Dynamic Series Compensation for the Reinforcement of Network Connections with High Wind Penetration

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Government Targets

Scottish Targets -

- **80% of power from Renewables by 2020**
- Interim target of 31% by 2011
- Currently at 25% (2008 figure)
- 20% of primary energy by 2020
- **Emission reduction target of 80% by 2050**
- Interim target of 42% by 2020

UK Targets –

- **32% of power form renewables by 2020**
- Currently at 7%
- 15% of primary energy by 2015
- **Emission reduction target of 80% by 2050**

Scotland's Market Strength in Onshore Wind

Country		Operational	Under Construction	Consented	In Planning
Scotland	MW Capacity	2267	976	1824	4040
	No of Turbines	1304	478	760	1613
England	MW Capacity	805	91	1363	1546
	No of Turbines	675	53	576	629
Wales	MW Capacity	350	27	145	964
	No of Turbines	449	14	62	404
Northern Ireland	MW Capacity	309	30	234	737
	No of Turbines	217	12	105	307
UK Total	**MW Capacity**	**3732**	**1124**	**3566**	**7287**
	No of Turbines	**2645**	**557**	**1503**	**2953**
	Percentage of Scottish MW against UK total	**61%**	**87%**	**51%**	**55%**

Offshore Wind Current Status

UK now has more installed capacity than the rest of the world combined as the 300MW Thanet project went online on September 2010

Current Capacity	Under Construction	With Planning Permission	In Pipeline	Total
3,653MW	1,152MW	2,620MW	43,238MW	50,663MW

Rest of the world installed capacity = 1,762MW

The **UK is the largest market in the world for offshore** wind and will remain so for the foreseeable future.

Major turbine manufacturers who have announced that they will set in in the UK include – Siemens, GE Energy, Gamesa and Mitsubishi Heavy Industries

UK ROUND 3 OFFSHORE WIND SITES - 32GW

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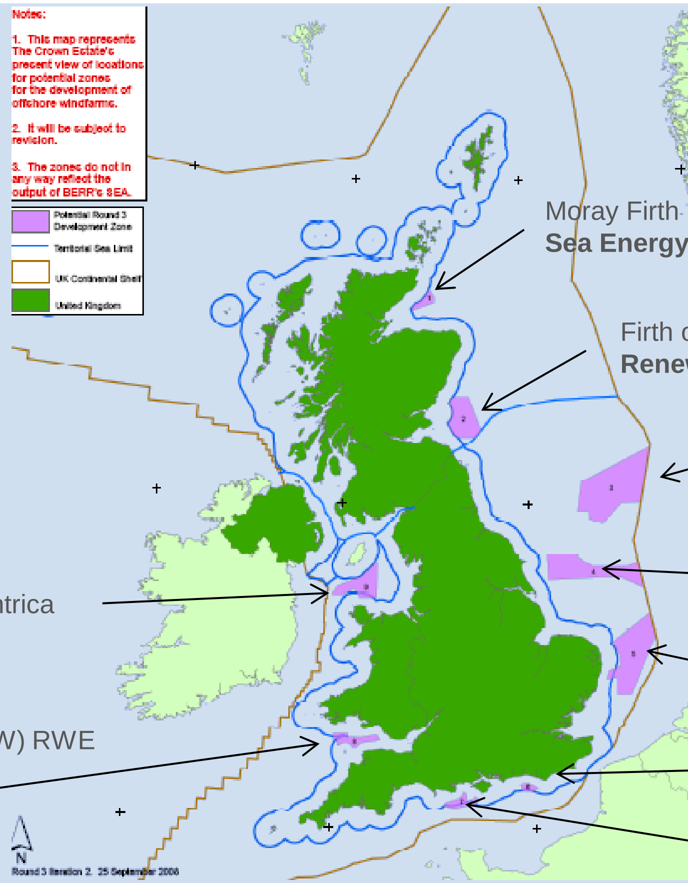


Moray Firth (1.3GW)
Sea Energy Renewables and EDPR

Firth of Forth (3.5GW),**SSE Renewables** and Flour

Dogger Bank (9.0GW) – Forewind
SSE Renewables, RWE, Statoil, Statkraft

Hornsea (4.0GW) –
Mainstream and Siemens

Norfolk (7.2GW) –
ScottishPower and Vattenfall

Hastings (0.6GW) - EON UK

Isle of Wight (0.9GW) – Eneco New Energy

Irish Sea (4.2GW) – Centrica

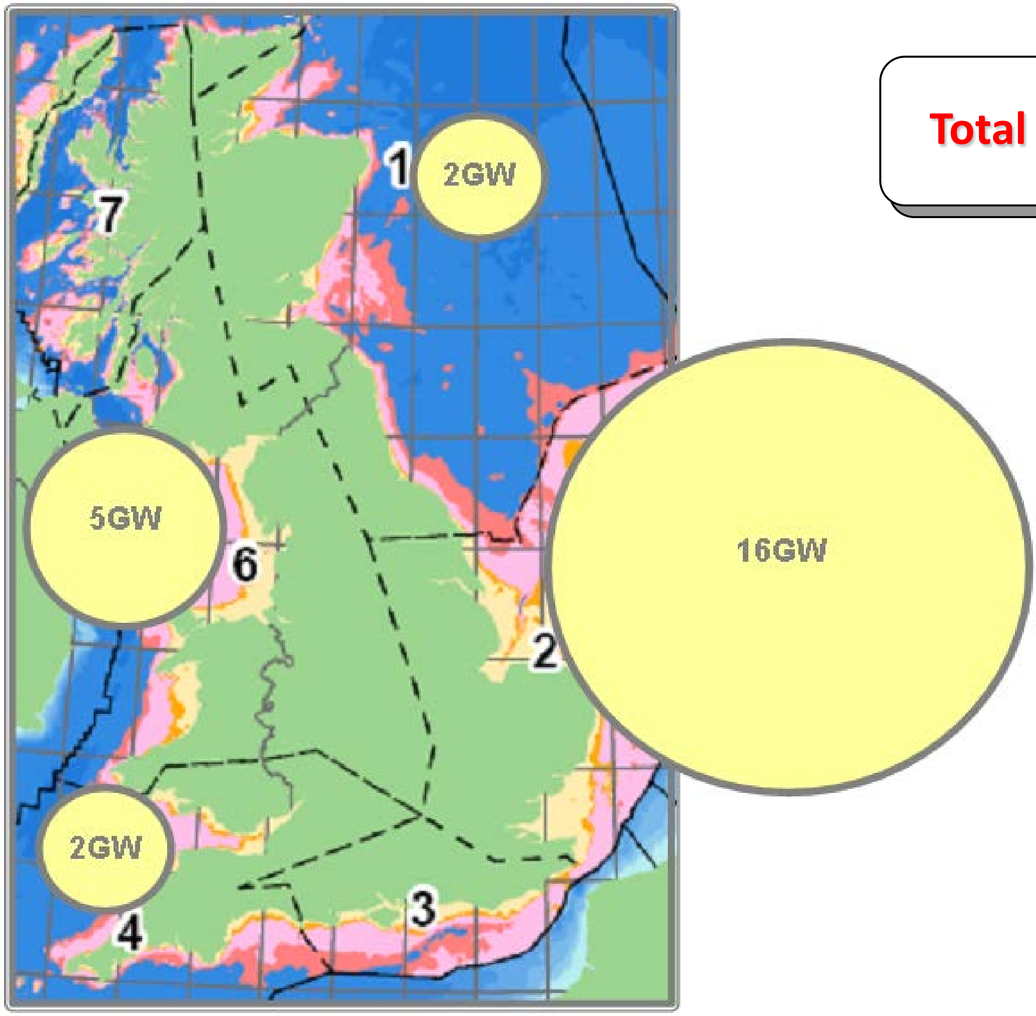
Bristol Channel (1.5GW) RWE nPower

£90Bn Capex Investment over the next 10 years
6,800 wind turbines

9 Development Zones of varying sizes

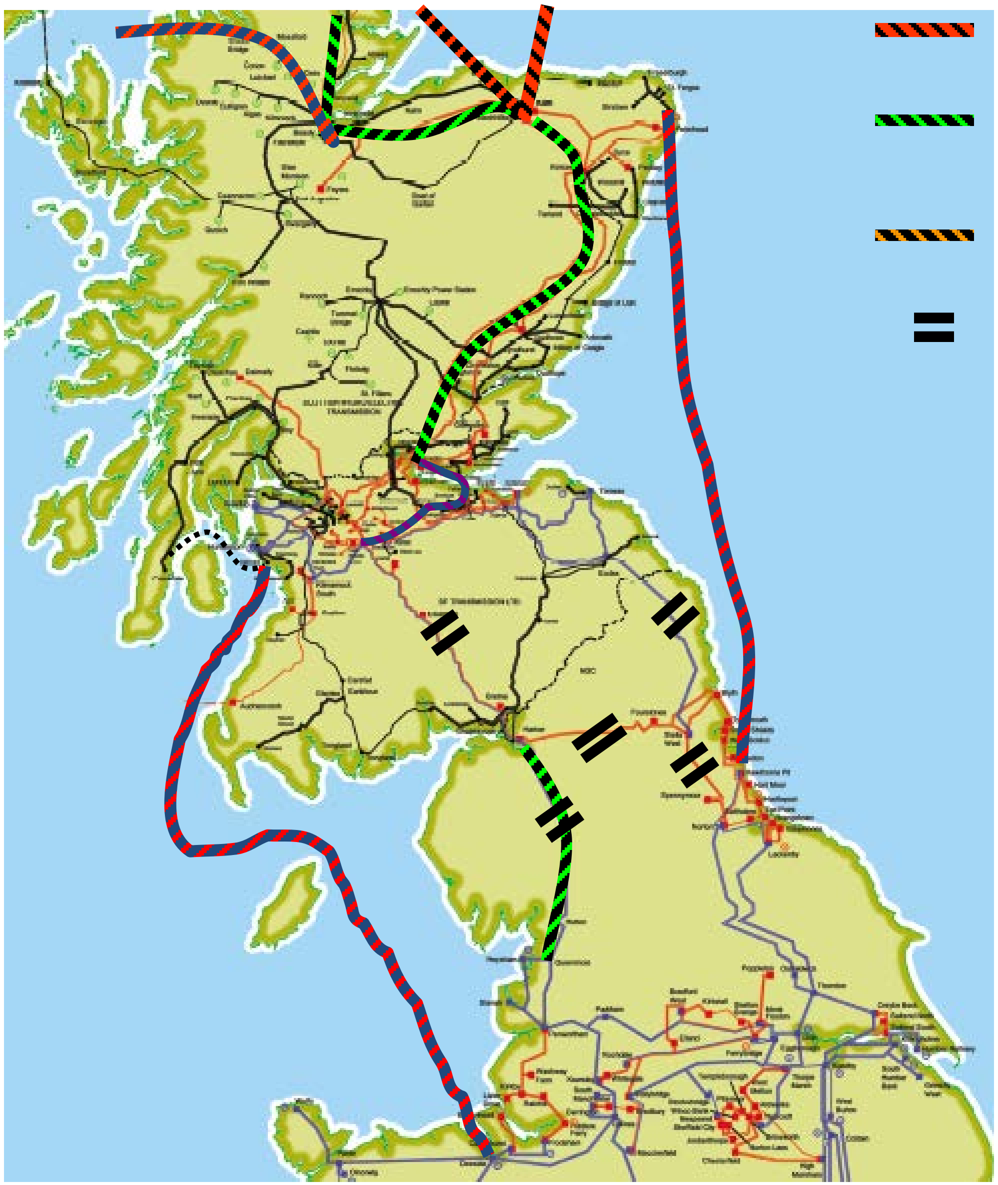
Grid availability and reliability

Total Capacity 25GW



Geographical Distribution of RD 3 Offshore Wind

Grid reinforcements – Scotland to England



HVDC circuit

Re-conductor or re-insulate existing double circuit overhead line route

Full re-build or new build double circuit overhead line route

Series compensation (equipment located at terminal substations)

Seeking to develop wide area monitor and control to enable:-

1) Maximise stability limits
2) Use Thyristor control on series compensation to maximise thermal transfers.

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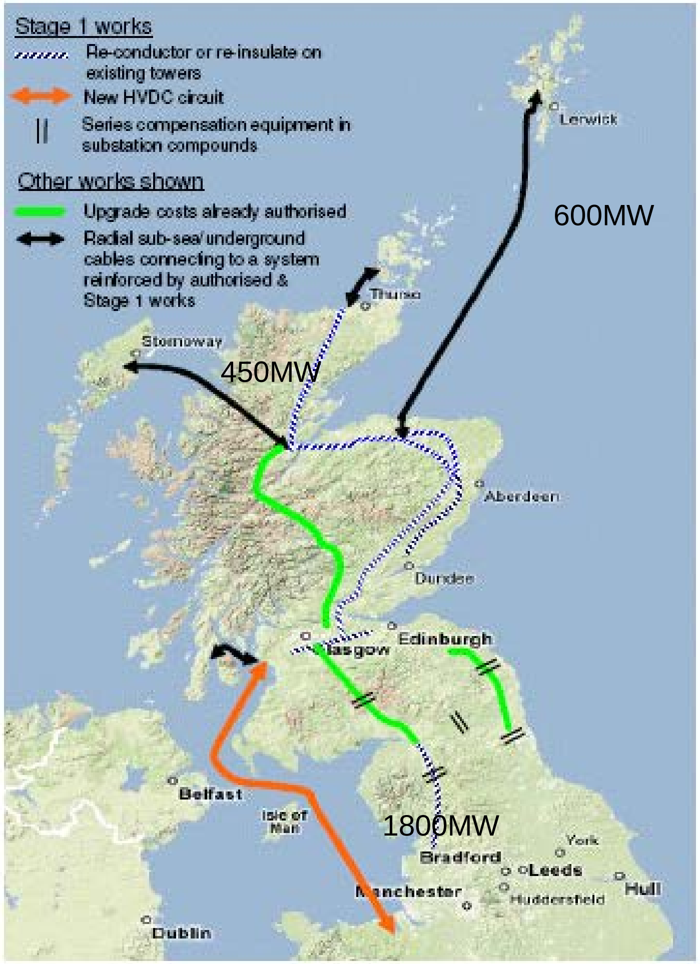
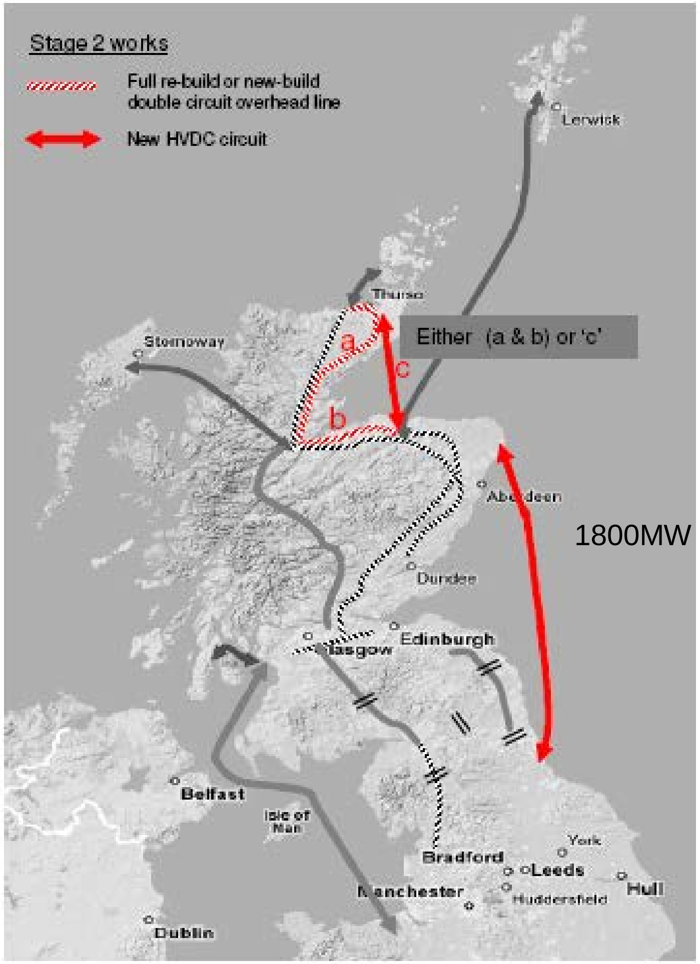
nationalgrid
The power of action.

Enabling Renewable Energy -The Grid

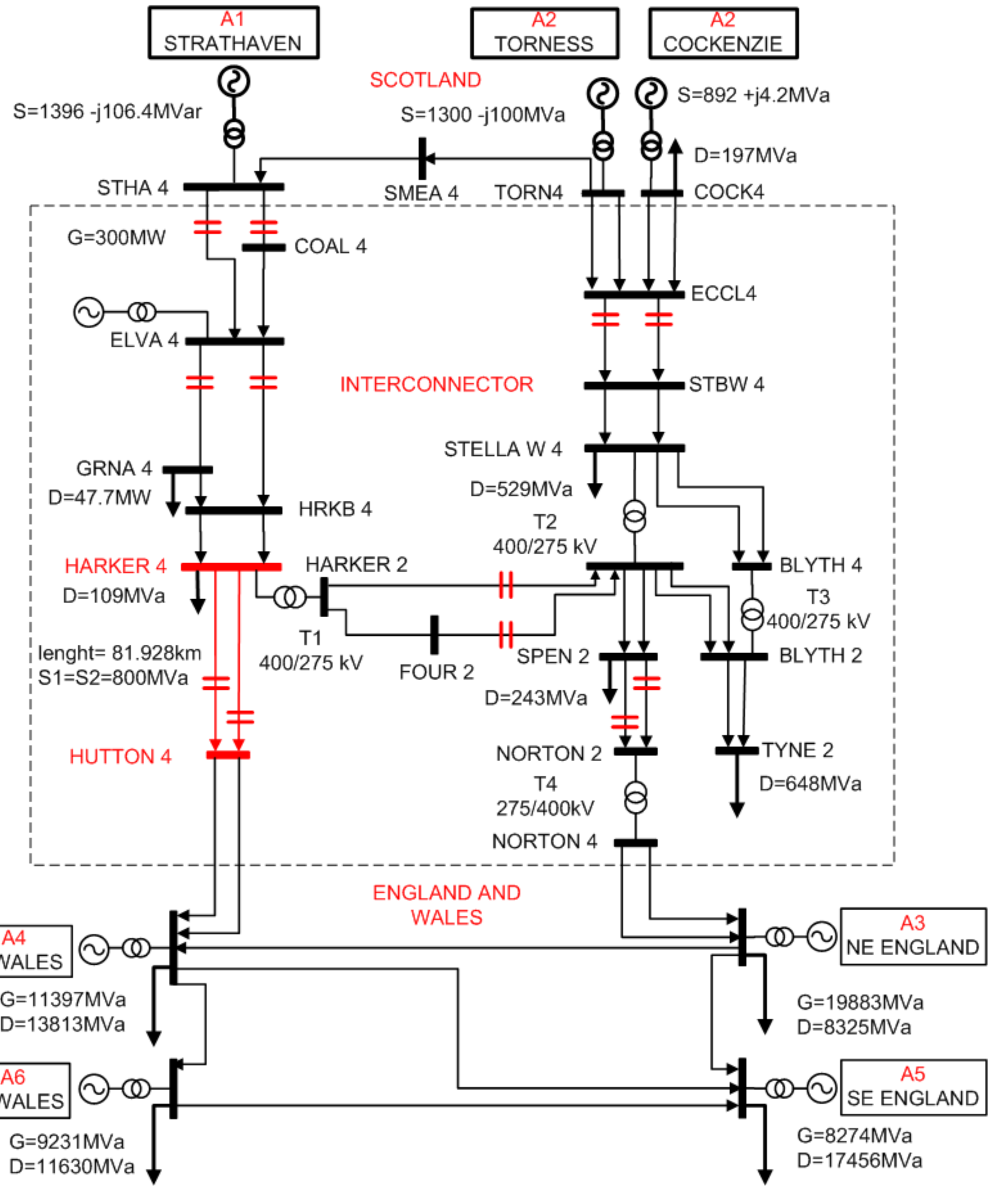




Energy Networks Strategy Group

£3.5Bn Capex Investment over the next 10 years

Simplified dynamic model



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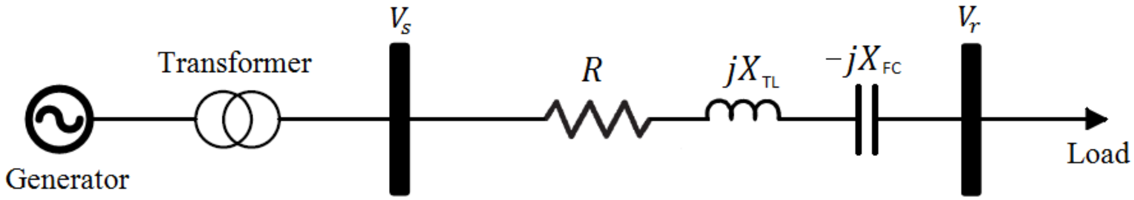
Series compensation

Series Compensation (SC) basically consist in connecting a Capacitor in series to a transmission line to cancel a portion of the reactive line impedance and thereby to increase its transmittable power capacity.

$$P = \frac{VsVr}{X_{eff}} \sin\delta$$



$$X_{eff} = X_{TL} - X_{SC}$$

The relation between the reactances of the transmission line and the series compensator is given by the series compensation ratio k, where,

$$k = \frac{X_{SC}}{X_{TL}}$$

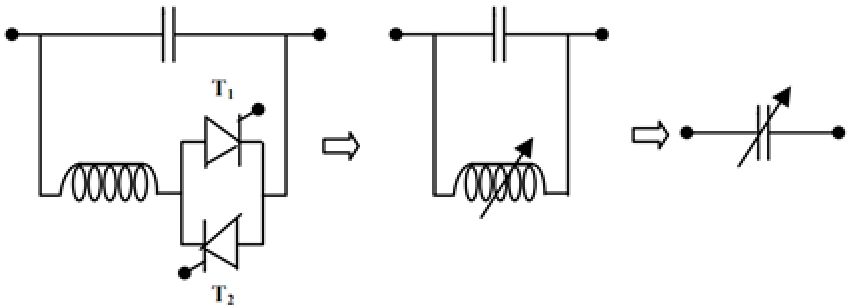
Thus, the effective reactance and active power in terms of the series compensation ratio are:

$$X_{eff} = X_{TL}(1-k)$$

$$P = \frac{V_s V_r}{X_{TL}(1-k)} \sin\delta$$

Dynamic Series Compensation: Thyristor Controlled Series Capacitor (TCSC)

A TCSC is a device which can behave as a variable capacitor or inductor, providing a range of variable reactance.



It is basically a fixed capacitor in parallel connection with an inductor. With a proper control of the antiparallel thyristors the inductor can vary its effective inductance and as such the TCSC can be controlled to behave as a variable inductor or as a variable capacitor.

$$X_{LC} = \frac{X_L X_C}{X_L + X_C}$$

Considering the end voltages and the impedance of the transmission line constant, the plot δ vs P for different k is shown below

$$P = \frac{V_s V_r}{X_{TL}(1-k)} \sin\delta$$

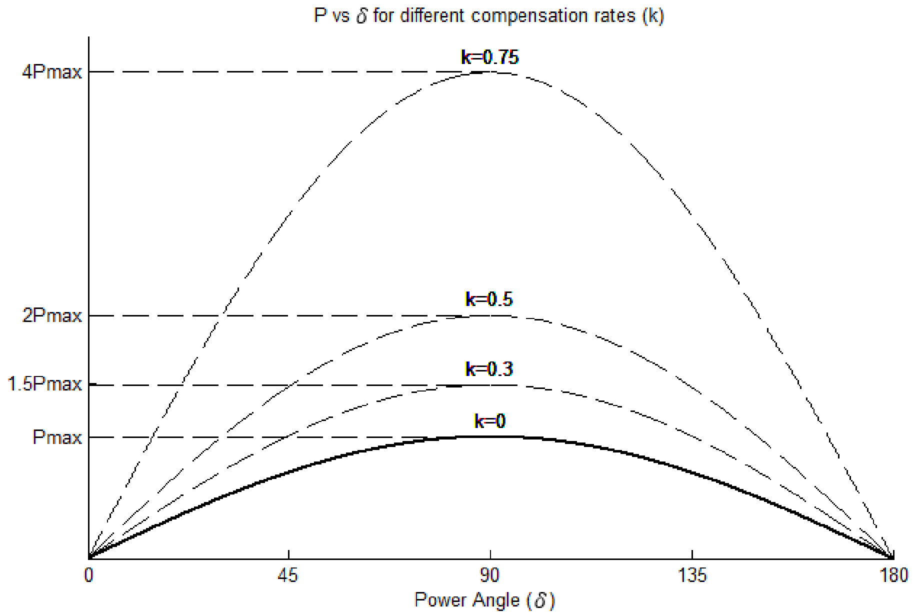
P_{MAX} occurs at δ = 90°

Where,

Sin90° = 1

Which means that,

$$P_{MAX} = \frac{V_s V_r}{X_{TL}(1-k)}$$



Series Compensation Ratio (k)	Maximum Active Power transference capability in terms of P_{MAX}
0	P_{MAX}
0.33	$1.5P_{MAX}$
0.5	$2P_{MAX}$
0.75	$4P_{MAX}$

Thyristor Controlled Series Capacitors (TCSC) capabilities

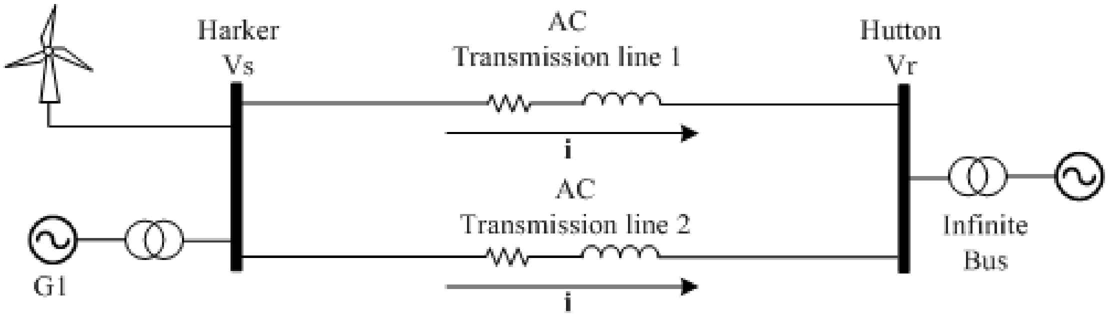
- **Upgrade of the Power Transmission capabilities of the path**
- **Damping of Power Oscillations**
- Improvement of the System Stability
- Reduction of System Losses
- Improvement of Voltage Profile at both Ends of the line
- Optimization of Power Flow between Parallel Lines
- Dynamic Power Flow Control
- Mitigation of Subsynchronous Resonance

Case studies

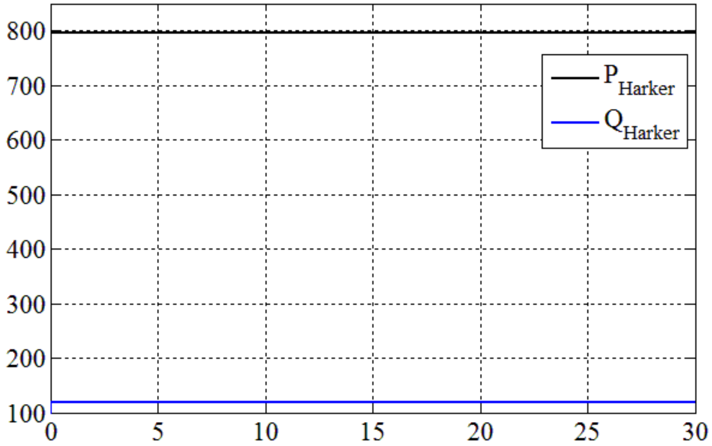
- Circuit 1. Double AC transmission circuit
- Circuit 2. Single AC transmission circuit // HVDC
- Circuit 3. Single AC transmission circuit with dynamic series compensation (TCSC) // HVDC
- Circuit 4. Double AC transmission circuit // HVDC
- Circuit 5. Double AC transmission circuit with dynamic series compensation (TCSC) // HVDC

Circuit 1. Double AC transmission circuit: The Harker-Hutton GB transmission path

Provides the parameters at which the transmission path between Harker-Hutton is operating

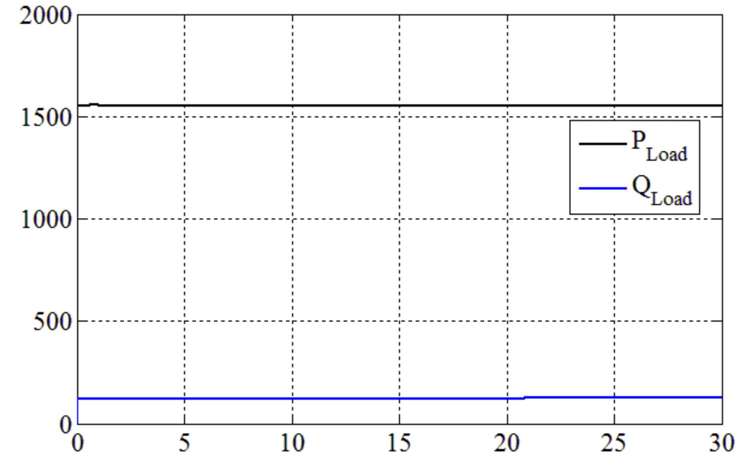


- The power injected to each transmission line at Harker is S=800+j120 MVA

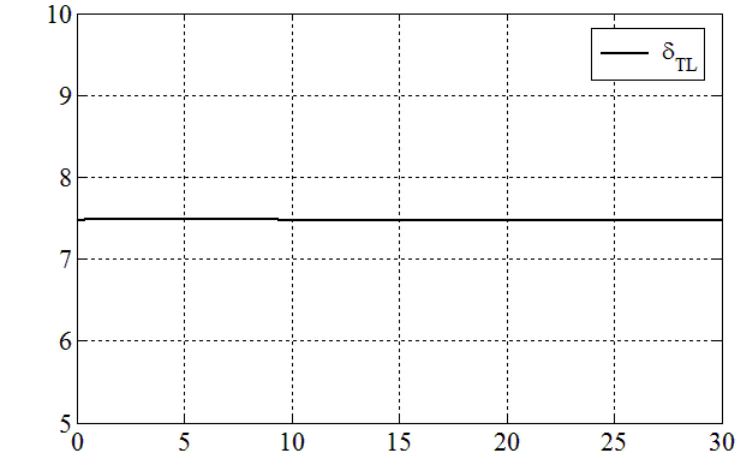


Power transmitted through each AC line

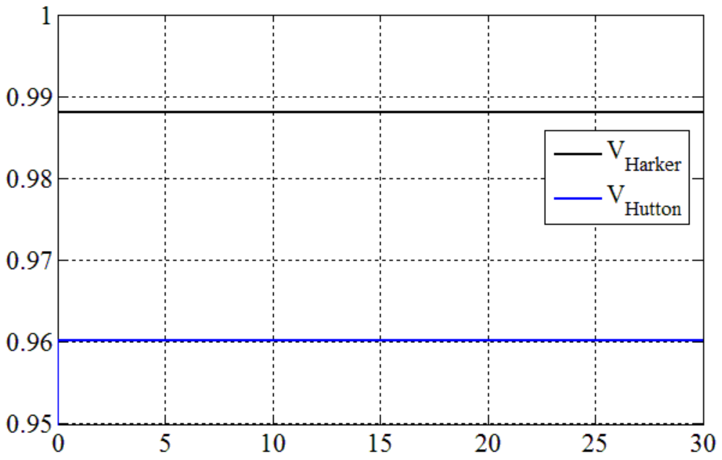
• The power delivered by both lines at Hutton is 1550 + j155 MVA



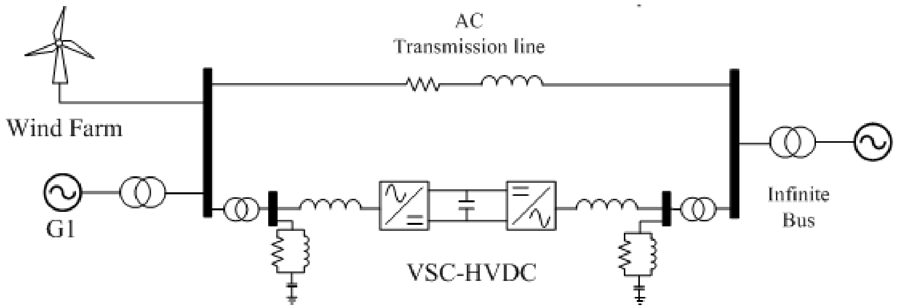
• The power angle generated between the Harker-Hutton transmission path $\delta_{H\text{-}H}$=7.49 degrees



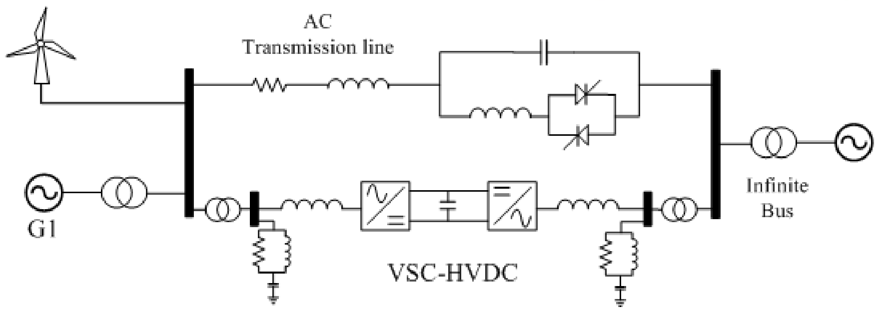
• The voltages at the receiving ends are V_s=0.98 pu and V_r =0.96 pu



Single Parallel AC-DC Circuits



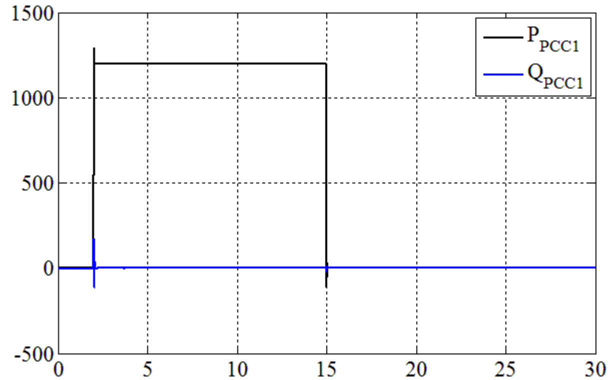
Circuit 2



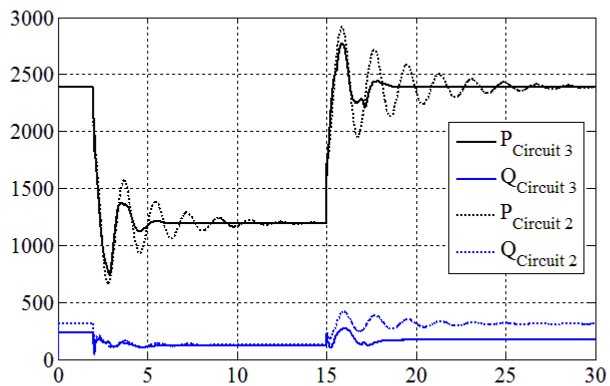
Circuit 3

- Power injected at the Sending End: 2.4GW (50% of increase with respect to Circuit 1)
- Under normal conditions it is desired that the HVDC link transmits 1.2GW and the leftover 1.2GW are transmitted by the AC line
- Both HVDC and TCSC start operating at t=2s
- The HVDC link is taken out of operation at t=15s
- The signals obtained by the simulation of Circuit 2 are displayed by the dotted lines, while the signals from Circuit 3 are displayed as full lines

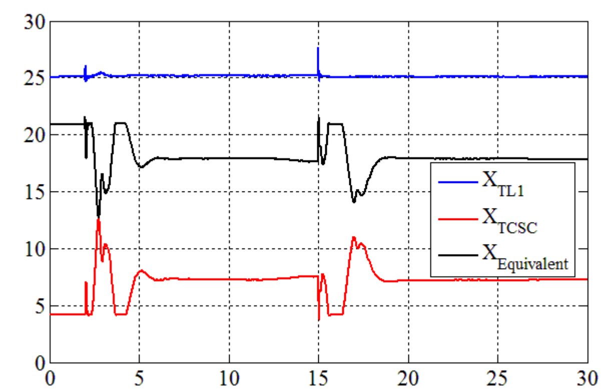
- 0s < t < 2s
  - Both the HVDC link and the TCSC are not operating



  - All the power is flowing through the AC transmission lines

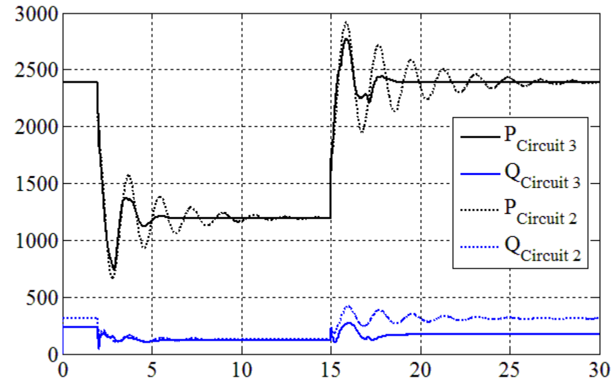


  - The TCSC provides a minimum compensation reactance of 15% (4.15Ω) which produces $X_{Equivalent}$ to decrease to 20.85Ω

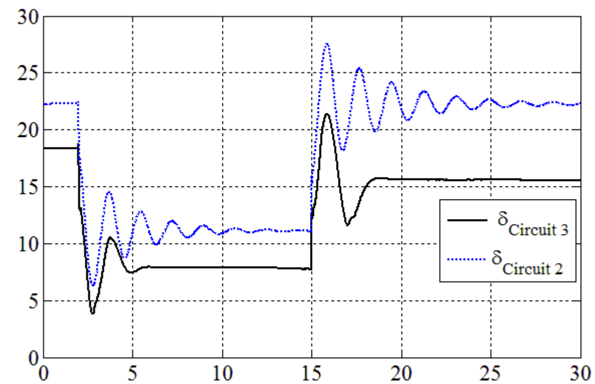


o Enhancements of Circuit 3 with respect to Circuit 2

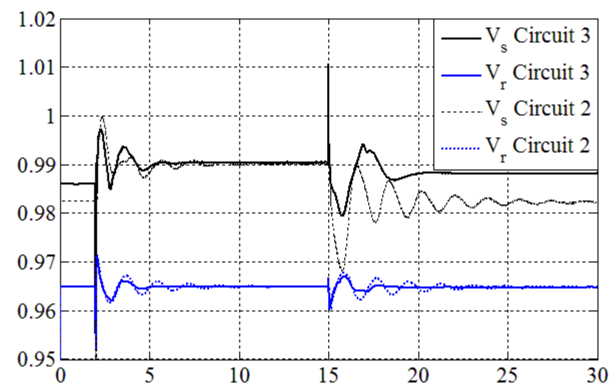
- Reactive Power consumed at the Sending End: 350MVar in Circuit 2, 250MVar in Circuit 3



- Power Angle Harker-Hutton ($\delta_{H\text{-}H}$): 22.5^0 in Circuit 2, 18.5^0 in Circuit 3

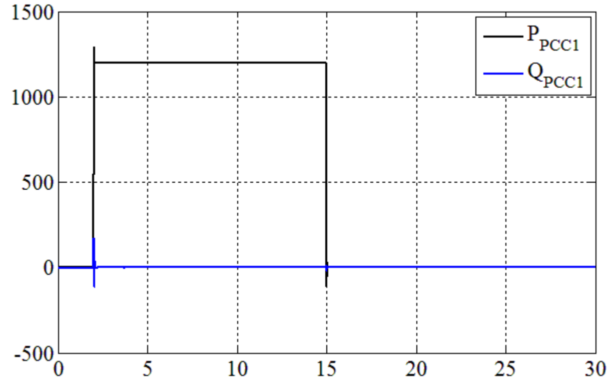


- Voltage profile at the Sending End: 0.982 in Circuit 2, 0.987 in Circuit 3

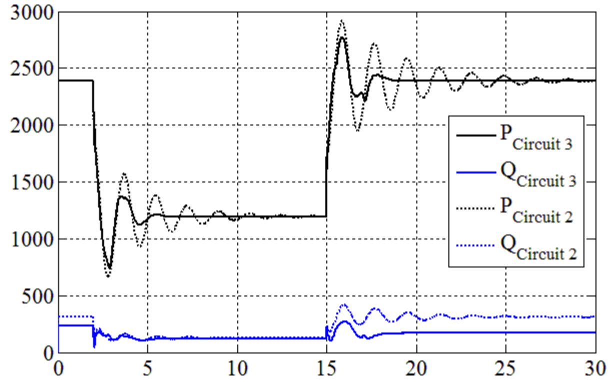


- 2s < t < 15s

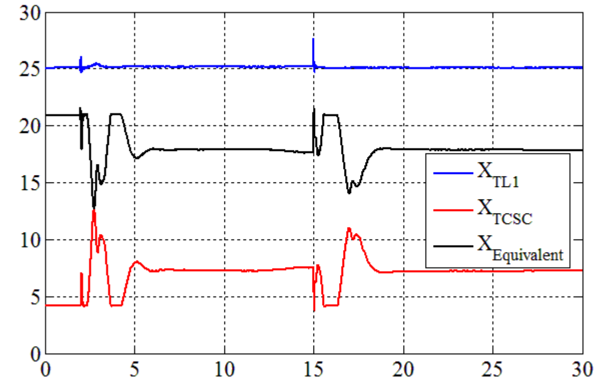
    - At t=2s both HVDC and TCSC start to operate
    - The HVDC immediately demands 1.2GW from the Sending End



    - Power oscillations with a frequency close to 0.6Hz occur at the AC side of the circuit
    - In Circuit 2 the Power Oscillations last for about 10 seconds (2s<t<12s)
    - In Circuit 3 the TCSC damping action is noticeable from the first Power Swing
    - The TCSC brings the system to a steady state after 4 seconds (at t=6s)



    - After the system reaches the steady state at t=6s, the TCSC sets its capacitive reactance at 8.3Ω which means 33% of Reactive Series Compensation



Conclusions

TCSCs allows for the increase in the power capabilities of a transmission line while the end voltages and the power angle of the transmission line remain close to the original values

TCSCs are capable to damp power oscillations and with this to improve the interaction between an AC-DC parallel circuits

Future Work

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Future works includes an analysis of parallel AC-DC circuits compensated by dynamic series compensation, where the HVDC converters provide AC voltage Control at the Point of Common Coupling (PCC).

Where it is expected that the AC voltage control obtained with the HVDC links provides an additional improvement in the power capabilities of a transmission line to the one obtained with the use of TCSCs.

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