STRATEGIC INVESTMENT MODEL FOR FUTURE DISTRIBUTION NETWORK PLANNING

Danny PUDJIANTO Goran STRBAC Sotiris GEORGIOPOULOS Panagiotis PAPADOPOULOS
Imperial College London – UK UK Power Networks - UK
d.pudjianto@imperial.ac.uk sotiris.georgiopoulos@ukpowernetworks.co.uk
g.strbac@imperial.ac.uk panagiotis.papadopoulos@ukpowernetworks.co.uk

ABSTRACT

This paper presents the applications of the developed Strategic Investment Model in the Flexible Plug and Play (FPP) project to determine the optimal network investment portfolio. The Model optimises the investment in smart grid technologies such as Quadrature-boosters, DLRs, SVCs, novel protection systems to improve reverse power flow capability as well as traditional network investment in lines/cables, and transformers. Furthermore, the Model also optimises the type of network access (firm or non-firm) in order to minimise the overall system costs. A set of selected case studies on the FPP test system is presented in this paper to demonstrate the capability of the Model and to highlight the key findings from this work.

INTRODUCTION

Flexible Plug and Play (FPP) is a Second Tier Low Carbon Network Fund (LCNF) project to demonstrate faster and cheaper integration of distributed generation (DG), such as wind power or solar, into the electricity distribution network by trialling new technologies and novel commercial solutions [1]. The increased penetration of DG being experienced due to the demand for low carbon generation often triggers network reinforcement. Instead of reinforcing the network using only traditional network solutions, the FPP project explored new smart technologies and control techniques that provide flexibility and release latent network capacity that has not been historically accessible.

In order to support this project, the Strategic Investment Model (SIM), a novel desktop network planning tool, was developed by Imperial College London to analyse the benefits of smart technologies and smart commercial arrangements that were trialled and demonstrated in the project. The SIM supplements and automates traditional network planning practices based on load flow analysis, and for the first time, provides the capability of optimising and coordinating a portfolio of smart and traditional investment decisions across multi-year time horizon. The investment decisions are optimised simultaneously with optimising operational decisions related to the settings of smart devices (such as tap settings, real and reactive power output of generators) within equipment settings limits, network thermal limits and voltage constraints.

This paper describes the simulation approaches used in the SIM, its applications in optimising smart grid technology investment options and analysing the costs and benefits of alternative distribution network planning strategic decisions investigated by the FPP project. The studies, carried out on the 33 kV distribution network in the FPP trial area covering 700 km^2 between Peterborough and March in the east of England, focus on a spectrum of applications of smart grid technologies including Dynamic Line Rating (DLR), Quadrature-boosters (QBs), Static VAr Compensators (SVCs), novel protection relays, smart generator controllers, Active Network Management (ANM) – which acts as the 'supervisor' of the smart devices and generator controllers – and smart commercial arrangements in order to improve the economic and technical efficiency of DG integration into the UK Power Networks' distribution network.

OVERVIEW OF THE SIM

In the SIM, the multi-year network-planning problem is formulated as a mixed non-linear integer optimisation problem. The objective is to minimise the total cost of multi-year investment in both smart grid technologies and traditional network assets and the operating cost across the time horizon of the planning study. The SIM takes into account the following costs:

- Investment cost including the cost of:
  - Adding/replacing conductors or building new network corridors;
  - Quadrature-boosters;
  - Dynamic line rating capability;
  - Reactive compensation;
  - Novel protection system to improve reverse power capability in a substation.
- Operating cost including:
  - Electricity cost for supplying load; this includes cost of importing power from transmission grid and DG production cost;
  - Lost revenue from curtailment of DG.

The optimisation is subject to the following constraints.

- Power balance between supply and demand for active and reactive power;
- Thermal capacity limits:

  - Bi-directional power flow limits;
  - With and without improvement from DLR.
- Voltage limits;
- Operating limits of:
  - Quadrature-boosters;
  - Tap-changing transformers;
  - Reactive compensators;
  - Distributed generators.

The SIM uses the AC power flow model to solve the network planning and set-points optimisation problem. The AC power flow model allows active and reactive power flows to be calculated and thus enables appropriate power flows and voltage control to be determined through optimisation.

In contrast to the traditional approach that uses few extreme operating conditions such as minimum demand maximum generation and maximum demand minimum generation for planning studies, the SIM uses a larger set of operating conditions derived from the combination of load and DG output profiles. This enables the SIM to estimate more accurately the network constraint driven operating costs, which are used to justify new investment. Details of the approach can be found in [2].

CASE STUDIES

A set of studies have been carried out to demonstrate the applications of SIM to:

- identify network constraints;
- identify a set of optimal investment options with the timing, and the operating strategies;
- quantify the benefits associated with various smart alternatives to network reinforcements; and
- analyse the strengths and weaknesses of individual alternative solutions and identify the most cost effective solutions.

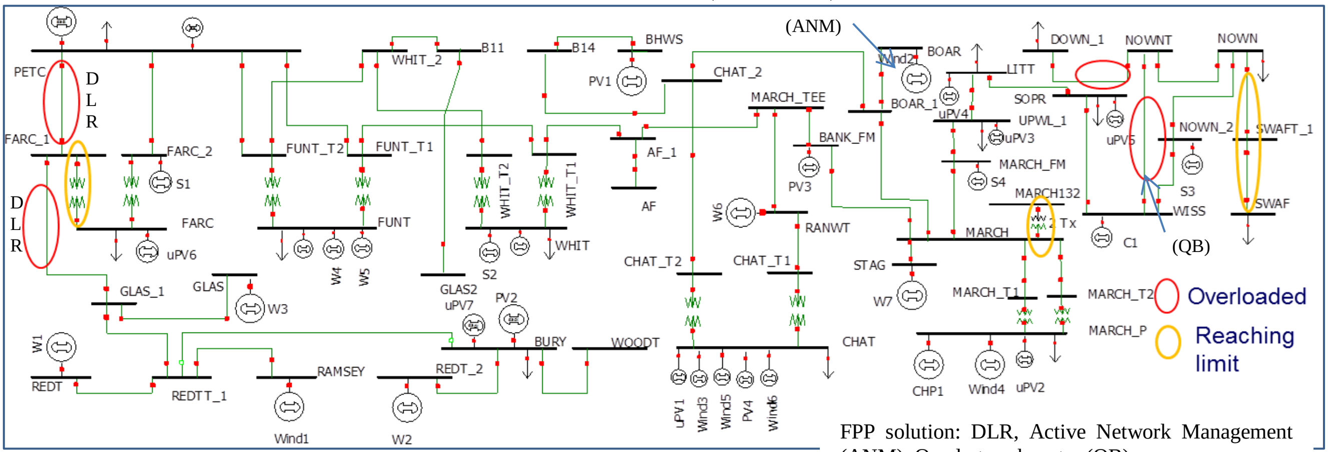
The applications of SIM to solve a number of network problems on a real 33 kV system in Peterborough and March area, e.g. the application of Quadrature-booster in Wissington, DLR along Peterborough Central and Farcet, reverse power flow enhancement at March grid substation and the ANM application in combination with smart commercial arrangement are discussed below.

Description of the FPP area network

The main test system used for the studies is the 33 kV EPN distribution network between Peterborough and March (Figure 1). The system is supplied by four grid substations: Peterborough Central, March Grid, Kings Lynn South (via Downham Market), and Swaffham. Only the 132/33 kV substation at March Grid is modelled in this system. It is important to note that only the constraints in the FPP area network were considered. The network upstream from the 33 kV has not been modelled and consequently constraints that may were triggered in the 132 kV part of the network have not been considered. However, the level of reinforcement around the Peterborough and March Grid Substation can indicate the amount of additional flows that need to flow upstream from these two substations.

Over recent years UK Power Networks has experienced increased activity in renewable generation development activity in this area and a rapid rise in connection applications. At the time of writing this paper, the system has to accommodate 240 MW of peak electricity load and 213 MW of DG including the new 34.5 MW of FPP generators (see Table 1) and micro PV generators (4.35 MW). Different DG technologies are connected to the system including wind power (92 MW), solar power (47 MW) and CHP (74 MW). The number of new connection applications is expected to increase further in future. The connection of this anticipated level of renewable generation is expected to require significant network reinforcement to mitigate network thermal and voltage constraints and reverse power flow issues.

By using SIM, network constraints have been identified. There are three main constrained areas. First, the network between PETC (Peterborough Central) and GLAS (Glassmoor) will be overloaded if no action is taken.



FPP solution: DLR, Active Network Management (ANM), Quadrature-booster (QB)

Figure 1 Flexible Plug and Play network and the identified constraints

Second, due to high increase in the connected DG capacity in March area, the maximum level of the reverse power flow at the March Grid 132/33 kV substation is close to the limit. Third, circuit Wissington (WISS)-Northwold tee (NOWNT) and Northwold tee (NOWNT) and Downham Market (DOWN_1) will be overloaded if no action is taken. Moreover, the Northwold (NOWN) to Swaffham (SWAF) circuits are also constrained. The third constraint is primarily driven by a CHP plant in Wissington with the total capacity of 80 MW and a 5.3 MW solar PV at NOWN_2. Details of this constraint can be found in [2]. Although voltage rise effects were observed in the studies, the voltages still varied within the statutory limits of 6%. It is noted that all of the identified constraints are associated with the low demand, high DG output operating conditions. It can therefore be concluded that the constraints are triggered by generators in this area.

In order to address the network constraints described previously, the relevant part of the network needs to be reinforced or the output of relevant DG needs to be curtailed. The lost revenue from curtailment for each FPP generator is shown in Table 1. The figures were calculated considering the lost revenue from the support mechanisms and also from the energy markets. More details on how the lost revenue was calculated can be found in [5].

Table 1 List of FPP generators as per July 2014

Name	Connection area	Rating MW	Lost Revenue from Curtailment (£/MWh)
Wind1	Peterborough	7.2	86.24
Wind2	March	10.25	86.24
Wind3	March	1.5	130.37
CHP1	March	0.5	49.97
Wind4	March	0.45	198.17
PV1	March	4.75	116.07
PV2	Peterborough	0.25	138.97
PV3	March	6.927	116.07
Wind5	March	1	130.37
PV4	March	1.2	116.07
Wind6	March	0.5	198.17

Quantifying the benefits of the FPP solutions

The SIM was used to evaluate the costs of different investment strategies that can be taken to solve the aforementioned network problems. There are five different strategies:

Strategy 1. Traditional network reinforcement
Strategy 2. Connect and Manage
Strategy 3. Smart grid with firm DG access
Strategy 4. Smart grid with smart commercial arrangements (FPP solution)
Strategy 5. Combination of smart grid, traditional, and smart commercial arrangements

The cost performance of different investment strategies is compared in
Table 2. The sums of annuitized costs within the 5 years period from 2014 to 2018 are expressed in real terms according to the value in 2014 using the present value calculation. In addition, the CAPEX of each investment proposition is also presented and compared.

For strategy no 4, the solution from the SIM is to install DLR for circuits between PETC and GLAS_1, to control output of DG Wind 2 by ANM, and to install a quadrature-booster at WISS-NOWN_T. This investment proposition (shown in Figure 1) is exactly the same as the solution proposed in the FPP use cases and therefore it is referred as the FPP solution.

The solution demonstrates that the smart grid technologies and non-firm network access for DG can provide more cost effective solutions when compared to traditional network reinforcement. In terms of CAPEX, the FPP solution (strategy number 4) saves £3.35 million in comparison with the cost of traditional network solution. This demonstrates the cost-effectiveness of the adopted FPP solution. In these studies, strategies 4 and 5 produce the same results as there is no need for traditional network reinforcements.

The results of the studies indicate the potential of deploying DLR technology in distribution areas with considerable wind cooling effect. DLR is very suitable to upgrade the system with high wind penetration but less

Table 2 Cost comparison across different solutions (period: 2014/18)

Strategy	Present Value (£m)				CAPEX (£m)		
	Lost revenue from DG curtailment	Smart investment	Traditional investment	Total cost	Smart investment	Traditional investment	Total cost
1. Traditional network solution	-	-	1.54	1.54	-	5.10	5.10
2. Connect and Manage	9.58	0.15	-	9.73	0.50	-	0.50
3. Smart grid with firm DG access	-	0.55	-	0.55	1.83	-	1.83
4. Smart grid with smart commercial arrangement	0.00	0.53	-	0.54	1.75	-	1.75
5. Combination of smart grid, network, and smart commercial arrangement	0.00	0.53	-	0.54	1.75	-	1.75

effective if the output of dominated DG technologies has low correlation with wind.

In the context of controlling the output of DG actively, the potential lost revenue seen by the generator customers due to the curtailment of their generation output will be an important factor. The higher the lost revenue from DG curtailment, this type of solution becomes less attractive.

With respect to Quadrature-booster, the FPP project was the global first to design and install one in the distribution network [4] and current costs for their procurement are relatively high as they have not yet achieved the advantage of economies of scale. However, their application in suitable locations is effective and can release headroom in constrained circuits as demonstrated in both the SIM and the trial.

The results of the studies also demonstrate the superior carbon emissions and cost performance of the FPP solution. For example, with the traditional network solution, the emissions are 12,730 tCO_2 and the cost is £1.54 million. With the FPP solution, the emissions increase slightly to 12,876 tCO_2 while the cost drops significantly to £0.54 million.

Table 3 Comparison of emissions and cost performance of different solutions

Solution	Emissions (tCO_2)	Cost (£m)
Traditional network with firm access for DG	12,730	1.54
Connect and Manage	13,693	9.73
FPP approach	12,876	0.54

It can be concluded that the CO_2 emissions benefits of the FPP solution, based on applying novel technical and commercial solutions, are nearly equal to those associated with traditional solutions that provide fully firm access to DG (no DG curtailment), but this is achieved at very significantly lower costs. This clearly demonstrates the superiority of the FPP paradigm over traditional network design and operation approaches.

Strategic versus incremental distribution network planning approach

The SIM has also been employed to analyse the cost performance difference between two investment approaches:

1) Incremental investment approach and
2) Strategic investment approach.

The strategic investment approach ensures the least cost development of the system in the long term while the incremental investment approach minimises the short-term cost but may lead to higher long-term cost as the short-term decisions may be sub-optimal.

A set of studies was carried out with the planning time horizon between 2014 and 2023 divided into 5 planning periods (epochs) each of 2 years. The load growth scenario is based on the UK Power Networks load forecast. The increased installed capacity of the HV connected wind and solar PV generation is based on the high growth scenario produced by the Smart Grid Forum while the projected growth of micro PV is based on the UK Power Networks forecast. In this scenario, the installed capacity of CHP is kept the same across all planning periods. The total installed capacity of various DG technologies used in the studies is summarised in Table 4.

Table 4 Installed DG capacities for each planning period

Technology	Installed capacity (MW)				
	14/15	16/17	18/19	20/21	22/23
Wind	91.7	133.1	145.2	149.8	150.8
PV	42.2	84.5	112.6	136.2	147.0
CHP	74.5	75.5	75.8	75.9	75.9
uPV	4.4	8.6	11.4	13.9	16.2
Total	212.8	301.7	345.0	375.9	390.0

The cost of the solution proposed for both incremental and strategic investment approaches are presented and compared in Table 5.

The results demonstrate that the decisions taken using the incremental approach may be sub-optimal in the future system and the cost of these sub-optimal decisions tend to exceed the short-term benefits. Conversely, the strategic investment approach ensures that any investment or operating decisions taken will also be suitable in the future and therefore the overall long-term cost is minimised. The total cost of the solution proposed by the incremental investment approach is £5.3 million while the cost of the strategic investment based solution is £5 million.

It is noted that the incremental investment approach suffers from the lack of coordination with future investment decisions due to its short-term investment focus and may result in sub-optimal decisions by not utilising the economies of scale opportunities. The incremental approach selects the minimum cost reinforcement to meet the short-term requirement; but this increases the risk that the same part of the network may need to be reinforced again in the future which would consequently increase the capital expenditure overall.

The strategic investment approach strikes the balance between the use of smart technologies and traditional network investment to reduce the level of DG curtailment, losses and emissions. Although smart grid

Table 5 Costs of the solution proposed by incremental and strategic investment approaches

	Incremental (£m)				Strategic (£m)			
	Present value of		CAPEX		Present value of		CAPEX	
Period	Lost revenue from DG curtailment	Investment cost	Smart	Traditional	Lost revenue from DG curtailment	Investment cost	Smart	Traditional
14/15	0	0.98	1.75	-	-	1.08	1.93	-
16/17	0.46	0.20	0.43	-	0.46	0.11	0.25	-
18/19	0.52	1.14	0.53	2.80	0.39	2.24	0.53	6.00
20/21	0.65	0.28	0.60	0.60	0.16	0.47	0.10	1.95
22/23	0.19	0.90	0.40	7.35	0.07	0.01	0.10	-
Total	**1.83**	**3.5**	**3.71**	**10.75**	**1.08**	**3.92**	**2.91**	**7.95**

technologies can defer traditional network reinforcement, the use of smart technologies may not always be the optimal first investment option. In some cases, it may be more economically efficient to anticipate the future needs by strategically reinforcing the network.

The strategic investment approach also optimises the balance between having the benefits from the economies of scale and depreciation cost of the assets in order to maximise the net benefits. The “anticipatory” investment can be justified if the benefit is greater than the cost. Considering the increased uncertainty with longer planning time horizon, it is appropriate to assess risks involved with alternative investment propositions.

The studies clearly demonstrate that the most appropriate approach to future network planning is to consider simultaneously both smart and traditional network reinforcement as reported in [2]. Relying only on smart grid technologies and ANM in the short term may not be the most cost effective in all situations since the network may need to be reinforced in near future. Similarly, curtailing DG output may not be cost effective if it is required for long periods of time and there may be a limit to enhancing the utilisation of the existing capacity by using smart grid technologies.

The results of the analysis demonstrate that best practice is to allow all investment options including both smart technologies and the traditional network reinforcement to be considered, so that the overall cost across the multi-year time horizon is minimised. This can be challenging under current regulation which requires that DNOs offer the ‘minimum cost’ scheme to the customers unless strategic investment that will lead to more sustainably and economically efficient network while maintaining appropriate levels of security of supply has been explicitly agreed with the regulator.

CONCLUSION

The analysis carried out using the SIM demonstrates its unique capability to:

a) Determine the optimal portfolio and location for implementing smart grid technologies within the FPP trial area, which can be extended to any part of the distribution network where FPP technologies are being considered;
b) Evaluate the costs and benefits of alternative distribution network planning strategies considering both smart technologies and traditional network reinforcement over multi-year time horizons; and
c) Inform optimal operating strategies and investment policies.

In the context of the FPP project, the SIM was found to be an effective tool for addressing increasing complexity of future distribution network planning with smart technologies and novel commercial arrangements.

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