STEADY-STATE MODELLING FOR THE INTEGRATION OF A BI-DIRECTIONAL AC-DC-AC FLEXIBLE POWER LINK

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ABSTRACT

In the UK, Western Power Distribution (WPD) will be trialling a "Flexible Power Link" (FPL) as part of the Ofgem-funded Low Carbon Networks (LCN) Fund project, Network Equilibrium. The FPL is a power electronic AC-DC-AC device that allows for bi-directional transfer of real power and independent control of reactive power at each side. The trial device will be sited in WPD's network in the south west of the UK, allowing the interconnection of two separate areas of the network that could not normally be interconnected with AC only. This will allow for the balancing of power flows and management of voltages in the networks, enabling increased network utilisation and the integration of new loads and generation.

This paper introduces the FPL concept and provides details of the method and results of a study used to understand the FPL's impact on the network, in particular its operational ranges of real power, reactive power, and voltage control set points.

INTRODUCTION

Historic and regional network design in the UK has the consequence that distinct areas of distribution networks must, in all circumstances, remain split (no flow of electrical current) due to issues such as phase rotation, fault level, or earthing arrangements. Network design, coupled with changes in demand and the uptake of low carbon technologies (LCTs) such as solar PV and wind generation, is resulting in voltage, power or current related barriers to further utilisation of existing networks.

WPD has received funding through Ofgem's LCN Fund for the Network Equilibrium project [1], which is trialling a number of methods to improve network utilisation. Among these methods is the installation of an FPL, which is a power electronic device (AC-DC-AC) that will allow two distinct areas of network to interconnect at 33 kV. As shown in Figure 1, the FPL device is to be sited at a normally open point (NOP) between the two areas, and allows the transfer of real power (P_t, in MW) between the areas, such as for the transfer of generation power to a heavily loaded network or vice-versa. The FPL can also export or import reactive power (Q_1 and Q_2, in MVAr) independently on each side, allowing it to have a positive effect on network voltage.

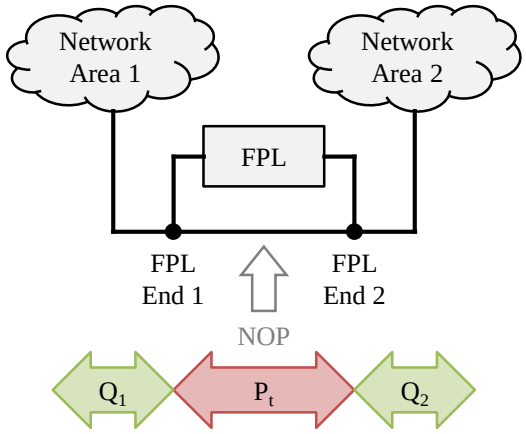

Figure 1 – Illustrative schematic of the FPL concept

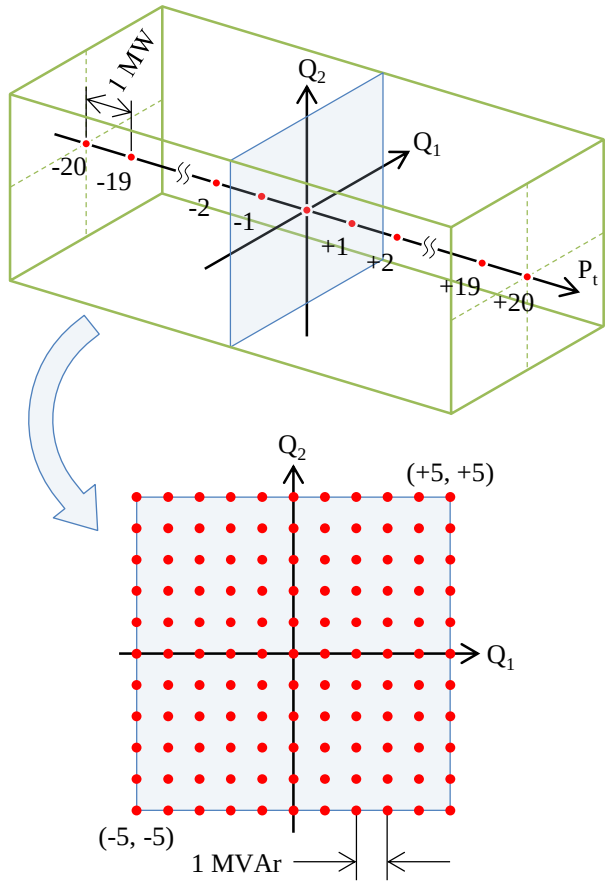

Figure 2 – Visualisation of the operational envelope concept for the FPL

FPL OPERATIONAL ENVELOPE

In this paper, the "operational envelope" of the FPL refers to the range of real and reactive power values within which the FPL can operate. A candidate operational envelope of ±20 MW (P_t, with positive transfer being defined in the direction from FPL End 1 to End 2) and ±5 MVAr (for both Q_1 and Q_2, with positive flow indicating export of reactive power) was used as an input for this study, which was then refined based on the results (as described in "Results & Analysis" section). The operational envelope can be visualised in three dimensions, as shown in the top half of Figure 2.

MODELS

The network in the vicinity of the proposed FPL location was modelled for this study, including the areas of 33 kV and 132 kV networks upstream of both ends of the FPL, and the in-feeding 275 kV and 400 kV transmission network that is common to the upstream networks on both sides of the FPL.

The FPL is to be located at WPD's Exebridge 33/11 kV substation, which was considered to be FPL End 1 for this study. The 33 kV network upstream of FPL End 1 consists of a radial overhead line circuit, which is fed by Taunton 132/33 kV substation.

FPL End 2, while located at Exebridge 33/11 kV substation, is on the other side of the NOP and is connected to WPD's South Molton 33/11 kV substation via a 21.5 km overhead line circuit. South Molton, in turn, is connected into a 33 kV network with a ring topology, which is fed by Barnstaple 132/33 kV substation.

The 33 kV networks on both sides of the FPL include 33/11 kV substations, which were modelled as lumped equivalents, and embedded generation (such as solar PV farms), which were included in the model.

Each end of the FPL was modelled as a universal machine with the real power of one end being the inverse of the other, in order to simulate real power transfer across the link without losses. Reactive power was independently settable for each end.

STUDY METHOD

The intention of the study was to determine the allowable operational envelope of the FPL, considering steady-state conditions and network limitations. The study and analysis comprised the following main stages:

1. Load flow studies were performed to sample a number of operating points within the candidate operational envelope.
2. Analysis of the study results to determine the allowable P_t range.
3. Analysis of the study results to determine the minimum Q_1 and Q_2 requirements across the range of P_t values.
4. Further load flow studies across the allowable P_t range of the FPL with each FPL end operating in voltage control mode, in order to determine potential voltage control set points (V_1 and V_2).

Study Process

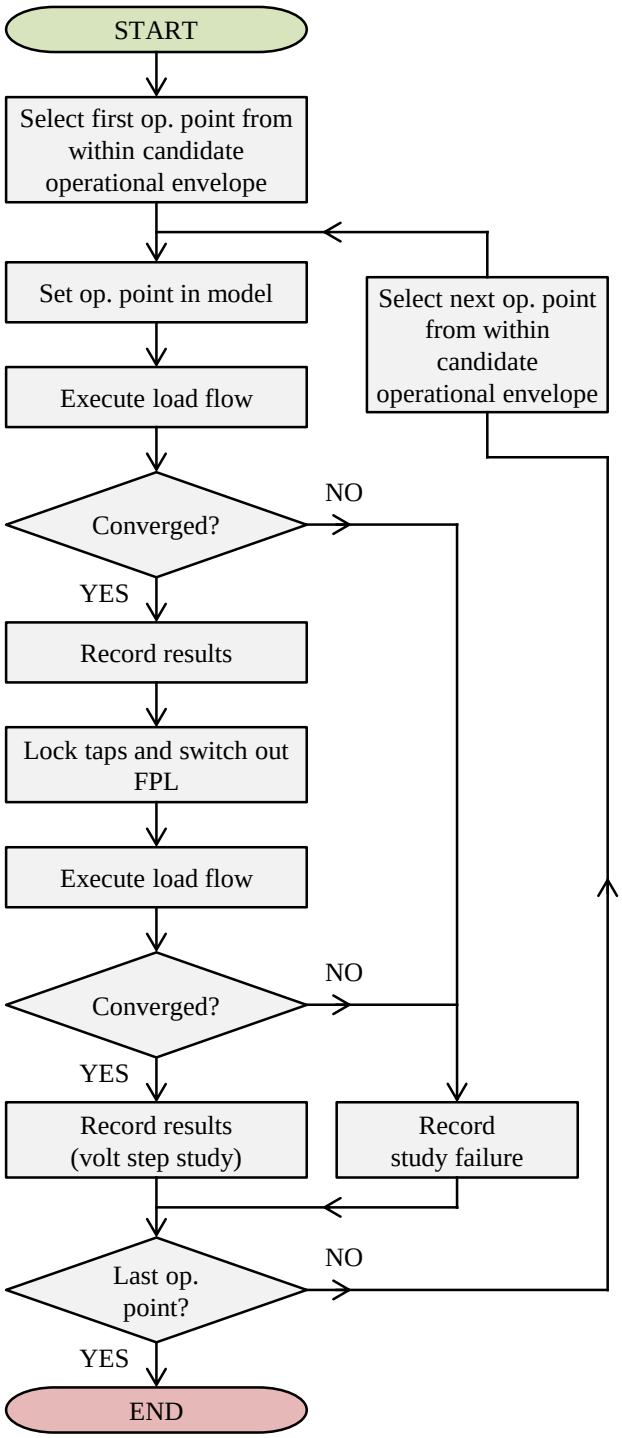

Figure 3 – Flow chart of load flow study process

Figure 3 shows the process used during stage 1 of the study. The process loops through all the sampled operating (op.) points in the candidate operational envelope, sets the appropriate real and reactive power at either end of the FPL, executes a load flow, and records results if the load flow converges. The results recorded are node voltages, branch loading (in kA at both ends) and transformer loading (MW and MVAr at each end). Following the load flow, a voltage step study is executed by locking transformer taps, switching out the FPL, executing the load flow, and then recording results (change of node voltages) if the load flow converges.

This process is repeated with different network states, which represented:

1. Network configuration: either the intact or one of six contingencies. The contingencies comprised network switching and single transformer outages upstream of FPL End 1 (contingencies 1A and 1B) and upstream of FPL End 2 (contingencies 2A, 2B, 2C, and 2D).
2. Loading scenario: either maximum demand (with minimum generation), or minimum demand (with maximum generation).

Therefore, 12 distinct network states were simulated in the study. Furthermore, for each state, operating points within the candidate operating envelope were sampled at unit intervals (1 MW steps for P_t and 1 MVAr steps for Q_1 and Q_2), as shown in Figure 2. In total, 41x11x11=4961 operating points were sampled per network configuration.

Stage 4 of the study followed a similar process to stage 1, but voltage control set points at each end (V_1,V_2) were sampled instead of reactive power set points (Q_1, Q_2).

Power system modelling and analysis was achieved using the IPSA software application [2]. The study process was automated using scripts written in the Python language [3] to control IPSA, record study results, and also to perform post-processing, analysis and visualisation.

Network Limitations

The following network limitations were considered based on UK standards and WPD network data [4]:

1. Steady-state voltage limits: ±10% for 132 kV nodes and ±6% for 33 kV nodes.
2. Voltage step change limits: it was assumed that the reliability of the FPL would be such that an FPL trip would be an infrequent occurrence, so a 10% limit was used.
3. Branch thermal ratings: with "cold" ratings used for the maximum demand loading scenario (winter), and "hot" ratings used for minimum demand (summer).
4. Transformer thermal ratings: nominal continuous ratings were used.
5. Transformer reverse power flow capabilities: this was assumed to be 100% reverse power flow capability for all transformers, except for one of the three 132/33 kV transformers at Taunton on the FPL End 2 side of the FPL, which was assumed to have 50% capability.

RESULTS & ANALYSIS

Real Power Range (P_t)

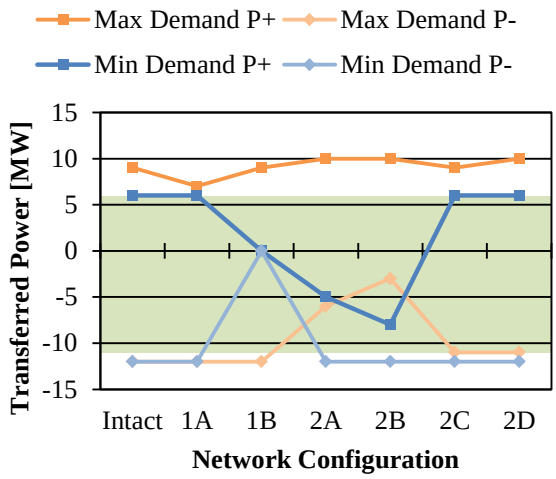

Figure 4 – Allowable real power ranges for different network configurations and loading scenarios

Figure 4 is based on the results of stage 1 of the study and shows the allowable P_t ranges for the different network configurations (intact and contingencies) and loading scenarios that lead to satisfactory network conditions. For each network configuration and loading scenario, the allowable P_t range considers all Q_1 and Q_2 values sampled from the operational envelope for each P_t value. For example, for network intact with minimum demand, the allowable P_t range is +6 MW to -12 MW. This means that for each value of P_t in that range there is *at least one* combination of Q_1 and Q_2 values that lead to no network limits being breached; furthermore, for P_t values outside the range (e.g. +7 MW) there are *no* Q_1 and Q_2 values that lead to satisfactory network conditions.

Figure 4 shows that the contingencies tend to restrict the allowable P_t range. Contingencies 1B, 2A, and 2B are particularly restrictive – for example, for 2B there is no single P_t range that can be used for both the maximum and minimum demand scenarios. Those contingencies were assumed to be abnormal operating configurations for the purposes of this study, for which the FPL would operate within restricted P_t ranges or be tripped off.

The green band in Figure 4 shows the allowable P_t range of the FPL if the restrictive contingencies (1B, 2A, 2B) are not considered, which is +6 MW to -11 MW.

Reactive Power Range (Q_1 and Q_2)

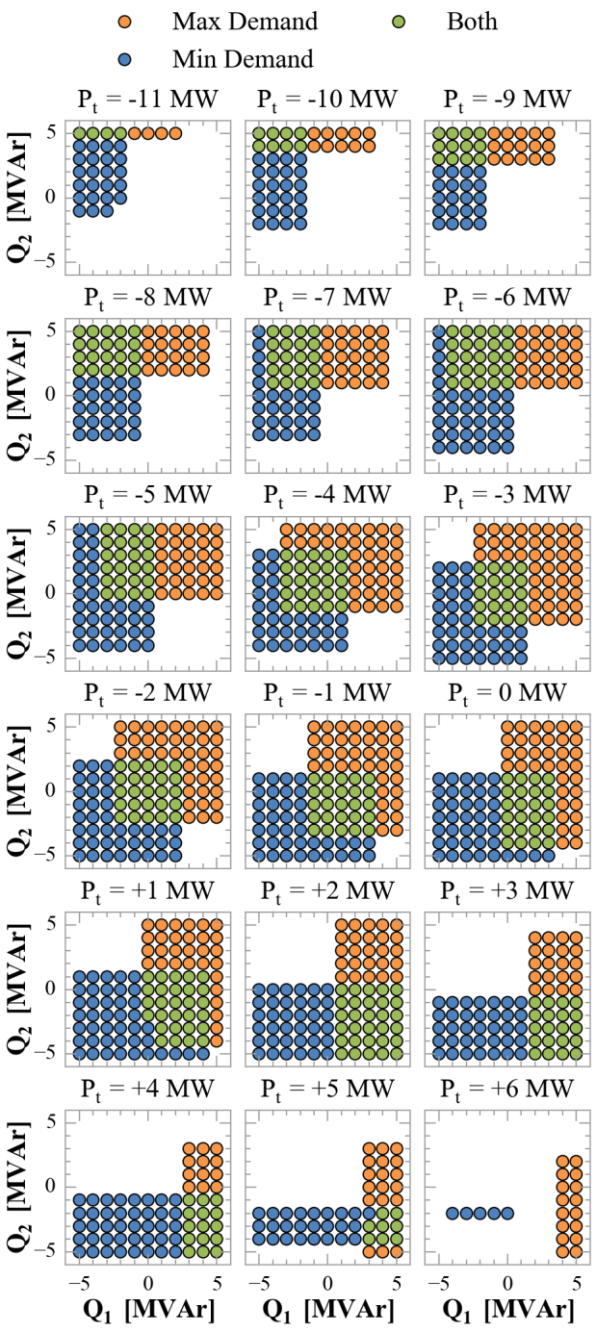

Figure 5 – Visualisation of the allowable reactive power operating points

Figure 5 shows the allowable reactive power operating points (Q_1 and Q_2) across the range of allowable values of real power transfer (P_t), considering the intact and allowable contingency (A1, B3, B4) network configurations. Each dot represents a reactive power operating point that leads to satisfactory network conditions for all the allowable network configurations and for either: (a) the maximum demand scenario, (b) minimum demand, or (c) for both loading scenarios.

Across the P_t operating range, the range of reactive power operating points that lead to satisfactory network conditions varies in size and location. As could be expected, at the reverse real power limit (-11 MW), reactive power must be imported at FPL End 1, in order to counteract the export of real power, while for FPL End 2 reactive power must be exported (+5 MVAr is required to satisfy the loading scenarios and network configurations considered) to counteract the import of reactive power. Towards the forward limit of real power transfer, the opposite holds.

Figure 5 also shows that there is no single Q_1 and Q_2 operating point that always leads to satisfactory network conditions, therefore, reactive power must be controlled within the allowable P_t range. Furthermore, the figure suggests that a reactive power range of ±5 MVAr would be appropriate.

Voltage Control Set Points

The stage 4 studies were performed to determine voltage control set points that lead to satisfactory network conditions, which were similar to the stage 1 studies but with the following exceptions:

1. The allowable P_t range was set to [-11,+6] MW.
2. Each end of the FPL within the model was set to voltage control mode, and the set point varied between 0.94 pu and 1.06 pu in 0.01 pu steps. The reactive power capability of each end was set to [-5,+5] MVAr.
3. Only the intact configuration and allowable contingencies (A1, B3, B4) were studied.

Figure 6 shows the results of the stage 4 studies. Each cell in the figure represents all the network states and P_t values studied for a particular combination of voltage set points for each end of the FPL; for example, the top left cell represents the studies performed with a set point of 0.94 pu used for both ends. The value displayed in a cell represents the percentage of studied states and P_t values that lead to satisfactory network conditions. For instance, the set point of 0.94 pu at both ends leads to satisfactory network conditions for only 71% of the studied network configurations, loading scenarios, and P_t values studied.

The cells showing 100% in Figure 6 – such as V_1=0.95 and V_2=1.05 – indicate voltage set point combinations that always lead to satisfactory network conditions across the allowable P_t range of [-11,+6] MW, for the network configurations and loading scenarios studied. Therefore, those voltage set points were recommended for FPL operation.

End 2 voltage set point [pu]	End 1 voltage set point [pu]												
	0.94	0.95	0.96	0.97	0.98	0.99	1.00	1.01	1.02	1.03	1.04	1.05	1.06
0.94	71%	71%	72%	72%	72%	72%	71%	73%	74%	73%	73%	70%	61%
0.95	90%	91%	92%	92%	92%	90%	92%	92%	92%	92%	92%	90%	86%
0.96	94%	95%	95%	94%	94%	94%	95%	95%	95%	94%	95%	91%	88%
0.97	94%	94%	95%	95%	94%	94%	95%	95%	94%	94%	95%	92%	89%
0.98	94%	94%	95%	95%	95%	94%	95%	95%	95%	95%	95%	92%	87%
0.99	93%	94%	95%	95%	95%	94%	95%	95%	95%	95%	95%	92%	92%
1.00	94%	94%	94%	95%	95%	94%	95%	95%	95%	95%	95%	92%	92%
1.01	94%	94%	94%	95%	95%	94%	94%	94%	95%	95%	94%	92%	92%
1.02	96%	97%	96%	97%	97%	96%	97%	96%	97%	97%	97%	93%	93%
1.03	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%	94%	92%
1.04	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%	97%	94%	94%
1.05	96%	100%	99%	99%	100%	100%	99%	98%	100%	100%	99%	97%	94%
1.06	88%	92%	96%	94%	93%	94%	94%	92%	94%	94%	93%	90%	88%

Figure 6 – Proportion of studied network P_t values, network configurations and loading scenarios that lead to satisfactory network conditions, with different voltage control set points used

OTHER STUDIES

These studies have focused on determining the operational envelope of the FPL so that it does not breach the steady-state operating limits of the network (voltage and thermal). However, other studies to more fully understand the impact of integrating the FPL into the network include:

1. Fault currents.
2. Transformer in-rush – this is important to understand as the proposed FPL device uses interface transformers.
3. Harmonics – depending on the control scheme and filtering used for the FPL, the device may improve or degrade the harmonic voltages within the network.
4. Dynamics – of particular interest are the interactions between the FPL and other control systems in the vicinity, such as tap changer controllers and generators.

CONCLUSIONS

An FPL is a power electronic device that offers to balance power flows between distinct – and previously isolated – network areas and provide voltage support. This will allow for enhanced network utilisation and the facilitation of new network demands and LCTs.

This paper has introduced the FPL concept and provided background on a trial of an FPL device in WPD's network in the south west of the UK. A study method was outlined with example results to determine the operational envelope of the FPL, in terms of the real power transfer range across the link, the reactive power ranges at both ends, and voltage control set points.

The study described in this paper focuses on simulating one aspect of FPL prior to the device being installed on the network; however, additional studies are recommended in order to have a fuller understanding of the impact of integrating this new device on the network.

The FPL device being trialled by WPD is to be installed and commissioned early 2018, followed by on-network operational trials to demonstrate its performance.

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