project

SlNo	Items	No's	Unit cost (£)	Total cost (£)
1	185 mm^2 triplex 33 kV EPR cable	200	200	40,000
2	Straight joint and installation	2	682	1,364
3	Excavation Roadway	200	50	10,000
4	66 kV farm substation complete	1	400,000	400,000
5	H poles with disconnector	1	50,000	50,000
6	66 kV CB	1	50,000	50,000
7	Miscellaneous	1	10,000	10,000
8	Telecontrol Facilities	1	20,000	20,000
	Total			£581,364

Rounded to: £600,000.

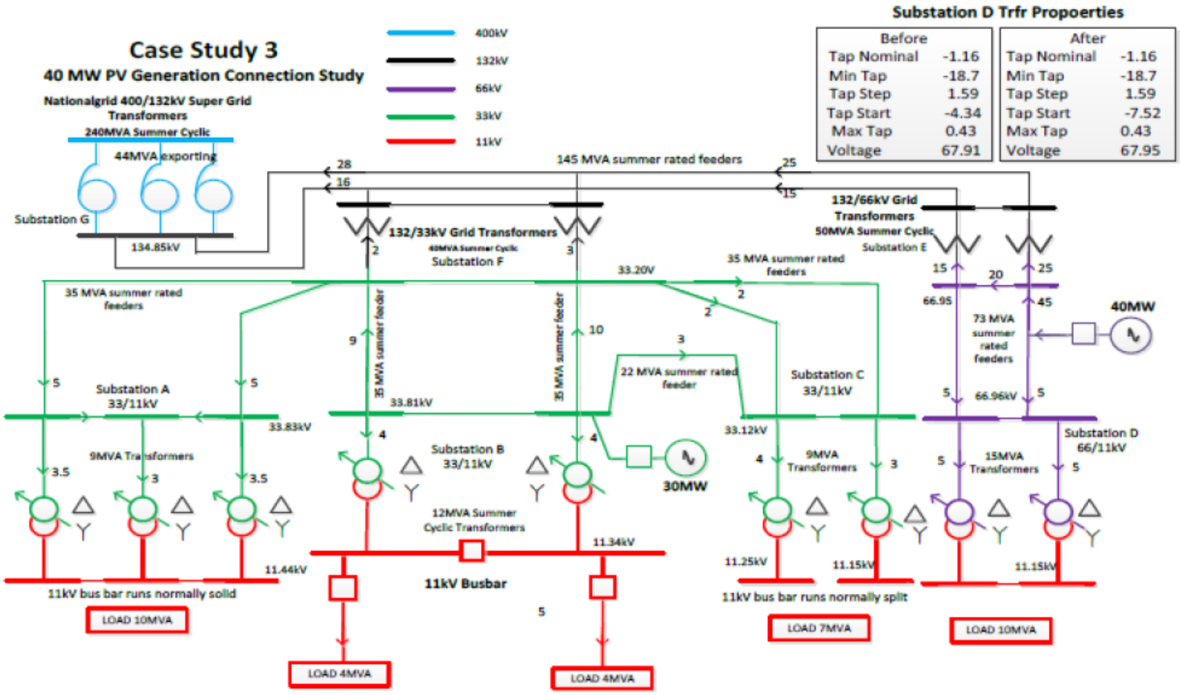

Figure 5: 40MW PV connection to 66Kv.

The farm is equipped with 50 1000kVA inverters and single 50000kVA transformer.

3.2.4.1. Feasibility Assessment

- 11kV option not considered due to the size of the PV generation.
- The full export capacity of the solar PV farm grid is 50 MW.
- Two 300 mm^2 840A summer rated AAAC OHL on Steel Tower is going close to the farm site.
- There is no 33kV and 66kV access in the nearest vicinity of the farm. 132kV connection option is in less than 100 m away from the farm site.

3.2.4.2. Electrical Assessment

The key electrical parameters are.

- Connection at 11kV circuit is cheap and best but the 50MVA cannot be connected to 11kV practically.
- Next option is to tee off the closest 132kV feeder as it got 191MVA summer rating. Since it is close to the PV farm, less cabling required. As the ends and addresses numbers are within the limits and the circuit is not unit protected, it is electrically possible to ‘tee off’.
- Connection to 132kV is justified due to the size of the farm. 66kV option is available but available 66kV point of connection is 200m away from the farm and cabling for 2000m will make the scheme expensive.
- Tee off to 132kV steel tower is the practical option identified and it is finally proposed to connect the generation to the 132kV OHL as a ‘tee’ connection.
- Voltage rise is within the statutory limit in connecting and neighboring substations. Transformer tap changers are also in control. No further issues identified in studies.
- Flow through the EHV circuits is still within the limit and no overloading identified. N-1 studies indicate no thermal or voltage issues.

3.2.4.3. Cost Analysis for the 66kV project

Table **4** shows the costs of grid connection for a 50 MW PV project. The total project costs is estimated to be around £800,000.

Table 4: Costs of Grid Connection for a 50 MW PV Project

SINo	Items	No's	Unit cost (£)	Total cost (£)
1	185 mm^2 triplex 132 kV EPR cable	200	150	30,000
2	Straight joint and installation	2	3000	6,000
3	Excavation Farm land	200	50	10,000
4	132 kV farm substation complete	1	400,000	400,000
5	132 kV Tower Replacement complete	1	250,000	250,000
6	132 kV CB	1	60,000	60,000
7	Miscellaneous	1	10,000	10,000
8	Telecontrol Facilities	1	20,000	20,000
	Total			£786,000

Rounded to: £800,000.

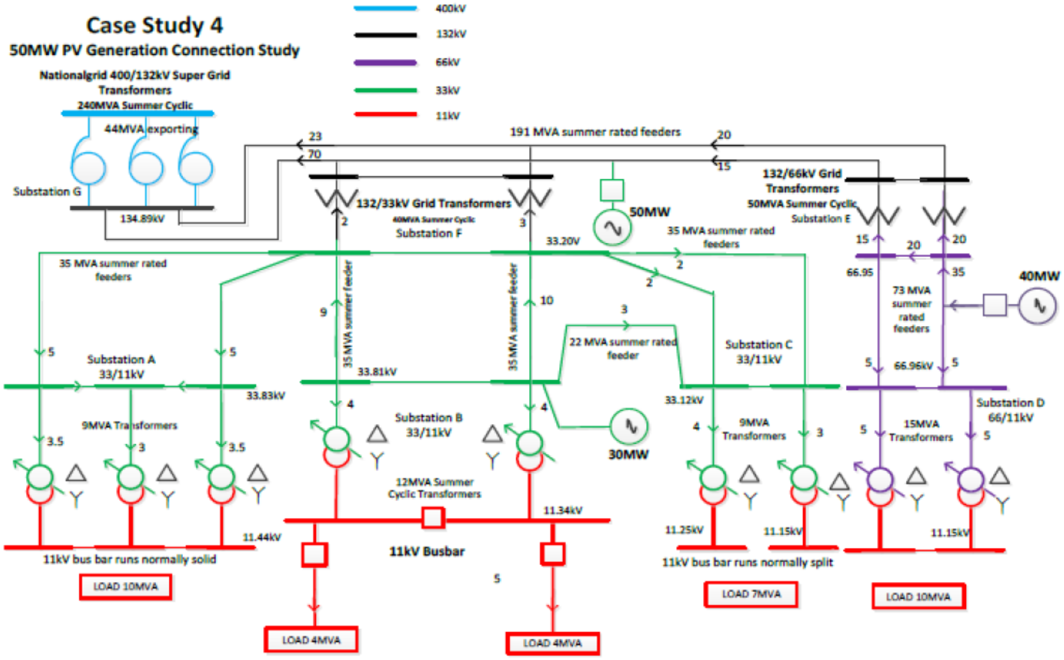

Figure 6: 50MW PV Connection to 132KV.

CONCLUSION

The aim of this study was to examine the potential of commercial scale PV generation in the UK and the issues related to its grid connection. The research showed that all agencies are currently encouraging the use of renewable energy technologies especially solar PV even though financial incentives are now reduced to an extent. DNOs are also seeing more interested investors to develop solar farms in various part of the country.

The study examined various farm with respect to costs to identify a farm with least grid connection costs.It was found that the most economic connection for a PV generation in the region of 5MW is 11kV if it can be integrated to the network with less cabling. Any connections above 11kV is economically feasible only if the amount of generation is high enough to justify the initial infrastructure investment. It was shown that the implementation of a standard method cannot be applied for the connection to DNO network. Though any generations are technically possible to connect to the grid, it would not be economically feasible in the long term and payback periods are far too long. The hope is the latest technologies that already developed or under development that can help to improve the efficiency of existing and new PV system and power network.

The work provides valuable information to the users who are not aware about different connection methods and feasibility analyses techniques adopted by network owners for distributed generations. This work also educates those who are interested about commercial scale solar generation and the potential of such big PV farms in the UK. This study explains s why a PV generator cannot be connected cheaply to some locations and why huge amount of reinforcement required for some connections. The study indicates the importance of the site selection for the PV farm in terms investment costs and reinforcement requirement.

REFERENCES

[1] Dusonchet L, Telaretti, E. Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. Energy Policy 2015; 65: 229-244.

[2] Strielkowski W, Štreimikienė D, Bilanc Y. Network charging and residential tariffs: A case of household photovoltaics in the United Kingdom. Renewable and Sustainable Energy Reviews 2017; 77: 461-473. https://doi.org/10.1016/j.rser.2017.04.029

[3] CEBR (2014). Solar powered growth in the UK. [Online] Retrieved from http://www.cebr.com/reports/solar-powered-growth-in-the-uk/.

[4] Jordan PG. The Solar Labor Market-Efficiencies and Productivity Solar Energy Markets 2014; pp.111-126.

[5] Cherrington R, Goodship V, Longfield A, Kirwan A. The feed-in tariff in the UK: A case study focus on domestic photovoltaic systems. Renewable Energy 2013; 50: pp. 421-426. https://doi.org/10.1016/j.renene.2012.06.055

[6] Canocchi, C. (2014). Solar panels could help slash £425m a year from energy bills by 2030 and boost the economy by £25.5bn, study claims. [Online] Retrieved from http://www.thisismoney.co.uk/money/bills/article-2769242/Solar-panels-help-slash-energy-bills-425m-2030.html.

[7] Barwell P (2014). Potential economic benefits of investments in solar PV. [Online] Retrieved from http://www.cebr.com/reports/solar-powered-growth-in-the-uk/.

[8] Balcombe P, Rigby D, Azapagic A. Investigating the importance of motivations and barriers related to microgeneration uptake in the UK, Applied Energy 2014; 130(1): 403-418. https://doi.org/10.1016/j.apenergy.2014.05.047

[9] Tucker R. UK's clean energy industry seeks Government's support. Renewable Energy Focus 2014; 15(5): 10-13. https://doi.org/10.1016/S1755-0084(14)70112-7

[10] DECC (2011) Ofgem Review: Final Report. [Online] Available at https://www.gov.uk/government/uploads/system/-uploads/attachment_data/file/48134/2151-ofgem-review-final-report.pdf.

[11] Kirby A (2014). Outlook is bright for UK's solar power potential. [Online] Retrieved from http://www.climatenewsnetwork.net/outlook-is-bright-for-uks-solar-power-potential/.

[12] Horne S (2014). Farm Power: Green energy opportunity offers earnings and security. [Online] Retrieved from http://www.fwi.co.uk/farm-energy/farm-power/farm-power-green-energy-opportunity-offers-earnings-and-security.htm.

[13] Newswire (2014). UK Rooftop Solar Moves into High Gear. [Online] Retrieved from http://www.chadbourne.com/-uk_rooftop_solar_june2014_projectfinance/.

[14] Bourne C (2014). UK Rooftop Solar Moves into High Gear – Distributed Generation, Residential, Commercial, Feed-In Tariffs, and Incentives. [Online] Retrieved from http://www.chadbourne.com/uk_rooftop_solar_june2014_projectfinance/

[15] Cavalcanti M, Azevedo, M. Efficiency Evaluation in Grid Connected Photovoltaic Energy Conversion Systems. Photovoltaic Specialists IEEE Conference 2005; pp 269-275 https://doi.org/10.1109/PESC.2005.1581635

[16] Anestis G. Anastasiadis AG, Kondylis GP, Papadimitriou, C, Polyzakis, A, Vokas G, CS. Psomopoulos, CS. Maximum Power Photovoltaic Units Penetration under Voltage Constraints Criteria in Distribution Network Using Probabilistic Load Flow. Energy Procedia 2019; 157: 578-585 https://doi.org/10.1016/j.egypro.2018.11.222

[17] Chalmers S, Hitt M, Underhill J, Anderson P, Ingersol R: IEEE Transactions on Power Systems 2006; 21

[18] Patapoff N, Mattijetz D.: Utility interconnection experience with an operating central station MW-Sized photovoltaic plant. IEEE Transactions on Power Systems and Apparatus 1985; PAS-104: 2020-24 https://doi.org/10.1109/TPAS.1985.318776

[19] Quezada V, Abbad J, San Roma´n T.: Assessment of energy distribution losses for increasing penetration of distributed generation. IEEE Transactions on Power Systems 2006; 21:533-40 https://doi.org/10.1109/TPWRS.2006.873115

[20] Behnke, M. (2012). Short circuit contribution from PV Power Plants. [Online] Retrieved from http://www1.eere.energy.gov/solar/pdfs/distribution_modeling_wkshp2012_behnke.pdf

[21] Horowitz KAW, Palmintier B, Mather B, Denholm P (2018). Distribution system costs associated with the deployment of photovoltaic systems, Renewable and Sustainable Energy Reviews 2018; 90: 420-433. https://doi.org/10.1016/j.rser.2018.03.080

[22] Parsons Brinckerhoff. (2013). Review of WPD Unit Costs. [Online] Retrieved from http://www.westernpower.co.uk/-docs/About-us/Stakeholder-information/Our-future-business-plan/Supporting-Business-Efficiency-information/Parsons-Brinckerhoff-review-of-WPD-unit-costs.aspx

---

Received on 20-12-2018 Accepted on 27-12-2018 Published on 31-12-2018

DOI: http://dx.doi.org/10.15377/2410-2199.2018.05.4