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Series Compensation to Increase Power Flow: A Case Study on the Irish Transmission System

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Abstract—Ireland presents an interesting case study for transmission network strengthening. The majority of load in the country is located at the nation's capital, Dublin, in the East, while most of the new conventional generation and renewable generation are found in the South-West. Power is transferred between the two via a 400 kV network. This leads to large cross-country power flows. This power distribution disparity is due to increase. A large thermal generating station which is connected to the 400 kV system in the West, will close by 2025. This generation will be replaced partially with wind generation in the South West, which is connected at 110 kV and 220 kV. This can cause power flow to avoid the 400 kV network, leading to less efficiency, overloading and other issues associated with power flow on lower voltage networks.

In this paper, the application of series compensation on the 400 kV transmission network in Ireland for increasing power transfer capability is investigated and a viable solution is found. The lower voltage network is modelled to investigate the effects of 400 kV series compensation on the rest of the network. With our series compensation solution on the 400 kV network, power flows are successfully reduced on the 110 kV network as the lower reactance of the 400 kV network now attracts power to flow through the more stable and less lossy 400 kV network.

***Index Terms*--FACTS, D-FACTS, Series Compensation**

I. INTRODUCTION

The characteristics of a power system evolve over time, as load grows, and generation is added. If the transmission facilities are not upgraded sufficiently, the power system becomes vulnerable to steady-state and transient stability problems, as stability margins become narrower [1]. A common solution for increasing transmission capacity has been to construct new transmission lines. Currently, there is pressure to increase power flow in existing right of ways using existing infrastructure as far as possible due to the increasing rejection of new electrical installations by the public [2]. This is where transmission line compensation becomes essential. Transmission line compensation means the existing lines are regulated. The sending end and receiving end voltages are maintained constant for all loads by using capacitors, inductors or electronic devices.

Series compensation is widely used worldwide as a method for increasing the power transfer capability on long transmission lines. There are currently no applications of series compensation in Ireland.

Eirgrid is the Transmission System Operator in Ireland. The Eirgrid Needs Report which was compiled in July 2017 [19] identifies a number of *Tomorrow's Energy Scenarios*. Two significant drivers that highlight the need to upgrade the transmission network by 2025 are [19]:

1. Increased demand on the East coast - There is an expected demand increase in the order of 900 MW due the connection of data centres. This is based on executed and offered connection agreements in the East of the country.
2. Integration of generation in the South and South West - Significant levels of new renewable generation have connected or are in the process of connecting to the grid in the South and South West. This is also where the newer and most cost-effective conventional generation units are located.

The two drivers above introduce the need for large cross-country power flows on the existing transmission system from the West to the East coast [19]. Figure 1 is a map of the transmission network in Ireland illustrating the main generation and load centres.

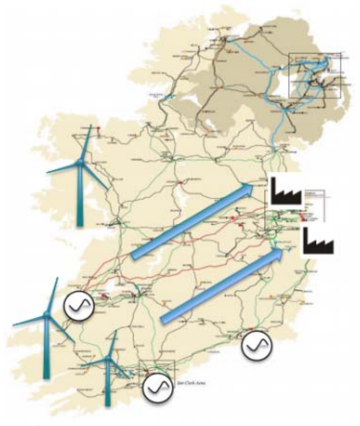

Figure 1 - Map of Ireland showing main generation and load centres

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Although series compensation is mature technology, it has never before been used in Ireland. Ireland's largest generating station is the 900 MW Moneypoint plant which uses coal to generate electricity. This plant, which is located in the West of the country, is due to reach the end of its operating life in 2025. As there is an expected demand increase of 900 MW in the East, this loss of 900 MW generating capacity would have the net effect of a 1,800 MW deficit in generated power. Therefore, new renewable generation in the West of the country will play a crucial role in supplying the load in the East of the country in the near future. This is why new and innovative methods for improving transmission capability between the West and East of Ireland are crucial.

II. RELATED WORK

A. *Options for Increasing Transmission Line Power Transfer*

Some typical options for increasing transmission line power transfer capability are [2][4][5]:

- Build additional transmission lines and cable circuits.
- Increase existing transmission line voltage (for example from 220 kV to 400 kV).
- Increase current density using high tension low sag conductors (HTLS).
- Use AC lines to transmit DC power (using AC-DC and DC-AC converters).
- Dynamic rating of transmission lines.
- Series or shunt compensation (fixed and/or power electronic methods)

B. *What is Series Compensation?*

Series compensation has been used to improve power transfer in long-distance transmission systems worldwide [6]. A series compensator (usually a capacitor) is typically installed in series with a transmission line to increase or decrease the effective reactive impedance of the line, allowing control of real power flow between the two buses [3].

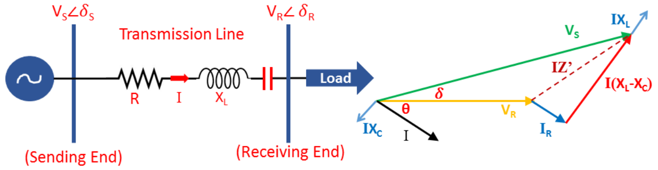

Figure 1 - Series compensation on a transmission line

The received power is increased depending on the value of capacitive reactance (Xc) added in series with the transmission line as per the below equation:

$$P_R = \frac{V_S V_R}{X_L - X_C} \sin\delta$$

C. *Types of Series Compensation*

Fixed Series Compensation (FSC):

This is the simplest and most cost-effective type of series compensation and is provided by Fixed Series Capacitors (FSC) [7]. The aim is to cancel part of the reactance of the line by means of series capacitors [8].

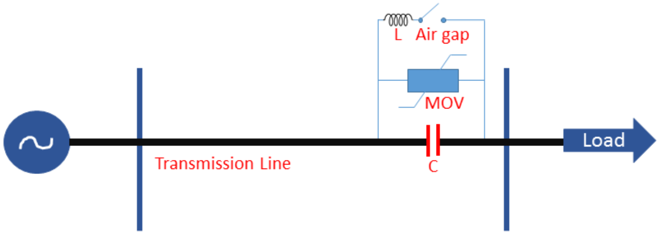

Figure 2. Fixed series compensation

Under normal operation, a zinc oxide varistor (MOV) of nonlinear type presents a high resistance [9]. When the voltage across the capacitor exceeds a protective level, the resistance of the varistor becomes very low and it conducts. It therefore diverts part of the fault current away from the capacitor. Since there is an upper limit for energy dissipation in the MOV, for its protection there is special circuitry which calculates the energy dissipated by the varistor and triggers the air gap to divert away from the series compensation unit [20]. There is a damping inductor (L) for the purpose of limiting the discharge current from the capacitor [10].

Variable Series Compensation (VSC):

With the advent of power electronic devices like the Thyristor and associated controls (Flexible AC Transmission Systems - FACTS), the usefulness of controlled series compensation has been widened [11]. Thyristor Controlled Series Capacitor (TCSC) is a FACTS device connected in series on transmission lines to control the dynamic power flow and enhance the power quality [4]. With a TCSC, it is possible to vary the degree of compensation rapidly, limited only by the speed of response of the electronic scheme used [11].

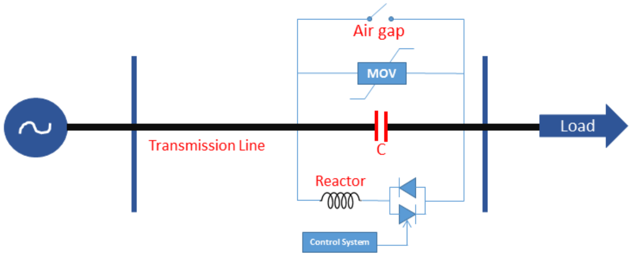

Figure 3. Variable series compensation

TCSC comprises of a series capacitor in parallel with a Thyristor Controlled Reactor (TCR). By varying the firing angle of the thyristor (to make the switch on/off), the TCSC can optimise the degree of compensation over a wide range under various network conditions. Varying the firing angle of the TCR is used to control the capacitive reactance of the TCSC [4][12]. Operationally, when the thyristors are firing, the TCR branch circulates current pulses, which add in phase with the line current. This boosts the capacitive voltage beyond the level that would be obtained by the line current alone [11]. Like with fixed series compensation, the TCSC is protected by a MOV.

D. Positive effects of Series Compensation

There are many positive effects of series compensation [11][13][14], including:

- Increases the loadability of long lines up to their thermal limits.
- Acts as a self-regulating device for better voltage regulation.
- Reduces overall transmission losses.
- Improves network stability – both voltage and angular.
- Enables balanced power sharing between parallel lines so as to achieve best possible utilisation of transmission lines.

E. Negative effects of Series Compensation

Some negative effects of series compensation [15][16][17] include:

- Sub-synchronous resonance possibility.
- Protection over reach and under reach issues.

F. Series Compensation Example

A successful example of series compensation is in Finland. Two series capacitors, rated at 369 Mvar each, were installed on Fingrid's 400 kV grid to strengthen the power transmission capacity in northern Finland and to assure power system security. The series capacitors both went on line in 2009 [20]. These series capacitors add transmission capacity towards neighbouring Sweden by some 200 MW, using the existing network. They are needed to meet the rising market demand on power transmission between northern Finland and Sweden and also internally in Finland. Series capacitors enabled added transmission capacity on existing power lines and helped maintain grid stability in the Finnish power system. The series capacitors were designed to compensate 70% of the existing lines reactance. The result of this 2009 installation of two FSC's is strengthened power transmission capacity and assured power system security in northern Finland.

III. SERIES COMPENSATION IN IRELAND

The area of network that was considered for this study is highlighted in Figure 4. The two 400 kV circuits are illustrated in red, the 220 kV in green and the 110 kV in black.

Figure 4 - Irish transmission map (Source: [7])

The transmission map from Figure 4 is translated into an electrical equivalent Single Line Diagram (SLD) in Figure 5.

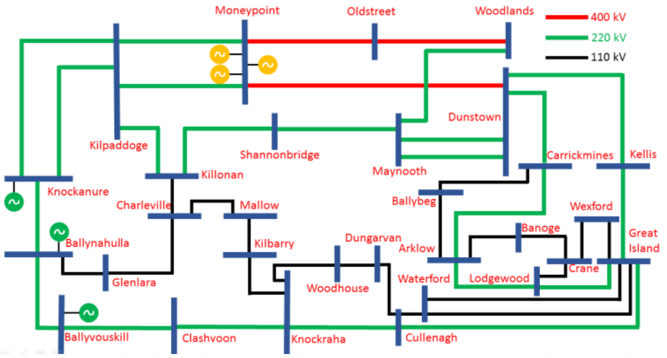

Figure 5. Single Line Diagram of the Irish Transmission network in question

The largest generating station in Ireland, Moneypoint (900 MW) connects directly to the 400 kV network in the West of the country. This model analyses the network when 50% of the generation output of Moneypoint is replaced by wind generation in the South-West of Ireland. The four cases in Table 1 are analysed using PSS®E software.

Table 1. Four cases analysed

Case	Series Compensation	Moneypoint (MW)	Wind (MW)	Combined (MW)	Moneypoint Reduction
1	No	843	146	989	0
2	70%	843	146	989	0
3	No	422	567	989	50%
4	70%	422	567	989	50%

- **Case 1** - the current network configuration is analysed as a base case.
- **Case 2** - 70% series compensation is applied to both of the 400 kV circuits.
- **Case 3** - half of the capacity of Moneypoint generating station is replaced by wind generation in the South West connected to the 110 kV and 220 kV network. There is no series compensation on the network.
- **Case 4** - half of the capacity of Moneypoint generating station is replaced by wind generation in the South West

connected to the 110 kV and 220 kV network. There is 70% series compensation on the 400 kV network.

IV. RESULTS

When half of the capacity of Moneypoint is replaced by wind generation on the South West, the power flow on the 400 kV network is reduced. This is undesirable as losses are the smallest on the 400 kV network. As generation must be matched with demand at all times, the power that previously flowed on the 400 kV network now flows on other lower voltage sections of the network. This equates to higher losses. When series compensation was added to the 400 kV network, power flows on the 400 kV network increased to values similar to that when Moneypoint was supplying the full 843 MW to the network as evidenced in Figure 6.

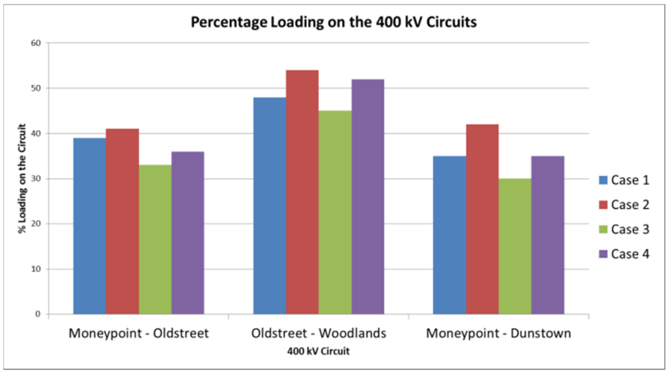

Figure 6 - Percentage loading on the 400 kV circuits

In recent years, the 220 kV grid in the South West of Ireland has been reinforced. This included the construction of three new 220 kV substations; Knockanure, Ballynahulla and Ballyvouskill, along with the associated circuits connecting these substations to the new Moneypoint 220 kV substation. Figure 7 shows that when 422 MW of wind generation is connected to these three substations, the loadings on the 220 kV network around the South West are substantially increased as shown in the dashed red box, as designed. The remainder of the 220 kV network remains generally unchanged.

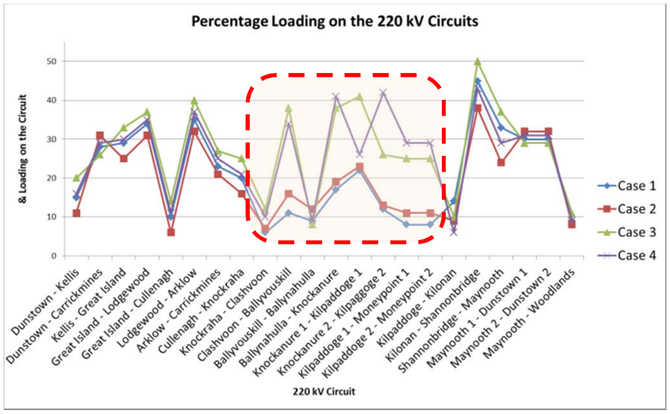

Figure 7 - Percentage loading on the 220 kV circuits

In Figure 8 it is evident that in case three, with the addition of wind generation, the loadings on the 110 kV network increase substantially. This is undesirable as the net system losses are higher and the 110 kV network is not as reliable as the 400 kV network. With the addition of series compensation to the 400 kV network, the loadings on the 110 kV lines reduce greatly. In fact, it can be seen that the loadings in case one, with Moneypoint generating 843 MW and case four, 50% of Moneypoint coming from wind generation and series compensation applied to the 400 kV network, the loadings on the 110 kV network are almost identical.

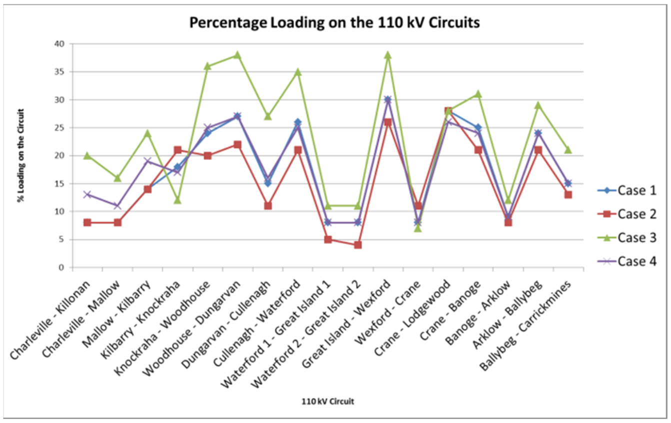

Figure 8 - Percentage loading on the 110 kV circuits

V. CONCLUSION

The aim of this paper is to investigate the effects of series compensation on the transmission network in Ireland, in particular on the 400 kV network. Electricity demand is growing in Ireland and there are 900 MW of executed and offered connection agreements alone for connecting data centres to the grid in the greater Dublin area by 2025.

Traditionally, the method for increasing power transfer capability in Ireland has been by building new transmission circuits. Worldwide, series compensation has been used to increase power transfer capability of long transmission lines, while exploiting the existing transmission lines and right of ways. Series compensation has never been deployed in Ireland.

A PSS®E model was used to investigate the effects that installing series compensation on the 400 kV network had on other areas of the network. The largest thermal generating plant in Ireland, Moneypoint directly connects to the 400 kV network in the West. This simulation scaled back the output of Moneypoint by 50% and replaced it with equivalent wind generation in the South West of the country. Analysis showed that this caused increased power flows on the 110 kV network, which is weaker and has higher losses than the 400 kV network. Current will take the path of least resistance. When series compensation was added to the 400 kV network, the power flow on the 110 kV network decreased. This power instead travelled through the 400 kV network because of its reduced reactance due to the application of series compensation.

This is the desired consequence, as the 400 KV network is stronger, has higher MVA ratings and provides a direct connection from the West to the East of Ireland, unlike the 110 kV network which connects through many nodes. Series compensation Enabled balanced power sharing between parallel lines so as to achieve best possible utilisation of transmission lines.

This paper has demonstrated the benefits that series compensation can bring to the Irish transmission system; increased power transfer capability while using existing assets, aiding the replacement of thermal generation with renewables, and increasing stability. This solution is applicable to other similar scenarios found on power systems throughout the world.

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