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Implementation and Operation of Power Flow Control Solutions for Transmission Systems

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Idaho National Laboratory
Jake Gentle
S M Shafiul Alam
Mucun Sun
Zach Priest

EPRI
Alberto Del Rosso
Dan Schweer
Swaroop Guggilam

Idaho National Laboratory

EPRI

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ABSTRACT

Power-flow controls (PFCs) technologies provide a suite of alternatives to more-efficiently direct the flow of power on the grid, improving flexibility and enabling the grid to be more responsive and resilient. PFCs can be used in many cases to mitigate overloads and consequently defer the installation of grid-expansion projects. They can also be suitable options in situations where new transmission lines cannot be built because of environmental constraints, land use, or other types of restrictions. Other uses include mitigation of unscheduled or loop flows, forcing of contractual or scheduled flows, reduction of congestion, and mitigation solutions during large maintenance or construction projects.

While many studies have demonstrated the potential economic benefits of PFC for different types of applications, the implementation implications of using multiple PFCs for system operation and reliability have not been analyzed in detail. The lack of information and practical experience on these aspects hinders adoption of this technology. One use case would be that multiple PFCs are required to coordinate congestion management. In such cases, multiple PFCs are deployed in a meshed power system to control power flows across a wide area. The challenges are associated with PFC interaction—namely, the self and sensitivity factor of each PFC, which must be accounted for in the calculation of the respective operating setpoints.

This report analyzes implementation and operation that must be considered in evaluating transmission solutions using PFCs. The report first analyzes attributes with which PFC-based solutions should comply, based on the objective and characteristics of each particular use case. It then describes different approaches for coordinated control of multiple PFC devices for different applications, including options to avoid adverse interactions and reduce risks due to inappropriate coordination. Control and operation are illustrated through case studies performed on both generic and actual power system models.

This report provides insights for transmission planners and operation engineers about the implementation of PFC-based transmission solutions; consequently, it will help them make informed decisions about the adoption of the technology.

KEYWORDS

- Power Flow Control
- Transmission System Planning
- Transmission System Operation
- Reliability
- Control Strategy, Setpoint

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GLOSSARY

Power-flow controller
The use of advanced control technologies to enhance the reliability, resilience, and flexibility of transmission and distribution systems by controlling the power flow through the system.

Transmission-system planning
A process that ensures the coordinated development of a reliable, efficient, and economical transmission system infrastructure to meet the long-term need of its users.

Transmission-system operation
The activities related to the short-term management and operation of the transmission system, which includes activities such as real-time operations, outage planning, and contingency management.

Reliability
The ability of the transmission system to perform its intended function of providing electricity to customers efficiently with a reasonable assurance of continuity and quality.

Control strategy
The application of control theory, technology, optimization methodologies, and intelligent systems to improve the performance and functions of power systems during normal and contingency operations.

Setpoint
The desired or target value for an essential variable, or process value of a control system. In terms of PFC, setpoint refers to the target operating settings of PFC required to regulate the power flow as intended.

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IMPLEMENTATION AND OPERATION OF POWER FLOW CONTROL SOLUTIONS FOR TRANSMISSION SYSTEMS

1. INTRODUCTION

1.1 Background

Grid development is determined by factors such as the increase of generating capacity from renewable-energy sources (RESs), the distributed energy resources (DERs), the electrification of transportation, the heat sector, and the incorporation of new types of large loads, such as data centers, crypto-mining facilities, and more recently, hydrogen electrolyzers. To accommodate the changing structure of grid users, system operators assess the need for grid development regularly and identify grid-development solutions among other to address the change in grid use and the increasing need for transfer capacity on the grid. Conventional grid-development solutions like the building of new infrastructure typically does not address the need for speed required for grid evolution that will meet needs today and in future, partially due to long planning and public-engagement processes. To bridge the gap between the time when transfer capacity is needed and eventually available, grid-enhancing technologies (GETs) could maximize the usage of existing grid infrastructure by dynamically adapting transfer capacity and controlling power flow through technologies like:[1]

- Dynamic line rating (DLR)
- Topology optimization
- Power-flow control (PFC)

While DLR is used to adapt the thermal operating margin on overhead lines to weather conditions, topology changes are used to modify circuit arrangements, which changes impedance along transmission paths and, effectively, power flow. While PFC also controls power flow, the main difference to topology optimization is in incremental change in the operating setpoints of PFCs, which allows control of the power flow in smaller steps. The relatively fast response time of some PFC technologies allowed them to react to contingency events, reducing power flows below the thermal limits of circuits and leveraging the thermal inertia of the system—i.e., the delayed increase of equipment temperature following a current increase.

Many studies have assessed the technical and economic benefits of GETs for different applications, mainly congestion management and deferral of transmission investment [2]. While those studies provide a valuable insight into the beneficial aspects of GET; few, if any, analyzed the implications of implementation and operational complexity and coordination of PFCs in the system.

For example, multiple PFC devices—used to control the power flow across a wide area of the system to mitigate overloads on lines for a given operating and fault condition—may be necessary to implement a centralized control to coordinate the PFC operating setpoints accounting for the self and mutual power flow sensitivity of each PFC and send control commands to all PFCs. Such a centralized control scheme, implemented in the control center and integrated with existing controls, would increase the complexity of operations. Therefore, the requirements for PFC solutions must be clearly defined, like those for special protection systems or remedial-action schemes (RAS).

System planners and operation engineers have valid concerns about the implication of added complexity in the planning and operation of the system resulting from PFC solutions. The absence of detailed information and industry experience hinders widespread adoption of the technology, especially in cases where multiple PFCs need to be controlled in a coordinated way.

1.2 Objective

Implementation of new technologies starts with a needs assessment, which foresees the technology's use on the grid. Among many options, transmission planners usually select those that are more cost-effective and present manageable technical implementation challenges. The assessment of new technologies involves a series of well-defined steps to ensure the technology meets system-reliability and operation requirements. Each technology comes with its specific opportunities and challenges with respect to implementation and operation.

This report analyzes implementation and operation aspects in the evaluation of transmission solutions using PFC. The goal is to help transmission planners to make informed decisions about the adoption of the technology and operation engineers to define specific operation and control procedures.

This technical report is structured as follows. Chapter 2 outlines the control scheme and performance requirements and gives an overview of potential PFC applications. Chapter 3 gives an overview of a conceptual controller implementation and operation for some PFC applications discussed in this report. Chapter 4 concludes with findings of the report.

2. ANALYSIS OF SOLUTION REQUIREMENTS

PFC solutions control the power flow on the grid during normal and emergency operations. If PFC solutions do not operate as intended, the impact on system security could be significant. First, this section describes the concept of PFC to provide background on the technical implication and operational limitation of PFC, in general. Next, the section on control-scheme design describes different forms of controller architecture before specifying technical and operational design aspects. This section concludes with some generic examples on PFC applications, outlining potential controller-scheme designs depending on need.

2.1 Concept of Power-Flow Control

To elucidate the requirements of control schemes for different applications, the implication of PFC on the power flow of the system must be outlined. The general purpose of PFC solutions is the control of active power flow through individual circuits or across a wider area of the grid. This could be achieved by changing electrical variables in the power system, such as bus voltages (V), bus phase angle (δ), and the electrical impedance[a] of the circuit (Z), which defines the line current (I) flowing through the circuit. The following equation describes the complex relationship between the electrical variables and the line current (Iij) of a circuit between the bus i and j.

$$\underline{I}_{ij} = \frac{\underline{V}_i - \underline{V}_j}{\underline{Z}_{ij}} = \frac{V_i \cdot e^{j}\delta^{i} - V_j \cdot e^{j}\delta^{i}}{R_{ij} + jX_{ij}}$$

where V_i and $V_j =$ denote the line-to-ground voltage on both ends of the line

δ_i and $\delta_j =$ describe the respective phase angles. Impedance along the line is defined by the resistance R_{ij} and reactance X_{ij}.

PFC technologies usually manipulate only one of these power-flow variables directly by adjusting the effective reactance of the line (ΔX)[b], manipulating the phase angle at one end of the line ($\Delta\delta$) or the bus voltage (ΔV).
By actively changing the power flow, the power system response results in an adjustment of the bus phase angles and voltages reacting to the change in electrical variables. The PFC capability to modify the respective electrical variable depends on the size of the PFC installation, which determines the maximum range of operating setpoint—e.g., a shifting angle range for phase shifting transformers or a maximum voltage injection range, both capacitive and inductive, for series synchronous static compensation (SSSC) or unified power-

a While both the resistance *R* and the reactance *X* define the electrical impedance *Z*, PFC aims to modify the reactance *X* because an increase in resistance is associated with increased losses and, therefore, higher operating costs.

b Series synchronous static compensation and unified power-flow controller could inject a voltage in series V_{SSSC} with the line which in combination with the line current I changes the effective reactance which could be described by $\Delta X = \frac{V_{SSSC}}{I}$ for an ideal voltage injection in quadrature to the line current.

flow controller (UPFC). For a technology-agnostic setpoint definition, the setpoint value is relative to the maximum PFC capability provided as a percentage; e.g., for phase-shift transformers with an operational range between -15 and 15 degrees, a setpoint of 50% is equivalent to 7.5 degrees. For an SSSC or UPFC with an operational range of series voltage injection between 10 kV (capacitive) and 10 kV (inductive), a setpoint of 50% is equivalent to 5 kV. A setpoint of ±0% refers to non-active ("idle") PFC operations equivalent to a setpoints of 0 degrees for phase-shift transformers (PSTs) or 0 kV for SSSCs or UPFCs. It could be concluded that the utilization of PFC is limited by the respective size of the PFC installation, but also by the implication of its action on the system and, therefore, its technical and operational limits.

The following discussion of technology-independent applications is abstracted from PFC specific variables and referred to as *setpoint* used to determine the effective operating setpoint of the PFC.

- PFC limitation: The absolute operating range is usually defined by a minimum ($setpoint_{min}$) and maximum ($setpoint_{max}$) value within which a $setpoint(t)$ could be varied over time. Depending on the technology, the operating range could be continuous, semi-continuous, or discrete. The maximum absolute change over a period is constrained by the applied maximum ramp rate ($\Delta setpoint_{max}$) for changing incrementally the operating *setpoint* ($\Delta setpoint$) over a fixed period[c] (Δt). The change in setpoint between two timesteps (t_1 and t_2) is limited by the maximum ramp rate and could be defined as follows:

$$\Delta setpoint = \frac{setpoint(t_1) - setpoint(t_1)}{\Delta t} \leq \Delta setpoint_{max}$$

- Circuit rating: The circuit rating is limited by nominal and emergency ratings, which could vary over time from seasonal to hourly[d]. It is normally defined by the thermal implication of the current on the sag of the circuit, the cooling capability, and thermal limits of the equipment connecting the circuit. With regards to PFC, the adjustment in power flow must account for its direct or indirect implication on the current and the respective rating of each piece of system equipment, which may reduce the operating range of PFC.
- Voltage limits: The operating voltage range is defined by a minimum and maximum value, which usually change between normal and emergency operations. Changes to power flow also change reactive-power generation and absorption, which directly affect voltage control. The direct and indirect implications on voltage control need to be considered and may reduce the nominal operating range of PFC.

Because PFC impacts extend beyond the circuit it actively manipulates and results in a change of bus voltages and phase angles, the power-system response to PFC action must be

c For discrete simulation using a timestep greater or equal to Δt or steady-state simulations, the applied ramp rate is negligible.

d In combination with other GETs like DLR, the algorithm should be able to adapt power flows according to dynamic rating.

evaluated to ensure the system operates within limits[e]. It could be assumed that the system impacts increase with the size of the PFC installation and the absolute *setpoint* magnitude.

To calculate the setpoint for a PFC device d, the system operator must comprehend the power-flow impact caused by a change in $\Delta setpoint$ on the line of the PFC device d and all remaining lines on the power system. This could be expressed by the sensitivity factor, which could also be referred to as self and mutual power-flow sensitivity. Sensitivity factors can be linearized for a specific system state and are applicable for minor variations of parameters. The factors are approximated by the linear relationship (f) between the incremental change in active power flow ΔP on the line l caused by the setpoint change $(\Delta setpoint)$ of PFC device d.

$$f_{d,l} = \frac{\Delta P_{d,l}}{\Delta setpoint_d} \quad \forall d \in D, l \in L$$

where

$Number\ of\ PFC\ Devices = D$

$Number\ of\ Power\ Lines = L.$

Assuming each PFC device d has an incremental impact for a change in operating setpoint, $\Delta setpoint_d$, on the power flow $\Delta P_{d,l}$ of line l, the sensitivity factor is given by $f_{d,l}$ for a given system state[f]. Because sensitivity factors are only applicable for an incremental change to the system state, sensitivity factors must be updated following a change in system state to be an accurate approximation for PFC impact.

2.2 Control-Scheme Design

The general control scheme used to operate PFC could be defined as a cascade controller, where two or more controllers work together to regulate one or more process variables. The basic concept includes a primary and secondary controller for which the primary controller influences the setpoint of the secondary controller. Essentially, a primary controller "gives orders" to a secondary controller by adjusting its *setpoint*. A feedback loop is incorporated to inform the primary controller about the actual response of the secondary controller. Figure 1 shows a simplified example of a PFC control scheme.

e The system operator needs to verify, through studies, that the intended function of PFC does not violate the operating limits of the system equipment outside the monitored area of the primary controller.

f Due to the non-linearity of the power system the shift factors could only be approximated linearly piecewise.

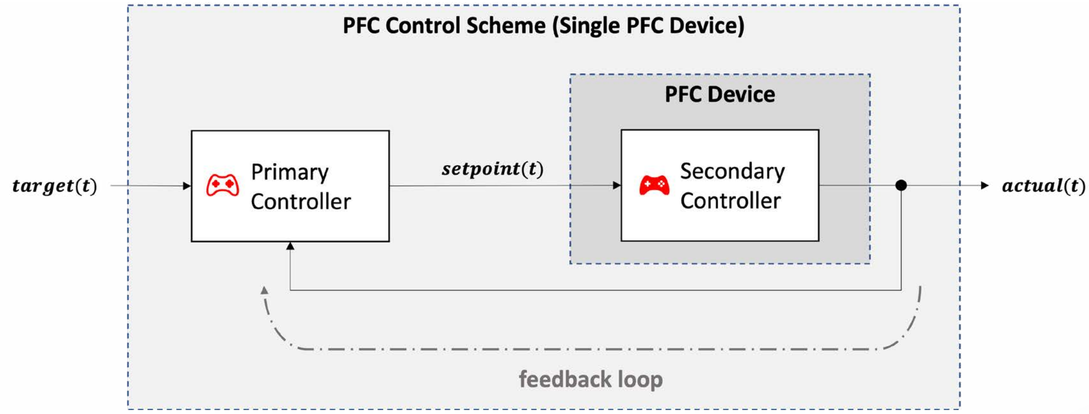

Figure 1. PFC control scheme for a single PFC device.

The input and output signals of the control blocks determine the communication interfaces required for the PFC scheme, and they indicate a total of three designed interfaces, namely $target(t)$, $setpoint(t)$, and $actual(t)$. The interfaces could be specified as follows:

- $target(t)$, the target state of the power system (e.g. a specific power flow on a circuit)
- $setpoint(t)$, the operating setpoints for each PFC device (e.g., the required setpoints to reduce or increase power flow on a circuit)
- $actual(t)$, the current state of the power system (e.g., the measure power flow on a circuit).

In the same PFC scheme, both primary and secondary controllers are considered separate black boxes that define a controller cascade. The output of the secondary controller is fed back to the primary controller to cycle PFC actions and their system implications.

- Primary[g], usually operates at the system level, which includes the algorithms required for specific PFC applications (see Section 2.3). The controller processes $target(t)$ as a target and compares it with $actual(t)$, the actual state of the system to calculate $setpoint(t)$ for PFC devices, aiming to minimize the difference between the target and actual system state.
- Secondary[h], is a device-level controller and would be included in the firmware provided by the original-equipment manufacturer (OEM) with each PFC device. The controller processes the signal $setpoint(t)$ and changes the power flow for which the power system response is captured as $actual(t)$ and fed back to the primary controller.

The relationship between the primary and secondary controller is that a single primary controller could either operate a single PFC device (see Figure 1) or multiple PFC devices (see

g Primary controller is often called Master Controller.

h Secondary controller is often called slave controller.

Figure 2). For multiple PFC devices, the secondary controller of each PFC device i receives a site-specific $setpoint_i(t)$ accounting for the self- and mutual-power-flow sensitivities, and technical and operational constraints of all PFC devices included in the control scheme (see Section 2.1). Furthermore, the dimensions of the signals increase with the number of PFC devices in the control scheme, and signal types are likely to differ between PFC technologies[i]. Both aspects increase computational and communication complexity, and the time required for the controller cascade to process the data and adapt the actual $(actual(t))$ to the target $(target(t))$ state due to self- and mutual-power-flow impact.

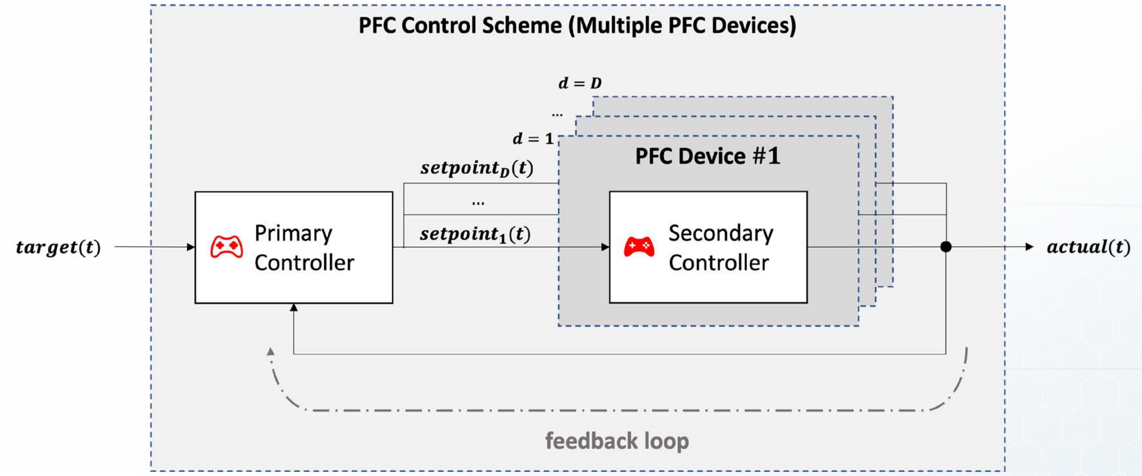

Figure 2. PFC control scheme for n PFC devices.

The input and output signals of the controllers are time variable and processed with a controller-specific sample rate; therefore they change over time with power-system conditions. The primary- and secondary-controller settings, such as look-up tables or configurable thresholds, used to define operating rules are usually considered fixed until proactively changed by the system operator.

With the secondary controller installed on site with the PFC devices, the architecture of the cascade controller is defined by the area of visibility, namely the type and range of signals available to the primary controller, which would usually determine the location of the primary controller (see Figure 3). The category of control architecture could be defined as follows:

- The **decentralized controller** operates on the device or substation level (i.e., the local area of visibility) and is calibrated to detect predefined system events $(target(t))$. Based on the local-sensor reading $(actual(t))$, the primary controller determines the change in operating setpoint $(setpoint(t))$ which is adapted by the secondary controller. The use of locally available signals reduces communication delay. The decentralized controller is limited by its visibility. It would be used for local applications such as balancing of power flow (see Section 2.3.1) and corrective

i Secondary controller is often called slave controller.

contingency management (see Section 2.3.4). The primary controller automatically determines the signals *setpoint(t)*, based on user-defined rules such as reduce flow if flow exceeds a set threshold. The operating rules must be specified and set in advance and may either be fixed or tunable over time. In this case the local PFCs act autonomously without active coordination with other PFC devices in the system. However, the exchange of data between the decentralized control and the control center of the system operators for visibility and controllability is still required.

- A **centralized controller** is a primary controller, implemented on a given control area within the system (with system-wide area of visibility). It receives the readings of various sensors *(actual(t))* from system control and data acquisition or the energy management system via appropriate communication infrastructure with an intrinsic delay. The centralized processing of data allows the controller to coordinate the effective setpoint *(setpoint(t))* for multiple PFC devices in the control area when a control action is needed $(target(t) \neq actual(t))$ and to send the control commands *setpoint(t)* to each PFC device. The centralized controller is most applicable for a PFC control scheme with multiple PFC devices which need to account for the mutual interaction and to coordinate operating setpoints to ensure secure operation. PFC applications requiring a centralized controller are balancing of power flow (see Section 2.3.1), mitigation of unscheduled flows (see Section 2.3.2), preventive contingency management (see Section 2.3.3), and corrective contingency management (see Section 2.3.4).
- A **hybrid controller** is a hybrid of centralized and decentralized controller schemes that could be used to allow PFC devices to react autonomously, but immediately, to a change in system state using locally available measurement in the decentralized controller (to "stop the bleeding") followed by a delayed and more-informed update of operating setpoints from the centralized controller accounting for wider-area information. An example for this PFC application is given in Section 2.3.4.

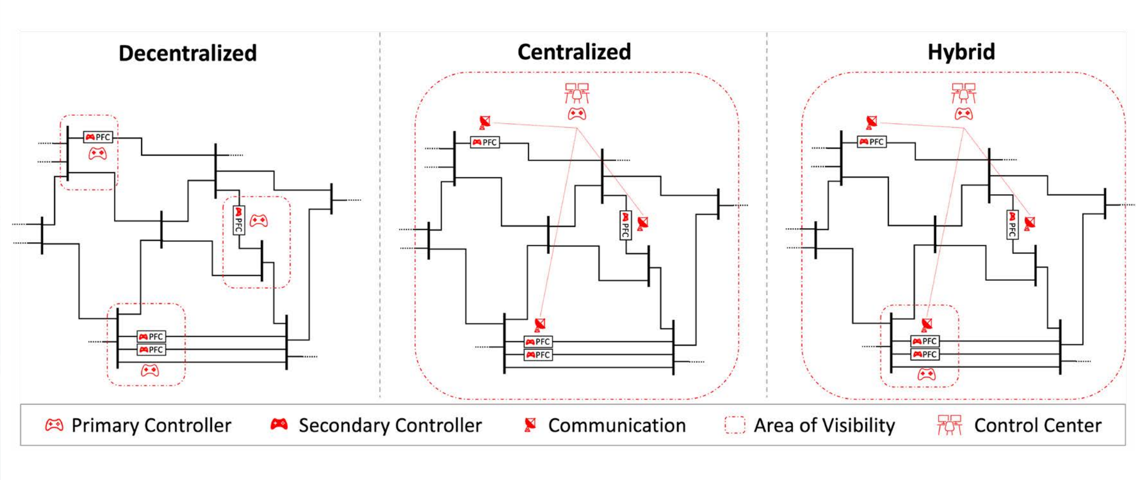

Figure 3. Qualitative illustration of the difference between decentralized, centralized, and hybrid controllers.

With several PFCs on a system, mutual impact on power flow may not be negligible. This drives the need for coordination and, therefore, a centralized- or hybrid-control architecture. The choice of control architectures impacts the secure communication infrastructure, the reliability of the scheme, and the complexity of setpoint computation.

It is understood that PFC control schemes are designed to operate under various system conditions, from normal to emergency operations. A failure or misoperation of the control scheme could result in violation of the operational limits of system equipment and might impact the secure operation of the grid. In general, in the design and implementation of a control scheme, the following attributes should be considered:

- Dependability, the measure of certainty that the control scheme will operate when required
- Security, the measure of certainty that the control scheme will not operate when not required
- Selectivity, the ability to affect the least amount of action when performing its intended function
- Robustness, the ability to work correctly over the full range of expected steady-state and dynamic system conditions
- Adaptability, the ability to be updated with minor changes to accommodate changes to and expansion of the power system
- Performance, ensuring that the control scheme responds within a certain time frame.

Control-scheme design requirements are defined by the application (see Section 2.3). In particular, the margin for failure or misoperation could change based on the security margin available to the system, defined by the difference between maximum and actual utilization of the system equipment (see Figure 4). In the case of lower grid usage, the margin for error tends to be greater due to the available security margin and may, therefore, be associated with lower control design requirements. In cases of higher grid usage, the system operates closer to its limits, which reduces the margin for failure or misoperation and is associated with higher requirements for the control-scheme design.

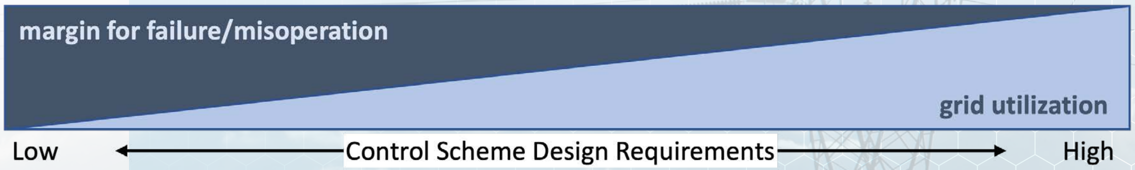

Figure 4. Qualitative relation between margin for error and grid utilization and impact on control-scheme design requirements.

2.2.1 Dependability

Depending on the application, the control scheme may be executed to monitor and control the power flow continuously, at any time or only during specific system events for which a specific signal triggers PFC operation. In any case, when PFC operation is required, it must be actuated effectively and correctly, even during and after system disturbances. Dependability could therefore be considered as a combination of availability and specific performance. To enhance dependability, the control scheme must be designed with sufficient redundancy, and the communication, processing and adaptation of signals must happen in a timely manner.

If PFC solutions are used to maximize the use of the existing infrastructure, the operating security margin tends to decrease, making an adequate and reliable response of PFC a critical requirement. The PFC solution should operate under normal conditions, in the event of system disturbances, and in the presence of a PFC-component failure. In the event of severe system disturbance or when a PFC component fails, the PFC device shall be capable of recovering and performing the intended function after an adequate recovery time.

To address the availability and performance of PFC responses under various operating conditions, including unforeseen failures or disturbances, these aspects should be considered, categorized as follows:

- Fault tolerance—PFC solutions shall be able to ride through various power-system disturbances and continue to function effectively even during software failures and communication disruptions.
- Self-healing—this includes specification of self-healing capabilities that allow the PFC solution to automatically restore normal operation following failures or disturbances, such as over-current, over-voltage, or re energization. For PFC technologies using power electronics, this may also extend to the resynchronization of a phase-locked loop.
- Redundancy—the design implements a mechanism to ensure the PFC device works as intended. This may include duplicate components and alternative communications paths to provide an interim fallback solution in case of failure. Depending on the granularity of the solution, the partial isolation of individual components or units may be applicable allowing the PFC solution to operate with reduced capacity.

These attributes emphasize the need for technologies to maintain consistent dependability during disturbances and provide backup mechanisms to ensure continuous grid operation. The objective of this requirement is to ensure that PFC devices can operate reliably over time, withstand faults, and employ redundancy measures to prevent single points of failure.

2.2.2 Security

The PFC control scheme should be designed to be resilient, safe, and secure. The idea is to ensure the control system withstands threats to cyber- and physical security, but also false or corrupted sensor readings. The security of control systems is often enhanced by using validation and models of the power system for verification. The PFC control scheme should be capable of detecting inconsistent signals and commands in the primary and secondary controller and should issue alarms to the system operator to disable or modify operating procedures. [3]

Thus, to fulfill the requirement of security attribute, a control scheme shall be designed to:

- Avoid false and harmful operation while experiencing any credible failure
- Define and validate operating ranges for all signals and settings
- Minimize mistakes during commissioning, adaptation, and testing.

Verification of the integrity of specified control-scheme logic is carried out through extensive simulation studies, systematically covering the whole range of anticipated system operating conditions and contingency events

2.2.3 Selectivity

Selectivity is the ability to determine an effective response that prioritizes PFC, which has the highest impact on the power flow, to meet its intended function. It shall also consider the self- and mutual-power-flow sensitivities associated with PFC because the reduction in flows is accompanied by an increase in flows to other circuits and vice versa. In any case, the control scheme should be able to maximize and constrain PFCs to operate the system within the defined limits.

2.2.4 Robustness

In control systems, higher robustness can be achieved through a closed-loop design, which means that the system operates in a closed loop when the decision to take an action relies on the measured effects of previous actions. In other words, the amount of control is adjusted in real-time to the current system state.

The closed-loop design becomes a challenge in the presence of transient phenomena that require fast (on the order of milliseconds) controls, such as short-term voltage instability. However, a closed-loop PFC control scheme to alleviate congestion or overloads in the power system is less time critical and would be expected to operate at a much-lower sampling, usually on the order of minutes.

2.2.5 Adaptability

A control scheme design should be able to evolve in time to adapt to changes in grid usage and topology, and potentially also in grid operations, using them in combination with other GETs. To enhance adaptability, communication interfaces between control blocks should be defined and, ideally, standardized, which could ease the integration of new PFC devices independent of OEM or generation of technology. Furthermore, the simplicity and modularization of the PFC control scheme, where each module has a single responsibility, leads to a better abstraction between modules, reduces the complexity of each module and makes maintaining and extending easier.

2.2.6 Performance

Performance describes the ability of the PFC control scheme to recalculate and adapt the operational setpoint following changes in system state. It quantifies how quickly the actual PFC output converges to the setpoint and remains within an acceptable tolerance. The performance is impacted by various factors, including power-system dynamics, control algorithms, inherent delays[j], and the hardware limitations associated with the change of setpoint. The control requirement for the performance could be categorized by the following elements:

- On-time—following a change in system state $(actual(t) \neq target(t))$, the processing of updated input signals and recalculation of new operational setpoints $(setpoint(t))$ by the primary controller must be timely. Depending on the application of PFC technologies, the recalculation of PFC setpoints to reflect the new system state shall be within milliseconds to minutes. For thermal overloads, a control response on the order of minutes is usually acceptable due to the thermal inertia[k] of system components, but eventually depends on the pre-contingency loading and magnitude of overloads.
- Setpoint ramping—the update of an operational setpoint $(setpoint(t))$ is applied by the secondary controller and changes the power flow on the system over a specific time $(actual(t))$ depending on the PFC ramping behavior in discrete steps or continuously (see Section 2.1). The maximum ramp rate is usually defined by technology. The absolute magnitude of setpoint change in combination with the ramp rate determines how long it takes the PFC to adopt a new setpoint, which may range from 100 milliseconds to minutes. For the mitigation of thermal overloads, lower ramp rates could be acceptable to support the settling of the system and avoid interactions with other system equipment.
- Accuracy and effectivity—accuracy is defined by the controller cascade of the primary and secondary controller and influenced by various factors, such as the power-flow sensitivity, the granularity of the step change in setpoints (discrete vs. continuous), error tolerance of sensors and sample rate of controllers. Depending on the PFC capability range and its power-flow sensitivity, the accuracy shall be specified on case-by-case basis, which enables the system operator to effectively control the power flow within an acceptable error band.

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j Inherent delays refer to the time lags that naturally occur in dynamic systems. These delays can be due to various factors as the signal transmission, processing or even the time it takes to adapt a control command.

k Thermal inertia is the time delay that the temperature of equipment, such as a conductor, adapts in response to change in current.

These attributes describe the capability of PFC devices to respond promptly and effectively to a new setpoint. The objective shall ensure that the control scheme calculates *(setpoint(t))* and reaches the targeted system state *(actual(t)=target(t))* in a specified time.

2.3 PFC Applications Scope

The following subsections discuss various PFC applications regarding the solution requirements and the related operational challenges.

2.3.1 Balancing of Power Flow

PFC solutions could be used to dynamically adjust the power flow to balance the utilization of the network, thus reducing overloads and congestion.

2.3.1.1 Control Scheme

The type of control scheme is determined by the number of PFC locations and the expected mutual interactions of PFCs across the system.

2.3.1.1.1 DECENTRALIZED

A decentralized control scheme is used to adjust local power flows to balance the power flows for a specific topology or power-flow condition. Figure 5 shows an example of a simple example of applications to balance the power flows on a grid corridor defined with three parallel circuits. The imbalance could be caused by differences in electrical-circuit parameters due to line length or conductor types.

To compensate for the imbalance, at least two[I] PFC devices are required to align power flows across the three parallel circuits. For a decentralized control scheme, the primary controller could be located in the substation of Bus 1 with visibility just over the current on the lines *(actual(t))* at Bus 1. With the objective to balance the power flows on the three circuits *(target(t))*, the primary controller could determine the power flow difference between the circuits and adjust the *setpoint(t)* for the secondary controller of each PFC device.

I Assuming each of the PFC devices could push and pull power, the power flow on the circuit without PFC device could be controlled indirectly using the mutual power flow sensitivity.

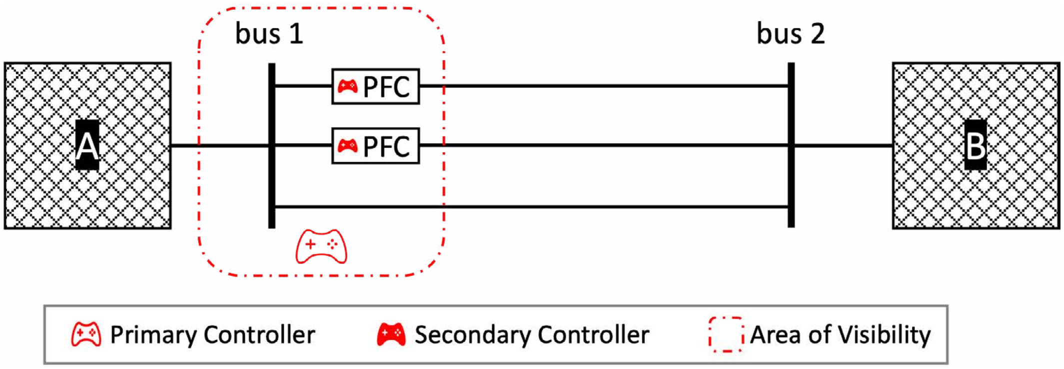

Figure 5. Decentralized control scheme determined by local grid topology.

In this example, the control sequence could be as follows:

1. *Calculate the average flow of the three parallel circuits between A and B*
2. *Determine the difference between the actual power flow per circuit and the average flow*
3. *Adjust the $setpoint(t)$ to converge power flow on each line with average flow.*

In this case, the decentralized controls could use line current as a control variable, reducing the number of required input signals and allowing the reading from either Bus 1 or Bus 2.

2.3.1.1.2 CENTRALIZED

In a meshed system with multiple PFCs, the calculation of the effective operating *setpoints* needs to be more comprehensive. Due to self- and mutual-power-flow sensitivities, the setpoint adjustment of each PFC needs to account for the mutual impact on the remaining system and PFC. Further, power flows can continuously change due to variable RESs or DERs, making power-flow patterns less predictable, changing system operating state and, therefore, sensitivity factors. Hence, the implementation of a centralized control scheme would be most suitable with a systemwide area of visibility to coordinate the effective operations of PFCs.

Figure 6 shows an example of areas for which the power flows are impacted by the respective PFC devices within which the mutual power-flow impact is not negligible. The significance of the impact area depends mainly on system condition and topology, and the sensitivity factors tend to decrease with increasing electrical distance—namely the network impedance—to the PFC location. The example indicates overlapping impact areas, which shows the areas within which multiple PFCs have an impact on the power flow, depending on sensitivity factors. The impact of several PFCs on the circuits could either complement or cancel each other. For an effective wide-area control scheme, the *setpoints* of the PFCs shall be coordinated by the primary controller accounting for the self- and mutual-power-flow sensitivities of PFCs.

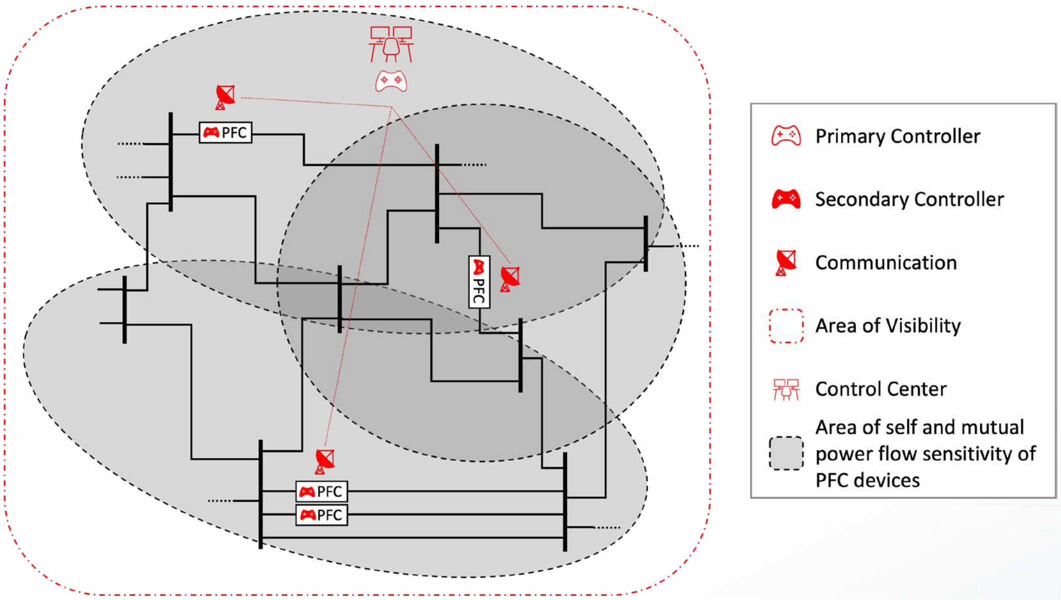

Figure 6. Self- and mutual-power-flow sensitivity area of PFC in a meshed network.

The coordinated calculation of effective operating setpoints ensures that PFC locations with the highest marginal impact are selected first to perform the intended function. In case of multiple objectives, the centralized control could also account for a hierarchy of objectives prioritized by the system operator. The centralized primary controller would usually be implemented in the control-room energy management system. The impact of the calculated setpoints could be verified by a simulation, and the setpoint could be actuated either automatically or after review and approval from the system operator.

The centralized control scheme has the advantage of being able to adapt to changing system conditions caused by changes in generation dispatch, load, or topology and to tailor the *setpoints* to maximize the effectiveness of PFCs.

2.3.1.2 Operational Requirements

The power flow across the network will be altered due to changes in such system operating conditions as ramping of generation or load or the switching of generators or transmission circuits. These changes may trigger the recalculation of PFCs *setpoints*. During normal operations, this application is expected to be in the steady-state domain, which means that both the calculation and adapting of setpoint could happen slowly—e.g., over the operational timeframe between 5 and 15 minutes.

First, the primary controller updates the setpoints $(setpoint(t))$ for the secondary controller as a response to the change $(target(t) \neq actual(t))$ to align power flows with the available transmission capacity on the system. The updated setpoints will be communicated and applied to the secondary controller of the PFC devices. To support settling of the power system following a change of system condition, the actual PFC setpoint should be changed gradually to slowly converge the target power flow. During the settling of the system and ramping of the PFC devices, the setpoint *(setpoint(t))* may need to be updated depending on the accuracy of setpoint calculation, and sampling and processing rate of the signals. The actual PFC setpoints will eventually converge on operating setpoints meeting the objective *(target(t) = actual(t))*.

The change in system state may also result in some minor disturbances, such as system dynamics and transients. Depending on the technology, it could be expected that if the tolerance of the PFC is high, it would not be affected by minor disturbances. If that is not the case, it should be expected that the PFC devices, such as those using phase-locked loop technology, are going to self-heal following a disturbance. In any case, the PFC should be able to operate normally within the order of minutes.

Redundant communication between the controls and the PFC devices as a failsafe and for reliability purposes would be needed to allow effective operations. In case of lost communication, the PFC device should have a failsafe mode, ensuring a predictable and deterministic operating setpoint, such as a controlled ramp down after a specific communication timeout and the disengagement of the respective PFC device. Any unavailability needs to be reported and accounted for in the control scheme, such as operating with reduced capability and disabling the PFC location. Depending on the severity of the loss of a PFC device, the control scheme may still be able to continue operation with a reduced—i.e., less effective—PFC capability using the remaining, functional PFC devices.

2.3.2 Mitigation of Unscheduled Flows

Unscheduled flows[m] are power flows resulting from the difference between the energy contracted to flow through a transmission interface[n] and the actual flow dictated by the impedance configuration of the network. These unscheduled flow patterns can overload transmission facilities even though these facilities could accommodate the nominal scheduled flow. Unscheduled flows can cause congestion in neighboring systems and limit power transactions in zones not involved in the original transaction. Unscheduled flows may also appear on transmission facilities internal to the control areas.

For unscheduled-flow management, three aspects must be considered in the calculation of the effective operating setpoint:

1. *The PFC sensitivity factor on the directly affected line*
2. *The load-flow impact on the neighboring control areas*
3. *The load-flow impact on the own control area.*

The objective is to align the actual with the contractual flows to mitigate unscheduled flows.

m Unscheduled flows are also known as loop flows or parallel flows.

n In North America, the interface is normally identified between control areas whereas, in Europe, it normally refers to international cross-border interface.

2.3.2.1 Control Scheme

Figure 7 shows a simple example with three network areas connected by three tie lines. Assuming a portion of the power flows from Bus 1 to Bus 2 through the Network Area C is unscheduled, it should consequently be reduced to the contracted flow. The PFC is installed on the line between Bus 1 and Bus 3 to set or limit the power flow through the circuit, namely unscheduled flow. The primary controller would receive a target power flow *(target(t))*. To determine the operating setpoint *(setpoint(t))* for the secondary controller, the primary controller only requires the actual flow on the line *(actual(t))* which limits the area of visibility to the line itself.

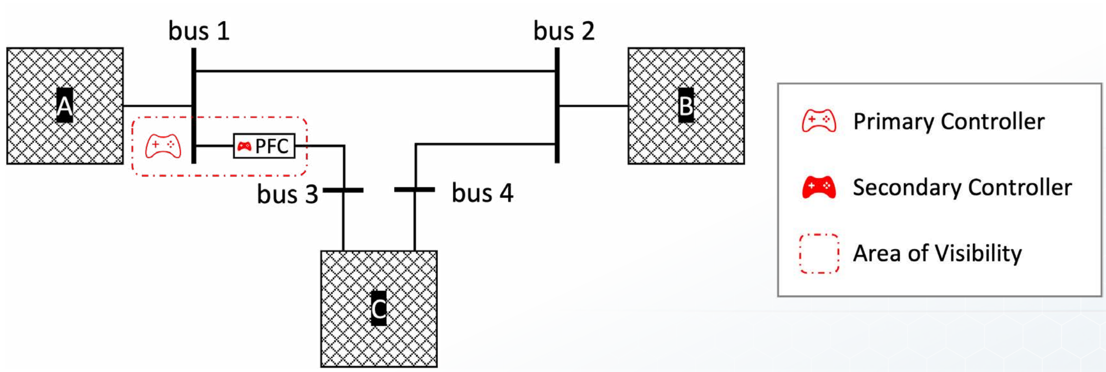

Figure 7. Example for unscheduled-flow management.

The control scheme must account for impact on different systems that are potentially operated by different entities. The effective operating setpoints need to be coordinated with the affected system operators to ensure system security. For unscheduled-flow management, either a decentralized or centralized control scheme would be suitable. In any case, the control scheme must be capable of adjusting *target(t)* to match with either the contracted flows or targets based on communication received from other system operators.

A control algorithm would use power-flow threshold for a single circuit or a range of circuits to compare with the actual power flows to calculate the effective operating setpoint. Before the updated setpoints are applied the change of operational setpoints needs to be verified and communicated between affected operators. [4]

2.3.2.2 Operational Requirements

The schedules of the power flow on the interconnections are determined by settlement of the electricity market. The operational granularity of the schedules sets frequency of the PFC-setpoint updates. The actual magnitude of the setpoint is defined by the contracted power flows, and they potentially have a margin for unscheduled flows, which would be set by the system operator.

The setpoint calculation is performed in advance and communicated to the primary controller.

The PFC technology should have a high fault tolerance or a reasonably fast self-healing process to recover from system disturbances. In case of a permanent PFC failure, the impact on the power system in terms of congestion or overloads must be mitigated using an RAS, which should be coordinated with the loss of a PFC device.

2.3.3 Preventive Contingency Management

Evaluation of power-system security is necessary to develop ways to maintain system operation when one or more elements fail. A power system is secure when it can withstand the loss of one or more elements and continue operation without major problems. Contingency analysis (CA) is one of the security-analysis applications in a power-utility control center to analyze the power system to identify the overloads and problems that can occur due to a contingency. A contingency is the failure or loss of an element (e.g., a generator, transformer, or transmission line), or a change of state in a device (e.g., the unplanned opening of a circuit breaker in a transformer substation) in the power system. Therefore, CA is an application that uses a computer simulation to evaluate the effects of removing individual elements from a power system.

The severity of a contingency event can range from:

- None, when the power system can be rebalanced after a contingency without overloads to any element
- Severe, when several elements, such as lines and transformers, become overloaded and risk damage
- Critical, when the power system becomes unstable and will quickly collapse.

Current electric utility operating policies (such as North America Electric Reliability Corporation's) require that each utility's power system be able to withstand and recover from any first contingency, or any single failure.

Preventive contingency management is a proactive approach that involves taking measures before a contingency event to prevent potential contingencies from causing violations in the power system. The measures include activities such as rescheduling of power generation, adjusting phase shifter positions, switching of flexible alternating-current transmission-system devices and high-voltage direct current transfer. The objective of preventive contingency management is to ensure that the power system operates within its security constraints under normal and contingency conditions.

The preventive actions derived from the CA would usually accommodate the occurrence of all simulated contingency events. In terms of PFC, the control scheme would aim to increase the operational headroom by reducing the grid use during normal operations to prevent overloads for all potential contingency events. PFCs taking part in preventive measures are less effective because only a single operating setpoint per PFC would be applied to control flows across various system conditions, such as normal operations and all potential contingency events.

2.3.3.1 Control Scheme

The applicable control scheme is centralized. The setpoint calculation in the preventive contingency management should be coordinated with the CA to ensure system operation within the emergency limits following a contingency event. A single *septoint* for each of the PFC accounts for all defined contingency events simulated in CA. The PFC is expected to operate with the same setpoint prior, during and after any contingency and not to take immediate action triggered by the actual contingency event. The coordinated setpoints should be retrieved from and verified by the CA and set for each PFC on the system in advance.

2.3.3.2 Operational Requirements

In the CA, the effectiveness of the PFC setpoints must be verified to consider the error tolerances of sensors used in the centralized controls and the granularity in which the setpoint could be adjusted by the appropriate PFC devices.

While preventive contingency management is not expected to change the setpoint *(setpoint(t))* from the primary controller post-contingency, the *target(t)* may be refined to accommodate any further corrective actions taken by the system operator, depending on the severity of the contingency.

PFC devices should be able to ride through a disturbance. In case a PFC device is not capable of withstanding the disturbance due to current transients or magnitude, it should recover reasonably fast to ensure secure operations. Recovery time is determined by preloading the power system and thermal inertia of the power system, which prevents the system equipment from overloading instantaneously. A reasonable recovery time for the PFC towards normal operation shall be specified to alleviate any potential overload in a timely manner—e.g., within minutes, provided thermal inertia allows.

2.3.4 Corrective Contingency Management

Corrective contingency management is a reactive approach that involves taking corrective actions after a contingency has occurred. Assuming a contingency violates the operating limits of the power system—either immediately or with delay due to thermal inertia—a corrective action must restore system operations without violations. Depending on the severity of the system problem caused by a contingency event and the required response time to alleviate system violations, an adequate corrective action must be identified. An example of a corrective action to alleviate thermal overloads could be the use of PFC. In case no applicable corrective action can be identified, the specific contingency event must be accounted for in the preventive contingency management[o] (see Section 2.3.3).

While the PFCs already operate for preventive actions prior contingency at a specific, but fixed, setpoint *(setpoint(t))*, the corrective actions are defined for a specific system event

o Corrective contingency management is a complement to preventive contingency management.

and actuate a specific response with its occurrence. The response of the PFC control scheme is more effective because it is tailored to a specific load-flow condition defined by normal operations or a specific contingency event. While this leads to an increasing utilization of the grid and reduction of preventive constraints, it also reduces the margin of failure or misoperation of the PFC control scheme (see Figure 4). With the evolution of computational capabilities, CA has already been used as an online support tool in system operations using the real-time measurement from the energy management system or in intraday schedules to refine preventive actions. Like many security-analysis applications, measures would usually be identified and actuated in advance to reduce the operational risks. Nevertheless, system operators are exploring the use of CA as an online tool to identify corrective actions for potential contingency events before they occur and to actuate the respective action in the event of contingency.

For the corrective contingency management, each system set defines a set of conditional operating setpoints for PFC $(target(t))$. In the event of a contingency, the operating setpoint $(setpoint(t))$ of PFC is updated by the primary controller tailored to the specific system state to prevent overloading $(actual(t))$ and limit potential cascading outage of other circuits. When applying corrective contingency management, the power system is operated closer to its limits, with a smaller security margin. It is important that the corrective action of the PFC is immediate and coordinated among PFCs to be effective and ensure system security for all types of contingencies.

The objective of corrective contingency management is to enhance grid usage by minimizing preventive grid constraints prior to any contingency event. The corrective measures would have been identified on line, but in advance[p], and stored in a database. In the event of contingency, the specific corrective measures are selected from the database once the event has been detected and applied shortly after.

2.3.4.1 Control Scheme

For local impact and deterministic post-contingency loading, a decentralized control scheme may be applied to respond immediately (to stop the bleeding). For multiple PFCs, the coordination of corrective actions to facilitate multiple single-contingency events, a centralized control scheme is required to guarantee effectiveness.

It is important to coordinate the ramping performance of the PFC in a contingency event and the system-protection relays ensuring the corrective actions applied by the primary controller are fast enough to reduce potential overloads below the emergency rating before system protection kicks in.

2.3.4.1.1 DECENTRALIZED

A decentralized control scheme is applicable where immediate corrective action is required to alleviate local overloading. Figure 8 illustrates an example of a decentralized control scheme,

p Corrective actions are defined based on CA results using the most-recent system snapshot available in real-time operations.

with the primary controller located in the substation of bus 1 monitoring power flow on the lines from Bus 1. In case of the loss of one of the three parallel circuits, the power flow drops to zero on one circuit while it increases on the remaining two circuits. Post contingency, the power flow through the remaining circuits is unbalanced. Based on the local measurements from Bus 1 *(actual(t))*, the primary controller calculates the operating setpoint for the remaining PFC device *(setpoint(t))* to either push or pull onto the circuit to balance line loadings *(target(t))* among the two remaining circuits.

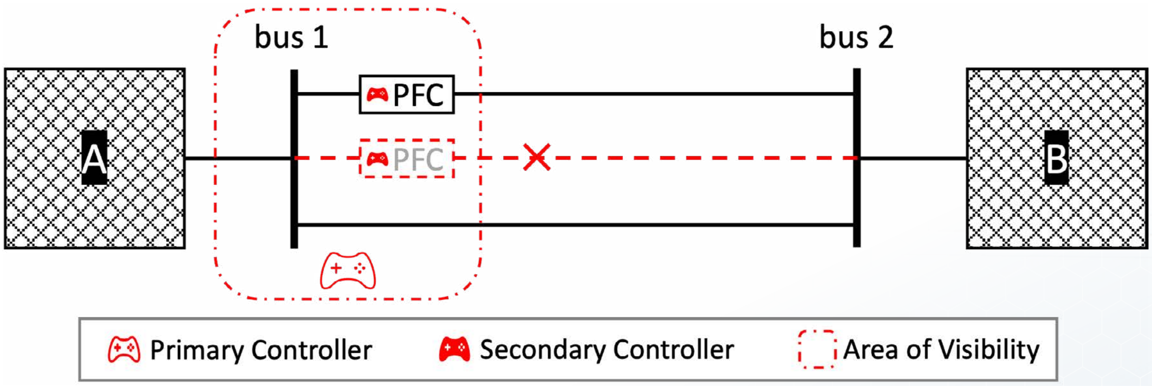

Figure 8. Corrective contingency management using a decentralized control scheme.

The corrective action[q] is triggered by the contingency event—e.g., as soon as the input signals of the primary controller exceed a pre-defined threshold *(target(t) ≠ actual(t))*. After the event has been detected, the primary controller calculate s the operational setpoint for the PFC *(setpoint(t))* which will then be adapted by the secondary controller.

2.3.4.1.2 CENTRALIZED

The PFC setpoints in a centralized control scheme are applied post-contingency events, but remedial actions are identified and planned on-line, based on the system conditions. While the most-effective PFC setpoint could be calculated prior to or after the contingency, a prior contingency calculation would be preferred due to the faster response to a contingency event. Here remedial actions for all considered contingency events are identified and scoped in a rolling analysis performed every 5–15 minutes using the latest data available in the energy management system of the system operators. The remedial actions would be available in a buffer storage of the centralized controller as a lookup table and communicated to the PFC devices as soon as the respective contingency occurs. The advantage is that the computation of the remedial action is performed in advance, which ensures a quick response of PFC following the communication of updated *setpoints*. The downside is the use of perfect foresight for the computation of the *setpoints* assumes a predictable system condition, which may not reflect the actual power system response, depending on severity. For post-

q Due to limited visibility of the decentralized controller, the system operator needs to verify through studies that the intended function of PFC does not violate the operating limits of the system equipment outside the monitored area of the primary controller.

contingency calculation, the input signals reflecting the actual system conditions are used to determine the most-effective remedial actions. Depending on the complexity of the control scheme, the remedial action is identified and applied with an intrinsic delay, during which an overload could occur in the system. The post-contingency calculation would therefore only be suitable for contingency events with a low level of severity.

Figure 9 shows a subset of contingency examples that change the network topology, which could completely change, and in some cases even invert the sensitivity factors of PFCs. It outlines the overlap of the impact area for each of the PFCs and emphasizes the need for a centralized control scheme to coordinate the remedial action. This ensures the application of the most-effective corrective action as a response to a specific contingency event.

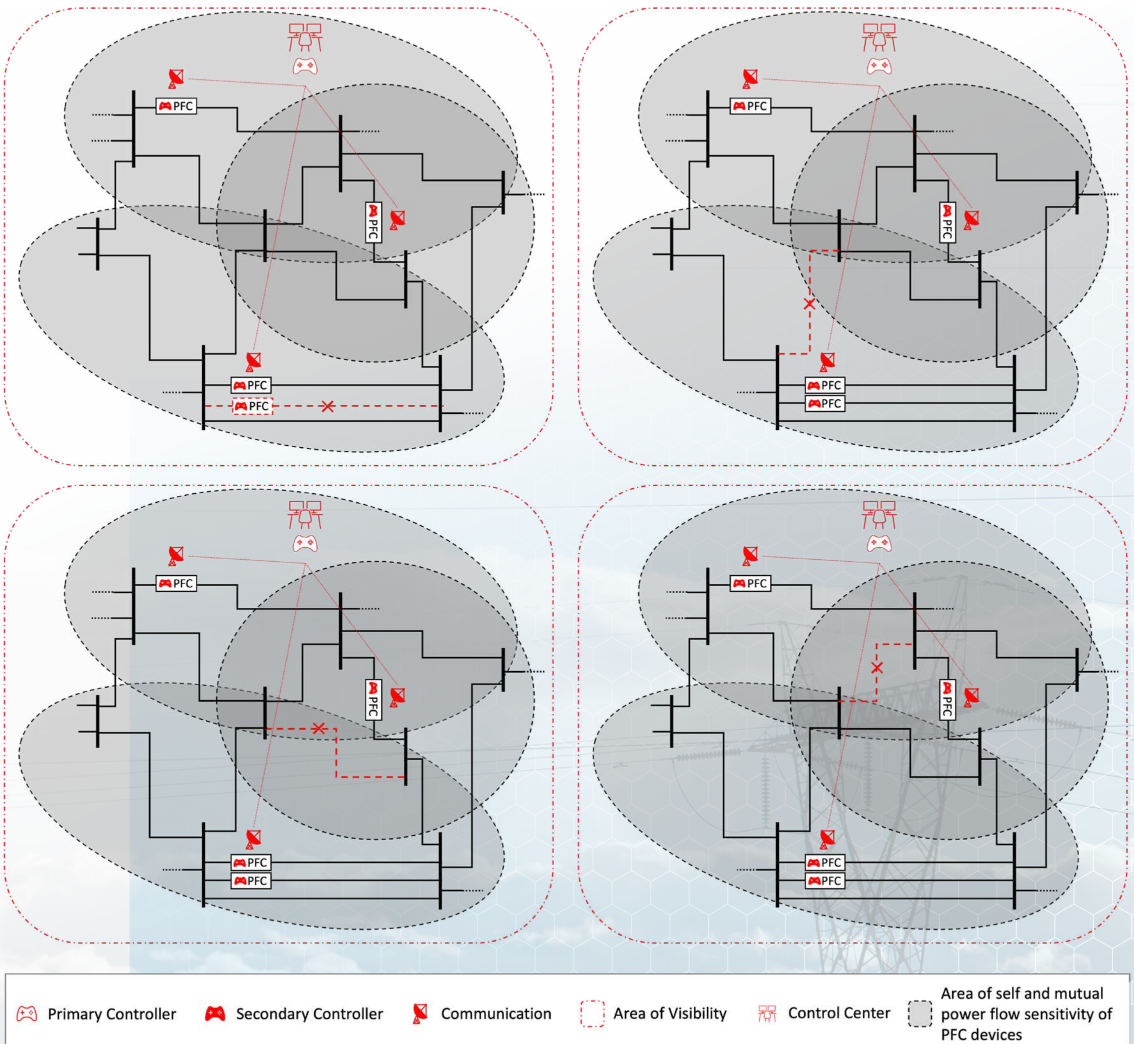

Figure 9. Corrective contingency management using a centralized control scheme.

For some specific contingency events, a hierarchy of control schemes could be used, starting with corrective actions based on prior contingency calculations, which would then be refined by a post-contingency control scheme.

2.3.4.1.3 HYBRID

A complementary control scheme could be applied to use a decentralized controller to alleviate immediate overloading to push or pull power on a specific circuit, followed by a slower but coordinated setpoint update using a centralized control.

Figure 10 shows an example of a hybrid control scheme. The centralized control that monitors the power system is located in the control center while the decentralized control monitors only the three circuits. After losing one of the three monitored circuits, the decentralized control triggers an immediate response to balance flows on the two remaining parallel circuits. Both the loss of the circuit and the action of the PFC impact the power flows in a wider area, as indicated by the area of self- and mutual-power-flow sensitivity, which the centralized control accounts for with a delay.

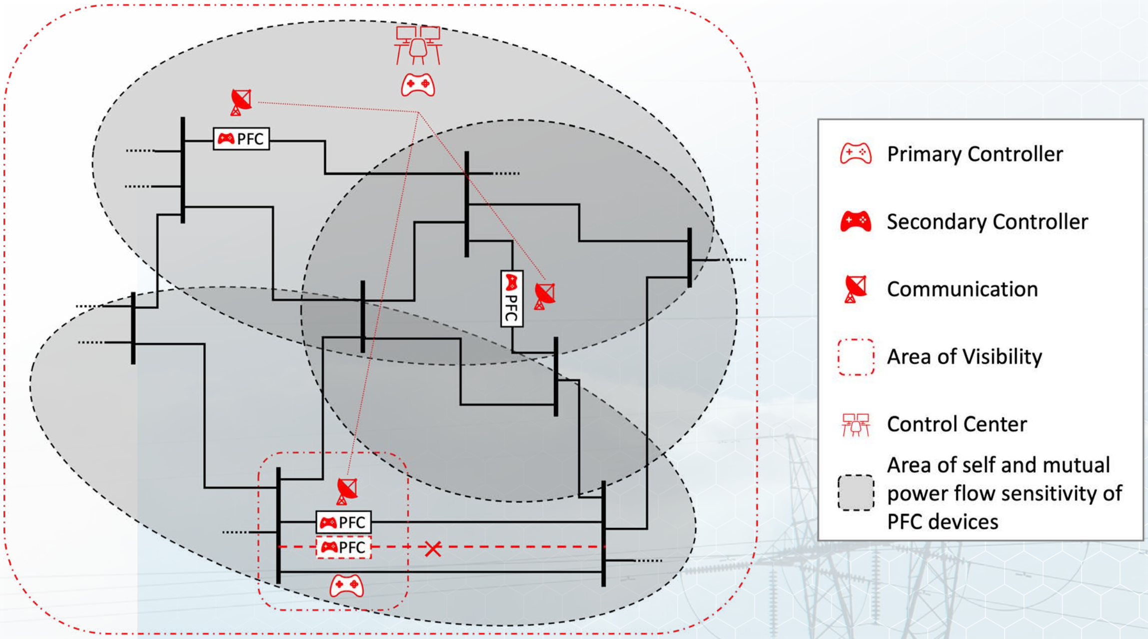

Figure 10. Corrective contingency management using a hybrid control scheme.

For hybrid control schemes, the hand-over between the decentralized and centralized controls must be coordinated, which requires the prioritization or coordination of input signals, namely *target(t)*, of the primary controller that defines the secondary controller inputs *(setpoint(t))*.

2.3.4.2 Operational Requirements

Remedial action should be applied as fast as required to alleviate the thermal implication of the contingency event on the equipment of the power system. To improve the immediate response after a contingency, a decentralized control could be applied to ensure a fast local PFC response triggered by the impact of the contingency event. A centralized controller would be used to coordinate the PFC setpoints. A hybrid controller would combine the decentralized with the centralized controller to refine and overwrite the remedial action of the decentralized scheme and increase the effectiveness of PFC on the power system. The control-scheme design—decentralized, centralized, or hybrid—depends on its purpose, defining the minimal performance and selectivity requirements.

The PFC should be able to ride through a disturbance. If a PFC device cannot withstand the disturbance due to current transients or magnitude, it should recover reasonably quickly to ensure secure operations. The recovery time is determined by the power system's preloading and the power system's thermal inertia, which prevents the equipment from overloading instantaneously. A reasonable recovery time for the PFC after any power system disturbance to continue the intended operation could be less than a minute.

3. ANALYSIS OF COORDINATION METHODS

This section illustrates examples for a conceptual implementation and operation of some PFC control schemes described in previous sections (see Section 2.3, namely Section Preventive Contingency Management and Section 2.3.4). Case-study examples using generic or actual power-system models are used for this purpose; however, the list of examples is not exhaustive.

3.1 Preventive Contingency Management

The South Carolina 500 bus system [5] is used to explain the characteristics of a preventive control scheme. The system model contains 500 buses, and 231 transmission lines are monitored for overloads. The tool CPLANET [6] has been used to determine the PFC size, location, and setpoints for a total of nine, scenarios based on three normal operating conditions and a respective set of two N 1 contingency conditions. Figure 11 indicates the topology of the network and the five locations of PFCs in red.

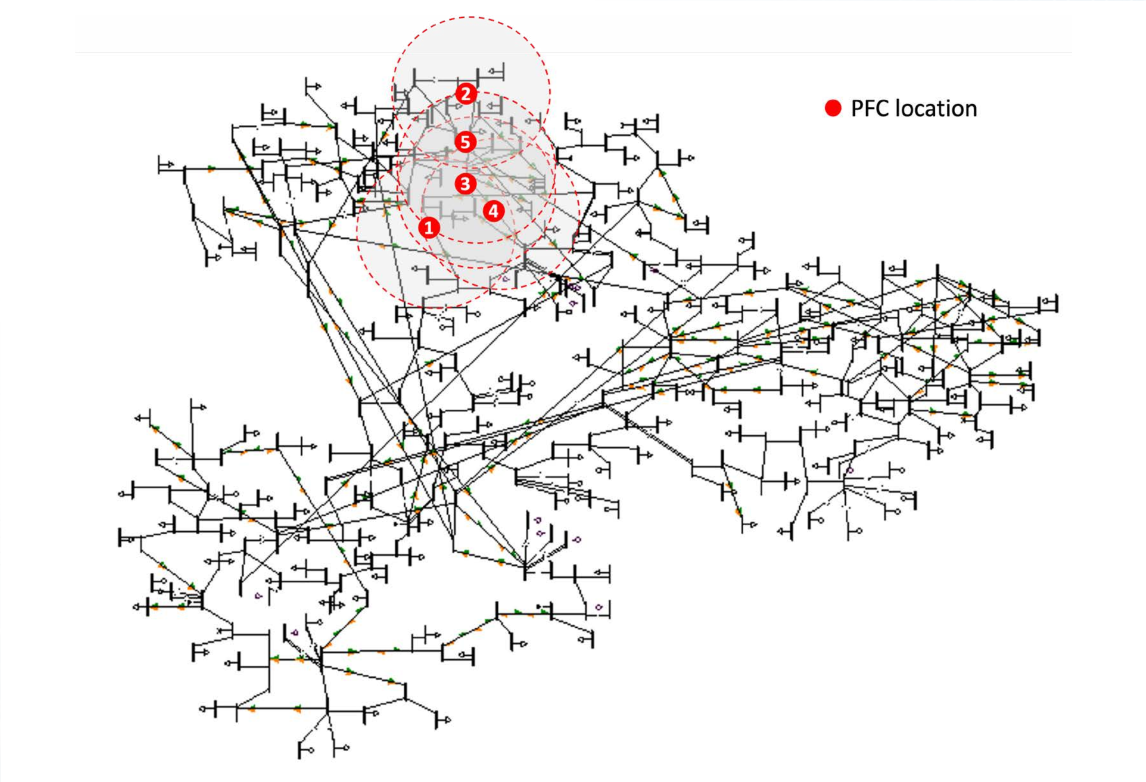

Figure 11. Network topology and PFC locations for the case study of preventive contingency management.

The PFC locations are electrically close to each other, which requires a centralized primary controller to account for the self- and mutual-power-flow sensitivity in the setpoint calculation. For preventive contingency management, the PFC setpoints need to facilitate various normal-operating and predefined contingency conditions. The update frequency of the setpoints depends on the approach taken by the system operator, which is distinguished in this report as follows:

Fixed setpoints: the PFC setpoint is determined to facilitate multiple normal operating and contingency conditions. The setpoints stay constant over the duration the conditions are applicable. This approach may be used to define and apply a fixed setpoint $(setpoint(t))$ for a specific period, such as peak/off-peak hours, 24 hours, an entire week, month, season, year, etc.

Conditional setpoints: The PFC setpoint is applicable only to a specific set of operating condition, such as normal operations and a set of contingency events. It is expected that the setpoints $(setpoint(t))$ change during system operation in timesteps potentially as small as 5–15 minutes, depending on the granularity of the time slots in system operation and power-flow dynamics.

The following subsections describe the difference between fixed and conditional setpoints in detail.

3.1.1 Fixed Setpoints

Table 1 shows the setpoints relative to the PFC capability for each of the five PFC locations for three consecutive normal operating conditions and two specific contingencies for each operating condition. For the fixed-setpoint approach, the setpoint $(setpoint(t))$ remains the same for each location and all operating condition and does not change with the occurrence of a contingency.

Location	Condition 1			Condition 2			Condition 3		
	N-0	N-1 (#1)	N-1 (#2)	N-0	N-1 (#1)	N-1 (#2)	N-0	N-1 (#1)	N-1 (#2)
1	-53%	-53%	-53%	-53%	-53%	-53%	-53%	-53%	-53%
2	62%	62%	62%	62%	62%	62%	62%	62%	62%
3	66%	66%	66%	66%	66%	66%	66%	66%	66%
4	71%	71%	71%	71%	71%	71%	71%	71%	71%
5	100%	100%	—[r]	100%	100%	—	100%	100%	—
	Fixed Setpoint 1								

- Positive signs denote a setpoint to push flow away (increase of effective circuit reactance); negative signs are for setpoints to pull flow on the circuit (decrease of effective circuit reactance).
- Setpoint is technology agnostic and provided relative to the operational range of PFC technology in percentage. For PSTs with an operational range of -15 to 15 degrees, a setpoint of 50% is equivalent to 7.5 degrees. For a static synchronous-series compensator with an operational range of -10 kV (capacitive) to 10 kV (inductive), a setpoint of 50% is equivalent to 5 kV.

Table 1. Overview of applied fixed PFC setpoints

The fixed setpoint is calculated by the primary controller in advance, based on predicted system states that define the power-flow conditions on the system. The calculation time of fixed setpoints facilitating normal operating (N-0) and two contingency events (N-1 (#1) and N-1 (#2)) increases with the number of conditions for which it accounts in the integrated setpoint calculation.[s] If a single set of fixed setpoints is calculated—e.g., day ahead for the next day—the calculation and verification of the setpoints is performed once in advance and all setpoints must be communicated and set for each PFC location before the beginning of Condition 1 at the time t_n.

Figure 12 shows the timeline along with the system state describing the consecutive operating conditions and PFC setpoint that denotes the duration for which the fixed setpoint is applied. Assuming Condition 1 starts at t_n, the setpoint calculation shall be performed by the primary controller in advance starting at $(t_n - \Delta t_{opt})$ with Δt_{opt} denoting the time the primary controller requires to calculate and communicate the fixed setpoints. This ensures the timely communication of the setpoints to each of the PFC locations with the start of Condition 1 at tn. Each PFC will ramp and settle on the Fixed Setpoint 1 with a ramping delay of $\Delta t = \frac{\Delta setpoint(t_n)}{ramp}$[t]. While the system state may change at the time t_{n+1} and t_{n+2}, the fixed setpoint remains the same. The setpoint is applied once at t_n and held for an extensive period until primary controller reissues new fixed setpoints.

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r For Contingency 2, the setpoint at Location 5 could not be applied because the contingency trips the circuit on which PFC 5 is installed.

s Integrate-setpoint calculation refers to a set of fixed setpoints $(setpoint(t))$ which cover a multiple system conditions or topology variations.

t The ramping time Δt_{ramp} may be sensitive to the direction *(up* or *down)* in which the setpoint changes, and is a function of the absolute magnitude of setpoint change $(\Delta setpoint)$ (see Section 2.1).

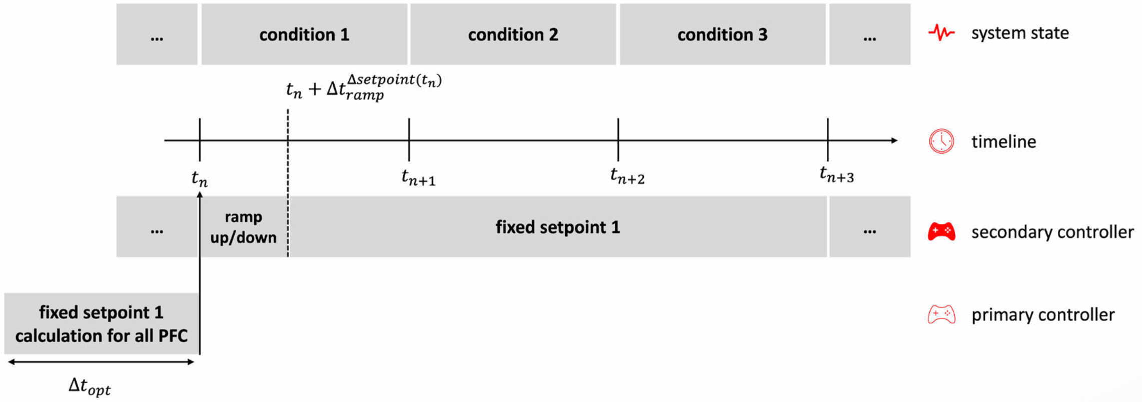

Figure 12. Controller and communication sequence for fixed PFC setpoints.

Fixed setpoints are calculated for an extensive period in advance, based on assumptions at the time of $(t_n - \Delta t_{opt})$ such as predicted system states, network topology, set of contingencies, number of PFC devices on the system, etc. In case of an unplanned event, such as an outage of a circuit or PFC device, the assumptions under which fixed setpoints for the PFC control scheme have been calculated may not be valid anymore. For these cases, the system operator must review and update the fixed setpoints to account for the new system conditions and their impact on the self- and mutual-power-flow sensitivity. For the delay in fixed-setpoint calculation and communication (Δt_{opt}), the system operator may consider options to apply further preventive contingency measures until the PFC control scheme adapts to the new system condition.

3.1.2 Conditional Setpoints

Table 2 gives an overview of the setpoints relative to the PFC capability for each of the five PFC locations for the three consecutive operating conditions and two respective contingencies. The setpoints are calculated specifically for each operating condition and the respective set of contingencies. Positive signs denote the inductive PFC used to push power of a circuit. Negative signs are for capacitive PFC used to pull power on to the circuit where the PFC is installed.

Location	Condition 1			Condition 2			Condition 3		
	N-0	N-1 (#1)	N-1 (#2)	N-0	N-1 (#1)	N-1 (#2)	N-0	N-1 (#1)	N-1 (#2)
1	-54%	-54%	-54%	-53%	-53%	-53%	-50%	-50%	-50%
2	-4%	-4%	-4%	22%	22%	22%	18%	18%	18%
3	37%	37%	37%	49%	49%	49%	46%	46%	46%
4	59%	59%	59%	84%	84%	84%	84%	84%	84%
5	-48%	-48%	—[u]	87%	87%	—	86%	86%	—
	Conditional Setpoint 1			Conditional Setpoint 2			Conditional Setpoint 3		

- Positive signs denote a setpoint to push flow away (increase of effective circuit reactance); negative signs are for setpoints to pull flow on the circuit (decrease of effective circuit reactance).
- Setpoint is technology agnostic and provided relative to the operational range of PFC technology in percentage. For PSTs with an operational range of -15 to 15 degrees, a setpoint of 50% is equivalent to 7.5 degrees. For a static synchronous series compensator with an operational range of -10 kV (capacitive) to 10 kV (inductive), a setpoint of 50% is equivalent to 5 kV.

Table 2. Overview of applied conditional PFC setpoints.

The calculation of the conditional setpoints is rolling and is performed in advance, based on the predicted system state. In comparison to the fixed setpoint, the calculation time is expected to be shorter because a lower number of total system conditions are accounted for in the integrated setpoint calculation. In any case, the setpoint calculation by the primary controller must be performed with a lead time of at least the longest calculation time Δt_{opt} of the setpoints, ensuring the setpoints are communicated and applied before the expected system conditions occurs. Depending on the predictability of power-flow conditions, the calculation of the primary controller could be executed online or hours in advance.

The update frequency for PFC setpoints depends on the duration of the expected operating conditions and could change depending on the time frame of system operation—e.g., update cycles of 5, 15, or 60 minutes. Depending on the setpoint ramping performance of the PFC technology, either the step change between consecutive setpoints may be limited, or the time window of the operating condition must be extended to ensure that the conditional setpoint could be ramped and settled within the operating time window. While the setpoint at PFC Location 1 only experiences a small step change of less than 10% between the conditions, the PFC setpoints at Locations 2 and 5 have step changes that involve both a polarity change from capacitive to inductive, and a larger relative change of up to 135% (= 87% - [48%]). While the maximum operating range is -100% to 100%, the primary controller needs to ensure that the adjusted conditional setpoint can be ramped and settled by the secondary controller within the adequate time window $\Delta t = \frac{\Delta setpoint(t)}{ramp}$, which may vary with the magnitude of absolute setpoint change assuming a fixed ramp rate.

u For Contingency 2, the setpoint at Location 5 could not be applied because the contingency trips the circuit on which PFC 5 is installed.

Figure 13 shows the timeline of the system state and its expected operating condition and the duration for which the conditional setpoints are applied. At time t_n, Conditional Setpoint 1 is applied for the duration of Condition 1 until t_{n+1} when the Conditional Setpoint 2 is applied and adapted following a ramping delay $(\Delta t = \frac{\Delta setpoint(t_{n+1})}{ramp})$ to match the system state of Condition 2.

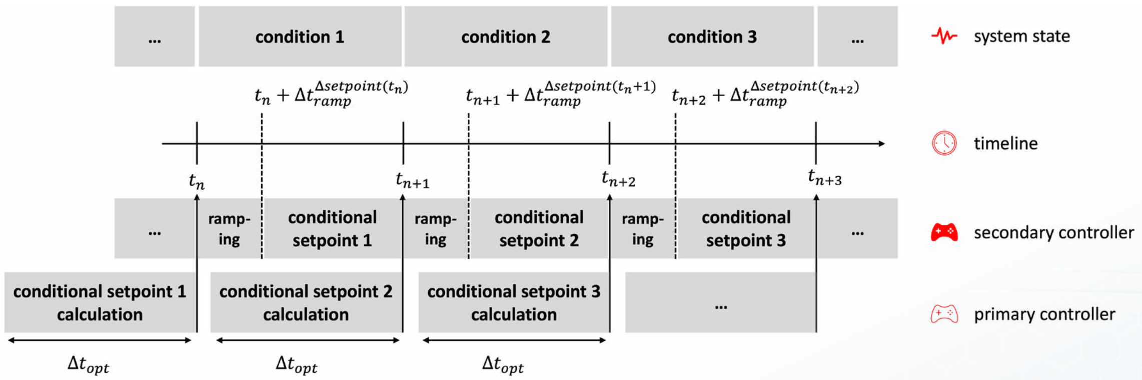

Figure 13. Controller and communication sequence for conditional PFC setpoints.

In case of a malfunction or unavailability of PFC locations, the calculation of the conditional setpoints needs to be performed by the system operator, accounting for the loss of PFC locations. The updated setpoints are then communicated and applied with a delay of Δt_{opt} . Depending on the self and sensitivity factor of the unavailable PFC location the updated setpoints may be less effective and may require additional mitigation actions to account for the reduced capability of the PFC portfolio.

3.2 Corrective Contingency Management

3.2.1 Decentralized Control

In a case study for the Southwest Power Pool transmission system, the contingency of a 345 kV circuit results in the overloading of a 138-kV circuit. Figure 14 shows a single-line diagram of the network with the contingency on the 345-kV circuit (bottom right) and the overloaded 138-kV circuit (top left).

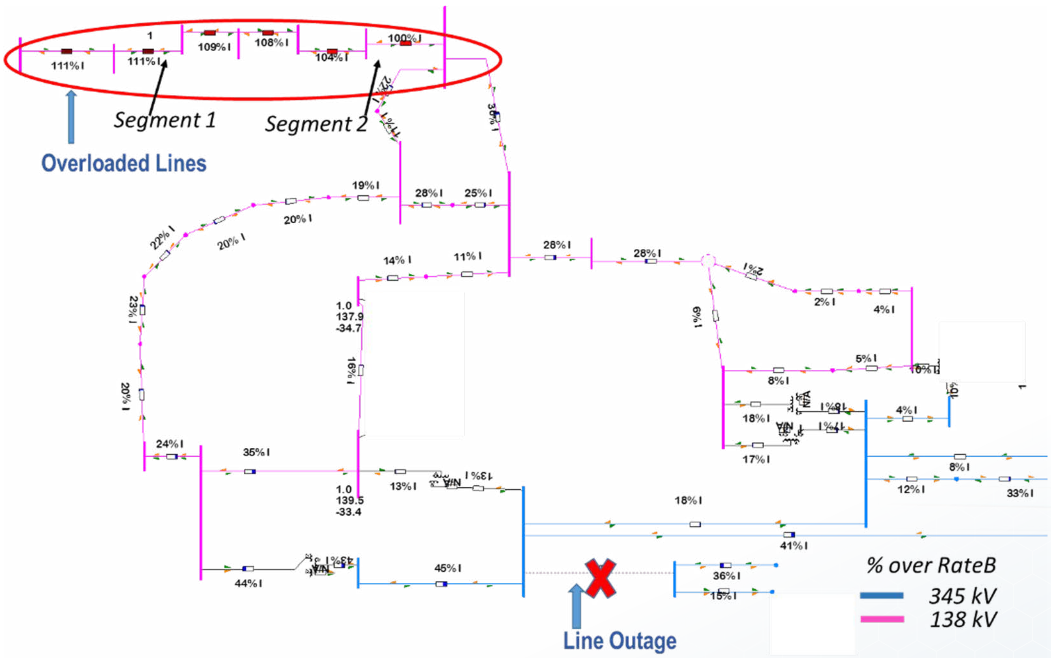

Figure 14. Contingency of 345-kV circuit causing overload on the 138-kV circuit for the Southwest Power Pool.

The post-contingency loading of the 138-kV circuit exceeds the emergency rating of the same by up to 11%. Studies have found that the overloading could be reduced by installing PFC devices along the 138-kV circuit to push power away, reducing the loading to within the emergency limits [7]. Figure 15 shows the case of two independent PFC devices installed along the 138-kV circuit, with a primary controller each that monitor only the respective power flow on the line on which a PFC is installed. The PFCs could then be used to actively reduce loading during and following the contingency of the 345-kV circuit if the flow on the respective 138-kV circuits exceeds a threshold. The effective loading with the PFC engaged reduces to less than 95% of the emergency rating.

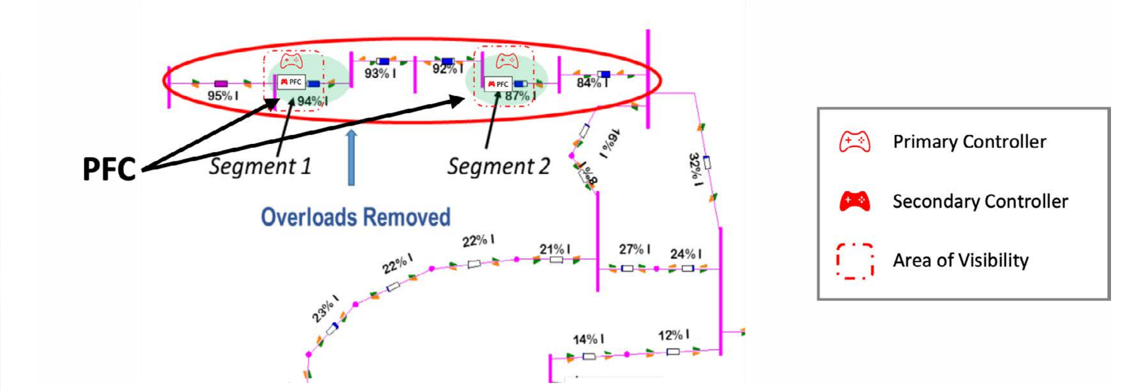

Figure 15. Alleviate overload on 138 kV circuit using PFC in series.

Assuming that the 138-kV circuit only experience overloads during the loss of 345-kV circuit, a decentralized controller scheme could be used to reduce the line current by increasing the effective impedance or reducing the phase angle along the circuit. Figure 16 illustrates a potential decentralized control scheme which activates and coordinates the corrective action to reduce overloads if the local line current exceeds a predefined upper line current limit (I_{max}^{UB}), which in the example case would be a value less than or equal to the emergency current rating of the 138-kV circuit.

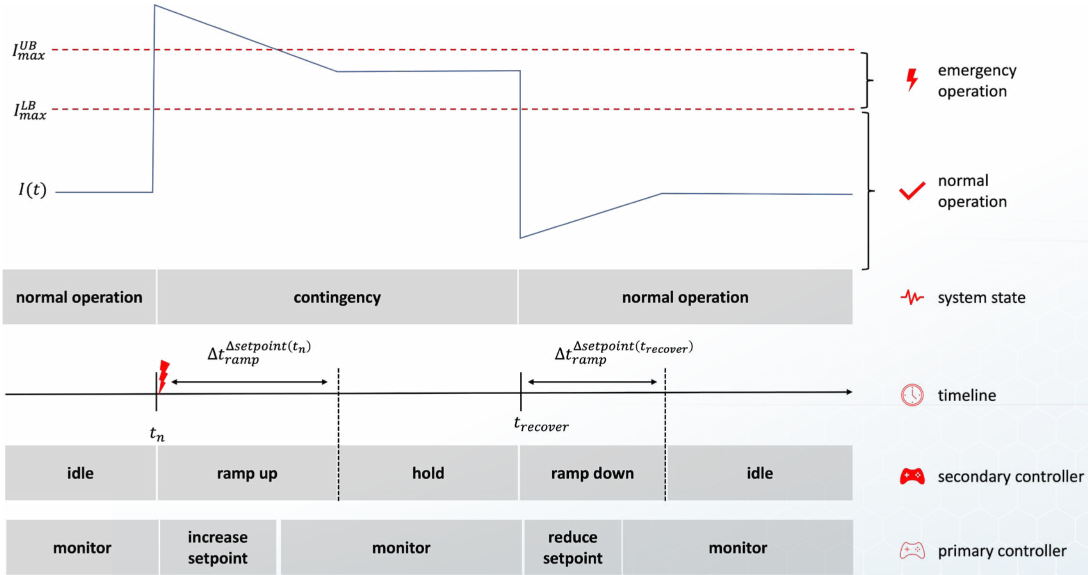

Figure 16. Corrective decentralized-control scheme solving local overload.

For the control scheme, the primary controller would monitor local measurements of line current of the 138-kV circuit. Following the contingency of the 345-kV circuit, the line current on the 138-kV circuit exceeds the emergency limit (I_{max}^{UB}), defining the upper bound for the line current, triggering the primary controller to increase the setpoint and push power off of the circuit. The primary controller updates the target setpoint while the current is still above the upper bound followed by the secondary controller ramping the actual setpoint accordingly. Due to the dynamics of the system, the ramp of the secondary controller should be faster than the sampling rate of the primary controller as it allows the line current to settle within the emergency operation dead band (defined by upper (I_{max}^{UB}) and lower bound (I_{max}^{LB}) of the line's emergency current ratings). After the system recovers from the contingency, the line current will drop below the lower bound which transitions the primary controller to monitor mode and the secondary controller to idle mode, triggering the ramp-down of the PFC devices.

Because the PFC capability is additive along a path, the PFC locations could be distributed along the 138-kV circuit to improve redundancy. In then case that a PFC is unavailable along the 138-kV circuit, the control scheme would still be operationally active to the available PFCs.

3.2.2 Centralized Control

For the application of the centralized control scheme in corrective contingency management, the test case using the synthetic power-system model of South Carolina [5] is used. The system contains 500 buses and 231 transmission lines. To determine the size, location, and setpoints for PFC for corrective contingency management, CPLANET software tool [6] was used. In total, nine scenarios have been defined using three normal operating conditions and a respective set of two N 1 contingency conditions. The PFC locations of three devices[v] are shown in red in Figure 17.

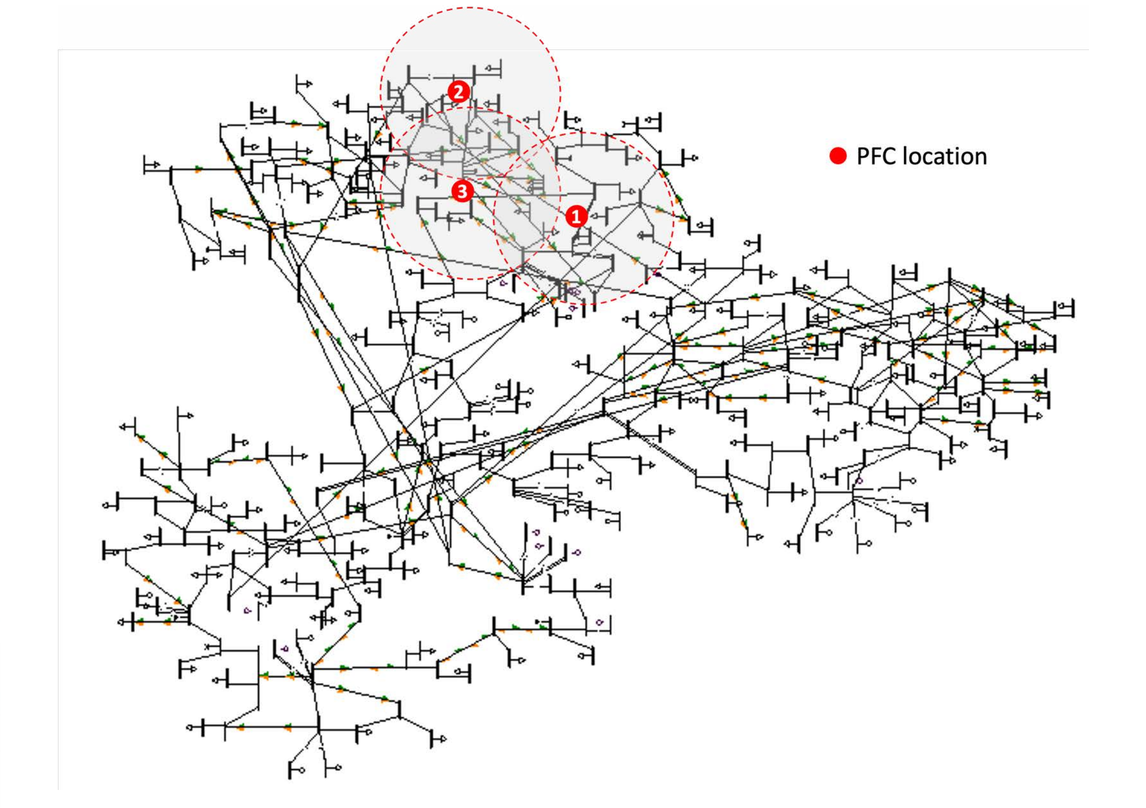

Figure 17. Synthetic network topology and PFC locations for corrective contingency management.

Table 3 details the specific PFC setpoints for the underlying base condition and respective contingency events. The setpoints *(setpoint(t))* are calculated and coordinated centrally by the primary controller. Following the change in condition or the occurrence of a contingency, the applicable set of setpoints is selected by the primary controller and communicated to the PFC locations. Because each setpoint set is tailored to a specific power-flow condition, the PFC operating setpoints vary across all scenarios.

v Compared to preventive contingency management, fewer PFC devices are required because the corrective actions are more effective because the operating setpoints are tailored to the impact of the contingency (see Section 2.3.4).

Location	Condition 1			Condition 2			Condition 3		
	N-0	N-1 (#1)	N-1 (#2)	N-0	N-1 (#1)	N-1 (#2)	N-0	N-1 (#1)	N-1 (#2)
1	0%	89%	0%	0%	75%	0%	0%	71%	0%
2	0%	19%	25%	0%	5%	41%	0%	2%	38%
3	0%	62%	0%	0%	52%	97%	0%	51%	95%

- Positive signs denote a setpoint to push flow away (increase of effective circuit reactance); negative signs are for setpoints to pull flow on the circuit (decrease of effective circuit reactance).
- Setpoint is technology agnostic and provided relative to the operational range of PFC technology in percentage. For PST with an operational range of -15 to 15 degrees, a setpoint of 50% is equivalent to 7.5 degrees. For an SSSC with an operational range of -10 kV (capacitive) to 10 kV (inductive), a setpoint of 50% is equivalent to 5 kV. Hence, a setpoint of ±0% refers to non-active PFC operations (idle) equivalent to a setpoints of 0 degrees for PST or 0 kV for SSSC.

Table 3. Overview of applied corrective PFC setpoints.

For the prior contingency setpoint calculations, the system condition needs to be predicted based on data such as real-time measurements, generation, and load forecasts. To reduce uncertainty and increase setpoint-calculation effectiveness for the primary controller, a rolling online execution is required to calculate PFC setpoints for the next consecutive operational interval based on the forecasted snapshot at the beginning of the current operational interval; e.g., assuming the setpoints are calculated for an operational interval of 15 minutes starting at 1:15 PM, the forecast snapshot data available at 1:00 PM shall be used in the primary controller. Consequently, the PFC setpoint calculation time must be less than the duration of an operational interval. Each potential contingency event is assessed individually and independently which allows to scale the number of required setpoint-calculation processes by parallelizing the computation within the primary controller.

For the setpoints detailed in Table 3, the timing of the setpoint calculation by the primary controller for each system state is shown in Figure 18. With the beginning of Condition 1 the setpoint calculation for this interval has already been completed and stored in a lookup table. At the same time, the setpoint calculation for Condition 2 is started using the information available at the beginning of Condition 1. In this example, the primary controller calculates the set of setpoints for different scenarios in a condition and stores the conditional setpoints in a buffer available for the next operational interval. Because the setpoints are all 0% for each of the N-0 system states, the secondary controller is in idle mode and requires a setpoint command to actuate.

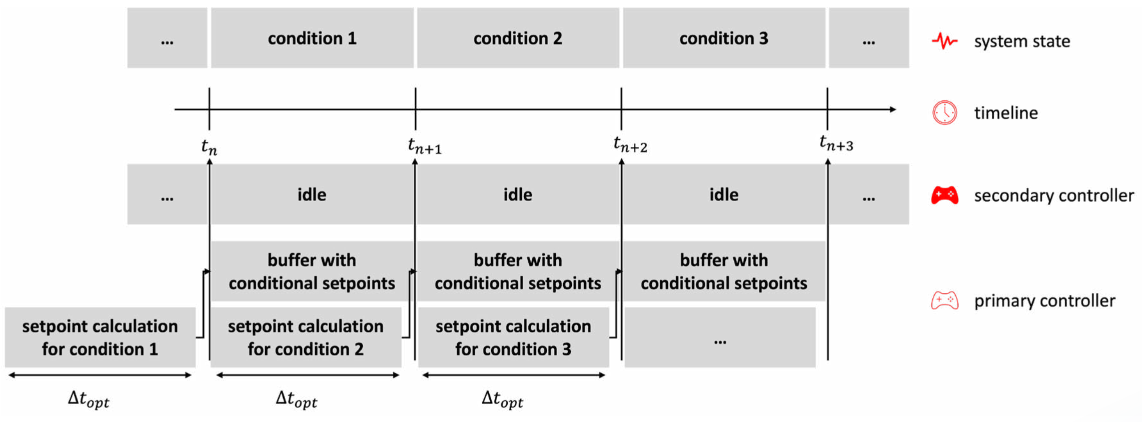

Figure 18. Application of PFC setpoints in normal operations.

Storing the conditional setpoints in a buffer for the operational interval allows the primary controller to respond quickly in the event of a contingency, without the delay associated with the process of setpoint calculation Δt_{opt} . With the conditional setpoints available, the primary controller could select the PFC setpoints for the specific contingency event and communicate the conditional setpoints with minimal delay after event detection. Figure 19 outlines the sequence in updating the PFC setpoint following a contingency event.

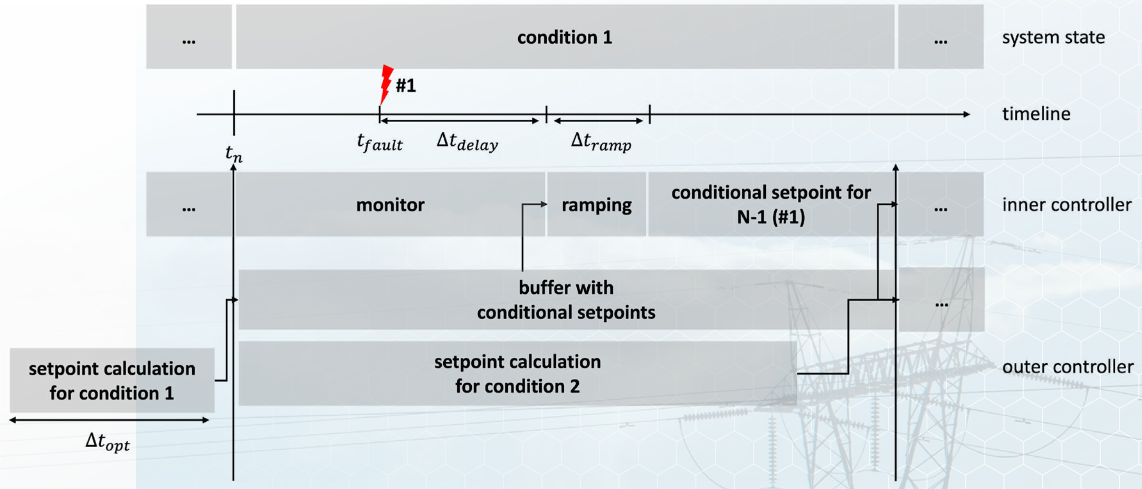

Figure 19. Application of corrective PFC setpoints after contingency occurrence (with clearance).

The fault occurs at t_{fault} and must be detected and communicated to the primary controller, which selects the conditional setpoints for the required corrective action from the buffer. The time delay Δt_{delay} between fault and communication of the new setpoint to the secondary controller is defined mainly by communication and process delays of the primary controller, but not the setpoint calculation Δt_{opt} . A fast and reliable communication of system state to the primary controller and between primary and secondary controller is crucial. A failure in communication could result in a cascade triggered by protection due to persistent violation of operating limits.

With intact communication, the conditional setpoint for the specific contingency event is selected by the primary controller and communicated to the secondary controller of the PFC. Depending on the setpoint ramp rate and absolute change in setpoint prior to and after the contingency, the secondary controller ramps up and settles the new setpoint over a duration of Δt^{up}_{ramp} [w]. During the ramping, the power flows will converge towards the intended target values and incrementally alleviate overloads or congestions on the system.

With the contingency cleared at $t_{cleared}$ before the beginning of Condition 2, and the precontingency state restored, the setpoints are reverted to the precontingency values, which are 0% in this example. The updated setpoints are communicated and applied with a delay Δt_{delay} to ramp down the setpoint by the secondary controller over a period of Δt^{down}_{ramp} .

In case the contingency is not cleared within the same operational interval (Condition 1), the N-1 (#1) contingency event extends to Condition 2. The conditional setpoint for the scenario N-1 (#1) calculated at the beginning of Condition 1 needs to be updated from the buffer and communicated by the primary controller. The secondary controller receives the conditional setpoint for N-1 (#1) and Condition 2 at the beginning of Condition 2 and adapts the change in setpoint. N-1 (#1) is the new reference at the beginning of Condition 2; hence, the setpoint calculation for Condition 3 at the beginning of Condition 2 must account for the new reference system state, defined by the new topology arrangement, namely N-1 (#1), and calculate the setpoints for a potential consecutive N-1-1 contingency event. Figure 20 illustrates the described sequence.

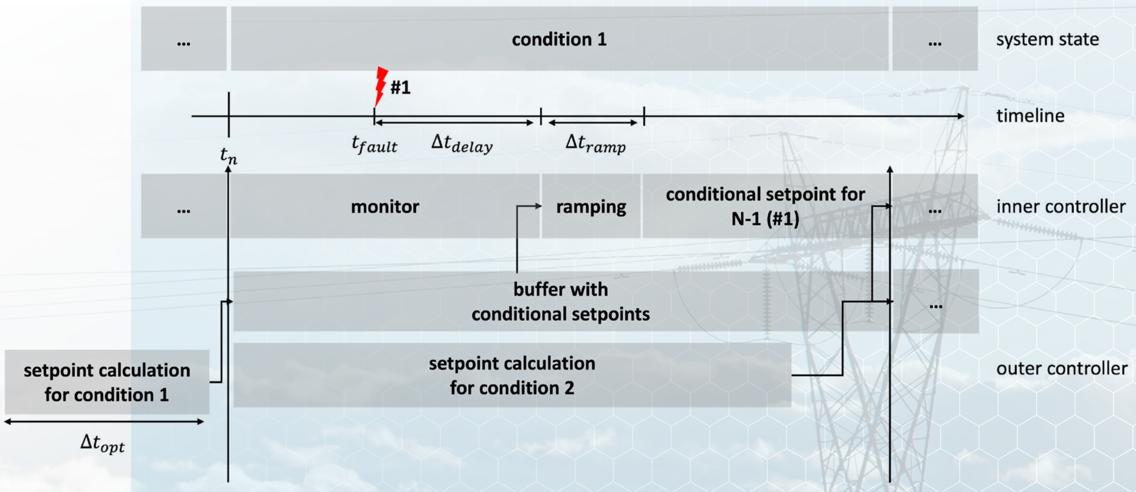

Figure 20. Application of corrective PFC setpoints after contingency occurrence (without clearance).

w The ramping time Δt_{ramp} may be sensitive to the direction (*up* or *down*) in which the setpoint is changed.

4. CONCLUSION

While the benefits of PFC solutions for different power systems have been demonstrated in various studies, this report gives an overview of the general requirements for the implementation and operation of PFC solutions with their associated control schemes. It describes different PFC applications and the need to coordinate the PFC solutions depending on the intended application and size of the PFC portfolio.

The intended application determines PFC solution requirements whereby the severity corresponds with the available security margin of the power system and the maximal time for the PFC to adapt the operational setpoints at each location. Both requirements set the boundary for potential operational errors and, therefore, the degree of the dependability, security, selectivity, robustness and adaptability of the control scheme and the effective performance of PFC. For example, an application intended to balance power flow among different circuits would be associated with a margin for errors relatively greater compared to the corrective contingency management due to the level of grid utilization and stress in the operating system.

The application cases described illustrate the level of complexity associated with the implementation and operation of PFC solutions. Control schemes could be implemented in a decentralized, centralized, or in a hybrid manner, as defined by the signals available to the scheme and the level of potential coordination of and communication among PFCs. PFCs could be operated with a fixed operational setpoint to serve many different system conditions or could use a conditional setpoint specifically calculated for a single system condition. Because PFC control tends to impact a wider area, the self- and mutual-power-flow sensitivities should be considered to ensure PFCs are not cancelling or amplifying each others' efforts. Depending on the power-flow sensitivity of each PFC and the number of devices, a centralized control scheme could be required to calculate and coordinate effective operating setpoints.

It is understood that PFC solutions increase the complexity of system operations, but PFC solutions also create opportunities to enhance the operations of power systems and accommodate the increasing dynamics in power flows caused by RESs and DERs. To take advantage of PFC solutions and their capabilities, it is important to define PFC-solution requirements specific to the application to ensure the intended performance and system security.

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