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ORIGINAL RESEARCH

Communication-free decentralized power flow control of unified power flow controllers and phase-shifting transformers in high voltage transmission systems

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Abstract

Conventional phase-shifting transformers (PST) have been utilized for power flow control in transmission networks for many years. Compared to the slow reacting PSTs, recently trending unified power flow controllers (UPFC) enable much faster power flow control. This paper introduces a decentralized power flow control scheme for power flow controllers (PFCs) without the need for communication between the PFCs. For each PFC, an influence area is defined. The line loading of the transmission lines in this influence area is monitored in real-time operation and if there is an overloading of a line, a feedback control scheme is used to mitigate the overloading of the line. As the power flow control of UPFC is dependent of the network topology and the UPFC converter limit, additional control measures are introduced to circumvent potential critical scenarios. Supplementary control measures are also developed to increase the robustness of control scheme for the simultaneous operation of UPFC with slow reacting PST. Using RMS simulation in DIgSILENT PowerFactory, the developed control method is validated in the IEEE 68-Bus NETS/NYPS test bench network. The method is also validated for UPFCs with overlapping influence areas and the combination of fast acting UPFCs and slow acting PST devices.

1 | INTRODUCTION

With the massive increase of share of renewable energy sources in the electrical energy supply mix, as well as the continuous increase of load demand, present-day power systems are greatly stressed. Since the expansion of the transmission grid is unsuitable due to high costs, environmental constraints and public policies, the existing grid is becoming heavily overloaded and incurring high costs for redispatch measures. In the future, however, the load demand would increase even more, and the compliance with n-1 safety criteria can no longer be guaranteed. For a safe and secure grid operation, it is necessary for the system to react to disturbances in such a way that any overloading of a line is quickly eliminated.

The power flow in an electrical network is determined by the impedance of the transmission line for a given generation and load situation. Any alteration in the power flow without changing the grid configuration is only possible by changing the generation or, more rarely, the load. With the help of additional PFCs, the power flow in the network could be influenced, by means of variable impedance or injection of an additional voltage [1]. These PFCs are classified as FACTS (Flexible AC Transmission System) devices. The operating point of the PFCs can be determined on the basis of capacity allocation on the electricity market, which takes place several weeks to one day before the actual time of operation. Based on the market results, the transmission system operators (TSO) perform an Optimal Power Flow (OPF) and system security calculations to determine the new operating point. OPF based power flow control method has been popular in relieving congestion [2–5], as it provides an economically attractive solution to alleviate line overloads.

Phase-shifting transformers (PST) have been utilized as conventional PFC device in the industry for many years. However, with the fast paced development and the changing conditions in the power system industry, mechanical switching for power flow control might not be the optimal solution. Modern UPFC devices, on the contrary, improve the security of existing networks by quickly redirecting line flows to avoid overloading of lines as well as fulfil the contractual agreements between the network participants. Due to the fast acting power electronics based control, it is technically feasible for a UPFC to quickly alleviate congestion caused by component outages or intermittent generation. Several centralized coordination methods based on OPF for a network containing UPFC are available [6–11]. The determination of the optimal UPFC setpoint through these methods for a multi-PFC network requires a compromise between the calculation time and the simplifications made in the assumptions. Linearization of the power flow equations and limited consideration of potential topology changes are generally the simplified assumptions for these methods. During real-time operation, not all network parameters are known at all locations, so, in order to deal with the limited information, authors in [12] have proposed a decentralized OPF by dividing the large-scale optimization problem into subproblems for each TSO. In order to solve the subproblem, a coordinated iterative exchange of information has to take place between the involved TSOs until the optimal solution is found. On the contrary, decentralized control uses less communication and utilizes only locally available data. Approaches such as the multiagent systems are used for achieving an adaptive real-time power flow control [14, 15]. With the development and system wide installation of wide area measurement systems, phasor measurement units (PMUs), real time control and system protection of the power system is getting very attractive and feasible [16]. The control scheme developed in this paper considers monitoring the line loading of transmission lines in real-time operation. For each UPFC an influence area is defined and the loading of lines positioned within this influence area is controlled within their thermal limits through a feedback control of the UPFC. In order to simultaneously work with slow reacting PSTs in the network, additional control strategy is provided, which also warrants that the active power setpoint automatically returns back to the original value when no corrective action is required.

The paper is structured as follows: The operating principle and modelling of the UPFC is discussed in Section 2. In Section 3, the studied test network structure and the installation location for UPFC as well as the PST is discussed. The influence areas of the PFC in the network is also introduced in this section. In Section 4, the development and implementation of the the control methods are discussed. The developed control method is then validated in the test network developed in DIgSILENT PowerFactory. This validation is tested in Section 5. Section 6 then concludes the paper.

2 | OPERATING PRINCIPLE AND MODELLING OF UPFC

The UPFC implements real-time control of AC transmission systems and provides the flexibility of controlling the line

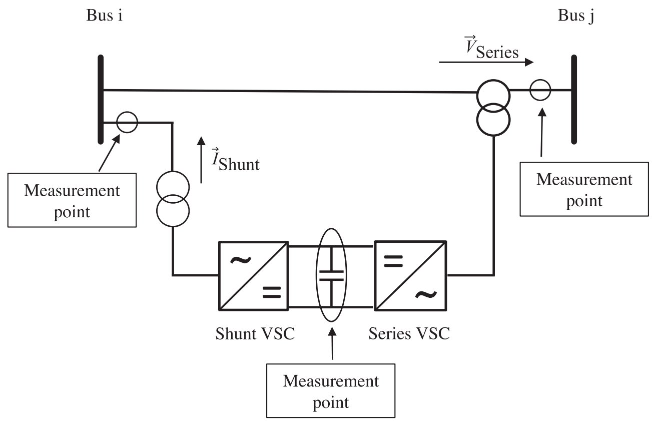

FIGURE 1 Single line diagram of a general UPFC and the measurement points in the model

parameters, including voltages, phase angle and line impedance [1]. The UPFC consists of a shunt voltage source converter (VSC) and a series VSC. These two converters are connected via a common DC link. The shunt VSC is coupled to a bus via a shunt transformer. The shunt VSC is able to regulate the DC voltage and set an active power exchange with the series VSC to meet the control demand. The complex injected voltage $\vec{V}_{\text{Series}}$ produced by the series converter can influence the active and reactive power flows in the transmission line. Figure 1 shows a single-line diagram to illustrate the structure of UPFC. In addition to control the power flow, the UPFC can control the voltage magnitude and angle. Due to this large degree of freedom in control, these devices have great advantage for the power utilities.

As can be seen from the figure, the UPFC is connected to the grid via two buses, between which the series transformer is located. The rated data of the corresponding elements are listed in Tables A.1, A.2 and A.3 in the appendix. For both VSC converters the active and reactive power must be controlled. The controls implemented for this purpose are based on DIgSILENT PowerFactory models and are presented in the following two subsections [17].

2.1 | Series VSC control

The structure of the control model for the series VSC is shown in Figure 2. The "Series VSC" block contains a predefined RMS model of the VSC converter as given in DIgSILENT PowerFactory [18]. For clarity, the remaining components of the control are divided into individual blocks. The block "Power Flow Control" contains the power flow control developed in this study, which determines the active power setpoint P_{ref} and it is passed to the "Active Power Control" block. The rate of change of the active power setpoint is internally limited to 0.2 p.u./s in this block to avoid negative effects such as too fast voltage changes in the grid. The "Measurement" block measures the line currents, the node voltages and also the active and reactive power exchanges through the lines. This measurement point can be

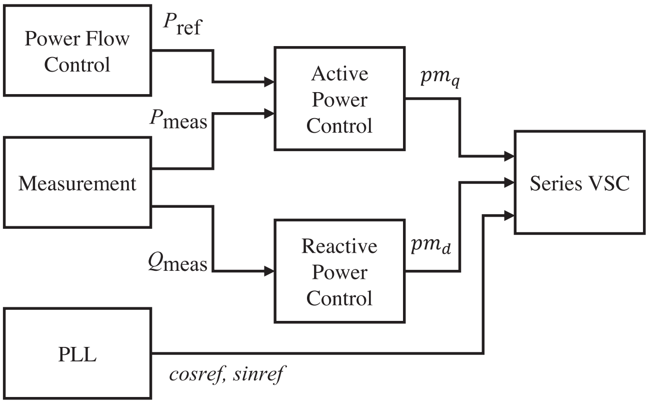

FIGURE 2 Structure of the control system of series VSC

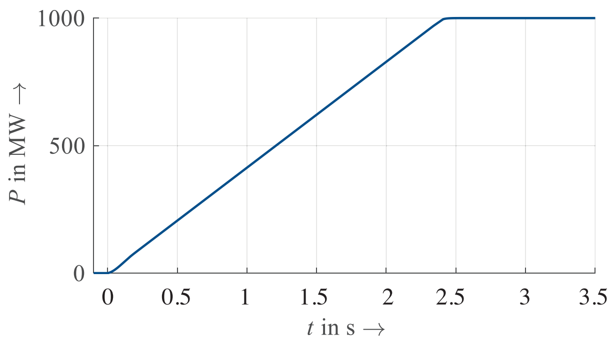

FIGURE 3 Step response of the UPFC setpoint for a step from 0 to 1000 MW

seen in Figure 1. From this block the current active and reactive power values are then given to the power controllers. The reference angle for the series VSC is determined by means of a phase-locked loop (PLL) at the measurement point.

The "Active Power Control" block contains a PI controller and determines the modulation index pm_q necessary for setting the current active power setpoint. The block "Reactive Power Control" contains the control of the reactive power of the UPFC. This sets a fixed reactive power value that can be stored in the control. Analogous to the control block for the active power, this block contains a PI controller and outputs the modulation index pm_d. The RMS model of the VSC converter is controlled with the two modulation indices and the reference angles from the PLL [18]. Figure 3 shows an example of the step response of the UPFC to a setpoint step change of the active power from 0 MW to 1000 MW. The rate of change limitation is clearly visible here, which is noticeable by the constant increase of the active power. The time constants for the PI controller could be set faster, but it is not desired for the network.

2.2 | Shunt VSC control

The control structure of the shunt VSC shown in Figure 4, is similar to that of the series VSC presented in the previous subsection.

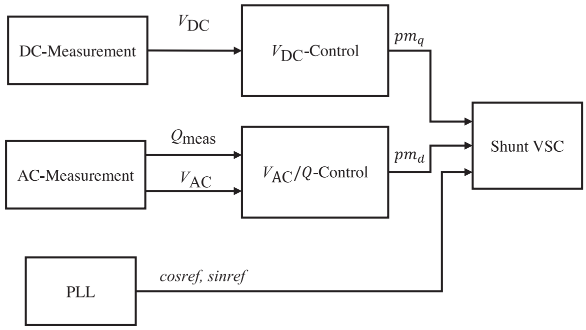

FIGURE 4 Structure of the control system of shunt VSC

The measuring block as seen in Figure 1 for the shunt VSC and the also for the DC link, provide the measured values of current, voltage and powers. The PLL determines the voltage angle and frequency. The "V_{DC}-control" block controls the active power of the shunt VSC with a PI controller to a constant DC link voltage. The modulation index pm_q is the output signal. The "V_{AC}/Q-control" block contains the control of the reactive power of the shunt VSC. Analogue to the active power control, a PI controller is used here and the required modulation index pm_d is determined. The setpoints as well as the decision for the variable to be controlled can be specified in the control structure. In this study, the control mode for a constant voltage value is used. The "Shunt VSC" block contains the RMS model of the VSC converter, which is controlled via the modulation indices pm_q and pm_d and also receives the reference angles of the PLL.

Generally, a transmission line overloading is measured based on the current magnitude. Due to this reason, the power flow control of the UPFC is limited to handle only active power overloading issues. Thus, for the control strategy introduced in Section 4, reactive power control is not considered.

3 | INTRODUCTION TO THE TEST GRID AND INFLUENCE AREA OF THE UPFC

For the investigation of the power flow control, the New England Test System/New York Power System (NETS/NYPS) benchmark network is introduced in this section [19, 20]. Since the test bench is a well researched and a popular network in the power systems academia, instead of the original schematic of the network, a relevant DIgSILENT PowerFactory single-line diagram of the network is presented in Figure 5. This network has a total of 68 AC nodes, 87 overhead lines, 35 loads and 16 power generation units. To achieve the project goal, additional UPFCs for power flow control are installed on selected lines to investigate their influence on the power flow in the grid. The network has a nominal voltage of 345 kV and 230 kV. The power plants are modelled as synchronous generators with a rated voltage of 22 kV and a rated capacity of 1000 MVA, each containing standard voltage regulators and speed regulators. The load is modelled with a constant current characteristic in the active power component and a constant

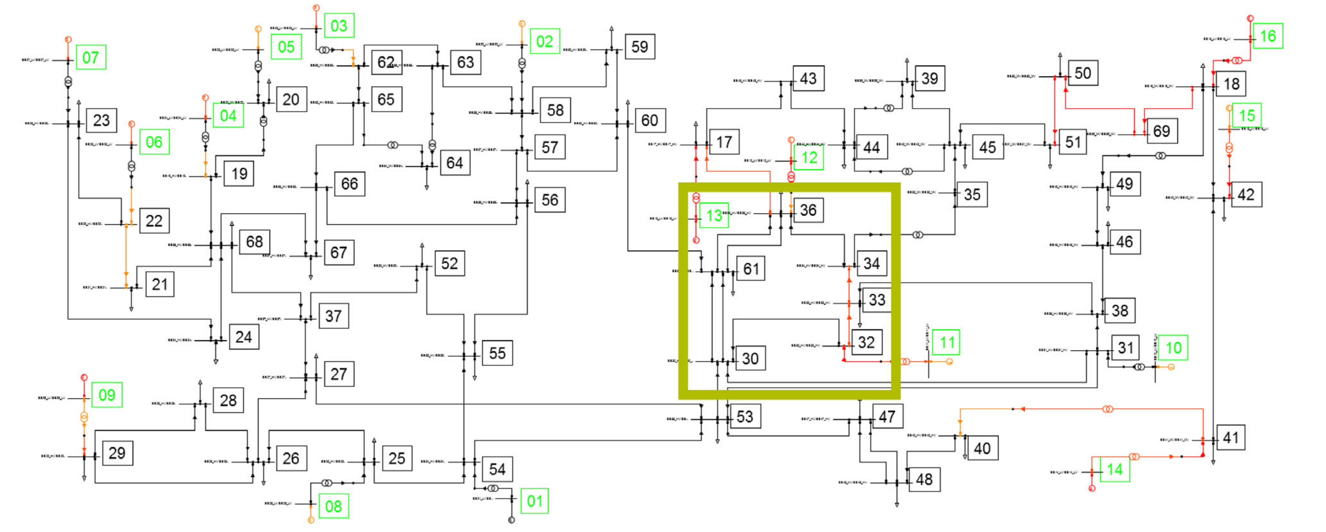

FIGURE 5 Single-line diagram of New England Test System and New York Power System (NETS/NYPS) in DIgSILENT PowerFactory

impedance in the reactive power component. In order to demonstrate the utilization and benefits of the PFCs, the rated thermal limit power of the lines are reduced to a value of 1.6 kA, to produce indicative utilization situations and to represent a realistic transmission grid loading distribution.

The placement of the FACTS device in the network plays a decisive role in the functioning of such a device. Throughout the literature, a variety of methods have been proposed to determine the optimal placement of FACTS device in a network depending on various optimization methods [21–25]. In this paper, the placement of the UPFC has been determined on the basis of the contingency analysis based on the initial power flow of the network [28]. UPFCs are connected at specified lines to control the connected bus voltage, phase angle and impedances of the lines situated nearby to the UPFC. For increasing the transmission capacity, the location of the UPFCs are selected in such a way, that the power output of the existing generating units are properly utilized. During the investigation of the power flow control strategy, it is observed that the UPFCs only affect the lines that are located within the mesh containing a UPFC. Hence, the network section as shown below is suitable for the placement of the devices. As seen from Figure 5, the green box signifies the meshed network section where the UPFC is placed. In this network section a line outage can cause overloading in nearby situated lines. Figure 6 shows the meshed example network in detail with the three UPFC installed between the nodes as follows:

UPFC 1 : Between nodes 34 and 36
UPFC 2 : Between nodes 30 and 61
UPFC 3 : Between nodes 33 and 38

As mentioned in the next subsection, each UPFC has an influence area, which lies in the meshed network section. In order to observe the influence of the power flow control within the parallel lines UPFC 1 and 2 is placed in the parallel path. The functionality of UPFC 3 is to divert the power out of the

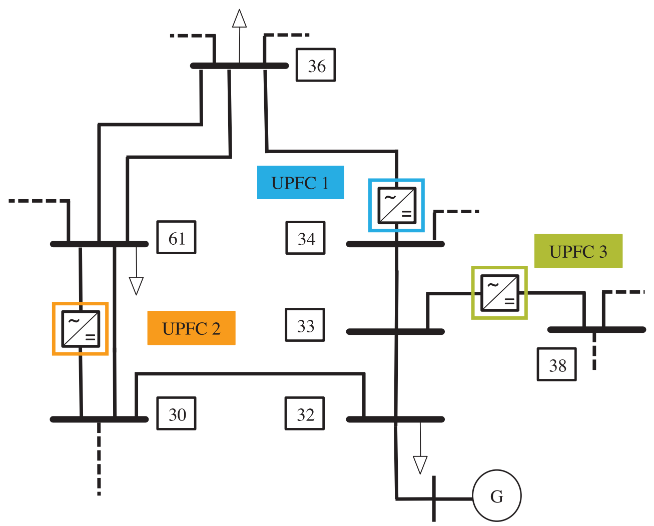

FIGURE 6 Network section with the installed UPFC

parallel path. For this reason three UPFCs have been installed in this meshed network section. For UPFC 2 it is observed that the controllability of the UPFC is strongly limited due to the circulating currents in the parallel line. The UPFC is therefore installed in series to both parallel lines. For the implementation in DIgSILENT PowerFactory, the parallel line is removed and the rated power of the UPFC is doubled. The modified network is shown in Figure 7.

3.1 | Influence area of the UPFC

There can be various interactions between the UPFCs if they are installed electrically close to each other or control the same transmission line. In order to determine the influence areas, the UPFCs are operated individually with their minimum and maximum possible operating point, while the other UPFCs

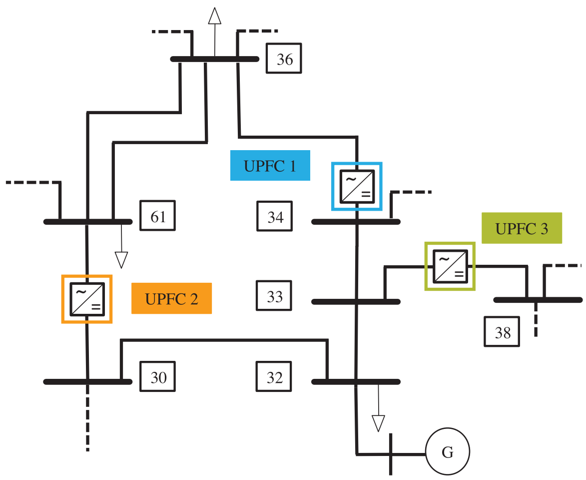

FIGURE 7 Modified network section with the installed UPFC

TABLE 1 Minimum and maximum setpoints of UPFC

UPFC	$P_{UPFC,min}$ (MW)	$P_{UPFC,max}$ (MW)
UPFC 1	200	750
UPFC 2	450	1100
UPFC 3	−320	100

remain inactive. The sensitive lines based on the changes of setpoint value are evaluated. The power flow control presented in Section 4, reacts when the current flowing through a line in the respective area exceeds a predefined value (in this case it is 1.6 kA). It also regulates the operating point of the UPFC until the line loading is reduced to an acceptable value. However, there may be restrictions on the control process for some lines if they have overlapping influence areas. The maximum and minimum possible values of the setpoints for the UPFC are given in Table 1.

In Figure 8 the influence area of all of the UPFCs are represented. From this figure, it can be observed that there are certain lines in the network that are within the influence area of two or three UPFCs. As as result, there would be an interaction between controllers of the respective UPFCs. This interaction is taken into account for the development of the control strategy and is provided in the following section.

4 | DEVELOPMENT AND IMPLEMENTATION OF THE CONTROL METHOD

In this section, the power flow concept for a multiple UPFC network is developed and presented. In addition to the necessary preliminary considerations, the developed power flow control and other necessary additional controls are presented in detail. The control system is validated by means of simulations in the NETS/NYPS model network in Section 5. Furthermore, the robustness of the control concept for the additional use of slower PST is also examined.

4.1 | Prerequisite conditions

The purpose of the control system is to react to overloading of lines following fault events such as line outages in the grid. The control system should be decentralised, that is, it should be located at the device level and require as little information from the grid as possible. Furthermore, the interaction of several PFCs in electrical proximity is to be considered. Their actions should be coordinated by the control concept in order to avoid negative interactions such as control countermeasures or surging. The requirements for the control concept can thus be summarised in the following four points:

- Response to line overloads caused by fault events.
- Decentralised control with limited information about the entire network.
- Appropriate coordination of several power flow controlling devices in one network section to avoid negative interaction.
- No or minimal additional communication between devices.

4.2 | Determination of the direction and setpoint change

In principle, the UPFC can either increase or decrease the active power setpoint in order to eliminate overloads on lines. Therefore, in the power flow control, it must be determined for each line in the influence area, in which direction the UPFC must change its active power setpoint in order to eliminate the

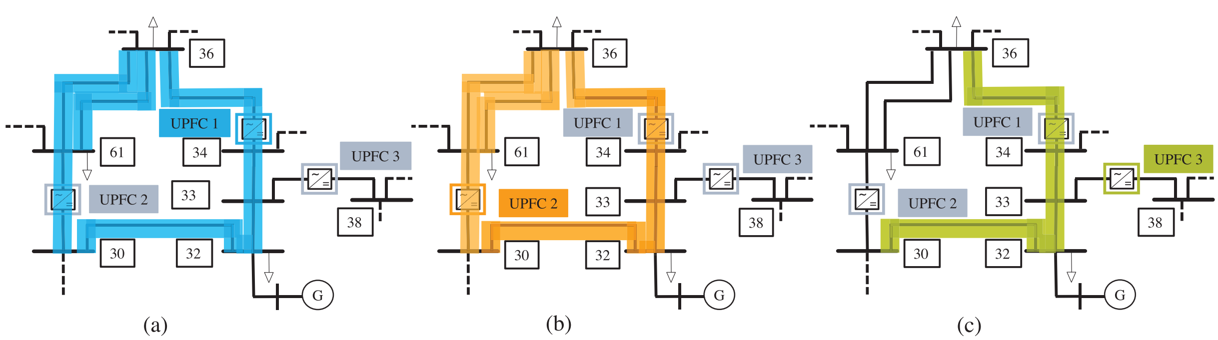

FIGURE 8 Influence areas of (a) UPFC 1, (b) UPFC 2 and (c) UPFC 3

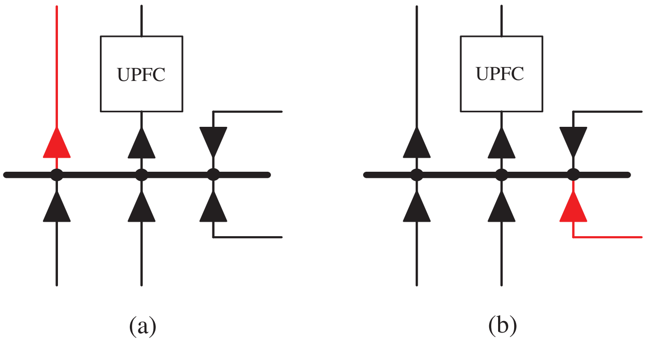

FIGURE 9 Determination of direction for setpoint change of the UPFC for a node: (a) Setpoint increase would relieve the line. (b) Setpoint decrease would relieve the line

overloading. For this purpose, the lines that are connected to the same node as the UPFC, are considered first. According to Kirchhoff's Current Law, the sum of the currents flowing into and out of the node is equal to zero. Hence, in order to reduce the power in a connected line, the power of another element connected to the node must also be changed. The resulting considerations are illustrated for an example in Figure 9. The direction of the power flow on the lines is shown by arrows. In the example in Figure 9a, the power flows out of the node on the overloaded line shown in red. To reduce the overload on the line, the UPFC must draw more power in this case and increase its output power setpoint. Another case is shown in Figure 9b. Here, the power flow on the overloaded line flows into the node, while the power flows out of the node through the UPFC. In order to reduce the load on the overloaded line, the UPFC must draw correspondingly less power and therefore reduce its active power setpoint.

This can be summarised into the control measure, that the UPFC must increase its active power setpoint if the device and the overloaded line have the same power flow direction with respect to the node (Figure 9a). In the opposite case, the UPFC must decrease its output power if the power flow directions are opposite with respect to the node (Figure 9b). The required reaction of the UPFC can thus be derived from the comparison of the power flow directions. The direction of the current is used to determine the power flow directions. For each line situated in the area of influence of the UPFC, the sign of the current is needed to determine the power flow direction in addition to the current magnitude to determine the line loading. The measures presented can also be applied to nodes further away, if it would be easy to determine whether the power flow driven by the UPFC flows into or out of the node. This is the case, for example, with lines and nodes that are in series with the UPFC. In the case of nodes that are further away and a high degree of meshing of the network, the influence of the UPFC may not be apparent. In these cases, more detailed investigations must be carried out.

4.3 | Power flow control

If a power flow controlling device is considered as a UPFC, which sets a certain active power setpoint P_{UPFC} into a branch, the following basic actions are possible for the control of the device:

- Maintain P_{UPFC}
- Decrease P_{UPFC}
- Increase P_{UPFC}

Based on the requirements as defined in the previous subsection, the control should respond to line overloading and eliminate the congestion. As long as no overload occurs, the controller maintains the current operating point. If an overload occurs one of the two possibilities have to be selected and the operating point of the UPFC must be changed until the overload is relieved. Based on this considerations, the power flow control structure of the UPFC is shown in the following Figure 10.

As can be seen from the figure, the control structure is divided into certain blocks. The input parameter for the control system is the current I_{L} of the monitored line located within the influence areas for each UPFC as described in the previous section. The direction of the current (sign convention) is also determined in the way mentioned in the previous subsection.

- Block (a) fulfills the function of activating the control system when the line is overloaded. The block also gives an output of $\Delta R_L = I_L / I_{L,\text{limit}}$. Where, $I_{L,\text{limit}}$ is the thermal limit of the line.
- Block (b) is used to determine the sign convention of the signal based on which the setpoint of the UPFC should be either reduced or increased.
- Block (c) is a proportional element that signifies line sensitivity based on the change of setpoint of a UPFC. The value of K_{Sens} can be adjusted according to the sensitivity of the lines.

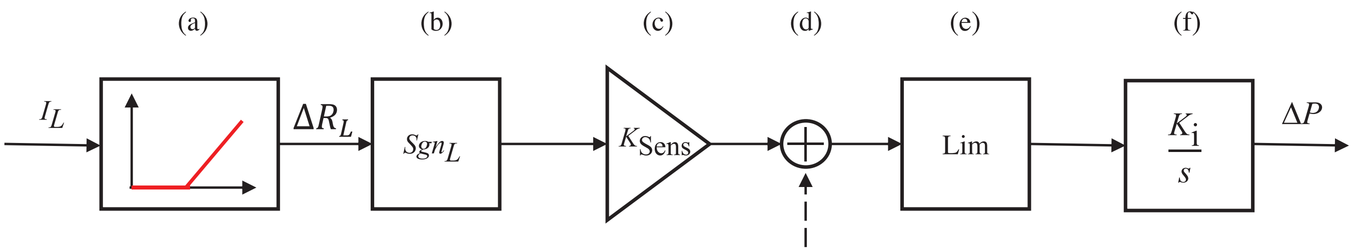

FIGURE 10 Structure of the power flow control

- Block (d) is a summation for the signals generated by all the predetermined lines situated in the influence area of the UPFC.
- Block (e) is used to limit the control signal in order to implement a maximum rate of change of active power of the UPFC.
- Block (f) is an integrator, used to amplify and integrate the control signal which adjusts the active power setting as follows:

$$P_{\mathrm{ref,new}} = P_{\mathrm{ref,old}} + \Delta P, \tag{1}$$

where $P_{\mathrm{ref,new}}$ and $P_{\mathrm{ref,old}}$ are new and the active power setpoints, respectively, and ΔP is the integrated control signal. The setpoint is then changed until the overload is cleared.

In the basic configuration, the control signal of all monitored lines located within the influence area is equally weighted, that is, the gain K_{Sens} has a value of 1 for all lines. The control therefore works with the aim of minimizing the deviation formed at the summation point (Block (d)). A thorough investigation with varying line sensitivities is out of scope of this paper and hence will not be considered in the case studies. The power flow control presented here only reacts when a defined line load is exceeded and controls the operating point of the UPFC until it falls below this value again. If the power flow changes after the fault event and the line loading decreases further, the original operating point is not restored. This behaviour must be taken into consideration when short-term changes are considered in addition to stationary changes in the power flow. For example, after line failures, the targeted line utilisation can be exceeded for a short time, for example, due to power balancing processes or briefly occurring power oscillations of generators. To prevent the power flow control from reacting to these brief overloads and permanently changing the operating point of the UPFC, a delay is built into the power flow control. In the implementation for this study, a deadband of 0.5 s is set. Short-term overloads thus do not lead to a change in the UPFC operating point.

4.4 | Additional control measures

In the investigations carried out in this study, it has been observed that in the event of faults in the grid, there might be some situations that limit the function of the power flow control described in the previous section. These situations are: (1) The UPFC cannot set the desired operating point and the series VSC reaches its operating limits. (2) Due to a line failure, the UPFC can no longer influence lines that are actually in its area of influence. In order to guarantee the function of the UPFC during these situations, additional measures are required, which are briefly presented in the following subsections.

4.4.1 | Additional control measure for exceeding the rating of the series VSC

As described in Section 2.1, the UPFC injects an additional voltage via the series VSC and the series transformer, and influences the power flow. If there is an altered power flow in the network as a result of a fault, the voltage required to set the pre-fault operating point may exceed the rated voltage of the series VSC. The series VSC, therefore, is not able to set the desired operating point and reaches its operating limit. The operating point of the UPFC must be adjusted in such cases. The aim of an additional control is to find a new operating point that the UPFC can set without reaching the limits of the series VSC.

The pulse modulation indices with which the series VSC of the UPFC is controlled are used to detect the limitation. Up to a pulse modulation index of 1, the output voltage of the VSC increases linearly, beyond which the non-linear range follows until the maximum output voltage is reached for the value of $4/\pi \approx 1.218$ [29]. The VSC cannot increase the output voltage any further and is in saturation. In the additional control, a maximum pulse modulation index of 1.2 is used to detect the reached limit. Generally, only the magnitude of the pulse modulation index is limited as the output real power is set on the basis of the angle of the injected voltage and not the modulation index. In order to approach a new operating point that can be set for the UPFC, the additional control continuously changes the operating point until the series VSC is no longer at the operating limit. An integral controller is used for this purpose. To determine how the operating point of the UPFC must be changed, a comparison between the pre-fault operating point and the operating point at which the UPFC reaches saturation, is made. If the performance of the new operating point is lower than the original one, the setpoint must be lowered; in the other case, it must be raised accordingly. While the series VSC is in saturation, the UPFC cannot set a new active power value and thus cannot react to overloads in the network. The integrator included in the power flow control is therefore deactivated when the series VSC is in saturation to prevent further integration of the control signal.

4.4.2 | Detection of critical topology change

As described in Section 3.1, each UPFC monitors all lines in its area of influence. However, the area of influence may be reduced by line outage, as the UPFC can no longer influence some lines due to the failure. This must be recognised, as the UPFC may otherwise try to compensate for overloads over which it no longer has any influence. This can be illustrated by the network section shown in Figure 11.

As seen in the figure, lines 1–5 form a mesh in which the UPFC can control the power flow. If there is a fault in line 2, this mesh is interrupted and lines 1, 3 and 4 can no longer be influenced by the UPFC. If an overload occurs on line 3 after the failure of line 2, the UPFC would try to compensate for it. However, since the UPFC no longer has any influence on the power flow on line 3 after the fault, the UPFC would continue to change its operating point until it runs into limitation or other overloads occur. To avoid this situation, all lines in the area of influence of the UPFC must therefore be monitored for line failures.

For this purpose, the changes in the area of influence resulting from the line outages must be determined in the planning

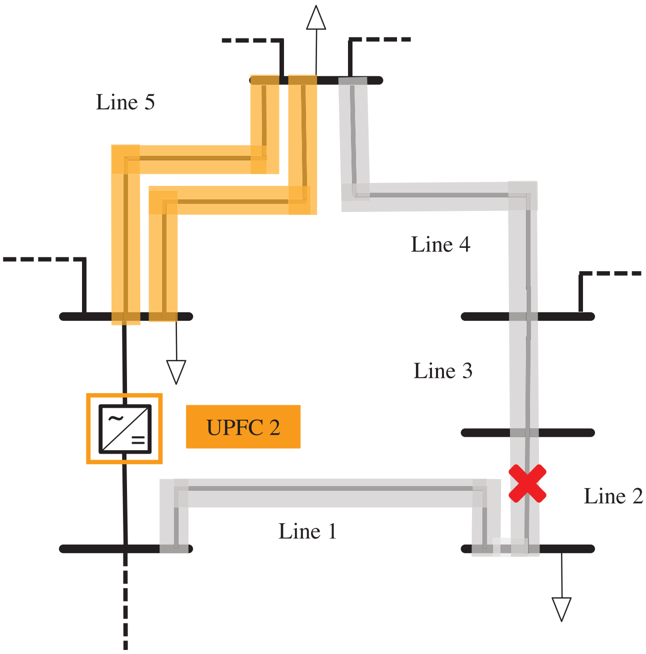

FIGURE 11 Change in the influence area due to a line outage

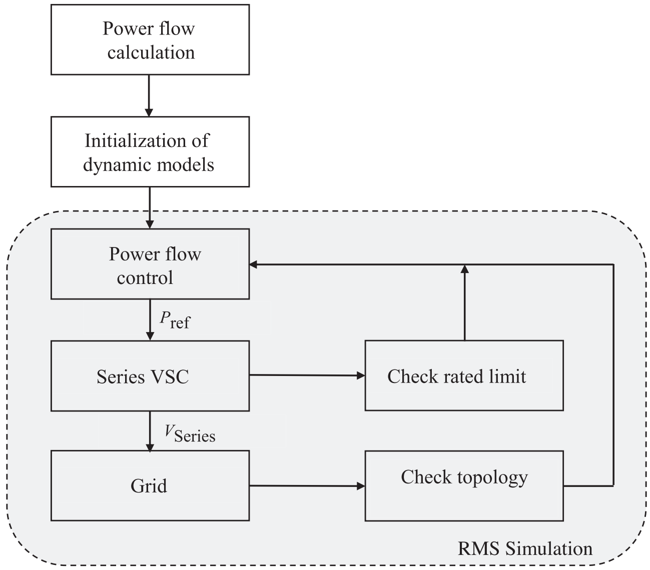

FIGURE 12 Flowchart of combined power flow control with additional control measures

phase. In the example shown above, after the fault in line 2, lines 1, 3 and 4 can no longer be influenced. These regulations must be defined in the control system so that, when a line outage is detected, the corresponding lines are no longer taken into account in the power flow control. For the implementation of this additional control measure, it is considered that, if the current of a line is zero for a certain period, it is to be evaluated as a line outage. This period is set to 100 ms for the simulation.

4.4.3 | Combination of the control measures

After each control measure has been presented individually in the previous sections, the flowchart of the whole process and the function of the control scheme is illustrated in Figure 12.

After the initial power flow calculations and the initialization of the dynamic models, the power flow control block specifies an operating point P_{ref} for the UPFC. The internal controller of the series VSC adjusts the series voltage $\vec{V}_{Series}$ as injected by the VSC accordingly. This influences the power flow in the grid, which is also represented by the controlled system in the figure. The resulting power flow is in turn evaluated again by the power flow control. If an overload occurs on one of the monitored lines, a new operating point P_{ref} is determined. The additional control method to detect critical topology changes and along with that the associated change in the influence area of the UPFC, is done on the basis of failure of critical lines and measurement of line current. If such a failure occurs and certain lines that could previously be influenced, can no longer be influenced by the UPFC. Whether the specified power setpoint can be set by the series VSC is also determined as an additional control method. If it is not the case, the reached limitation of the series VSC is recognised and the integrator of the power flow control is temporarily deactivated. Subsequently, the target operating point of the UPFC is changed until the target value can be set.

TABLE 2 Initial setpoint of UPFC

UPFC	From node → To node	$P_{UPFC,initial}$ (MW)
UPFC 1	34 → 36	540
UPFC 2	30 → 61	800
UPFC 3	33 → 38	−120

5 | CASE STUDY AND VALIDATION

The control concepts presented in the previous section are implemented in the NETS/NYPS network in order to validate the control concepts through the simulations for different scenarios. The benchmark network is introduced in Section 3. The simulation scenarios are performed with RMS simulations in DIgSILENT PowerFactory 2020.

5.1 | Initial power flow situation

The operating point of the UPFC are set according to the power flow in the grid without UPFC. Accordingly, the active power flow in the grid changes only minimally due to the installation of the UPFC. Figure 13 depicts the initial power flow directions in the network section based on the power flow calculations without the installation of the UPFCs.

Table 2 represents the initial setpoints of all three UPFCs in the network. The table also provides the initial power flow

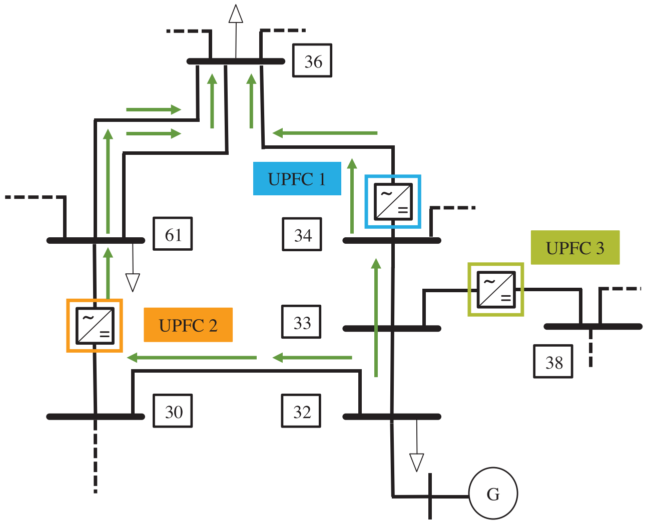

FIGURE 13 Schematic of power flow in the specified section of the benchmark network - without control of the UPFC

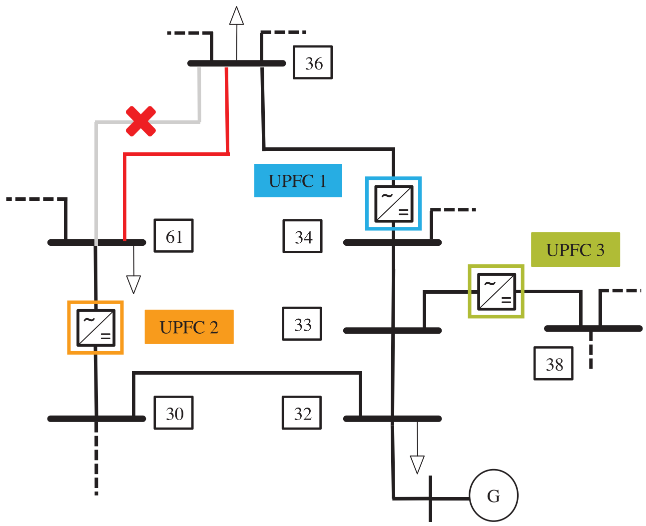

FIGURE 14 Case 1: Outage of one parallel line between the nodes 36 and 61

direction as influenced by the UPFCs. For example, the initial power flow direction for UPFC 1 is from node 34 to 36. As can be seen from the Figure 13 the power generated by the generator G is transmitted from south to north. The RMS simulations are carried out for a simulation duration of 50 s each and the respective fault events are triggered 5 s after the start of the simulation. During the simulations, the overload of the lines is depicted with red color.

5.2 | Simulation scenarios

With the aim of increasing the security of the grid by installing the power flow controlling devices, it is of great relevance to choose the simulation scenarios and use cases in such a way that the benefits of installing the devices are captured accordingly. In order to limit the scope of the study, only line outages are simulated for the case studies. As a result, it can lead to an overload of other transmission lines. The maximum thermal limit of the lines are represented by 1 p.u. of current (with a base current value of 1.6 kA). So when the current magnitude crosses 1 p.u., it leads to a overloading of the line. With the aim of relieving these overloading of the lines with the help of UPFC, the following use cases are defined.

5.2.1 | Case 1: Line outage between nodes 36 and 61 (lines 36-61)

In this case, the outage of one of the parallel lines between nodes 61 and 36 is considered. Due to the failure of the line, half of the transmitted power would additionally overload the other parallel line. This event can be seen in the following Figure 14.

The controls of UPFC 1 and UPFC 2 intervene to eliminate the overload. As can be seen in Figure 15, UPFC 2 reduces its power output due to the control action so that the line overload

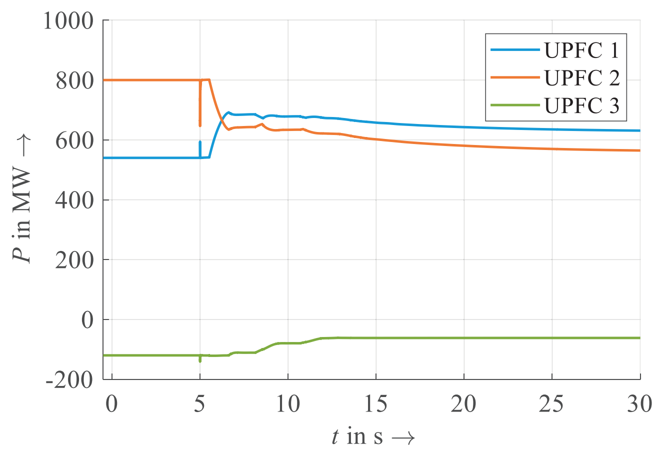

FIGURE 15 Case 1: UPFC active output power

is removed. At the same time, UPFC 1 increases its power output to supply the power lost due to the line outage. It could also be seen that UPFC 3 has a small influence on reducing the overload. From Figure 16, it is observed that the current in Line 36-61 crosses the thermal limit for a short time and then again is reduced to an acceptable value. The currents in the other transmission lines are within their threshold values.

5.2.2 | Case 2: Line outage between nodes 32 and 33 (lines 32-33)

In this scenario, an essential connection line between the feed-in and the load is simulated to be disconnected due to a fault, as shown in Figure 17. Such a fault changes the topology of the network and at the same time the meshing of the considered network section is lost. The area of influence is reduced because the UPFCs can no longer influence some lines. This needs to be

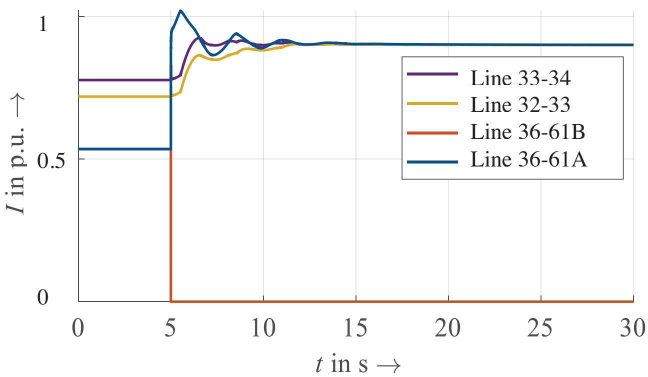

FIGURE 16 Case 1: Current flow in lines in the network section

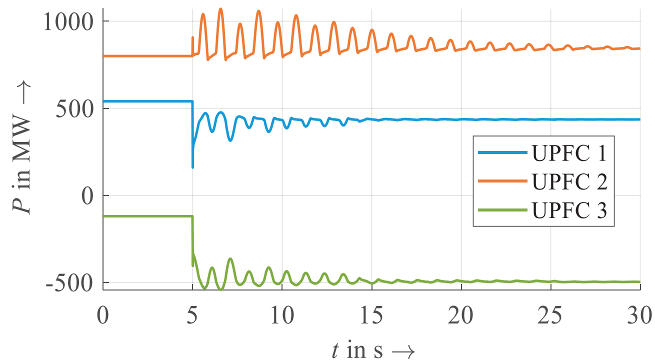

FIGURE 18 Case 2: UPFC active output power

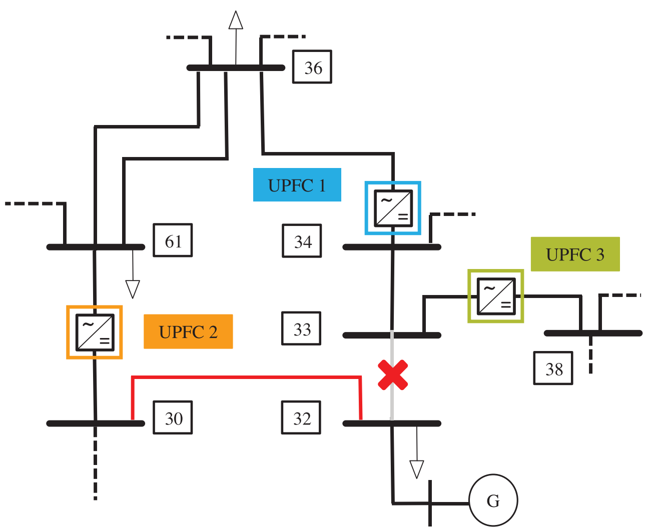

FIGURE 17 Case 2: Outage of line between the nodes 32 and 33

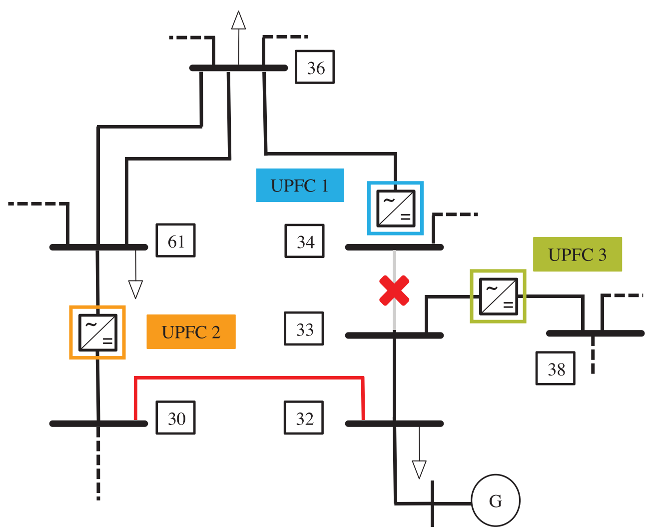

FIGURE 19 Case 3: Outage of line between the nodes 33 and 34

recognised, as the UPFCs may otherwise try to compensate for overloads over which they no longer have any influence.

Due to the outage of line 32-33, the power fed in by the generator at node 32 can only be transmitted in the direction of node 30. After the outage of line 32-33, no mesh can be formed with UPFC 2 and line 30-32. Therefore, the line overload cannot be eliminated by controlling UPFC 2. The UPFC reaction to the line outage is shown in Figure 18.

As described in Section 4.3, due to the additional control measures, UPFC 2 does not react to the overload after the topology change of the network is detected by UPFC 2. As can be seen in Figure 18, the active power output remains constant because it is not possible for the UPFC to compensate for the overload. The oscillations seen in the figure are not caused by the UPFC itself, but due to the nearby oscillation-prone generator. The change in the impedance in the grid due to the line outage triggers the oscillations in the converters. UPFC 1 and UPFC 3 have no influence on the overload due to the topology change. However, due to the changed power flow, they can no longer adjust their pre-fault operating point. Hence, the additional control becomes active and changes the operating point to a new value, which can be seen also in the figure. Hence, it is evident that the UPFCs are not able to relieve the overloading of line 30-32 for such a critical case.

5.2.3 | Case 3: Line outage between nodes 33 and 34 (line 33-34)

For this simulation scenario, line 33-34 is disconnected from the grid. The following Figure 19 shows the network diagram during the fault. As soon as the line is disconnected, there is an overload on line 30-32. It can be observed in Figure 20.

To react to this overload, UPFC 3 increases its active power setpoint. This changes the direction of the power flow. Due to the line failure, the power originally transported through line 33-34 shifts to the left path with UPFC 2. This can, therefore, no longer set its pre-fault operating point and reaches its limit. The additional control therefore increases the active power setpoint of UPFC 2. These two actions reduce the power flow on line 30-32 and the line overload is eliminated. As seen from Figure 21, due to the line failure, UPFC 1 can no longer reach the power setpoint and enters into the non-linear modulation index range. The additional control therefore reduces

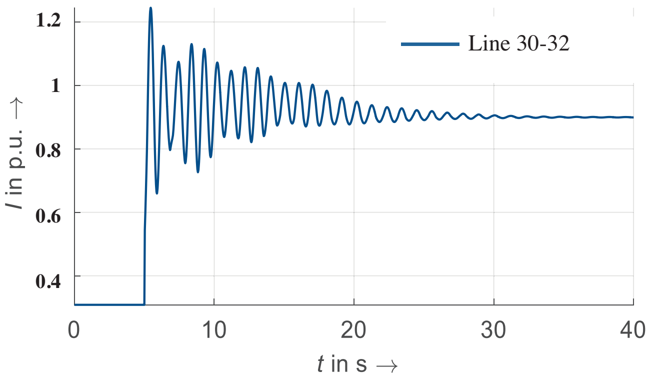

FIGURE 20 Case 3: Current flow in lines in the network section

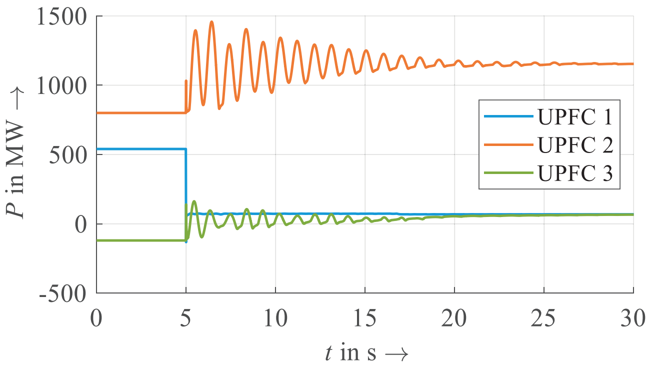

FIGURE 21 Case 3: UPFC active output power

the power setpoint close to zero. It is evident from Figure 20, the action of all UPFCs could successfully eliminate the overload of line 30-32 with the developed control strategy. Thus, the control concept for the power flow controlling devices can be successfully validated in the test system.

5.3 | Combination of UPFC and PST

After considering the combination of several UPFCs for power flow control in a network, the combination of UPFCs with other power flow controlling devices such as PSTs is investigated. This is particularly interesting because the two devices have very different control dynamics. While the UPFC can adjust the active power very quickly and continuously, the PST can only adjust the active power comparatively slow and, moreover, only in discrete steps due to its mechanical tap changer. From the point of view of the PST, the behaviour of the UPFC can therefore be compared with that of a power source, since the power flow through the UPFC is constant and cannot be influenced within the time horizon of the control of the PST. In contrast, the PST injects a fixed additional voltage per tap position, which remains unchanged until the next tap. The power flow through the PST can therefore be changed by the UPFC. Seen from the time constant of the UPFC control, the PST therefore behaves like a voltage source. The interaction of the UPFC and PST is examined in more detail in the following section. In addition, the necessary adjustment to the power flow control for the dynamics is presented.

5.3.1 | Adaptation of power flow control for PST

The PST contains a dead band of several seconds when changing between two stepping positions. This behaviour must be taken into account when designing the high-level power flow control. In order to be able to use the power flow control presented in Section 4.3, the integral controller included in the available model needs to be designed for a slower time constant. This means that the entire power flow control of the PST would be much slower than the already slow dynamics of the tap changer, which is not practical for the intended application. Hence, the overlapping power flow control is implemented for the PST without an integral controller. This control is realizable for the PST, as it can only adapt discrete values and a deadband is always present when changing between the taps. In summary, the power flow control evaluates whether overloads occur for the current tap position. If an overloading exits, the tap is selected either upwards or downwards. After the tap change, it is again examined whether the overload has been eliminated.

5.3.2 | Additional control measures for the PST

The power flow control described above works for all overloads that the PST can eliminate. A critical case is, for example, if the PST shifts power from an overloaded line to another, but then an overload also occurs on this line. In this case, the power flow control must find the best possible distribution on both overloaded lines. With the power flow control described in Section 4.2, this is the operating point at which the sum of the signed overloads of the two lines is zero. In this case, both lines are equally overloaded. For the UPFC, the setting of this operating point is possible, as it can continuously control the operating point. Due to the discrete step changes, a PST is not able to relieve such a congestion case, as the required setpoint lies in the range between two adjustable operating point. The power flow control will therefore oscillate between the two closest operating points. This is illustrated in Figure 22.

In the figure, the sum of the signed deviation (dp_{Sum}) of the monitored lines is shown. To prevent the oscillations, an additional control is necessary and such behaviour with the additional control is shown in orange and dashed line in the figure. The basis for this additional control is to compare the achieved sum of deviations with the old tap position after each tap change. If there is no improvement, the old tap position is returned to and retained. Since the sum of the overloading evaluated for this purpose also represents transient compensation processes after the steps, no instantaneous values can be used for evaluation. Instead, a moving average value is evaluated, which smoothens the momentary fluctuations. The value of the sum of the deviations is used to evaluate a tap position. If a total value of zero cannot be achieved, the best tap position is the one for which the summation value is closest to zero. It

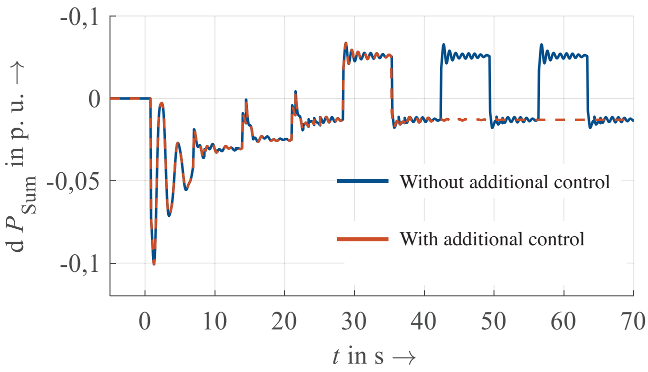

FIGURE 22 Plot of the total line overload dP_{Sum} with and without additional control of PST for a case of an unrecoverable overload

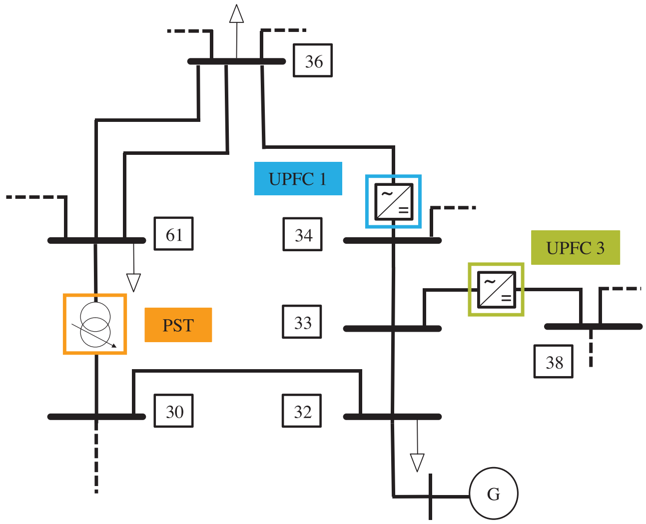

FIGURE 23 Network section of the benchmark network for validating the combination of PST and UPFC

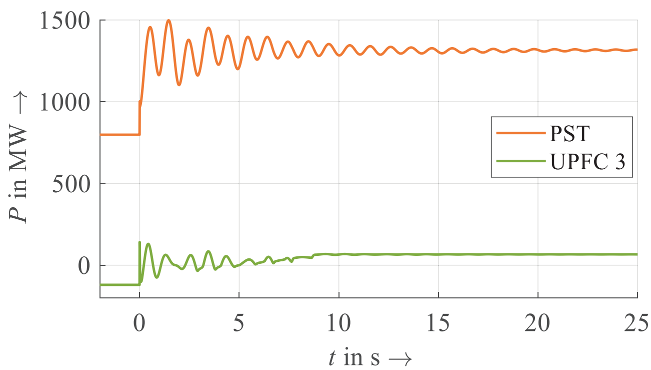

FIGURE 24 Case 3: Reaction of the PST and UPFC 3 to the line outage between nodes 33 and 34

can be observed at approx. $t = 35\,s$, as the PST returns to and maintains the tap position closest to zero. The main function of the additional control, to prevent oscillation of the tap changer position, can basically also be implemented with an additional deadband in the power flow control. However, the study has shown that this would have to be of different range for different use cases. In order to prevent oscillations in all cases, the deadband must be selected with a corresponding range. As a result, the power flow control no longer reacts to certain overloading cases, even though these could be improved or eliminated by a controller with a smaller deadband. The additional control measure presented here is able to function for the combination with the UPFC, which is presented in more detail in the next section.

5.3.3 | Validation in the test system

The combination of UPFC and PST for the power flow control is considered in the same network section as in Section 5.2. Here, UPFC 2 is replaced by a PST in the line between nodes 30 and 61, as shown in Figure 23.

The rated data for the PST is given in Table A.4. Some special features of this combination is explained in more detail in the following subsection using the use cases defined in Section 5.2. First, the line failure between nodes 33 and 34 (case 3), is considered. The power flow control reaches a power flow without overloading after approx. 10–15 s. Figure 24 depicts the reaction of the UPFC 3 and the PST to the line outage. The reaction of UPFC 1 is not considered further here, as it no longer has any influence on the overloaded line due to the topology change and is not involved in the elimination of the overload.

In this case, the overload is removed before the PST could react. The transformer perceives the overload of the line between nodes 30 and 32 for a short time, but is not able to react quickly. The overload, on the other hand, has been removed by the quick reaction of UPFC 3. In the figure, the lack of reaction of the PST can be seen in the absence of the step changes in the active power output of the PST. This example shows the behaviour as expected in the considerations in Section 5.3. From the point of view of the UPFC, the PST behaves like a voltage source. Thus, the power flow through it can be changed by the UPFC. After the line outage, UPFC 3 detects an overload in its area of influence and changes its operating point and thus the power flow accordingly. The power flow control of the slower PST therefore only comes into play if the overloaded line is not already in the area of influence of a UPFC or if its reaction is not sufficient to eliminate the overload.

Such a case is considered below with the failure of one of the parallel lines between nodes 61 and 36 (Case 1). While the overloading for this line outage can be relieved with the power flow control with three UPFCs in Section 5.2.1, this is not possible with unchanged load and generation when a PST is installed. In this situation, the problem of the different control dynamics of UPFC and PST becomes apparent. In order to react to the overloading, The UPFC will set a new operating point before the PST changes to the next tap position. Instead of finding operating points with each other, the UPFC always reacts to the step of the PST and sets a new operating point for itself. If the overloading is not relieved by an action of one of the two

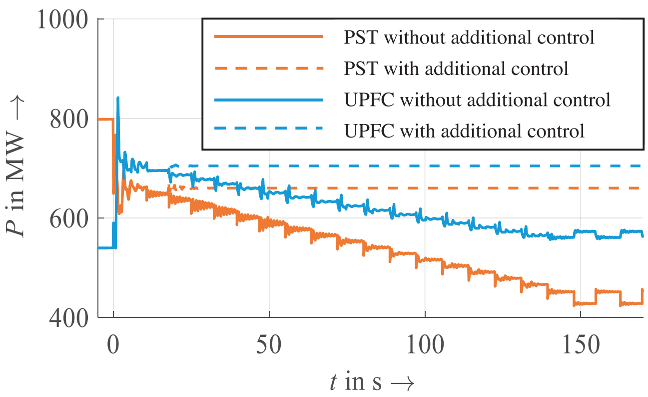

FIGURE 25 Case 1: Active power output of UPFC and PST for a non-recoverable overloading with and without additional control

devices, the interaction between the PST and UPFC continues uninterrupted. This can be seen in Figure 25.

The solid curves show the reaction of UPFC 3 and the PST without individual additional control. The cascading reaction of both devices can be observed. Since the overloading cannot be completely eliminated in the case under consideration, the cascading change in setpoints only ends when the UPFC reaches the maximum series voltage. Thus, the additional control measure of the UPFC described in the previous section prevents a further lowering of the operating point. The PST then oscillates around its step position while the UPFC reacts to each step change, taking into account the rated limit. This oscillation can be prevented with the additional control measure as presented in Section 5.3.2. This is shown by the dashed curves in the figure. After the third step (approximately 20 s), the additional control is able to detect, that further step action would lead to worsening of the summed overload in the area of influence. The PST then shifts down and retains this tap position. For this final tap position, the UPFC sets the optimal operating point for itself, so that a new power flow in the network is set within 30 s. Hence, it can be seen that, even though the cascading interaction between the UPFC and PST can be prevented with additional control measures, the overloading of the line for this case could not be relieved.

It can be stated that the power flow control developed in the study is suitable for the combination of power flow controlling devices with different control dynamics. It is also observed that for certain scenarios, however, a cascading interaction can occur due to the different control dynamics. This must be counteracted by additional controls, but there might be some limitations depending on the network structure and the power flow condition.

6 | CONCLUSION

In this paper, a UPFC-based decentralized power flow control strategy is presented for power system security enhancement, which provides a technically attractive approach to relieve line overloading without incurring high costs for redispatch action.

With the proposed power flow control, the line loading of the transmission lines is monitored in real-time operation and is controlled within their thermal limits through a fast and efficient dynamic control of UPFC. The control scheme is validated to examine the coordination with other UPFCs in a network with multiple installed UPFC devices. This control method works without any communication between the devices and can be used for a decentralized operation. The function of the proposed power flow control is validated with simulations in the NETS/NYPS benchmark network. The interaction of several UPFCs in a network section is considered and it is shown that the occurring overloading can be eliminated even without communication between the UPFCs. Finally, in order to test the robustness of the developed control scheme, the simultaneous operation of PFCs with different control dynamics (such as UPFC and PST) has been validated. Due to the slow reaction of the PST, caused by the mechanical tap changing, a further additional control measure is required. The functionality of such control scheme has been demonstrated for the combination of UPFC and PST.

AUTHOR CONTRIBUTIONS

Soham Choudhury: Conceptualization, investigation, methodology, validation, visualization, writing - original draft, writing - review and editing. Andreas Saçiak: Conceptualization, formal analysis, investigation, methodology, validation, visualization. Jutta Hanson: Conceptualization, funding acquisition, supervision.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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APPENDIX A: UPFC and PST data for the benchmark network

TABLE A.1 Converter data of UPFC

Parameter	Value
Rated AC-voltage	48.5 kV
Rated DC-voltage	96 kV
Rated power	110 MVA
No-load losses	200 kW
Resistive loss factor	120 mΩ

TABLE A.2 Series transformer data of UPFC

Parameter	**Value**
Rated high voltage	53.3 kV
Rated low voltage	48.5 kV
Rated power	2076 MVA
Short circuit voltage	14%
Copper losses	331 kW
Iron losses	73 kW
No-load current	1%

TABLE A.3 Shunt transformer data of UPFC

Parameter	Value
Rated high voltage	345 kV
Rated low voltage	48.5 kV
Rated power	130 MVA
Short circuit voltage	14%
Copper losses	557 kW
Iron losses	30 kW
No-load current	0.033%
Additional voltage angle	0°
Number of steps	±12
Voltage per step	2.5%

TABLE A.4 Data of PST

Parameter	Value
Rated high voltage	345 kV
Rated low voltage	345 kV
Rated power	1200 MVA
Short circuit voltage	10%
Copper losses	1200 kW
Iron losses	150 kW
No-load current	1%
Additional voltage angle	90°
Number of steps	± 32
Voltage per step	1.4%
Step time	7 s