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

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***Abstract* — This paper analyses the benefits brought about by the use of voltage control and reactive power control in a VSC-HVDC link that is connected in parallel to ac transmission lines, where this parallel connection is possible due to the use of Thyristor Controlled Series Capacitors (TCSC). TCSC devices are used for damping power oscillations, for improving the capacity of ac transmission lines and for enhancing the voltage profile at the line terminals.**

***Keywords*—HVDC, TCSC, ac-dc parallel connection, system reinforcement**

I. INTRODUCTION

Following the targets set by the European leaders in March 2007, known as the "20-20-20" targets [1], the UK Government issued a project for building around 40GW of new renewable electric power [2]. This 40 GW of electric power will represent around 30% of the total UK installed capacity, which goes beyond the goal specified by the European leaders (20%). Most of this new renewable power will be produced by the construction of offshore wind farms placed all around the GB mainland, where the biggest wind farm will be the so called Dogger Bank, which will produce up to 9GW of power [2]. In order to connect and transport such amounts of power to the main GB power system, it will be necessary to reinforce existent ac transmission paths and to build new transmission paths including dc links with VSC-HVDC technologies.

VSC-HVDC is the preferred technology used to deliver high amounts of new power generation, because of the several benefits that these dc circuits can provide to the power systems. However, VSC-HVDC technologies are not commonly used in parallel circuits with ac lines because this configuration could cause the system to experience power oscillations of subsynchronous frequency.

Thyristor Controlled Series Capacitors (TCSC) are series compensation devices capable of providing dynamic reactive series compensation, a feature that, among other benefits, can be used to increase the transmission capacity of AC transmission lines, to contribute to the reduction of power oscillations, and to improve system stability [3].

This paper analyses the interaction between an ac transmission line with a TCSC as a means of series compensation and a dc link based on VSC-HVDC technologies when placed in a parallel circuit. This research has a special interest in comparing the behaviour of this parallel circuit with different control configurations of the HVDC link, such as voltage control and reactive power control at the HVDC terminals.

1. PARALLEL AC-DC CIRCUITS

VSC-HVDC links can provide several benefits to the power system, such as transportation of high amounts of power with low losses, reactive power compensation at the HVDC Points of Common Coupling (PCC), control of ac voltage level at the HVDC terminals, among many others. However, when an HVDC link is connected in parallel to an ac line, the power reschedule effect can make the system fall into power oscillations of subsynchronous nature that can affect the system's stability.

A TCSC is a device that can provide several benefits to the ac transmission systems, such as [5]:

- Upgrade of power transmission capabilities of the line
- Damping of power oscillations
- Reduction of the line power angle (and with this improvement of the power system stability)
- Improvement of voltage profile of the transmission lines
- Optimization of Power flow between parallel lines
- Dynamic Power Flow Control
- Mitigation of subsynchronous resonance

Although all the features mentioned before are desirable in a transmission system, the use of TCSC devices does not mean that all of them will be reflected in the circuit at once. It is for this reason that the study presented in this work focuses on the upgrade of power transmission capabilities of the lines, the damping of power oscillations provided by the use of TCSC devices and the different effects caused by reactive power control and voltage control provided by the construction of new parallel dc links with the ac lines.

Three circuits will be used for the study presented in this work; these circuits are:

- Circuit 1. Double ac transmission circuit,
- Circuit 2. Single ac transmission circuit in parallel with a dc link,
- Circuit 3. Single ac transmission circuit with dynamic series compensation (TCSC) and a parallel dc link.

Each of these three circuit configurations was simulated in Simulink/Matlab and their results are presented in this work in order to compare the behaviour of each configuration.

The ac side of these circuits is based on the parameters of the double transmission circuit between Harker and Hutton from the Scotland-England Interconnector. Circuit 1 represents this transmission path and it is used for the analysis of the rest of the circuits. For the design of Circuits 2 and 3, one of the ac lines of Circuit 1 is replaced by an HVDC link. The difference between Circuit 2 and 3 derives from the inclusion of dynamic series compensation in the ac line of Circuit 3.

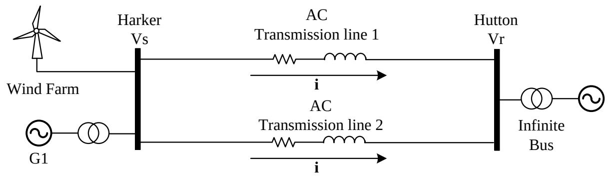

Fig. 1. Circuit 1: Double ac transmission path

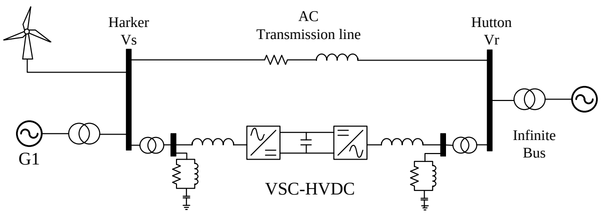

Fig. 2. Circuit 2: Single Parallel AC-DC circuit

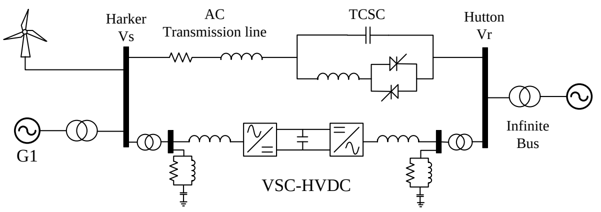

Fig. 3. Circuit 3: Single Parallel AC-DC circuit with Dynamic Series Compensation

II. Description of the components used in each circuit

All the circuits presented are simple 2 node models. Each model has a synchronous generator connected at the sending end and an infinite bus, acting as a load, connected at the receiving end.

The Synchronous Generator used is of the steam turbine type and works at 20kV and 50Hz. It also has a 20kV/400kV Δ/Yg transformer.

The ac transmission circuit used in the circuits is based on the transmission path between Harker and Hutton, which is part of the Scotland-England interconnector from the GB Electrical System. This Harker-Hutton transmission line is a double 400kV AC circuit, with a length of 89km, where each conductor has a total impedance of $Z = 2.62 + j24.98$ (not considering the susceptance of the line) and transports 800MW[4].

The HVDC is based on Voltage Source Converter technologies. It has a DC bipolar transmission line of 400kV and it is able to produce up to 1.2GW of Active Power. The HVDC used for this study possesses the capability of controlling the bidirectional injection of Active and Reactive Power and it also has the alternative for regulating the level of voltage at the Point of Common Coupling (PCC) of both Converters, also referred to as Vac control in this paper.

TCSCs use Enhanced Constant Power Control (ECPC), which is considered to be one of the best controls for damping Power Oscillations [5]. The TCSC used in this work can provide Variable Reactive Series Compensation to the transmission lines between the ranges of 15% to 45%. This range of operation has been chosen following the plans stated by the National Grid that stipulate that the transmission path Harker-Hutton is already working close to its thermal limits. Therefore, there is a plan to install 33% of reactive series compensation. This amount of series compensation allows for an increase of 50% of the transmittable power capacity, while remaining under the thermal limits of the transmission lines [2].

Following this recommendation the TCSCs used in this study include a control that, under steady state operation, provides for a constant reactive compensation of 33% and that, during transitory conditions, can provide a variable compensation between the range 15% to 45%.

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

The simulation of circuit 1, Fig. 1, provides the parameters at which the transmission path between Harker and Hutton is operating. These parameters represent a point of comparison for the simulations of the rest of the circuits of this study. Thus, the signals obtained from the simulation of circuit 1 are shown in Fig. 4.

The power injected to each transmission line at Harker is S=800+j120 MVA; this can be observed in Fig. 4a. The power delivered by both lines at Hutton is 1550+j155 MVA, figure 4b; this amount of power is equal to the power injected at the Harker minus the Power lost in the transmission lines. The power angle generated between the Harker-Hutton transmission path ($d = 7.49^0$) can be observed in Fig. 4c; this angle is calculated instantaneously in Simulink/Matlab through the power angle equation:

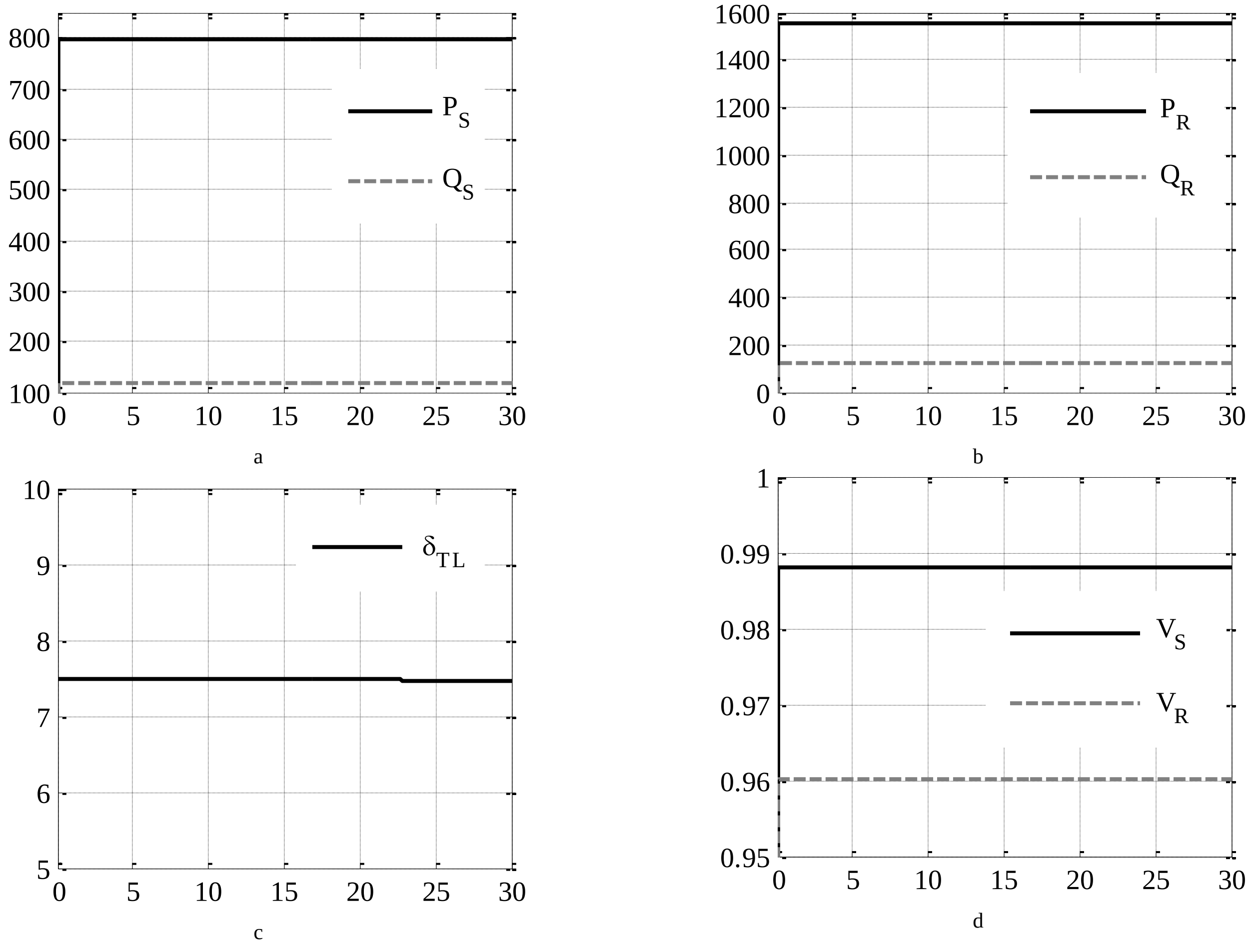

Fig. 4. Simulation signals of Circuit 1

$$d = \sin^{-1}\left(\frac{PX_{TL}}{V_s V_r}\right)$$

Finally, Fig. 4d shows the voltage profiles at the Sending and Receiving Ends.

IV. Single Parallel AC-DC Circuits

Since one of the objectives of this research is to provide an enhancement in the power capabilities of the transmission line circuit Harker-Hutton, the power transference for Circuits 2 and 3 (Fig. 2 and 3 respectively) has been set to 2.4GW, which represents an increase of 50% with respect to the power transmitted by the original Harker-Hutton in Circuit 1. Under normal operating conditions, it is desirable that the HVDC link transports 1.2GW of the 2.4GW total, with the ac transmission line transporting the remaining 1.2GW.

For the study of Circuits 2 and 3, the HVDC link starts operating at t=2s. This action causes the circuits to suffer a power reschedule effect where all the power is initially flowing through the ac line and it starts flowing through the HVDC link at t=2s producing power oscillations in the ac side until the circuit stabilizes. The analysis of this work is presented in four study cases, two for Circuit 2 and two for Circuit 3.

Thus, one study case involves the observation of the circuit behaviour when the Vac and Q controls of the HVDC link are started with the HVDC at t=2s and another study case when it is fully operating at t=15s for each Circuit. These four study cases allow us to observe the benefits brought about by the use of Vac and Q control of the HVDC link in Circuit 2 and the benefits derived from the inclusion of TCSC devices in Circuit 3. In all the figures of each study case, the signals resulting from three different HVDC control strategies are analyzed. These control strategies are:

1) No control (Q= 0MVa). The legend “no control” is a nickname, in reality the HVDC is working under Q control, but is set to provide 0MVa at both PCCs. This analysis is included for comparing the use of Vac and Q controls with the case in which no reactive power is injected by the HVDC link to the circuits.

2) Vac control. For this control both VSCs of the HVDC are set to regulate the voltage level at the Points of Common Coupling (PCC) to 1pu. In order to do so the converters inject reactive power at the PCCs until the desired voltage level is reached.

3) Q control. Q control is used for the HVDC converters to provide reactive power at the PCCs with the purpose to enhance the voltage profile of the ac buses to which the HVDC link is connected. Thus, Q control can used to make that the HVDC to provide the necessary reactive power to make the voltage profile to reach 1pu at each PCC. However, sometimes the reactive power necessary to achieve this voltage level can be very high and the physical limitations of the converters

components cannot provide these amounts of reactive power. It is for this reason that the reactive power provided by the HVDC Q control has been limited to 550MVa, which is already a very high amount of reactive compensation.

The four study cases are presented in the following sections.

A. Circuit 2

With the use of Circuit 2, it is possible to observe the behaviour of an ac-dc parallel circuit for the cases in which the Vac and Q HVDC controls start operating with the HVDC at t=2s or with a small delay at t=15s.

- Study case 1. Vac and Q HVDC controls start operating at t=15s

For this study case, Vac and Q controls are activated at t=15s. This action allows us to appreciate the improvements obtained through the use of these controls in comparison with the case in which no reactive power is injected by the HVDC to the system (signals provided by the no control analysis).

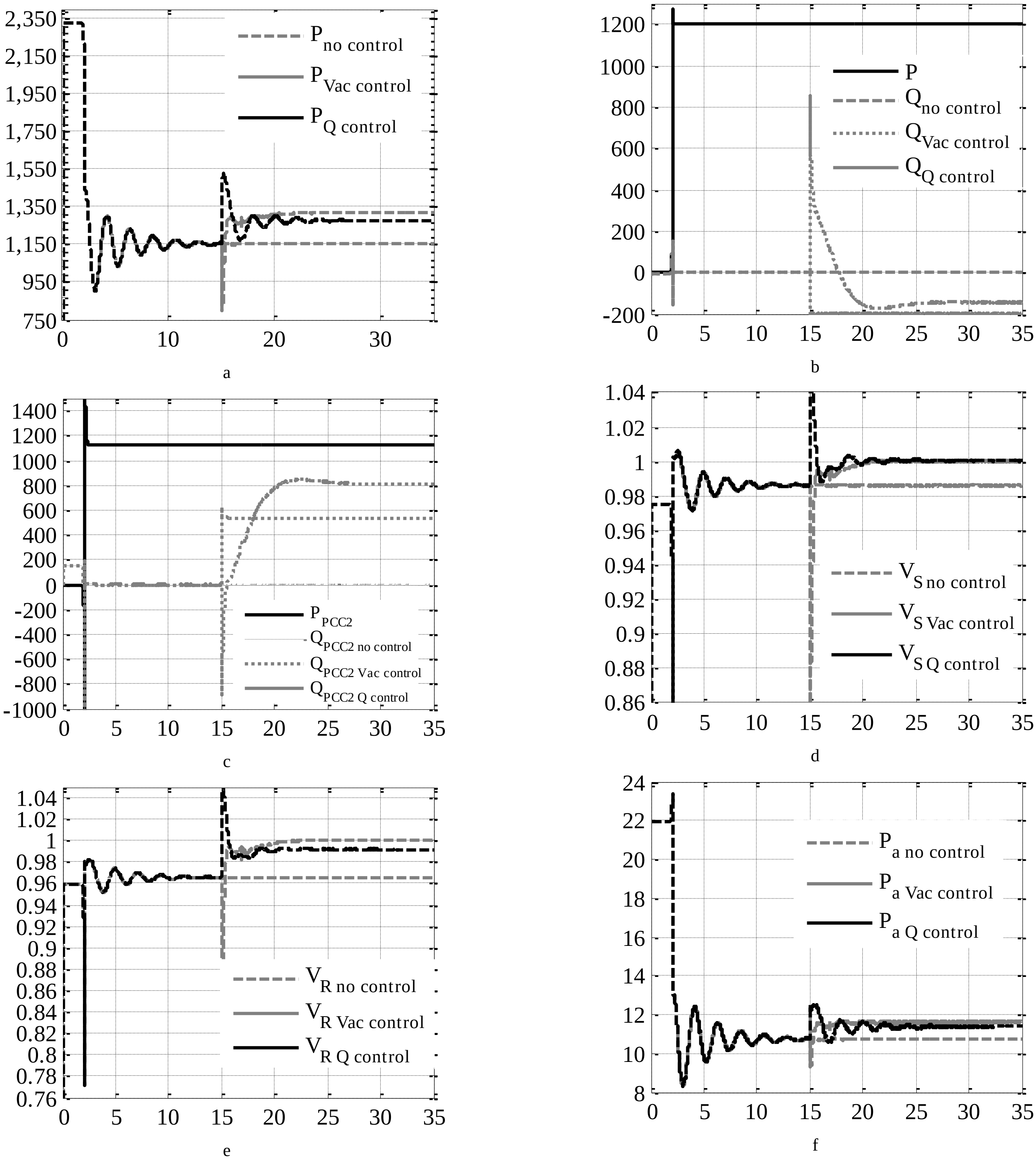

Fig. 5. Signals obtained from Circuit 2 when the Vac and Q controls start operating at t=15s.

No control analysis.

Following the no control signals (gray dashed lines), provided in Fig. 5, it is possible to observe the next phenomena. Fig. 5a shows that the sudden activation of the HVDC at t=2s, observed in figure 5b, produces subsynchronous oscillations with an approximated frequency of 0.4Hz. Once the system gets close to stability at around t=16s, it is possible to observe some effects in the system, such as: when the system gets stable it delivers P=1150MW; the first power swing reaches a magnitude of -250MW; the oscillations are extinguished in around 14s; the voltage at the sending and receiving ends are 0.985pu and 0.965pu respectively (Fig. 5d and 5e) and the power angle of the transmission lines will reach a value of $d_{TL} = 10.8^0$ (Fig. 5f), which is 3.3^0 higher that the power angle from Circuit 1.

Vac control analysis.

The Vac control signals are provided by the grey full lines from Fig. 5. As mentioned before, for this study case, the Vac control starts to operate at t=15s; before this time the HVDC is operating under a “no control” scheme (Q=0MVa). For this reason, during the period 0s< t< 15s, the grey full line representing the Vac control signals in figure 5 are identical to the “no control” signals. At t=15s the Vac control is started, producing a transitory negative reactive power injection by the HVDC converters at the PCCs. Once the effect of this transitory injection passes at t=27s, the HVDC regulates the voltage level of the sending and receiving ends to 1pu (Figs. 5d and 5e) by injecting 150Mva and 820MVa at PCC1 and PCC2 respectively (Figs. 5b and 5c). The injection of this reactive power at the PCCs produces an increase in the voltage level of approximately 0.02pu and 0.04pu at the sending and receiving ends respectively.

The increase in the circuit voltage also produces an increase in the active power injected in the ac line of approximately 180MW in comparison with the power delivered when the HVDC operates under the “no control” scheme. Finally, since the active power flowing through the ac transmission line is increased, the power angle produced by the line will also increase by around 1 degree, Fig. 5e.

Q control analysis.

The signals that show the behaviour of the circuit working under the Q control scheme, for this study case, are represented by the full black lines in Fig. 5. As it occurs for the Vac control, the Q control starts to operate at t=15s and for the period 0s< t< 15s, the behaviour of the system is the same as the behaviour of the no control and the Vac control configurations. At t=15s the Q control of the HVDC starts to operate and the VSC 1 is set to inject 200MVa at PCC1 while the VSC 2 injects 550MVa at PCC2, observed in Figs. 5b and 5c respectively. Since the reactive power injection is produced in a step way, the system will suffer from some power oscillations. However, when the system stabilizes at t=24s, it is possible to observe that the injection of such amounts of reactive power causes the voltage levels of both transmission line ends to increase to 1pu for the sending end and 0.99pu for the receiving end. It is true that the receiving end does not reach the same voltage level as the one reached with the Vac control, however, this action requires a very high amount of reactive power injection that, in practical application, the HVDC converters may not be able to produce. For this reason it was determined that the HVDC would inject 550MVa at PCC2, which is still a very high amount of reactive power injection, in order to allow the circuit to reach a voltage of 0.99pu at its receiving end.

The increase in the voltage level at the circuit ends also allows for an increase in the active power transported by the ac line from 1150MW to 1300MW. However, just as it happened with the Vac control, the increase in the active power flowing through the ac transmission line produces an increase in the power angle of approximately 0.9 degrees.

- Study case 2. Vac and Q controls start at t=2s.

For this study case, Fig. 6, the Vac and Q controls are activated together with the HVDC at t=2s. This allows us to observe the system behaviour when both controls are activated with the HVDC. This study case shows that when the system reaches stability at approximately t=20s, the system reaches the same working conditions as the ones obtained in study case 1, when the system reaches stability after the activation of the Vac and Q controls. The main difference between this study case and the previous one derives from the fact that the system does not experience two transient effects, because it is not subjected to two different events. For this reason it is preferable to start whatever control is selected (Vac or Q controls) at the same time when the HVDC is started. In this sense, study case 1 is only recommended as a didactic practice that allows us to observe the difference between a system working with reactive power control and the one working without it.

B. Circuit 3

Circuit 3 allows us to observe the benefits brought about by the inclusion of dynamic series compensation in an ac line that is connected in parallel with a dc link. In other words, circuit 3 demonstrates the benefits of including a TCSC as a reactive series compensation device in the ac line of circuit 2. The analysis is presented in the next study cases, 3 and 4.

- Study case 3. Vac and Q controls start at t=15s.

This study case presents the same conditions as study case 1; the difference derives from the inclusion of a TCSC device in the ac line, which provides variable reactive series compensation. The TCSC device is set to enter in operation at the same time as the HVDC, this being at t=2s. However, TCSC devices have a fixed capacitor in their structure, which sets the minimum amount of capacitive series compensation that the TCSC can provide. Therefore, even when the TCSC is in a non-operating state it can provide a minimum amount of reactive series compensation, which for this circuit is 15%. The benefits brought about by the inclusion of this minimum series compensation limit can be appreciated with the comparison of the signals obtained for whatever study case of circuit 2 and whatever study case of circuit 3. Thus, for the period of time 0s< t <15s in which the TCSC is not operating (and where the HVDC also is not operating), some small improvements in the system conditions are noticeable; such conditions are presented in the table 1.

From the parameters shown in table 1, the most noticeable improvement is caused by the reduction in the transmission line power angle from 22 to 18.3 degrees, which confirms that

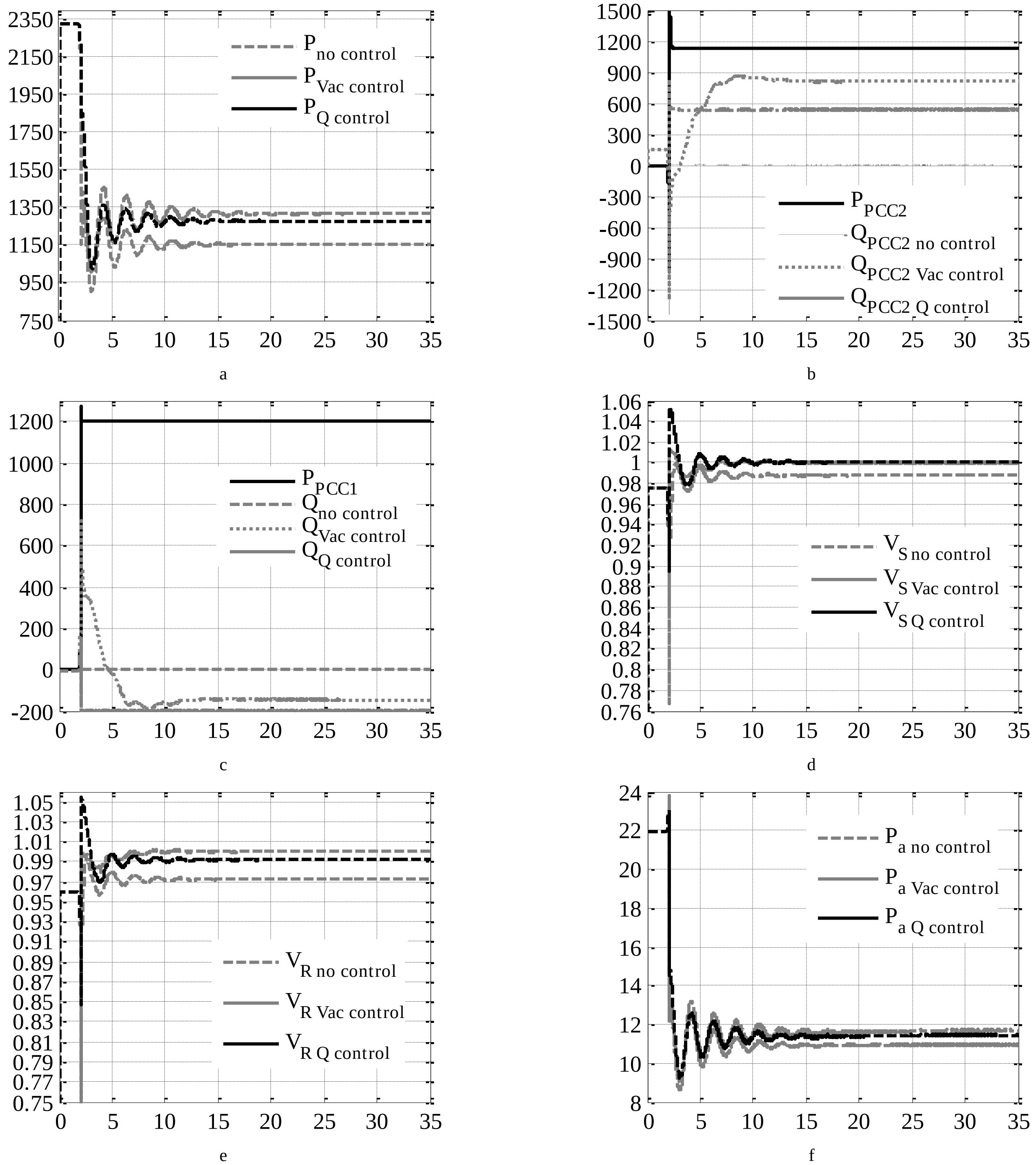

Fig. 6. Signals obtained from Circuit 2 when the Vac and Q controls start operating at t=2s.

Table 1. Improvement in the system conditions in circuit 3 with respect to circuit 2, caused by the inclusion of the TCSC when it is not operating.

Variable	Circuit 2	Circuit 3
Ps	2320MW	2350MW
Vs	0.976pu	0.98pu
Vr	0.957pu	0.961pu
Pa	22 degrees	18.3 degrees

the TCSC fixed capacitor increases the capability of the transmission lines, even when the TCSC is not operating.

Fig. 7a shows four signals, one of them the slim grey dashed signal, represents the active power from study case 1 for which the HVDC is operating in the no control scheme (Q=0MW) and the circuit does not include a TCSC. The purpose of including this signal into this figure is to compare the response of both circuit configurations. There are two main differences between the results obtained from the study cases 1

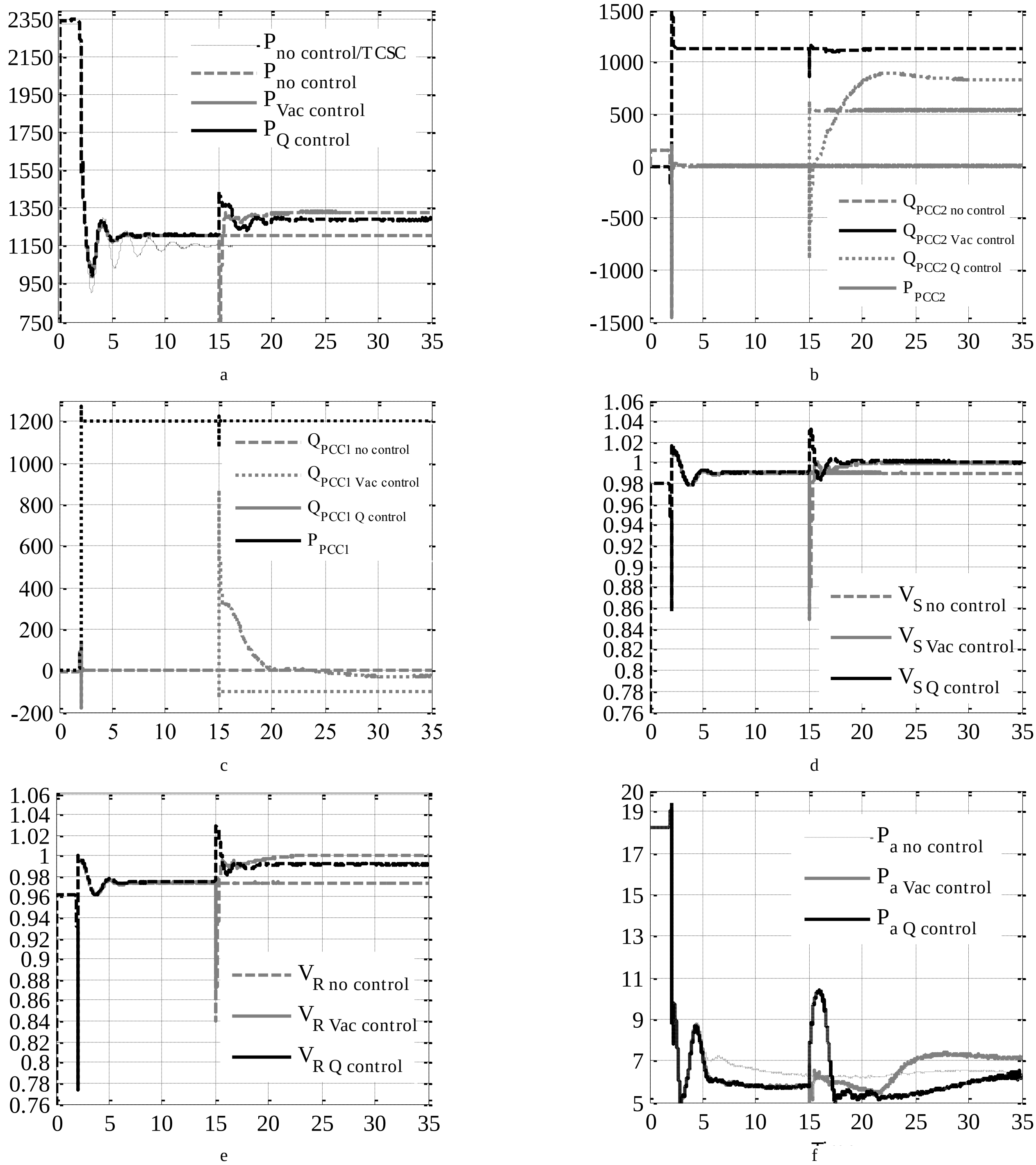

Fig. 7. Signals obtained from Circuit 3 when the Vac and Q controls start operating at t=15s

and 3; the power oscillations produced by the start of the HVDC and the VAC and Q controls are damped and the power angle gets reduced. Both actions are caused by the control of the TCSC.

Damping of power oscillations.

For the period of time 2s< t< 15s, in which the system is adapting to the reschedule of power between the ac and dc lines, the first power swing in the ac side of the circuit still reaches a value close to -250MW just as in study case 1.

However, the second power swing gets reduced from 200MW to 100MW and the system enters into a stability state after 4s, while, in respect of study case 1, the system takes 14s to reach stability. Fig. 7a also shows that by the TCSC action alone the active power is increased from 1150MW in Fig. 5a (from study case 1) to 1200MW in Fig. 7a. For the period of time 15s< t< 35s in which the HVDC controls (Vac and Q controls) enter into operating state, the TCSC also makes its effects noticeable in the parallel circuit. The first power swing produced by the start of the Q control, Fig. 7a black full line, gets damped by

TCSC action, reducing it by about 200MW (in comparison with the result obtained in Fig. 5a).

Increase in the ac transmission line power capacity.

The most important marker in the increase of the ac transmission line capacity by action of the TCSC is caused by the reduction of the transmission line power angle. In this sense Fig. 7f shows how the TCSC action provokes that the transmission line power angle diminishes to a value close to 6 degrees, while for the case in which no TCSC is used the power angle stays close to 11 degrees as shown in Fig. 5f.

Another noticeable effect caused by the use of a TCSC is the reduction in the required reactive power injected by the HVDC converter 1 for reaching the same results as in study case 1. For circuit 3, the HVDC requires an injection of 30MVa with the Vac control and 100Mva with the Q control, while in circuit 2, it requires to provide 100MVa with Vac control and 200MVa with Q control for achieving the same results, all of this happening at the PCC1.

- Study case 4. Vac and Q controls start at t=2s.

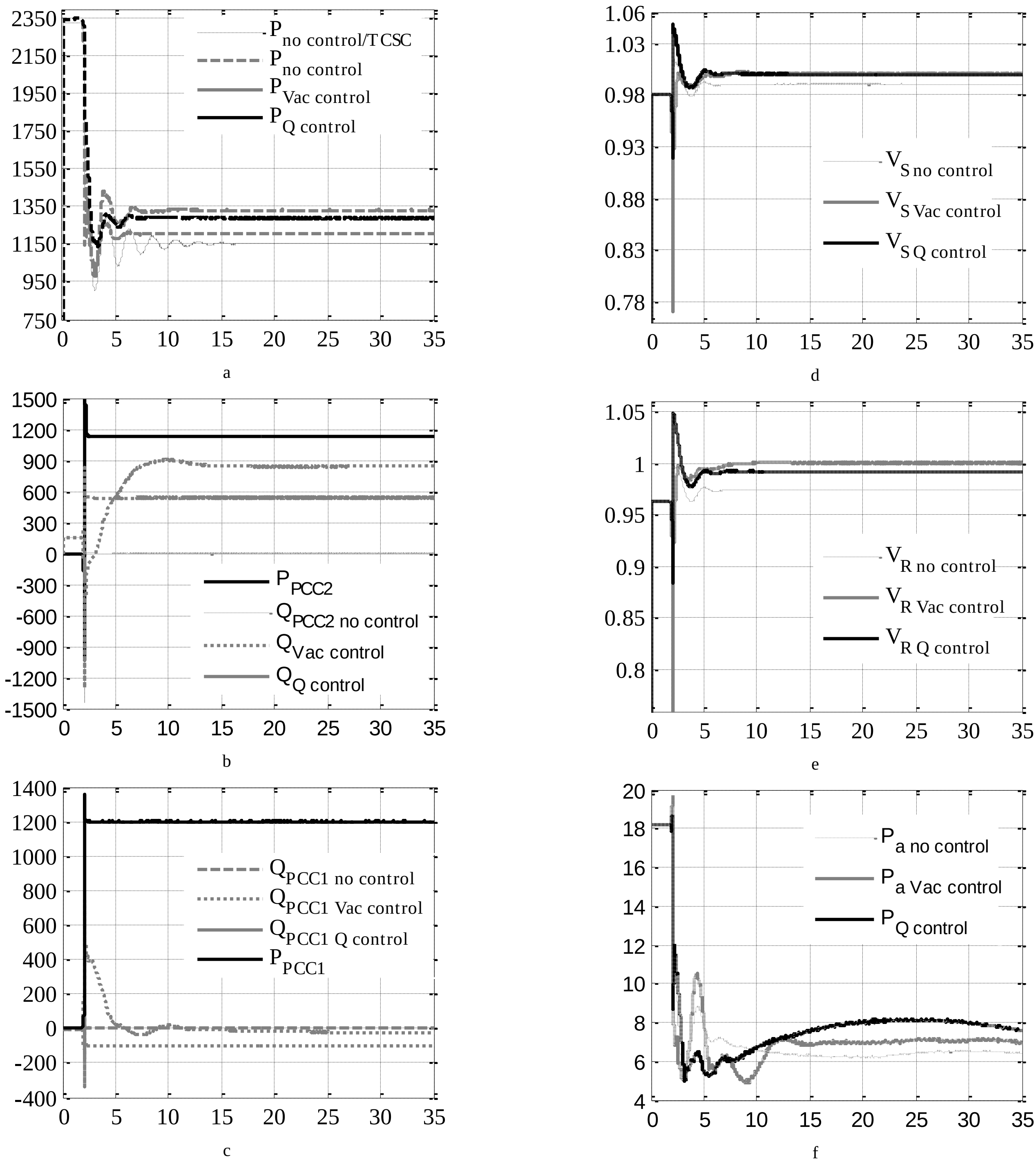

Fig. 8. Signals obtained from Circuit 3 when the Vac and Q controls start operating at t=2s.

For this study case, Fig. 8, all HVDCs and their reactive controls (Vac and Q controls) and the TCSC control start to operate at the same time (t=2s). For this study case, the system faces only one transitory effect given by the activation of all controls at t=2s and the power schedule effect derivate from this action. When the system reaches stability, ti also reaches similar working conditions than the ones obtained in the study case 3 when the system reaches stability after the activation of HVDC Vac and Q controls (t=24s).

This study shows remarkable effects caused by the mutual operation of the controls of the HVDC and TCSC, such as increase in the power transmission, the voltage profile and the reduction in the power oscillations. However, other important phenomenon can be observed in this study, this is the considerable reduction of the first power swing caused by the mutual operation of the TCSC and HVDC Q controls. This reduction can be observed through the black full line in Fig. 8a.

CONCLUSIONS

TCSCs allow 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 of damping power oscillations and hence, can improve the interaction between AC-DC parallel circuits.

The use of reactive power injection by the HVDC Converters at the PCCs allows for an improvement in the voltage profile at the ac line buses.

The reactive power injection caused by the HVDC converters also allows for an increase in the level of power transmitted through the ac transmission lines.

The use of HVDC Q control, when brought into operation at the same time as the TCSC power control, provides for a potential way to dampen the first power swing that is a result of such connection.

REFERENCES

[1] European Comission, Climate Action, http://ec.europa.eu/clima/policies/package/index_en.html

[2] ENSG. ENSG Our Electricity Transmission Network: A Vision for 2020. Full Report. ENSGR 2009-026, July 2009.

[3] Meikandasivam,S. Kumar, Rajesh. Behavioral Study of TCSC Device-A Matlab/Simulink Implementation. World of Science. Engineering and Technology 45 (2008)

[4] National Grid. National Electricity Transmission System Seven Year Statement, May 2010.

[5] R. Mohan Mathur, Rajiv K. Varma. Thyristor-Based FACTS Controllers for Electrical Transmission Systems. IEEE Press Series on Power Engineering. Whiley-Interscience. Piscataway, NJ. 2002

[6] R. Kundur. Power system stability and control. MacGraw-Hill Inc. New York, 1994.

[7] Zhou X, Lian J. Overview of Control Schemes for TCST to Enhance the Stability of Power Systems. IEE Proceedings-Generation. Transmission and Distribution, 1999. 146(2): 125-130.

[8] Ding Yu-jiang, Tang Hai-yan, QU Gou-quan, Zhang Tao. A survey on Design of TCSC Controller. Power System Technology, 1000-3673.0.2006-SI-041.

[9] XU Zheng. Dynamic analysis of AC/DC power systems. Beijing: China Machine Press, 2004.

[10] Amirnaser Yazdani, Reza Iravani. Voltage-Source Converters in Power Systems: Modeling, Control and Applications. IEEE Press. John Wiley and Songs, Inc., Publication. New Jersey, 2010

[11] Giddani O. Kalcon. Control and Stability Assessment of VSC-HVDC networks for Large-Scale Offshore Wind Integration. PhD Thesis. University of Strathclyde. September, 2011.