

Modeling and Application of Hybrid Power Flow Controller in Distribution Systems

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Abstract—The smartening of distribution systems with distributed generation, storage devices, and intelligent loads have created challenges for the operation of distribution feeders, which can be addressed with power-electronics based controllers. However, the capital intensive nature of these controllers is an obstacle for their wide use. The Hybrid Power Flow Controller (HPFC) is shown here to provide an adequate solution to the application of Flexible AC Transmission Systems (FACTS) controllers to distribution systems, and hence the merits and the added value of this controller are discussed here through detailed modeling and simulations, examining its impact on a distribution system under different conditions. Thus, in this paper, a detailed dynamic model of the HPFC is developed and implemented in PSCAD, describing and proposing control strategies to properly operate this controller in distribution system applications, such as an effective and simple procedure for starting-up the device. The developed model is used to demonstrate the effectiveness of the controller for solving problems in distribution systems, such as voltage sags associated with feeder faults and power flow fluctuations due to intermittent renewable generation using a benchmark network as an illustrative example.

Index Terms—FACTS, modeling, dynamics, HPFC, renewable power, voltage sags.

I. INTRODUCTION

THE challenge facing electric distribution systems nowadays is its operation and management with increasing penetration of distributed generation, storage devices, and intelligent and active loads [1]. An option to help with these challenges is the use of Flexible AC Transmission Systems (FACTS), which are able to rapidly control voltages and power flows in distribution systems, and thus effectively improve the system's operation [2], [3]. For example, in [4], different popular topologies for converter-based FACTS are compared, and their benefits for integrating renewables in distribution systems are illustrated; however, it is shown that economy concerns can constrain the ratings of such controllers, resulting in limiting the possible applications of these controllers in distribution networks.

A cost-effective FACTS controller, the Hybrid Power Flow Controller (HPFC), was introduced in [5]. This controller offers a similar performance to that of a Unified Power Flow Controller (UPFC), which can independently control various power flow variables, such as node voltages and line flows, but more economically. The advantage of the HPFC with respect to a similarly-sized UPFC is that it comprises self/line commutated converters as well as passive elements

(e.g. capacitor banks), and its converters are half the size of the UPFC converters [6]. Hence, an HPFC can retrofit an already installed capacitor bank and augment its capabilities by adding two relatively small converters, which justifies considering the HPFC as an alternative to other inverter-based technologies.

The HPFC was introduced somewhat recently compared to other well-known FACTS controllers, and hence there is a limited number of published works examining its modeling and operation [6]–[11]. Thus, in [7], a geometrical representation of the device's operating region is presented. An Electromagnetic Transients Program (EMTP) model of the HPFC is briefly studied in [8], and the performance of the HPFC for improving the power transfer capability of a system is compared with that of the UPFC in [9]. The authors in [10] implemented and studied the HPFC as a stabilizer in Simulink, but the details of controls and capability limits were not discussed. The steady-state models of HPFC for power flow and optimal power flow (OPF) studies are presented and studied in an application to Ontario's power system in [6] and [11]. However, the modeling and application of the HPFC and its detailed control procedure in the context of distribution systems are not available in the technical literature.

In an active distribution network where distributed generations are present, unusual power flows and voltage profiles over the network are an issue for the effective operation and protection of the distribution network [12]. Therefore, in this paper, the application of the HPFC to distribution systems is discussed in detail under voltage-sag conditions and in the presence of intermittent power supplies, using a benchmark system to examine potential improvements to distribution system operation. A model is developed that captures the main dynamics and controls of the HPFC, at a level of detail not available in the existing technical literature; thus, all the necessary controls to properly operate the HPFC are described and discussed in the paper, including its start-up procedures and controls for the initial charging of the dc link.

The rest of the paper is organized as follows: The basics of the HPFC and its components are reviewed in Section II, followed by the presentation of its detailed model and associated controls in Section III. In Section IV, the device is used to address two common concerns in distribution networks, namely, voltage sags and variable power of renewable generation; thus, several studies are performed on a test system based on a CIGRE benchmark distribution network to evaluate the performance and benefits of the HPFC, demonstrating the effectiveness of the device to solve relevant distribution system problems. Finally, Section V summarizes the paper's main conclusions and contributions.

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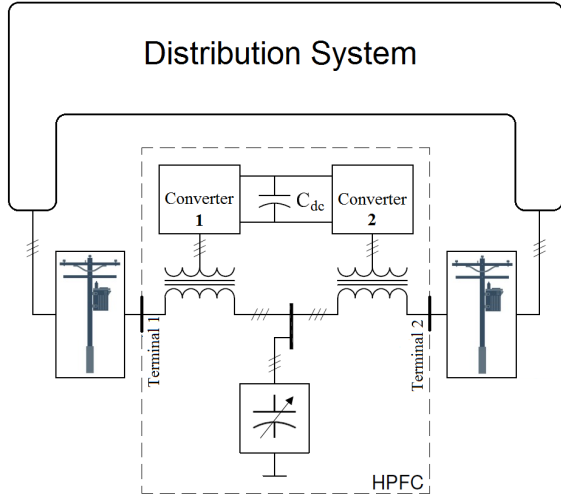


Fig. 1. Architecture of an HPFC.

II. HPFC REVIEW

The architecture of a typical HPFC connected to a distribution system is shown in Fig. 1 [11], with the main components of the device being a variable shunt susceptance plus two converters and their filters and transformers. The converters are connected through a common dc link to exchange active power; this active power exchange and related losses affect the dc voltage across the capacitor. The converter outputs as well as the shunt susceptance are controlled to regulate the power flow through the controller, and consequently the power exchange between its two terminals, so that power flows in distribution system loops can be directly or indirectly regulated. The HPFC can also be used to regulate its terminal voltages, as it has three degrees of control freedom as discussed later in the section.

The equivalent circuit model for the HPFC is shown in Fig. 2. The equations pertaining to the steady-state operation and control modes of the HPFC based on the equivalent circuit in Fig. 2 are as follows [11], [13]:

$$P = \text{Re} \{ (\mathbf{V}_Y + \mathbf{V}_M) \mathbf{I}_R^* \} \quad (1)$$

$$Q_1 = \text{Im} \{ (\mathbf{V}_X + \mathbf{V}_M) \mathbf{I}_S^* \} \quad (2)$$

$$Q_2 = \text{Im} \{ (\mathbf{V}_Y + \mathbf{V}_M) \mathbf{I}_R^* \} \quad (3)$$

$$\mathbf{V}_M = \frac{\mathbf{I}_S - \mathbf{I}_R}{jB_M} \quad (4)$$

The two system terminals are represented by Thevenin equivalents, with the two series converters modulating the power, based on the instantaneous voltage values at the main two terminals and at the shunt component. The latter helps to maintain the voltage at the mid-point based on a reference voltage or a given shunt susceptance. There is a filter connected to each converter to eliminate high-frequency components in the output. The main components and control strategies of the HPFC are briefly described next.

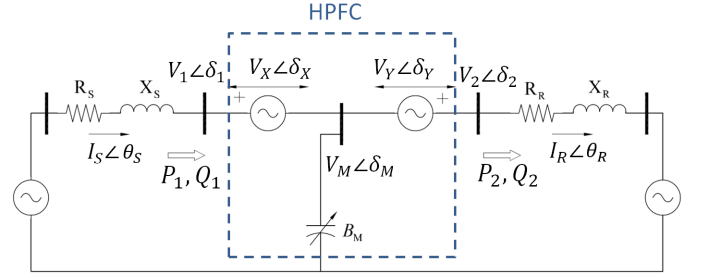


Fig. 2. Equivalent circuit model.

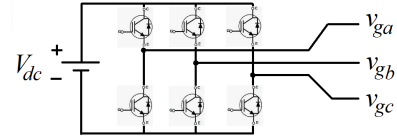


Fig. 3. Simple diagram of a VSC with bi-directional switches.

A. Converters

The core of the HPFC includes two series voltage-sourced converters (VSC) connected to the system via series transformers, which share a common dc link to allow power exchanges between them. Each converter is shown in Fig. 3 in its basic form, comprising six bi-directional switches (an IGBT, for example, and an anti-parallel diode), which are turned on/off based on a modulating signal and the reference voltage for the converter output. The switching frequency w_s is high enough to facilitate filtering while limiting losses and noise interference. Multi-level and other advanced forms of VSCs may also be used as converters.

B. Shunt Component

The converters modulate the powers based on instantaneous voltage levels at their terminals. Therefore, the shunt component can be used to provide reactive power support and help regulate the voltage at the mid-point between the converters. The voltage reference for the mid-point and the value of the shunt susceptance, made of capacitor banks, are assumed to be known based on the control strategy and mode used, as explained in Section II-D. These capacitor banks are inherently much slower than other parts of the controller, with the shunt susceptance changing in instantaneous discrete steps.

C. Harmonic Filter

The output of the converter before the filters changes rapidly between $+V_{dc}/2$ and $-V_{dc}/2$, and is hence not a sinusoidal waveform as the system requires. The harmonic filter, which includes the inductance of the transformer at the converter output, filters out most of the higher harmonic content and delivers a waveform close to a sinusoidal at the network terminals. A simple LC filter for Phase a , for example, is shown in Fig. 4, where v_{ga} is generated by the switches and v_{ta} is the filtered output. The filter's capacitor is not essential; however, it is useful to decrease the harmonic contents of the output current.

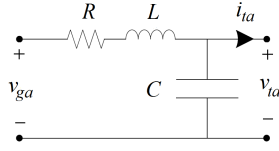


Fig. 4. LC harmonic filter with a resistor representing internal losses.

It is important to note that the filter affects the fundamental frequency component as well, and thus its impact on the output voltage and current should be considered in the model. The filter is designed based on the output rating and ripple requirements as well as the switching frequency according to the basic design procedure outlined in [14]. The resistor R mainly represents the controller losses including transformers, and it also provides resonance damping for the system.

D. Control Modes

The control modes of the HPFC and the transitions between them are based on the voltage/current limits of the controller components, as explained in detail in [11], [13]. Thus, the HPFC can control active and reactive power at its terminals, i.e. P_1 , Q_1 , P_2 , and Q_2 in Fig. 2. If there is no external source of energy/battery connected to the dc link, then $|P_1 - P_2| = P_{loss}$, where P_{loss} is the active power loss in the controller, including the transformers; hence, neglecting losses results in $P_1 = P_2$, which leads to three degrees of control freedom. Therefore, there are four control modes for the HPFC: PVV, PQQ, V, and Z; the transitions between these four control modes are shown in Fig. 5. The controller starts operating in the PVV mode, where setpoints for P , V_1 , and V_2 are defined. If the controller reaches its limits on at least one of the main variables, i.e. I_S , I_R , V_X , or V_Y , the controller switches to PQQ mode, in which setpoints for P , Q_1 , and Q_2 are defined to resolve the limit violation, so that these values are close to those corresponding to the PVV mode. The HPFC continues operating in the PQQ mode until the limit violations cannot be resolved by the modification of the P , Q_1 , and Q_2 setpoints, at which point the controller switches to V mode.

In the V mode, the two series voltage sources in Fig. 2 are bypassed, and the voltage magnitude at the shunt bus V_M is regulated at a given level by using the variable shunt susceptance B_M ; in this mode, $V_1 = V_2 = V_M$, so that the terminal voltages are regulated as well. This voltage regulation is feasible as long as the shunt device is capable of providing the required B_M value, but this is not always possible because of its limited capability, at which point B_M is fixed and the controller switches to Z mode. In this mode, the controller has its minimum regulation capability and behaves as a passive fixed shunt susceptance in the system. In the rest of paper, it is assumed that the HPFC is operating within its operational limits, and hence the controller is operating in PVV mode.

III. HPFC MODELING AND CONTROL

The detailed modeling and control scheme of the controller are discussed in this section, considering that the dynamic control of the HPFC is realized in the current space. Thus,

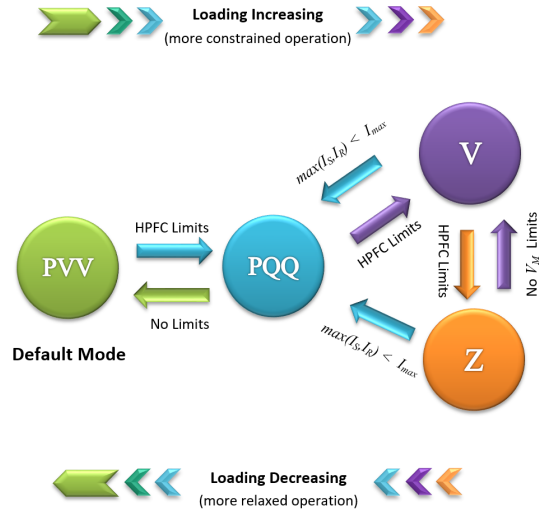


Fig. 5. Transitions between the four HPFC control modes based on operating constraints.

based on the power flow setpoints and other system variables, current reference points are obtained and fed into the main control loop to achieve the desired output. A master-slave control scheme is proposed here to regulate the shunt voltage magnitude while controlling the output power flow variables, since regulating the shunt voltage is necessary to keep the ratings of the converters low and thus make the controller more affordable.

The HPFC converters exchange active power through the dc link, with the flow through the link and losses in the controller components affecting the dc voltage level; thus, proper operation of the controller requires dc voltage regulation, which can be achieved via a designated control loop. Finally, a control procedure is required to start up the HPFC. All these different controls are described in detail next.

A. Current Control

The current reference is obtained based on the system measurements and power flow setpoints provided by the operator. In Fig. 6, assuming that active and reactive power output at the HPFC terminal (e.g. Terminal 2) is given as the setpoint, the dq components of the current reference are obtained. The effect of the transformer turn-ratio as well as its phase shift, based on the connection type, should be included in the calculations. Limiter blocks at the output remove any unreasonably large values or spikes. An auxiliary signal can be added to the active power reference point to account for internal losses and the dc-link voltage regulation, as explained in Section III-D.

The closed loop control of current is realized using proportional-integral (PI) controllers in the dq -reference frame. The output of the current control loop provides a voltage setpoint which is compared with a modulating triangular signal to create switch firing signals based on a Pulse-Width Modulation (PWM) scheme.

In Fig. 4, if the switching frequency w_s is significantly larger than R/L and the filter parameters are chosen properly, then the high-frequency components of the input does not

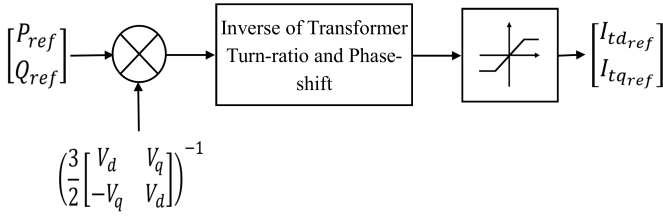


Fig. 6. Current reference based on power setpoint.

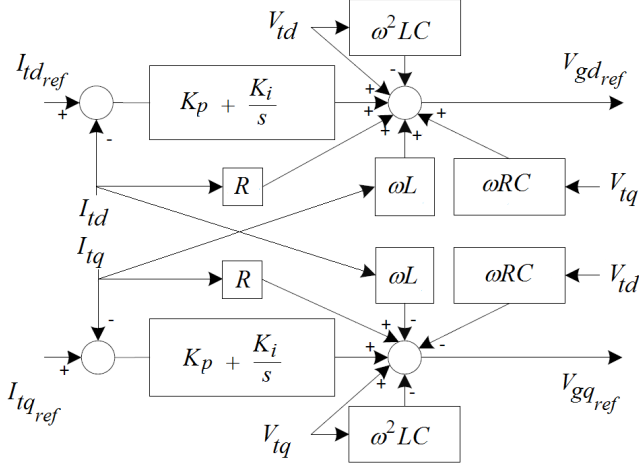


Fig. 7. Current control loop based on (5) and (6) [14], [15].

contribute significantly to the output and the ripple would be small. Under this assumption, the relationship between the in/out voltage and current in the dq -reference frame can be written as follows:

$$V_{gd} = V_{td} + wLI_{tq} + RI_{td} - w^2LCV_{td} + RCwV_{tq} \quad (5)$$

$$V_{gq} = V_{tq} - wLI_{td} + RI_{tq} - w^2LCV_{tq} - RCwV_{td} \quad (6)$$

These equations can be considered as an open-loop system with the currents I_{tdq} as the output and voltages V_{gdq} as the input; the control objective is to regulate I_{tdq} . This can be achieved via the closed loop system shown in Fig. 7, in which the reference command is compared with the measured value, and the error signal is processed by a PI controller to generate the desired output. The outputs of the PI controller and the control loop must be limited properly.

The parameters K_p and K_i of the PI controllers can be chosen to cancel the pole created due to the presence of L at the output of the converter. Therefore, the equivalent control path from the current reference to the output value becomes a first-order lag with a time constant τ . Thus, based on the values of the circuit elements R and L , and the design parameter τ :

$$K_p = \frac{L}{\tau} \quad K_i = \frac{R}{\tau} \quad (7)$$

It is important to note that the time constant τ should be small to provide a fast current-control response; however, this should be large enough so that $1/\tau$ is considerably smaller than the switching frequency w_s [15]. The upper constraint is required to be able to neglect high order harmonics, so that the output

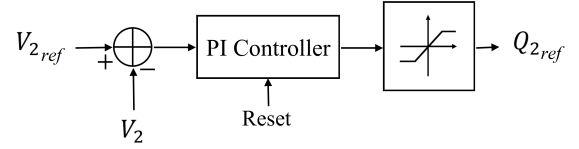


Fig. 8. Terminal 2 voltage control loop.

follows the fundamental-frequency component of the reference signal.

B. Terminal Voltage Control

In the previous section, it was assumed that reference values were provided for active and reactive power flows at the device terminals, as per Fig. 6. However, for distribution system applications, it is better to control the voltage magnitude at a given controller terminal rather than controlling the reactive power supplied/absorbed, due to the importance of maintaining adequate voltage profiles in distribution networks. Therefore, a control loop for regulating the voltage magnitude at the device terminal (e.g. Terminal 2 in Fig. 2) is required, as shown in Fig. 8, where the reference voltage for V_2 is compared with the measured value, and the error signal is passed through a PI controller to generate the required reactive power reference in Fig. 6.

The described control approach requires a nested control structure; therefore, the closed loop bandwidth of the outer loop (voltage control) should be adequately lower than the inner current control loop. In other words, the PI-controller parameters are chosen so that the time constant of the voltage control loop is considerably larger than the current-control loop time constant τ .

C. Shunt Voltage Control

The voltage magnitude on the inverters output depends on the shunt device voltage. It is desirable to keep the ratings of the converters low and thus affordable; therefore, it is important to be able to control the shunt voltage within an acceptable range while achieving the desired power flow setpoints. As stated previously, the HPFC can control three independent variables among the terminal variables (e.g. P_2 , Q_1 , and V_2 in Fig. 2); hence, one of these degrees of freedom can be used to regulate the shunt voltage V_M instead of a reactive power (e.g. Q_1).

The closed-loop control of the shunt voltage can be accomplished as follows: The control scheme for one of the converters (e.g. Converter 2) is preserved, as explained in the previous sections; namely the terminal active power and voltage magnitude are regulated at the controller terminal. Hence, the reference values used in the control loops of the other converter (e.g. Converter 1) can be obtained based on the desired active power flow and shunt voltage magnitude as well as the measured currents at the other terminal (e.g. Terminal 2). Referring to the parameters and variables defined in Fig. 2,

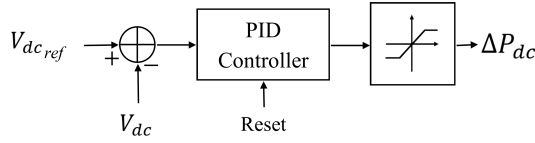


Fig. 9. DC voltage control loop during steady state.

this control scheme can be realized using the following set of equations:

$$2V_M^2 B_M^2 = (I_{Sd} - I_{Rd})^2 + (I_{Sq} - I_{Rq})^2 \quad (8a)$$

$$P_1 = P_{ref} \quad (8b)$$

$$V_M = V_{Mref} \quad (8c)$$

This set of equations after simplification results in equations in the dq domain, which have two sets of solutions for the current setpoint associated with two Q_1 reference values, which in turn are associated with two V_{Mdq} values equal in magnitude and 180° out of phase; a solution can be chosen based on the design requirements or operator preferences. Similarly to Fig. 6, the current reference should be limited and corrected for the transformer ratio and connection type before being used in the current control loop shown in Fig. 7.

D. DC Regulation

The dc-capacitor connecting the two converters provides a path to exchange power between them, while regulating the power flows at the HPFC terminals. However, the voltage level across this capacitor has a direct impact on the converters' performance. The controller losses and any net power flowing in/out of this capacitor would change its voltage and thus, might compromise the performance of the controller. Therefore, it is important to monitor and control the dc-voltage level V_{dc} by compensating for losses and the charging and discharging of the dc capacitor through the converters.

A PID (proportional-integral-derivative) controller is used here to regulate the dc-link voltage, since its steady-state error is zero and the transient performance is well-damped due to the derivative block as the feedback from the dc-capacitor current is proportional to the derivative of the capacitor voltage. This is accomplished by changing the active power setpoints of the converters by the ΔP_{dc} shown in Fig. 9. In other words, using the auxiliary signal in Fig. 6, ΔP_{dc} is shared between the converters equally to minimize the deviations from the original setpoints.

E. Start-up Control

It has been so far assumed that the dc-link is charged and initialized prior to the device utilization. Although one could use an external converter or energy storage device to initially charge the HPFC dc capacitor, a cold start-up is possible using the initialization procedure explained next.

The proposed charging procedure starts by using the anti-parallel diodes of one of the converters as a 3-phase diode rectifier bridge to charge the capacitor to a certain voltage level

TABLE I
DC-LINK START-UP PROCEDURE

Stage	Activity
I	Uncontrolled charging using diode rectifiers.
II	Charging to a given level through switch control.
III	DC-link control deactivated (buffer zone).
IV	DC-voltage regulation in normal operation using PID controller (Section III-D).

in an uncontrolled way. Then, the switches are appropriately controlled to charge the dc capacitor up to a desired voltage level. The control does not need to be precise, since it only serves to initialize the dc link. There is a buffer zone in which there is no dc-link control before the normal dc-regulator loop is activated, thus allowing V_{dc} to reach its steady-state value. Therefore, there are four stages in the proposed start-up procedure as shown in Table I. The results presented in the next section show that this strategy is quick, as it reaches steady state in seconds; flexible, as it can be tailored to any system; and economic, since no extra device/source is required.

In Table I, Stages I and III are straightforward, and Stage IV was discussed in Section III-D. Regarding Stage II, it is preferable to charge dc capacitors with a constant current instead of a constant voltage [16]. Note that the main control loop (Fig. 6) accepts power setpoints; therefore, it is necessary to translate a constant current to a power input during the dc charging in Stage II. Hence, the balance of power based on average values ignoring losses yields:

$$P_{in} = V_{dc} I_{dc} \quad (9)$$

where I_{dc} is the dc-link current, and P_{in} is the charging power flowing into the converter and absorbed by the dc-link. Assuming a constant charging current, one has:

$$V_{dc} = \frac{1}{C_{dc}} \int I_{dc} dt \Rightarrow V_{dc}(t) = \frac{I_{dc}}{C_{dc}} t + V_{dc0} \quad (10)$$

where V_{dc0} is the initial dc voltage achieved using anti-parallel diodes in Stage I. Substituting (10) in (9):

$$\begin{aligned} P_{in}(t) &= \frac{(I_{dc})^2}{C_{dc}} t + V_{dc0} I_{dc} \\ &= \alpha t + \beta \quad \alpha, \beta > 0 \end{aligned} \quad (11)$$

This power is given as an input to the power control loop in Fig. 6, so that $P_{ref} = -P_{in}(t)$, with $Q_{ref} = 0$; in other words, the reference power would linearly decrease. Note that (11) is an approximate formulation based on average values and does not result in an ideally fixed charging current; regardless, the proposed charging procedure is effective and simple to implement.

IV. CASE STUDIES

The HPFC can improve a distribution system in two main and distinctive ways, namely, it can supply/absorb reactive power and improve voltage profiles, and it can also regulate active power flow in a specific corridor. Therefore, in this

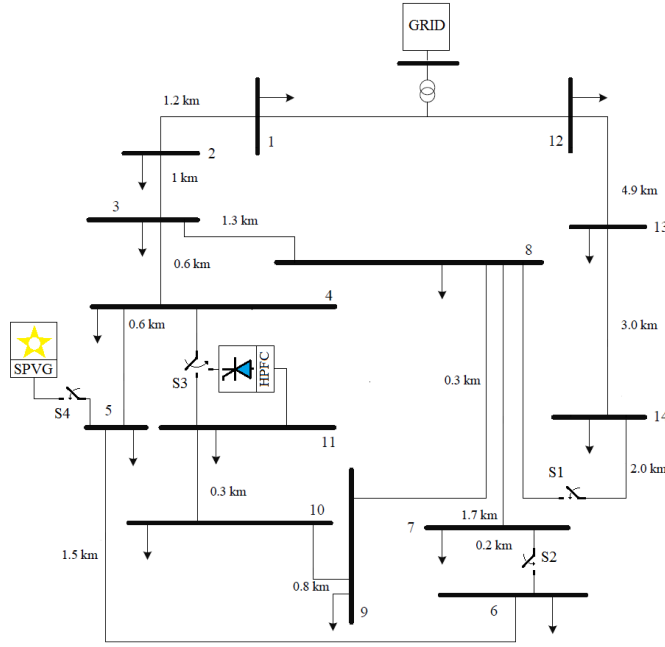


Fig. 10. Single line diagram of the test system.

section, the HPFC performance is studied under fault conditions, which lead to sudden voltage changes, and in the presence of intermittent energy resources, which cause active power fluctuations. It is important to highlight the fact that, although controllable Distributed Energy Resources (DERs) such as battery storage systems allow ameliorating the impact of system faults and intermittent generation, these do not directly regulate power in system branches like the HPFC, which thus provides unique and additional control capabilities not offered by controllable DERs.

A. Test System

The performance of the controller under different operating conditions is demonstrated using a 12.47 kV test system based on the CIGRE benchmark for medium voltage (MV) distribution networks [17]. This distribution network is a test system designed to benchmark and compare new/different control algorithms and system component models in distribution systems. It was originally designed based on an existing MV network in southern Germany, and reconfigured to represent a North American distribution network at 12.47 kV and 60 Hz. The North American configuration includes three switches to introduce loops and allow to test various DERs and new controllers under different topologies, in the context of intelligent distribution networks. The system and the controller at the switch level are implemented in PSCAD/EMTDC using standard library components [18]. The general schematic of the test system is shown in Fig. 10; the total load of the system is about 3 MW, distributed among the buses connected via feeders modeled as coupled-pi sections.

Switches S1 and S2 are assumed to be open; thus, there is no connection between buses 8-14 and 6-7. Switch S4 can connect a solar photovoltaic generator (SPVG) to Bus 5, as

TABLE II
HPFC PARAMETERS AND VOLTAGE/CURRENT RATINGS

Parameter	Value	Parameter	Value
L	68.75 μH	τ	0.5 ms
C	39.45 μF	K_p	6.85
R	10.4 m Ω	K_i	1040 s $^{-1}$
f_s	3060 kHz	B_M	0.0754 S
PI (Fig. 8)	(10, 100)	PID (Fig. 9)	(2, 25, 0.012)
VSC Vrat	0.56 kV	VSC Irat	1.5 kA
Shunt Vrat	12.47 kV	Transformers	1:10

discussed in Section IV-D [19]. Switch S3 has three possible positions, namely, open (O), closed (C), and closed through an HPFC (H), thus, creating three different system configurations; these study scenarios are referred here to as O, C, and H, respectively. The values of the main parameters of the HPFC are shown in Table II. The location of the controller was chosen based on the following criteria:

- The voltage magnitude at Buses 4 and 11 were among the lowest; thus, some reactive power compensation was needed at these buses, especially during fault conditions.
- Bus 4 was adjacent to the bus with the SPVG; therefore, the HPFC can help providing more connectivity to the DER, especially if the connection can be regulated, as in the case of an HPFC.
- There was a switch available at that location that could be readily replaced by a controlled switch like the HPFC, for the types of studies presented in the paper, which are relevant in the context of smart distribution networks.

B. DC Start-up and Regulation

The dc link of the converters needs to be initialized during the HPFC start-up and be properly regulated, as presented and discussed in this section. Thus, as mentioned in Section III-E, the anti-parallel diodes of one of the converters charge the dc capacitor to a certain voltage to start up the controller. The dc link voltage is shown in Fig. 11a with different sections depicting the various stages of the proposed start-up procedure, and Fig. 11b illustrates the dynamics of the average current in the dc capacitor.

In Fig. 11a, observe that the dc-link is initially charged to 1.7 kV, which is the peak-to-peak line voltage available on the primary side of the transformer, using the diodes of Converter 2 in Stage I. Note that the voltage curve resembles that of a charging capacitor through an RC circuit, saturating at some point. With the available initial voltage V_{dc0} , Converter 2 can then control the capacitor charging (Stage II). Thus, assuming $I_{dc} \simeq 1$ kA and a maximum $V_{dc} = 2.7$ kV, α and β in (11) can be obtained, and a linearly decreasing P_{ref} can be set in Fig. 6. The dc-capacitor current during this process is highlighted in Fig. 11b; observe the initial bump in the current around $t = 0.5$ s due to the controller's shunt ac capacitor, since Converter 1 is off and thus Converter 2 provides a current path for the shunt capacitor through the secondary side of the transformer.

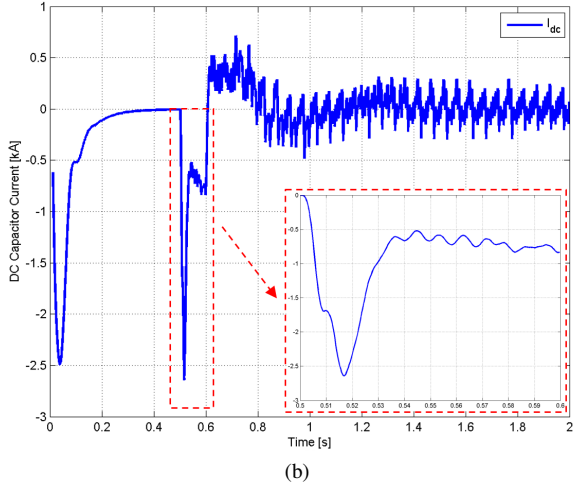
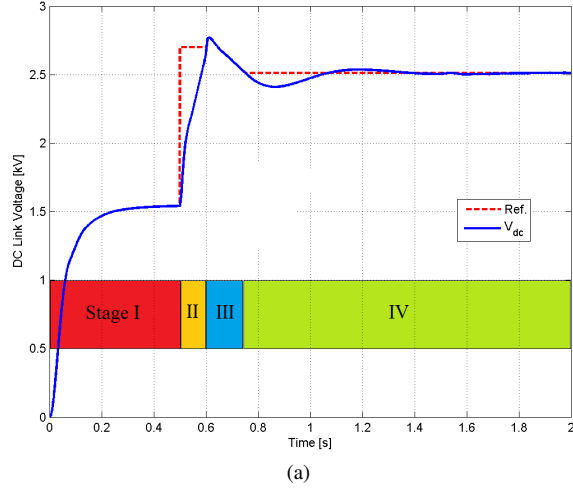


Fig. 11. (a) DC-link voltage and (b) average current during start-up stages (Table I).

In Stage III, the dc-control is deactivated and V_{dc} is allowed to drop to its steady-state value of 2.5 kV, as shown in Fig. 11a; this stage creates a buffer zone between the start-up procedure and the normal operation of the HPFC. Finally, in Stage IV, Converter 1 is connected and normal operation of the controller with regulation of V_{dc} starts roughly at $t = 0.75$ s, when the dc voltage reaches its nominal value.

C. Fault Conditions

During faults in distribution systems, voltage sags appear in feeders, which can be mitigated using FACTS [20], as presented here with the HPFC. A voltage sag is defined as a voltage drop below a threshold of typically 90% of a declared value, with a duration longer than half a cycle and less than a minute [21]. This can be characterized using the following voltage sag energy index, which can be expressed in cycles, milliseconds, or seconds [21]:

$$E_{VS} = \int_0^T \left[1 - \left(\frac{V(t)}{V_{nom}} \right)^2 \right] dt \quad (12)$$

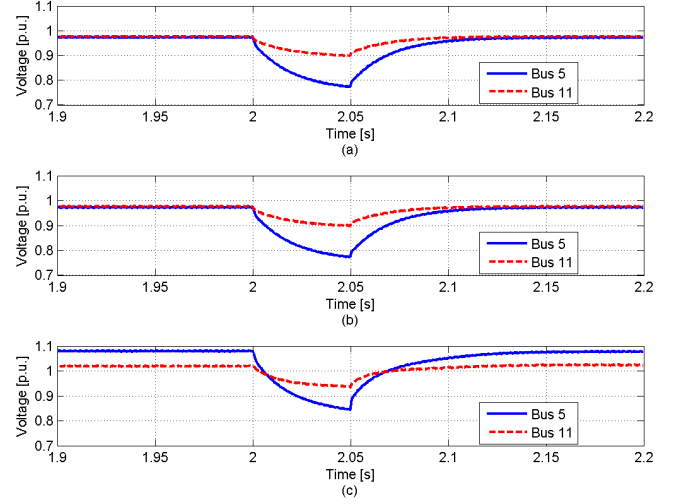


Fig. 12. Bus voltage magnitudes during a fault for (a) O, (b) C, and (c) H cases.

TABLE III
VOLTAGE SAG ENERGY INDEX FOR CASES O, C, AND H.

Case	E_{VS} [ms]
O	52.2
C	52.2
H	25.1

where T is the duration of the event, $V(t)$ is the voltage at the point of interest, and V_{nom} is its nominal value. The voltage sag energy index E_{VS} is related to the energy that has not been delivered during the sag. For repetitive sags, which are common in distribution systems, an approach based on standard ride-through capability curves can be used [22].

A three-phase fault at Bus 6 is applied at $t = 2$ s, and is cleared after 50 ms; this fault can be due to a tree branch that causes a brief resistive short circuit, as frequently occurs in distribution systems with overhead feeders. The voltages at Buses 5 and 11 are shown for the three O, C, and H scenarios in Fig. 12. Observe that the general shapes of the voltage sag for all the three cases are similar, but the sag values are not. In other words, although the HPFC, with the current control proposed in the paper, does not completely remove the voltage sag, it reduces its time duration, so that it is below a threshold value to mitigate its impact. The voltage sag energy index is calculated and added for all the load buses for the three system configurations, and the results are shown in Table III, indicating a considerable reduction in E_{VS} with the HPFC. Note that there is no significant difference between the results for cases O and C.

It should be mentioned that the voltage setpoint at the HPFC connecting bus was chosen at its highest level, but within the required limits, since this bus presented low voltage magnitudes before the controller addition. This improved the system response with respect to the voltage sag during the fault, since the higher this setpoint, the better the voltage profiles in the system overall, while maintaining all bus voltages within required limits.

D. Intermittent Resources

The reports and analyses of the recent solar eclipse in North America recommend better flow control and power regulation capabilities in the system to improve the system response to predictable and unpredictable fluctuations in the variable output of renewable energy resources [23], which can be accomplished with the HPFC, given its effectiveness to regulate power flows. To demonstrate this, an SPVG with variable power output is connected to Bus 5 [19]; at full capacity, the unit can equivalently generate 2.8 MW at unity power factor.

The SPVG is modeled using balanced 3-phase current sources in phase with the voltage phase angle measured at the point of connection, to represent pure active power injection associated with an SPVG in PQ mode. To accommodate this extra power generation the system loading is increased at Bus 8 by 1 MW. As depicted in Fig. 13, in this study, the SPVG unit is initially at steady state, operating at full capacity; at $t = 3$ s, the SPVG output suddenly drops to zero to represent sudden and significant cloud coverage; and at $t = 4$ s, the SPVG gradually ramps up to its initial full level by $t = 4.5$ s.

The three S3 configurations, i.e. O, C, and H, result in the active power flows between buses 4 and 11, normalized with respect to pre-event values, illustrated in Fig. 13; for O where S3 is open, the flow is zero. Case C shows the response of the system to the change in the power injection at Bus 5. Finally, with the HPFC in the system in Case H, the active power flow remains regulated at the pre-event value as desired. Observe that the current control scheme proposed here responds faster to active power flow deviations compared to voltage magnitudes. The reasons for this different dynamic behavior are the following:

- The voltage magnitude setpoint needs to be translated to an equivalent reactive power value using PI controllers with lagging time constants, and then used in the current control loop to actually regulate voltage, whereas active power is directly controlled, thus resulting in less delays for the latter.
- Voltage magnitude control is implemented using average RMS value calculations, which inherently leads to a slower dynamic response compared to the active power control which is instantaneous.
- The required interaction between V_M voltage control at the shunt susceptance terminal and the converters introduces another delay in the terminal voltage response.

The voltage waveforms at Bus 4 in steady state are shown in Fig. 14, containing an acceptable total harmonic distortion, up to the fifteenth harmonic, of 1.1%. Fig. 15 depict the current magnitudes at the HPFC terminals to better examine the response of the controller in this case. Note that the dq components of the currents follow the pertaining references with a delay of approximately 4τ .

V. CONCLUSIONS

A detailed dynamic model of the HPFC and its controls were proposed, developed, and implemented in PSCAD, including a simple and effective start-up procedure for the

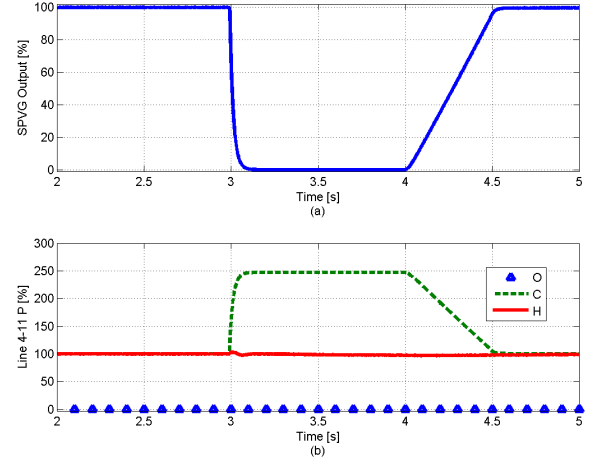


Fig. 13. Impact of solar power change on Line 4-11 flow: a) SPVG output, b) system response for cases O, C, and H.

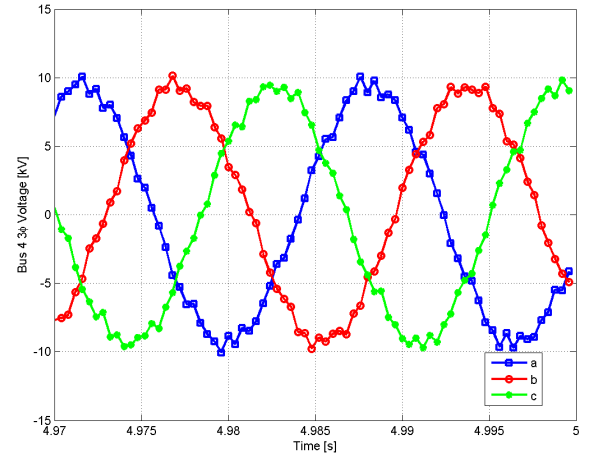


Fig. 14. Voltage waveforms at Bus 4 in steady state.

controller. The model was used to examine the impact of the device on a benchmark distribution test system under two different conditions, namely, a fault causing a momentary voltage sag, and power flow fluctuations due to a solar photovoltaic generator. The results show the capability of the controller to improve a distribution system's response using time-domain simulations. It was observed that, although the HPFC does not completely remove voltage sags under fault conditions with the proposed current controller, it effectively reduces its time duration and mitigates its impact. In the presence of intermittent sources and associated fluctuating power injections, the controller responded faster to power flow deviations than to voltage magnitude changes, mainly due to the delays present in the voltage control loop.

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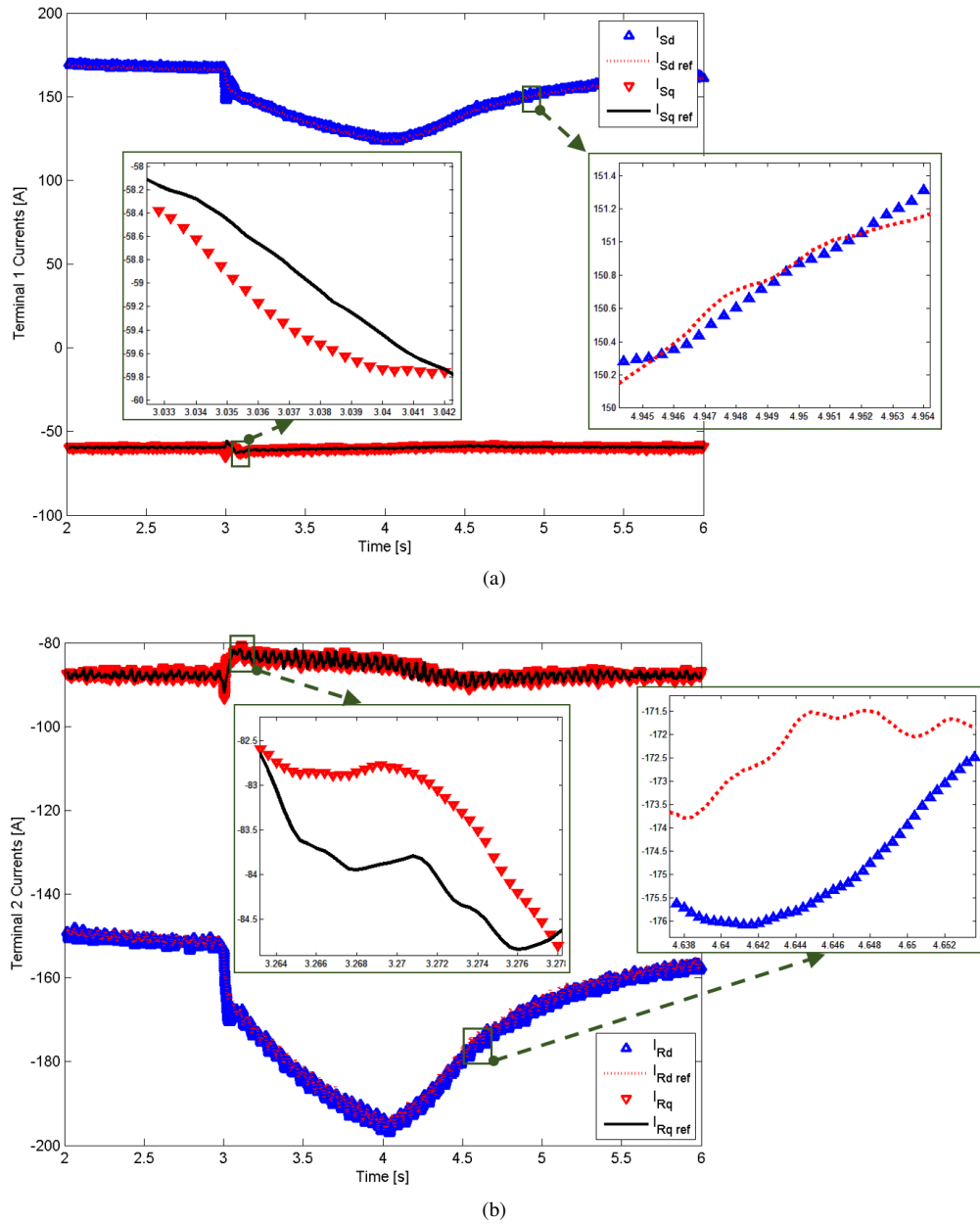


Fig. 15. Current magnitudes at (a) Terminal 1 and (b) Terminal 2 of the HPFC.

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