An application of modular FACTS devices to relieve transmission constraints and accelerate wind farm connections and firm access

Robert Fenlon
Smart Wires
Dublin, Ireland
robert.fenlon@smartwires.com

***Abstract*— The integration of wind and renewables into the generation mix has become a vital part of achieving global targets to reduce CO2 emissions and create a cleaner electricity grid. Attempts to facilitate large scale integration of renewable energy has highlighted similar issues occurring on grids globally often inhibiting the ability to meet renewable energy targets. Many electricity grids have high levels of congestion that prevent bulk transfers of renewable energy to demand centres. These have traditionally been mitigated with uprating lines or building new lines. The timing associated with the completion of these network reinforcements results in existing wind generators and other renewable generation being constrained and slows the connection of new customers. These problems are usually a result of the large scale nature of these solutions and the inflexibility of traditional large scale grid solutions to meet customers' needs in terms of scale and speed. Added to that, planning the needs of the future electricity grid is becoming even more difficult due to the mismatch in timing of grid project completion dates, generation connection dates as well as shifting patterns on the load side driven by the proliferation of electric vehicles, behind the meter solar generation and energy efficiency improvements. Planning the future grid to take account of this uncertainty requires flexible solutions that can minimise the overall investment risk and provide short, medium and long term certainty for operators and customers. Flexible solutions on the grid can provide renewable generation customers, such as wind farms, with greater certainty around the timing of their connection and access rights to the grid through faster mitigation of grid constraints.**

Transmission and Distribution companies around the world are investigating solutions to resolve network constraints allowing wind to integrate faster. The most innovative transmission companies are using leading edge smart grid technology to support and augment the traditional grid reinforcements. One particular group of technologies that is being adopted by TSOs in Australia, North America and Europe is the Modular Power Flow Control (MPFC) family of devices. MPFC devices are being adopted at a fast rate because they are flexible, fast to deploy and redeploy, can be scaled up or down to meet network needs and provide a wide range of functionality. The latest in the MPFC devices, the Modular Static Synchronous Series Compensator (MSSSC), has rapidly transitioned from a world-first pilot installation in 2017 on the Irish transmission system to being a widely adopted technology with projects being deployed around the world in 2019/20.

This paper explains the types of grid constraints that occur at transmission and distribution level that reduce wind and renewable generation and how MPFC can be used to create additional capacity quickly in ways not previously deemed cost effective or possible. The authors will demonstrate this through description of the development of MPFC technology, focusing on the operation of the MSSSC. By highlighting real applications around the world the authors will explain the business case for Transmission and Distribution companies to help resolve wind generation constraints, enable renewable generation gain access quickly and help meet climate targets.

***Keywords*— FACTS, SSSC, Renewables, VSC, Distributed, Modular**

I. Introduction

The rate at which renewable generation capacity has been added in recent years has rapidly increased with 105 GW of additional generation capacity worldwide connected in 2011 to 172 GW of additional capacity in 2017 and 170 GW in 2018. Wind has played a large role in the increase of generation capacity of renewables, with an additional 49 GW of wind generation capacity added in 2018 [1]. This has been driven in part by global and national emissions targets e.g. the EU has set a requirement to have 32% of all energy to come from renewable sources by 2030 in the latest Clean Energy for all Europeans package. In North America cities, provinces and states have committed to reaching 100% renewable energy targets and becoming carbon neutral [2]. The targets in Australia are similar to that of the EU in that they have set a target of 33,000 GWh or 23.5% of electricity generation to come from renewable energy sources by 2020. As of 2018 the share of renewables of total electricity generation in Australia was 18.9% [3]. It is clear that in achieving these targets further integration of renewables is needed. Wind generation is one of the leading sources of renewable electricity with installations taking place in almost every region of the world.

The energy transition from fossil fuels to renewable sources of energy has been partially hampered by the lack of grid infrastructure and the cost and lead time associated with traditional approaches to addressing this capacity issue. As renewable generation sources are not typically located near demand centres, the infrastructure transporting energy from these generation plants to demand centres is often insufficient and becoming increasingly congested. This can lead to delayed connection of renewables and increased curtailment of connected generation. Both of these problems, curtailment and lack of access, are making it increasingly difficult to integrate more wind generation and meet global, regional or national targets.

The grid reinforcements that are required to relieve the capacity issues and allow new connections take time to complete. These projects can take years to plan, obtain permits, procure and install the overall solutions. Projects regularly take 5 - 15years to complete, which in the case of countries with 2020 targets and 2030 targets is inhibiting the ability to meet renewables targets. The lack of new capacity and difficulties building new capacity leaves DSOs and TSOs across the world struggling to meet the deadlines with traditional solutions.

As more renewables are being integrated, power grids are experiencing lower levels of inertia, lower short circuit levels and increased risks to dynamic stability. Sub-Synchronous Resonance (SSR) is one of these stability issues that has become more prominent in high voltage grids in recent years. SSR is a major concern for TSOs and customers, as it can cause torsional damage to large generator turbines shafts and greatly reduce grid stability. Controller interaction is another new stability phenomena causing concern for TSOs and DSOs, with the increase in inverter technology through wind turbine controllers, solar inverters, HVDC and other power electronics. Along with controller interaction, power quality is another issue that is increasing with the proliferation of renewables. The increase in voltage harmonic distortion can have negative effects for large industrial customers and can cause major issues for transformers overheating. Resolving these issues add complexity to planning future grid reinforcement plans and in many cases require new individual bespoke solutions, all of which take time to design, procure and implement.

II. Traditional Solutions

Traditional solutions have some drawbacks that have reduced their effectiveness for integrating renewables in a modern grid. For large scale solutions such as new line builds, line uprates, substation refurbishments and traditional series compensation solutions can take years to complete from the time the need is identified. These long time frames for completion of projects can delay the connections of new wind farms and can prevent a wind farm from gaining firm access. This leads to loss of revenue for the wind farms and reduced integration of wind on the network. These long delays have been seen in Ireland [4], Scotland [5], the United States [6] and many other regions around the world.

Traditional solutions can also be extremely costly for TSOs and DSOs. Solutions are typically sized to meet the expected future needs of the grid over a 10-50 year time frame. There is often a high degree of uncertainty as to the scale and timing of those needs. The result of this uncertainty is that the capacity of the equipment installed is sized to meet a worst case scenario and can end up becoming stranded or semi-stranded. It is also possible that the equipment is undersized to meet future needs and eventually this increases costs as solutions need to be upgraded or the performance of the solution does not deliver a positive cost benefit result.

More often than not, TSOs are turning to grid utilisation technologies such as power flow control to maximise existing capacity and can typically be delivered much quicker than new line builds. However even these solutions present challenges to keep up with the pace of change in power grids; typical power flow controllers such as Phase Shifting Transformers (PSTs), series reactors and series capacitors are often of very bespoke design often become redundant over the course of their lifetime due to a change in need and change in grid configuration.

The third major problem for utilities in implementing traditional solutions is their inflexibility. Often these solutions are not as adaptive or flexible in their implementation, they have constraints in how they address future challenges. For example, a series reactor or series capacitor often provide bulk reactance or capacitance with very little discrete control. A PST has a limit on how fast the taps can be changed. Such solutions lack the flexibility to meet dynamic changes to power flow associated with wind and other renewable generation.

All of the described shortcomings of traditional solutions create future uncertainty for system operators (transmission and distribution) and for renewable developers. The uncertainty increases cost and makes planning investment difficult. The lack of flexibility means only certain scenarios have the optimum solution installed. These short comings have created a market need for solutions that are flexible and can help optimize investment in grid infrastructure and are flexible enough to meet future dynamic stability needs on the power grid.

III. Converter Based Power Flow Control

Converter based Power Flow Control (PFC) technology has been implemented in the past in the form of a Static Synchronous Series Compensator (SSSC), Unified Power Flow Controller (UPFC) as well as part of Thyristor Controlled Series Reactor (TCSR) Thyristor Controlled Series Capacitor (TCSC) solutions. In terms of the available solutions that offer continuous control over the injected voltage range, the SSSC is a device that can provide the widest range of functionality with a high level of controllability.

A. *SSSC Operation and Features*

The SSSC is a device that can inject a controllable voltage in series with a transmission line, this enables it to be used for PFC. The injected voltage is generated using a voltage source converter (VSC) technology. The voltage is ideally injected leading or lagging the line current by $\pi/2$, thus emulating a series reactor or a series capacitor with a single device. In reality there is some small amount of real power absorbed or discharged by the DC link in the VSC to maintain the output voltage, so the voltage is not perfectly in quadrature with the line current. Typically, SSSCs have been installed as large three phase devices with injection transformers, often part of a UPFC installations. Fig. 1 shows a typical SSSC with an injection transformer, bypass switch, power electronics converter and the DC link.

The injection transformer adds significant cost to the installation and ensures that the installation is a bespoke

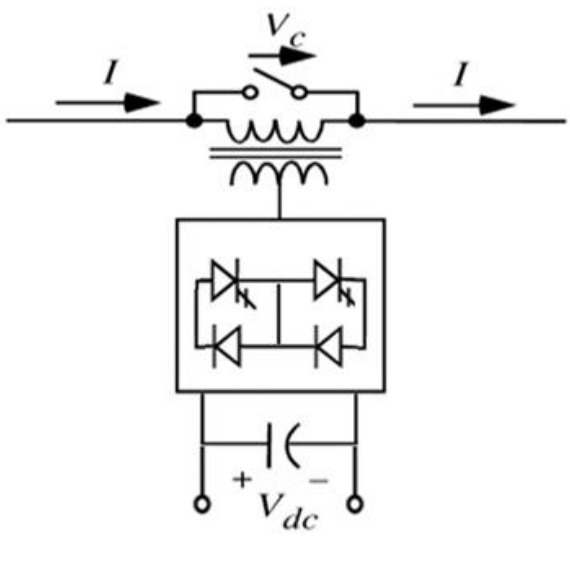

Fig. 1. Typical SSSC Setup

design that cannot be moved from one location. All large scale SSSC installations have also required an external circuit breaker bypass for protection. A large external bypass leads to additional cost and requires changes to existing control and protection schemes. The cooling of SSSCs and VSC based technology has always been an issue. The cooling system for these devices have often been large ground mounted units that are attached to the VSC valves in side of large valve halls. This large ground based cooling system is expensive to maintain and is often the largest source of outage time due to the low reliability of the cooling systems.

Overall the injection transformer, external bypass and large ground based cooling systems of SSSCs have made them a costly and space intensive solution. This has led to only a handful of standalone SSSC installations around the world. The most recent SSSC installation was in 2015 in Spain. For their application the SSSCs have been too inflexible, too costly and too unreliable to become a common tool used by TSOs and DSOs around the world. In order to compete with traditional solutions changes are needed to the technology.

B. *SmartValve^{TM} Operation and Features*

The SmartValve is a SSSC that has addressed many of the issues identified with the traditional SSSC installations. The SmartValve does not require an injection transformer, the SmartValve is a modular SSSC that is installed at line potential on a per-phase basis. This means that the SmartValve is designed to operate at the full line current and voltages up to 550 kV corona free. As the SmartValve is modular the number of devices can be scaled to get the required voltage injection using the multi-level converter topology of the devices.

The SmartValve also has its own internal fast acting bypass. This bypass can detect and bypass the internal semi-conductor components of the SmartValve in less than 1 millisecond after fault inception. The SmartValve can also carry the full fault current of 63 kA RMS for 1 second. This eliminates the need for a large scale circuit breaker bypass as the device is transparent to the existing protection scheme during faults i.e. the device is bypassed before the protection operates [7].

The SmartValve operates with each converter injecting a controllable voltage waveform. The entire deployment of SmartValves can be used to inject a voltage waveform using multi-level converter topology. This allows for the SmartValve deployment to inject a voltage waveform with low harmonic distortion into the network facility that is scalable and continuously controllable. The operating range of the SmartValve 5-1800i is shown in Fig. 2. The orange outline is the operating boundary of the SmartValve, the SmartValve can operate anywhere inside the grey area.

C. *SmartValve Components*

The basic component diagram of the SmartValve is shown in Fig. 3. The components are:

- Converters – These voltage source converters are composed of IGBT diode pairs and a DC Capacitor in a H-bridge topology.
- Bypass – The Bypass is composed of normally closed contactors called the Vacuum Series Links (VSLs), Silicon Controller Rectifiers (SCRs) and a Metal Oxide Varistor (MOV) Board. These components form the bypass segment of the SmartValve that are used to bypass the converters under different conditions.
- Sensing, Protection and Control – Within the SmartValve there are multiple current transformers (CTs) used for sensing and deriving power from the line. Within the SmartValve there are also control and communication boards.

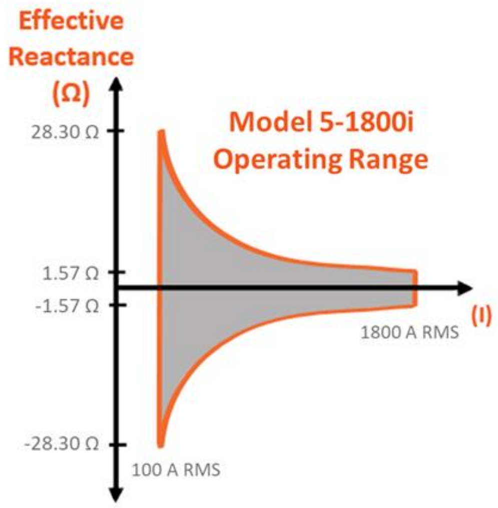

Fig. 2. Output Characteristic of a SmartValve 5-1800i

IV. Applications on TSO and DSO Networks

The SmartValve functionality can be demonstrated through a description of use cases and applications that are currently being assessed and implemented by Transmission and Distribution system operators across the world.

A. *Minor Impedance Changes to a Network for Optimized Used of Grid Infrastructure*

The SmartValve, as a modular solution, can be used in multiple small scale deployments to optimize the use of existing grid infrastructure. A case study was carried out using the network of a European TSO to examine ways to increase transfer capacity across one corridor on their network by 400 MW by balancing the flows on parallel lines. The traditional solution proposed was a large PST that can only be installed in a one of the three possible substations due to space constraints. A solution using SmartValve devices was developed to release an equivalent amount of transfer capacity at the same location. The cost of the equivalent SmartValve solution was 80% of the cost of the equivalent PST.

For a more optimized solution using SmartValve a case was developed whereby two small deployments were put into service at different substations. This approach greatly reduced the number of SmartValves and the cost was 30% of the cost of the PST project. The SmartValve, with its ability to be deployed in smaller increments, has much greater flexibility than a PST and other solutions. The SmartValve installation was not limited to one location due to its flexibility in deployment, it could be installed in any of the three substations.

The SmartValve modularity and flexibility allows for planners to develop optimized solutions for grid issues. By inserting small deployments in the network in substations with space constraints, the SmartValve can be used to increase the

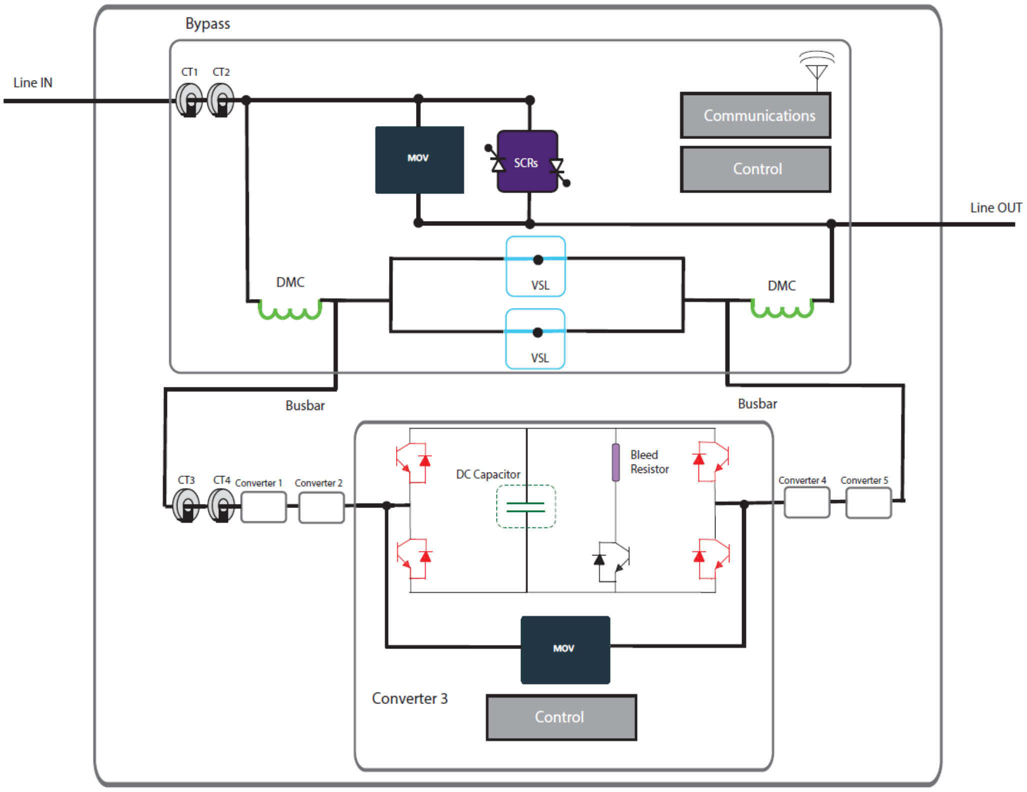

Fig. 3. SmartValve Component Diagram

network capacity and maximize the use of the existing infrastructure compared to traditional PFC solutions at a reduced cost. This allows utilities to better invest their capital in smaller projects and mitigate risks by scaling up and down deployments as needed.

B. *Increasing Transfer Capacity Without SSR Risk*

The SmartValve was chosen as the preferred solution for a large utility in the United States. The problem that that the utility was trying to resolve was increasing the capacity on their transmission network to allow generators firm access to the capacity market. Traditional solutions such as Series Capacitors were assessed, however there was a risk of SSR occurring when the series capacitor solution was analysed. The SmartValve has been designed and it has been demonstrated in studies that it does not contribute to SSR issues on a grid [8, 9] and can in fact dampen out SSR issues in certain cases. The other advantage that the SmartValve has over the equivalent series capacitor solution was that the SmartValve solution does not need an adjustment of the existing protection scheme.

This application shows the value of SmartValve in its interaction with existing protection and its lack of contribution to SSR. These are both important factors for TSOs and DSOs when selecting the optimum solution, as SSR mitigation and adjusting relays can be expensive and can take a long time.

The SmartValve can provide the same transfer capacity as a series capacitor, however the risk of SSR can be avoided. This allows the SmartValve to be used as a replacement for series capacitors.

C. *SmartValve as an Interim or Bridge Solution*

Due to the ease of installation of the technology and the flexible deployment methods available SmartValve can be used as an interim or short term solution to bridge the gap until long term solutions can be implemented. In the case of a fixed deployment the SmartValves are deployed on post-insulators and support structures in an array configuration. The units do not require any additional control, protection or power cabling as they are self-powered, self-protecting and control is done wirelessly to the substation control room. This makes the installation very quick to complete and, in the event that the units are re-deployed, the only sunk elements of the project are the foundations and line connections. The SmartValve also comes in the form of a Mobile containerised unit that can also be used for short term solutions. The SmartValves are mounted on a mobile trailer that can be driven to the required location and installed in less than a day.

A fixed installation of SmartValves is being proposed for a utility in Europe as an interim solution to allow firm access for 1000 MW of wind generation. The long term solution is a substation refurbishment but the refurbishment will not be complete until 2025. The proposed SmartValve solution has a delivery date in 2021. This allows the firm access to be accelerated for the wind farms 3 years earlier than it would receive it without the bridge solution. Once the enduring solution is installed the SmartValves can be relocated to another part of the network.

Similarly in the USA, a large utility has decided to use the SmartValve Mobile Unit to resolve an overload during a construction outage. This overload has prevented outages being available to undertake the reconductoring of a line for many years. When completed the reconductor will increase the transfer capacity by 450 MW and increase the integration of renewable generation in the region. After this project is complete the utility anticipate using the SmartValve mobile unit throughout its grid to resolve similar short term issues.

Using the SmartValve as an interim solution can greatly reduce the time that wind farms and other renewable generators experience constraints. The mobile SmartValve also provides the flexibility to allow faster completion of projects and less constraints during outage seasons.

V. New Use Cases To Enable More Wind

The SmartValve applications so far have only looked at more conventional ways of applying the SmartValve as an impedance controller to resolve system capacity issues. Due to the high speed control capability of the device it can also be used as a solution to more stability problems.

Smart Wires have identified applications that can use fast acting injection to increase transfer capacity. During cases where a SmartValve is installed on a line, parallel to a line that has tripped the transient stability limit can be increased by injecting a voltage that emulates a series capacitance very quickly. The change in transient stability limit is defined by the equation:

$$P = \frac{EV}{X_S(1-k)} \sin\theta \quad (1)$$

And the level of compensation is governed by:

$$k = \frac{X_C}{X_S} \quad (2)$$

Where P is the transmitted power down the line, E is the voltage at the sending end of the line, V is the voltage at the receiving end of the line, X_S is the reactance of the line, k is the level of compensation, θ is the difference in angle between the voltages and X_C is the injected reactance. The impact of changing the level of compensation on the transient is shown in Fig. 4. It is clear that decreasing the reactance of the circuit increases the transient stability limit. This application can be used to help integrate renewable generation on systems with transient stability issues.

The SmartValve has other possible applications due to its single phase modular design such a phase balancing and power oscillation damping and controller interaction damping. These applications are being developed for implementation in 2020 and beyond. As these applications will help improve the strength of the grid, they will enable the increase integration of wind and renewables on these grids.

VI. Using Innovation to Enable Wind Integration

As has been shown by the use cases in this paper the MPFC family of devices can be used to integrate wind and other renewables on a large scale by addressing the problems associated with traditional solutions. In particular, the flexibility of the MSSSC, its scalability and its redeployability makes it an attractive solution for resolving grid constraints. Therefore the MSSSC has been shown to not only provide the significant benefits of a SSSC for PFC, but also eliminate most of their remaining drawbacks.

The SmartValve can be used as a solution to the current grid issues related to congestion, uncertainty and SSR but also

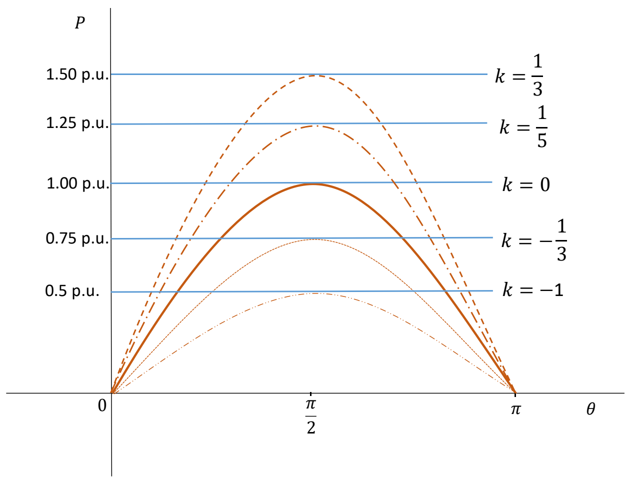

Fig. 4. Transient Stability Limit Change with series Compensation

to address emerging issues such as harmonic injection, transient stability and controller interaction. These issues are growing more prominent as more inverter based technology is being integrated into the system. To address these issues solutions that solve multiple issues will be required.

In conclusion the MSSSC is demonstrably a new and innovative technology that can be used to resolve large scale grid problems. The SmartValve has been assessed for multiple applications to further integrate renewables is being deployed on grids around the world. MSSSC has many advantages over traditional solutions namely, flexibility, modularity, redeployability and upgradability. These features will allow the MSSSC to increase wind and renewable penetration while avoiding problems associated with traditional solutions.

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