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Innovation Action

flexitranstore

An Integrated Platform for Increased FLEXIbility in smart TRANSmission grids with STORage Entities and large penetration of Renewable Energy Sources

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Report on Completion of Deliverable 8.3 – Validation of Key Performance Indicators by Demonstration in Greece

Reporting Date

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Abbreviations

ESO	Elektroenergien Sistemen Operator EAD
IPTO	Independent Power Transmission Operator SA
KPIs	Key Performance Indicators
MPFC	Modular Power Flow Control
RES	Renewable Energy Resources
SWE	Smart Wire Grid Europe Limited
TYDP	Ten Year Development Plan

Executive Summary

Smart Wire Grid Europe Limited ('SWE') is leading Work Package 8 as part of the FLEXITRANSTORE project. This work package requires the demonstration of SWE's Modular Power Flow Control ('MPFC') solutions on the Greek and Bulgarian Transmission networks. The aim of the project is to demonstrate the capability of MPFC solutions in resolving two of the key requirements of the European Energy Transition:

1. Increase Market Coupling across the European Union through the increase of cross border capacity; and
2. Facilitate the connection of greater levels of renewable generation through the relief of network constraints.

SWE installed the MPFC devices in a mobile container on the Greek Transmission System at Megalopolis in Greece in partnership with the Greek Transmission Operator, IPTO, in May 2019.

This installation and commissioning of the system was described in the report on Deliverable 8.2.

Following the installation and commissioning, IPTO undertook testing of the system to establish the extent to which the MPFC devices could control the power flowing on the lines at or near the substation. This involved placing the devices on a line that was heavily loaded to push power onto an alternative adjacent line and protecting against an unforeseen outage (N-1 event) on the adjacent line. Both tests were completed successfully demonstrated the ability of the MPFC devices to increase the available transmission capacity of the local grid and to protect against an N-1 event on a critical line in the grid whilst demonstrating that additional capacity may still be available under such circumstances.

The testing further demonstrated that the MPFC devices met the minimum standards of performance required for the purposes of the project.

1 Introduction

This report follows Reports D8.1, which looked at the conceptual design of the project and D8.2 which described the installation of the MPFC devices contained in the Mobile Container at IPTO's substation at Megalopolis in Greece.

Report D8.2 described the change of initial location from Bulgaria to Greece, the selection of the line on which the MPFC devices were installed, the installation itself, and the demonstration of the system at IPTO's National Dispatching Centre in Athens.

This report describes the operation of the system in Greece, the results of such operation, and the performance against Key Performance Indicators that were defined in Report D8.1 and the alignment of the project with a key objective of this Work Program of the Flexitranstore project, to increase the available transmission capacity of networks to permit additional renewable energy resources ('RES') to connect to the grid.

2 Network Saturation in the Peloponnese Region of Greece

A network revamp planned by the transmission system operator IPTO in the Peloponnese offers potential for further generation from RES development in the region, currently restricted by a saturated grid, while also promising appropriate conditions for lifting the restrictions imposed on the operations of a recently built gas-fired power station in the area.

Today, the region of Peloponnese in Greece is served solely by a 150-kV transmission system. However, an important project included in IPTO's Ten Year Development Plant ('TYDP') is the expansion of 400kV grid in the Peloponnese region, via the development of two prospective line projects. The first will stretch from Megalopolis to Patras. The second will connect Megalopolis to Corinth and, subsequently, to Attica. These projects promise to reinvigorate renewable energy growth in the region following seven years of stagnation due to network saturation. Furthermore, they will lift operational restrictions imposed on the Megalopoli V power plant, which is operating below nominal capacity (500MW out of 800MW). The plant's operation is restricted due to reasons concerning static security under N-1 contingency.

Until these projects are completed, however, potential congestion issues in this area have halted the integration of new renewable energy projects. Moreover, power flows in the area have caused some lines to operate near their capacity limits, while others are significantly underutilized.

One of the key targets of this this demonstration is to test how much power could be redirected from heavily congested lines to adjacent lines. This excess power capacity that is being "released" could then be used for new RES investments until the planned 400kV line is completed. Moreover, this demonstration will showcase an alternative way of mitigating the impact of N-1 contingencies in the area, which impose operational restrictions and therefore inadvertently might create market distortions. In any case, improving transfer capacity is critical to facilitate renewable integration and ensure economic operation of the power system.

2.1 Pre-screening phase studies

The main target of the pre-screening phase studies was to identify a suitable line to install the mobile MPFC unit and assess its impact on the power flows of the transmission system. The preferred transmission line would need to have comparable impedance in order of magnitude with the MPFC's nominal impedance, in order to achieve measurable results. The selection of a proper installation site would also need to consider substation spatial limitations, the topology of the overhead lines, and future system expansion plans.

Initial simulations were undertaken using PSS/E grid planning software, using both a current version of the grid, as well as a future version based on IPTO's TYDP. The simulation studies assessed the expected impact on different candidate lines, as well as the adjacent lines. After extended tests, the mobile MPFC application was modelled on one of two, short, 150 kV, parallel, single-circuit, overhead transmission lines which connect the Megalopolis HV Substation and the Megalopolis 2 Substation in the Peloponnese region. Results indicated that the mobile MPFC could significantly reduce a post-contingency overload by redirecting power flows to adjacent underutilized lines.

In Figure 1 a single line diagram of the area's grid is shown, with one of the two parallel lines connecting the Megalopolis HV Substation with the Megalopolis 2 Substation being out of service. At the top of Figure 1, the line connecting to circuit breaker P20 is overloaded, which is resolved with the deployment of the mobile MPFC technology, as shown at the bottom. In addition, two adjacent pairs of transmission lines are highlighted: the first connects the Megalopolis HV Substation with the

Megalopolis 1 Substation (lines with circuit breakers P10 and P30), and the other connects the Megalopolis 2 Substation with the Megalopolis 1 Substation (lines with circuit breakers P160 and P170).

This analysis indicates that the deployment of the mobile MPFC could reduce this thermal overload by 17%, by increasing the line's reactance and redirecting power flows through underutilised lines.

Table ***1*** provides an overview of the expected impact of the mobile MPFC installation on the power flows of the grid.

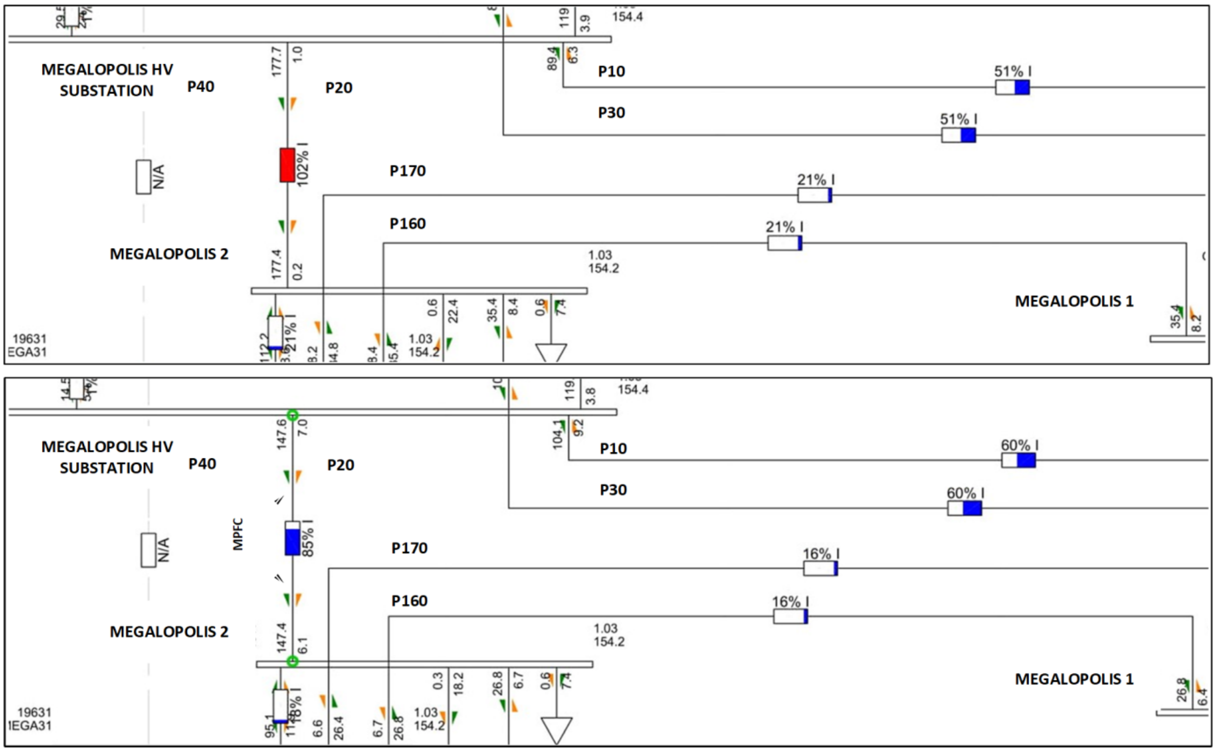

Figure 1 : N-1 contingency without (top) and with (bottom) the mobile MPFC device installed. The installation of the mobile MPFC device resolves the overload by redirecting power flows to adjacent transmission lines.

150kV Line	Circuit Breaker	Without MMPFC installed		With MMPFC installed	
		Loading	MVA	Loading	MVA
MEG. HV SUB. – MEG. 2	P20	102%	178	85%	126
MEG. HV SUB. – MEG. 1	P10	51%	96	60%	115
MEG. HV SUB. – MEG. 1	P30	51%	96	60%	115
MEG. 2 – MEG. 1	P170	21%	31	16%	24
MEG. 2 – MEG. 1	P160	21%	31	16%	24

Table 1 – Loading percentage and power flows on relevant 150kV transmission lines on the Greek system with and without the deployment of mobile MPFC.

Based on this analysis, the mobile MPFC device was installed on one of the two short parallel lines connecting the Megalopolis HV Substation with the Megalopolis 2 Substation, specifically on the line connected to circuit breaker P20.

3 Testing Protocols

IPTO undertook testing of the MPFC devices to measure the impact they had on line current levels in two ways, involving manual operation and automatic operation. During manual operation, the dispatcher selects whether to inject 50% or 100% of the MPFC device's nominal impedance into the transmission line. During the automatic operation, a pre-specified current threshold is set and the MPFC is expected to inject 100% of its nominal impedance when that threshold is exceeded. During the validation period, we assessed the impact of the MPFC devices both on the installation line, as well as adjacent lines. For this purpose, results were cross-validated with measurements obtained from the MPFC device's sensors and from IPTO's SCADA system.

3.1 Manual Operation

3.1.1 Description

The system was first tested in stepwise manual injection, which allows the dispatcher to select the impedance level. Given that each MPFC device is either in monitoring or injection mode and that two devices were installed per phase, this allowed the dispatcher to select between 50% and 100% of the MPFC devices' nominal reactance. With both parallel lines between Megalopolis HV Substation and Megalopolis 2 in operation, the dispatcher first injected 50% of the reactance available on the line. This means that one of the two power flow control devices per phase were in injection mode. After a short time period, the operator increased the reactance to 100% of the installed value.

3.1.2 Results

Figure 2 shows the impact of injection on the current of the affected transmission lines. Measurements were obtained from IPTO's SCADA system.

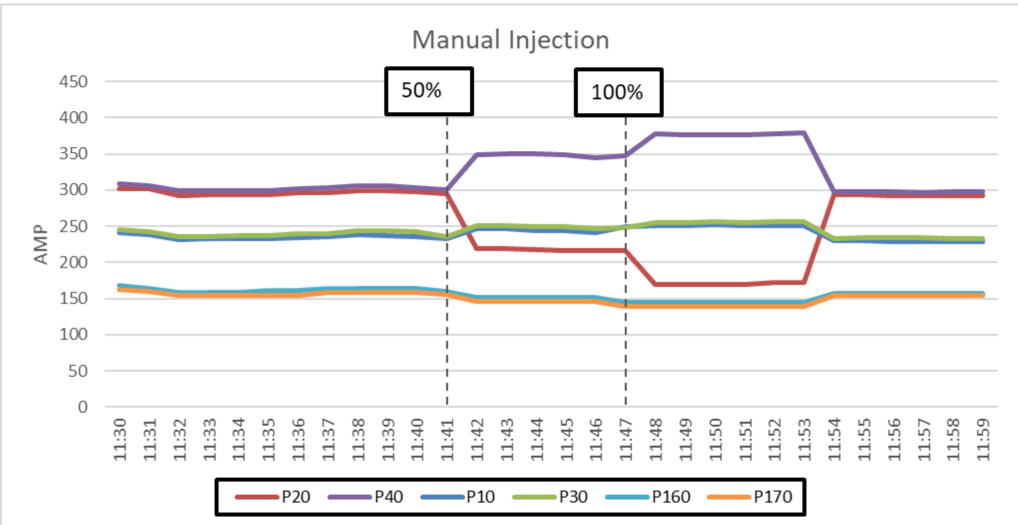

Figure 2: Line Current during Manual Injection

The MPFC devices are installed on the circuit connected to bay P20. When the reactance is increased, the line current on this circuit drops following a stepwise pattern. The current at P40 increases following a similar but inverse pattern. This increase in current is slightly smaller from an amperage perspective compared with the decrease on the circuit connected to bay P20. This is due to the fact that a portion of the power flow is redirected through other adjacent lines connecting Megalopolis HV Substation – Megalopolis 1 (circuit breakers P10, P30). As seen in Figure 1, the current on these lines increases slightly as well. A small decrease can be seen in the current of the lines connecting Megalopolis 2 - Megalopolis 1 (circuit breakers P160 and P170). These field results confirm the simulation results from studies undertaken on the impact of increased reactance on the circuit connected to bay 20 using PSS/E software.

The graph in Figure 2 has a sampling rate of 1 minute. Therefore, this data does not accurately capture the response time of the MPFC devices.

Figure 3 shows the same data obtained directly from the MPFC devices' sensors. These sensors have a sampling rate of approximately 10 secs. Line current is divided by the maximum current in order to show the power flow control devices' impact in relative terms.

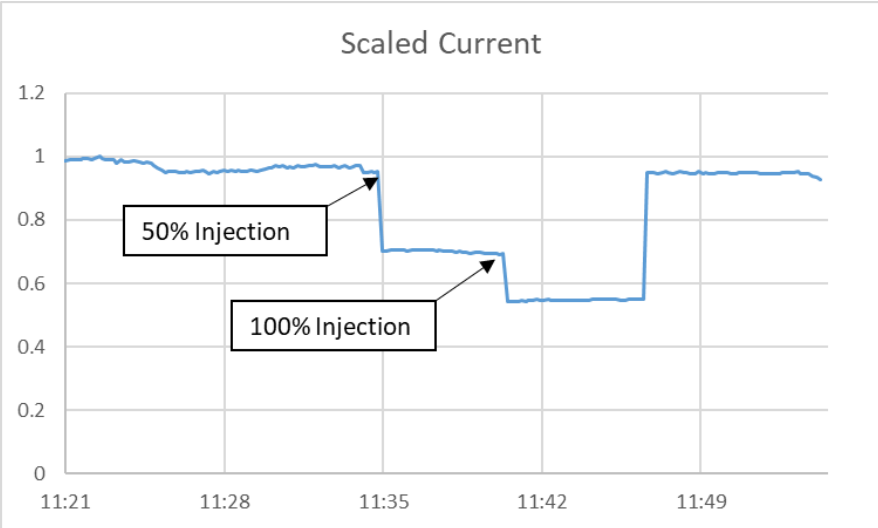

Figure 3: Scaled Current in line P20 during Manual Injection

Figure 3 highlights the response as the line's current drops between two sequential injection commands at 50% reactance and 100% reactance.

When 50% reactance was applied, the line current fell from 295 A to 217 A, and when 100% reactance was applied, the current fell further to 168 A. The difference between the current levels translates into a reduction of power on the line of 20.3 MW and a further 12.7 MW (to 33.0 MW) when 50% and 100% of reactance was applied, respectively.

These results verify the MPFC devices' ability to reduce the line current by approximately 27% when 50% reactance was applied and 43% when injecting 100% of the nominal reactance.

3.2 Current Limiting (Automatic) Operation

3.2.1 Description

Current Limiting operation is designed to replicate the impact of an N-1 event on an adjacent line, and the ability of the MPFC devices to manage it. The operation is fully automatic with no input required from the system operator, except for pre-specifying a current threshold.

When the pre-specified current threshold is exceeded, each MPFC device automatically injects 100% of its nominal reactance. In this case, the threshold was set at 270 A, prior to the simulation of the N-1 event.

The N-1 event was simulated with an outage on the adjacent parallel line (connected to bay P40 at the Megalopolis HV Substation) to the line on which the power flow control devices were installed.

3.2.2 Results

Error! Reference source not found. shows the lines' current during this test. The current on the line increased from 169 A to 204 A when line P40 was taken out of service, an increase of 21%.

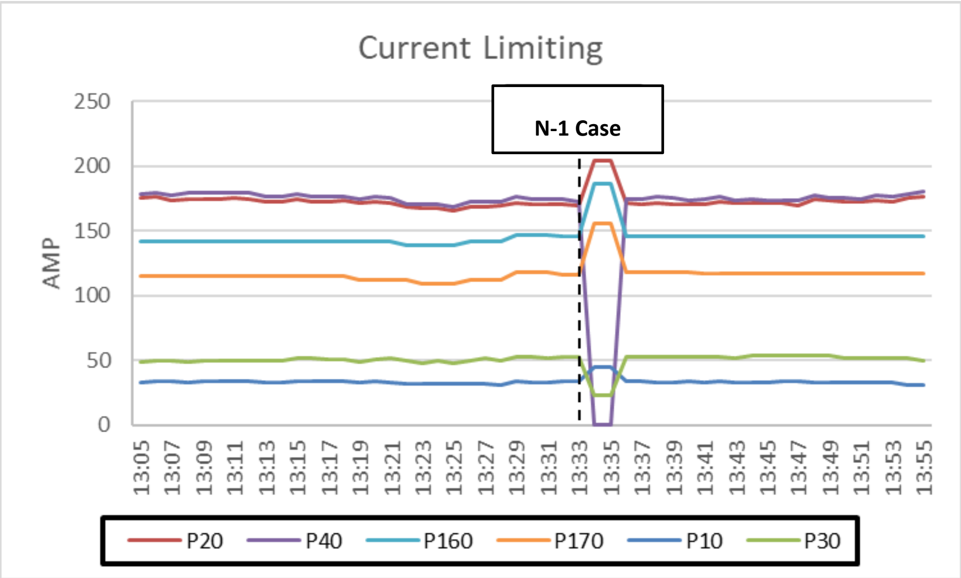

Figure 4 - Line Current during the N-1 Contingency Case

There was a significant increase in the current on the remaining line between Megalopolis HV Substation and Megalopolis 2 (P20) as current in its parallel line (P40) drops to zero. Since the power flow control devices injected 100% of their reactance during the outage, the current increase on P20 was significantly smaller than it would have been in the absence of these devices. Figure 3 shows that the pre-specified threshold of 270A was not exceeded during this test.

An increase in current is also seen in the adjacent lines connecting Megalopolis 2 with Megalopolis 1 (P160 and P170). These results demonstrate the MPFC device's ability effectively to control power flows during N-1 events, as in this case the excess power flow was redirected through adjacent lines.

The above results were validated by measurements taken directly from the power flow control devices which showed that the devices were in injection mode.

In terms of power flow, immediately before the outage was taken, the volume of power on the P20 line was 43.9 MW. At inception of the outage, power on that line increased to 53.1 MW, an increase of 9.2 MW. Given that the power on the P40 line was at about the same level, then 34.7 MW, or 79% of the power flowing on that line before the outage was moved to lines other than P20. If we assume that 50% of the power from the P40 line might have gone to the adjacent line (P20), then the power flow control devices were responsible for moving 29% of the power, or 12.7 MW, onto the other available lines.

These results demonstrate the effectiveness of the power flow control devices to resolve N-1 contingencies.

3.3 Evaluation of the Results

The two tests that were designed and implemented clearly demonstrate the ability of the MPFC devices to control power flows.

In the first test, stepwise manual operation was implemented whereby the dispatcher selects to inject either 50 or 100% of device's nominal impedance. The MPFC devices reduced power on the P20 line by 20.3 MW when 50% was applied and by 33.0 MW when the full 100% reactance was applied. This power was redirected elsewhere, but the aggregate capacity of the network was unchanged. The power flow control activities would have allowed up to an extra 33 MW of energy from RES to be dispatched. Indeed, this figure may be higher still; modelling of the network would show how much additional power could be dispatched whilst remaining within the current loadings of all the lines on the network.

The second test, the test of automatic operation under an N-1 condition, required only the setting of a current limit on the installation line. The results validated the device's ability to redirect power flows to adjacent lines and effectively mitigate congestion caused by the N-1 event. In this test, of the power on the P40 line, (43.9 MW – the same as on the P20 line), the MPFC devices on the P20 line limited the amount of power that moved onto that line to just 9.2 MW. The trigger threshold – 270 A, or 70.2 MW – was 17.1 MW above what the P20 line actually saw. If the 270 A (70.2 MW) figure is the maximum that would be allowed on the line under prevailing circumstances, then there is additional capacity within the network for at least a further 17.1 MW. (This figure may in fact be higher as some of this additional power would be directed to alternate lines; as the current level in the P20 line conductor increased, the conductor's reactance would increase also, acting as a further mini-power flow control device).

These results are very important to TSOs and other stakeholders, as they highlight an alternative way of managing transmission constraints, which requires significantly less lead time and investment when compared to grid expansion and could effectively facilitate higher RES integration. Given the results of this demonstration, the following could be identified as potential scenarios for installing such a device in the transmission grid:

- Installation of an MPFC device on a line that faces congestion due to high RES penetration. This is the most straightforward use case and one that allows to directly estimate an amount of RES capacity added. In such a case, assuming a line faces congestion due to the presence of a number of wind generation facilities, installing an MPFC would potentially avoid the need for curtailment during periods of high wind. Given the wind speed profile, the extra RES capacity capable of being dispatched by the grid could be determined through network modelling.

- Installation on an adjacent line that is affected by high RES penetration. Given the network topology, the case could be that high RES penetration in one part of the grid could lead to congestion on an adjacent line, which in turn may result in changes in the dispatch schedule. Ultimately, this will result in costlier power plants being in operation thus increasing the overall cost of production. In that case, the MPFC device could be used to ensure that the dispatch schedule is not affected, and the economic operation of the power system is not adversely impacted.
- Addressing N-1 contingency events. As the case in the Peloponnese region, operational restrictions might be imposed due to grid security concerns under N-1 contingency events. Results demonstrated that such events could be effectively mitigated via power flow control. Therefore, the installation of a controller could result in a more secure operation and help lift restrictions that might create market distortions.

4 Key Performance Indicators

4.1 KPIs from Report D8.1

Report 8.1 contained three KPIs, which are set out in Table ***2*** below:

Performance Indicator	Framework for Metrics	Target Values
8-1 Project Tracking / Meeting project objectives and timelines	8-1-1 Detailed project plan / Gantt Chart[1]	>70% on track (green)
8-2 Control Mode Testing	8-2-1 Power Guardian device response to control commands	Devices enter injection and monitoring modes as expected
8-3 Power Flow Impact	8-3-1 Inductance rating of the Power Flow Control devices	>90% of rated inductance delivered

Table 2 – Key Performance Indicators

4.1.1 Project Plan/Gantt Chart

The original project plan envisaged installation of the MPFC devices in Bulgaria in month 16 (February 2019). The updated plan described in Report D8.1 anticipated that this would take place in April 2019. In the event, and as explained in Report D8.2, the first installation took place in Greece in May 2019.

The reason for the delay was the need to ensure that the preparatory site works and the installation itself, both of which required outages to be taken on the line on which the MPFC devices were installed, could not be completed until after February 2019 it was not possible to take outages at that time. February is a period of high demand on power networks in the Northern Hemisphere and outages are not normally taken, except in emergency situations, until April at the earliest in any year.

4.1.2 Control Mode Testing

The MPFC devices always operated as expected when used in manual and automatic control modes as described in sections 3.1 and 3.2 respectively.

4.1.3 Power Flow Impact

The MPFC devices used in the project have two operating modes. The first, Monitoring Mode is where the units are available on the line and under the control of the operator but are not injecting reactance into the line. The second mode is Injection Mode, in which the devices react to instructions from the system operator to inject reactance into the line.

There are no intermediate states for the devices, and in Injection Mode, each device injects the full amount of reactance of which it is capable, 100% of its nominal reactance. With two power flow control devices installed on each phase, this allows for a stepwise control of the total available impedance (50 or 100% injection).

The testing done to date has provided data on the reactance injected when both MPRC devices per phase were in injection mode.

In the Manual Operation test described in this report, the current fell from 294.9A to 217.3A when one MPFC device per phase was put into injection mode. When the second MPFC device on each phase was put into injection mode, the line current fell further, to 167.8A. At this level, and for the duration of the period when two MPFC devices per phase were in injection mode, the injected reactance was on average 886.4 mΩ, with a range (due to minor current fluctuations on the line) of 885.5 Ωm to 887.3 mΩ.

Further Manual Operation tests showed similar results:

Test	Average	Range
1	881.5 mΩ	880.5 mΩ – 882.4 mΩ
2	885.6 mΩ	884.7mΩ – 886.6 mΩ
3	887. 4 mΩ	886.4 mΩ – 888.2 mΩ
4	887.7 mΩ	886.8 mΩ – 888.5 mΩ

In Current Limiting mode testing, average reactance during injection was 881.8 mΩ, with a range of 881.0 mΩ – 882.4 mΩ.

The specification for the Power Guardian 390-850 specifies minimum reactance of 427 mΩ at 50 Hz, therefore 854 mΩ in total for two devices. This minimum level corresponds to a maximum continuous current of 850A and is exceeded on all the tests:

Test	Average	Range
Manual Operation	103.8%	103.7% - 103.9%
Current Limiting Operation	103.3%	103.2% - 103.3%
Test 1	103.2%	103.1% - 103.3%
Test 2	103.7%	103.6% - 103.8%
Test 3	103.9%	103.8% - 104.0%
Test 4	103.9%	103.8% - 104.0%

The tests show that, in all cases, the minimum level of reactance achieved was significantly in excess of the 90% requirement.

5 Conclusion

The project has been delivered on time in line with the revised schedule.

The testing that has been undertaken has shown the ability of the MPFC devices to reduce current levels on the lines on which they were installed, both in a regime of manual injection and, in an automatic mode where devices were programmed to inject when a predetermined level of current was present on the line.

The test results further demonstrated a key objective of this Work Program, the ability of MPFC devices to increase the available transmission capacity of networks allowing higher levels of RES projects to connect to the grid.

The testing of the MPFC devices that was undertaken have shown that levels of reactance were comfortably above the minimum requirements for the purposes of the project.