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Advancing power quality via distributed power flow control solutions

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ABSTRACT

The growing demand for enhanced power quality and reliable transmission has driven advancements in power flow control technologies. The distributed power flow controller (DPFC) represents an advancement over the unified power flow controller (UPFC). In contrast to the UPFC, the DPFC removes the DC link connecting the shunt and series converters, and redistributes the series converters along the transmission line as single-phase static series compensators. This modification enhances grid performance while maintaining full power flow control capabilities. The DPFC offers several advantages over the UPFC, including higher reliability, improved controllability, and greater cost-effectiveness. The system comprises a shunt converter in conjunction with multiple series converters, each with its own control circuit, all managed by a central control unit. This article presents the implementation of a DPFC model in MATLAB/Simulink. The simulation outcomes indicate that the DPFC significantly contributes to improved voltage stability and enhanced power transfer capability, thereby reinforcing system performance and reliability.

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1. INTRODUCTION

Electricity has become increasingly integral to modern life since the establishment of the Edison Electric Light Company, which initiated the development of steam-powered power stations on Pearl Street in New York City under the leadership of inventor Thomas Edison [1], [2]. Over the past century, there has been a remarkable surge in both the consumption and generation of electricity [3], [4]. For instance, global electricity consumption has reached a staggering tens of Tera kWh, and this figure continues to grow [5]-[7].

An electrical power system comprises the processes of generation, transmission, distribution, and end-use of electrical energy, serving as the fundamental infrastructure for energy delivery to consumers. Electricity is typically produced in centralized generating stations and transported through interconnected transmission and distribution networks to reach end-users. Throughout the transmission phase, power flow—referring to the movement of both active and reactive power across transmission lines—plays a critical role in maintaining system efficiency and stability [8]-[10].

Over the past thirty years, the landscape of electrical power generation has undergone a profound transformation, marked by a remarkable surge in capacity. This surge has necessitated a fundamental restructuring of the power system's operational framework, demanding innovative solutions to accommodate the evolving demands of an increasingly electrified world. In tandem with this shift, the relentless march of technological progress has played a pivotal role in facilitating this transition, introducing cutting-edge tools and systems to enhance the efficiency and sustainability of power generation [11]. Furthermore, the intricate dynamics of the electricity market have been significantly influenced by the rapid proliferation of renewable energy sources, ushering in an era where clean and green energy alternatives are at the forefront [12]-[14]. This changing paradigm is also being steered by the advent of revolutionary devices like electric vehicles and distributed generation, heralding a new era in which the power system is intricately intertwined with diverse and decentralized sources of energy. The dynamic evolution of the energy landscape continues to reshape power dynamics, with the smart grid paradigm standing out as a testament to this ongoing transformation. In contrast to the traditional model, where power followed a unidirectional path from generation to transmission to distribution, the contemporary grid operates on a more agile and responsive platform. This shift has been particularly pronounced over the last decade [15], as advancements in technology have facilitated bidirectional power flow, ushering in a level of flexibility and adaptability previously unseen in the energy sector [16]-[18].

Distributed generation (DG) has become a pivotal element in the transformation of the electrical power system, particularly within the distribution sector. Characterized by the integration of small to medium-scale generation units often based on renewable energy sources such as solar and wind [19], DG is increasingly connected directly to distribution networks [20]-[22]. This shift aligns with international sustainability initiatives, including the Kyoto Protocol, which advocates for the reduction of greenhouse gas emissions and the promotion of clean energy technologies to address climate change [23], [24]. The widespread deployment of grid-connected DG units has significantly altered traditional power flow patterns, transitioning from a centralized and unidirectional model to a more decentralized and dynamic configuration. This evolution enhances grid resilience and supports overarching goals related to environmental protection and sustainable resource management [25]-[27].

Ensuring power quality is a paramount concern, especially when catering to large industrial consumers. The power sector has been undergoing reforms aimed at achieving its restructuring goals. High-power, high-voltage converters like unified power flow controller (UPFC) and interline power flow controller (IPFC) have been traditionally employed in transmission and distribution networks [28], [29]. However, a new entrant in the flexible AC transmission systems (FACTS) family, the distributed flexible AC transmission system (DFACTS) [30], [31], has garnered attention due to its various advantages over conventional FACTS devices. DFACTS offers cost-efficiency, enhanced reliability, and improved power quality compared to its predecessors, especially UPFC. While UPFC and IPFC are still utilized in practical applications, phase-shifting transformers, with limited control capabilities, are often chosen for economic reasons when power control demands are high [32]-[34].

In the context of FACTS, the distributed power flow controller (DPFC) represents a notable advancement. Derived from the UPFC, the DPFC differentiates itself by eliminating the DC link between the shunt and series converters. Its core innovation lies in the distribution of single-phase series converters along the transmission line, collectively operating as a distributed static series compensator. This configuration maintains the power flow control functionalities of the UPFC while offering improved reliability, enhanced operational flexibility, and reduced implementation costs. The DPFC architecture comprises shunt and series converters, each governed by dedicated control circuits, and coordinated by a central control unit that supplies the reference signals. This study presents the development of a DPFC model using MATLAB/Simulink and evaluates its performance through simulation, emphasizing its capability to enhance voltage stability and optimize power transfer.

2. DISTRIBUTED POWER FLOW CONTROLLER

2.1. Topology

The integration of the DPFC presents an advanced approach for enhancing control and stability within power systems. This technology leverages a coordinated configuration of shunt and series converters, providing a versatile and effective means of improving grid performance. The shunt converter operates analogously to a STATCOM, delivering reactive power support and maintaining voltage regulation. Meanwhile, the series component is based on the distributed static series compensator (DSSC) principle, wherein multiple autonomous single-phase converters are strategically deployed along the transmission line, replacing the traditional centralized three-phase converter arrangement [35]-[37]. Each DPFC converter operates independently and includes its own DC capacitor, enabling the generation of the necessary DC voltage without requiring a shared DC link. This decentralized design enhances system flexibility, reliability, and fault tolerance. The DPFC configuration is depicted in Figure 1.

The development of power flow control systems requires careful consideration of component selection and spatial arrangement. The DPFC, which integrates shunt and series converters, necessitates a shunt-connected high-pass filter strategically placed on the opposite side of the transmission line.

Additionally, Y-Δ transformers are installed at both ends of the line to support system functionality. The rationale behind these components will be explored in the following discussion.

In contrast, the UPFC employs a back-to-back configuration for its shunt and series converters, enabling seamless active power exchange [38], [39]. To ensure equivalent control capabilities between the DPFC and UPFC, a methodology must be developed that facilitates active power exchange among converters without relying on a conventional DC link. This shift toward innovative configurations highlights the ongoing evolution of power system control strategies.

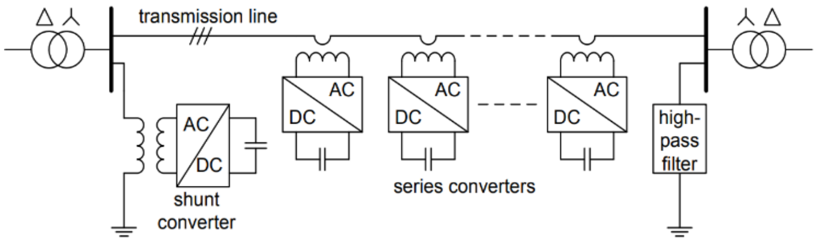

Figure 1. Internal schematic of the DPFC

2.2. Principle operation

Within the DPFC architecture, the transmission line functions as a shared path connecting the AC terminals of the shunt and series converters, thereby facilitating active power transfer through their AC interfaces. This mechanism operates based on the theory of power flow under non-sinusoidal conditions. Through the application of Fourier analysis, voltage and current waveforms exhibiting non-sinusoidal behavior are decomposed into a series of sinusoidal components at multiple frequencies, each characterized by a specific amplitude.

The active power corresponding to non-sinusoidal voltage and current waveforms is defined as the time-averaged value of their instantaneous product. This definition reflects the average power over a complete cycle of the waveform. The orthogonality of sinusoidal functions at distinct frequencies is fundamental in this context. Leveraging this property, the mathematical expression for active power can be succinctly articulated as the sum of the instantaneous products of corresponding voltage and current components at each frequency. This approach enables a comprehensive understanding and representation of the active power dynamics in the context of non-sinusoidal waveforms [40]:

$$\mathrm{P} = \sum_{\mathrm{i}=1}^{\infty} V_i \, I_i \cos \varphi_i \quad (1)$$

In (1), V_i and I_i correspond to the voltage and current at the $i - th$ harmonic frequency, respectively, while ϕi denotes the phase angle between these quantities. This relationship highlights a key theoretical insight: the active power contributions at different harmonic frequencies are independent of one another. That is, voltage or current at one frequency does not impact the active power associated with other frequencies. This frequency-domain decoupling enables a power electronic converter to inject active power at one frequency while simultaneously absorbing it at another, without necessitating an external energy source.

Within the context of the DPFC, this principle is applied by allowing the shunt converter to draw active power from the grid at the fundamental frequency and re-inject it at a harmonic frequency. This harmonic power is then conveyed through the transmission line to the series converters. These series converters, based on the system’s fundamental frequency power requirements, generate harmonic voltages that enable them to absorb the harmonic active power. Under the assumption of negligible losses, the amount of power absorbed at the harmonic frequency matches the power drawn at the fundamental frequency. Figure 2 depicts this dynamic exchange of active power between the shunt and series converters in the DPFC configuration. A high-pass filter integrated into the system architecture prevents the passage of fundamental frequency components while permitting harmonic components to flow. Together with the ground and the converter units, this filter establishes a closed-loop pathway for the harmonic current, ensuring effective power transfer through harmonic interaction.

Advantages of the DPFC system:

- Advanced control functionality: The DPFC provides precise and independent regulation of key transmission system variables, such as line impedance, power flow angle, and bus voltage magnitudes, thereby enhancing overall network controllability.

- Increased operational reliability: The modular structure of the DPFC allows continuous operation even in the event of individual series converter failures, as unaffected units remain functional and maintain system performance.
- Economic installation: Due to the absence of a direct high-voltage isolation requirement for series converter connections to the transmission line, the DPFC facilitates the use of single-turn transformers, resulting in reduced equipment costs and simplified deployment.

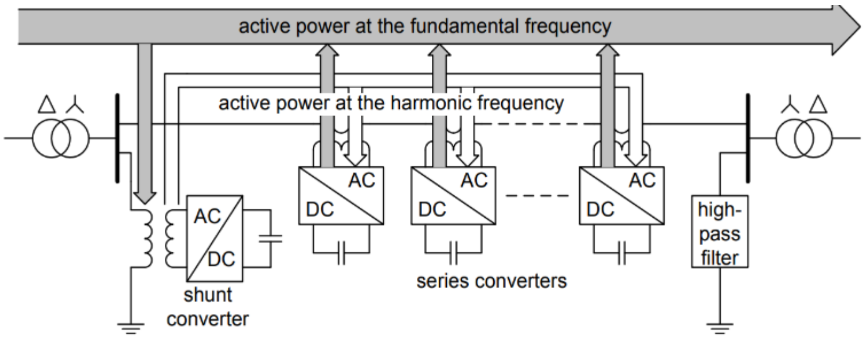

Figure 2. DPFC converters exchanging active power

3. STRATEGIC CONTROL DESIGN FOR DPFC
3.1. DPFC shunt conversion strategy

In DPFC systems, the shunt converter is a critical component that must be capable of producing voltages at both the fundamental and third harmonic frequencies. While a conventional three-leg, three-wire converter may initially appear suitable, it inherently behaves as an open circuit for third harmonic currents, thereby inhibiting their generation. This constraint has prompted investigations into alternative three-phase converter configurations. Options such as multi-leg, multi-wire converters or multiple single-phase units can address this issue; however, they generally require additional hardware, increasing system complexity and cost.

To overcome these limitations, an innovative shunt converter topology has been proposed for DPFC systems. This approach utilizes an existing Y–Δ transformer to facilitate third harmonic current injection into the power system. A single-phase converter is connected between the transformer's neutral point and ground, enabling the introduction of third harmonic currents into the neutral. These currents are then symmetrically distributed across the three phases by the transformer. An auxiliary back-to-back converter is incorporated on the transformer's low-voltage side to supply power to the single-phase converter. Figure 3 illustrates the complete schematic of this configuration. This novel design not only resolves the shortcomings of conventional converter topologies but also enables efficient and cost-effective third harmonic generation and distribution within the DPFC framework.

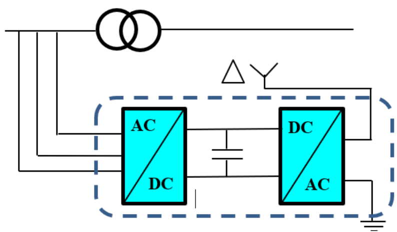

Figure 3. Shunt converter of DPFC

3.2. Three phase converters of shunt

The primary objectives in the control strategy of the DPFC shunt converter are twofold: to facilitate reactive power support by injecting a controllable reactive current at the fundamental frequency into the grid, and to maintain a stable DC-link voltage across the energy storage capacitor. As depicted in Figure 4, the control structure consists of two essential subsystems DC voltage regulation and injected current control. The inner current control loop is responsible for regulating the shunt current $I_{sh,1}$, forming the core of the current control module. The reference for the q-axis current component is supplied by the central control unit, while the reference for the d-axis component originates from the DC voltage control loop. To perform Park's transformation, a synchronous reference frame is employed, which is established using a phase-locked loop (PLL). The PLL locks onto the grid voltage waveform, using the bus voltage as its input to generate the necessary reference angle for coordinate transformation. For the DC voltage control block, and under the assumption of negligible power losses, the reference current can be directly derived from the power balance between the AC and DC sides.

$$\frac{1}{2} C_{sh} \times \frac{dv_2}{dt} = P_1 - P_3 \tag{2}$$

For the control block in use right now:

$$I_{sh,dc,1} \ = \ 3/2 \left(V_{sh,1,d,ref}\ I_{sh,1,d} \ + \ V_{sh,1,q,ref}\ I_{sh,1,q}\right) \tag{3}$$

Here, the stationary frame components (abc to dq) are converted to rotating frame components using Park's transformation:

$$V_{sh,1} = V_{ref,sh,1} \times V_{sh,dc} \tag{4}$$

Figure 5 depicts the current regulation loop of the three-phase shunt converter integrated into a DPFC system.

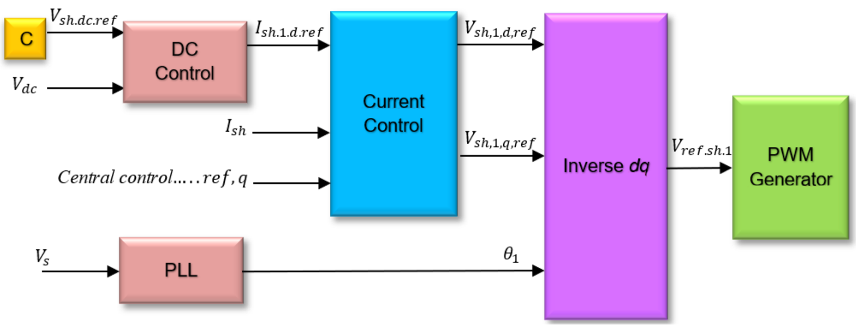

Figure 4. Shunt controller for a three-phase inverter

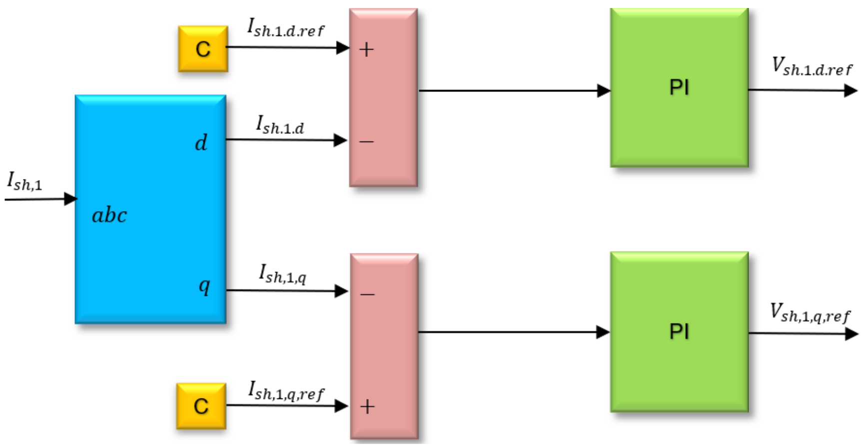

Figure 5. Controller for shunt current

4. RESULTS AND DISCUSSION

This section presents the simulation study of the DPFC model incorporating DQ-axis control, applied to a 7-bus power system using the MATLAB/Simulink environment. The simulation outcomes validate the effectiveness of the DPFC in enhancing voltage stability, controlling power flow, and improving energy transfer efficiency across the network. The parameters used for the simulation are listed in Table 1.

Figure 6 illustrates the DPFC simulation model developed in MATLAB/Simulink, which integrates both shunt and series converter components. Figure 7 depicts voltage sag and swell in the grid voltage when the DPFC device is not present. Furthermore, the resulting phase shift in the load voltage adversely affects connected equipment, reducing the reliability and quality of electrical power transmission. Figure 8 demonstrates that the incorporation of the DPFC device effectively mitigates voltage sag and swell. By eliminating phase shift effects, the DPFC enhances the controllability of the transmission system, improves power flow, and increases power transfer capability.

Table 1. System operating parameters

Parameter	Value
V_s $L-L$	415 V
V_L $L-L$	415 V
Line impedance (L)	10 mH
Load power	20 kW
Frequency	50 Hz
C_{sh}	1.6 mF
C_{se}	1.6 mF
V_{dc}	720 V

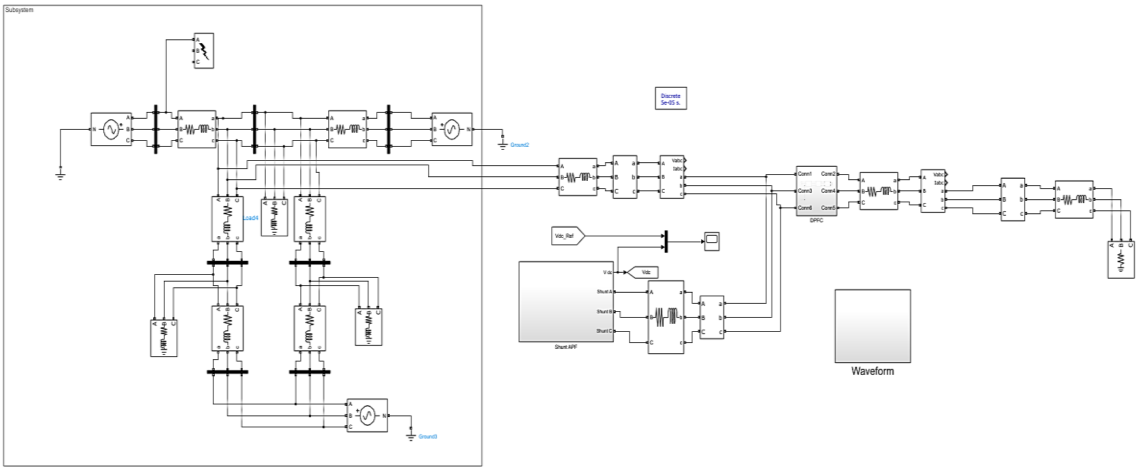

Figure 6. MATLAB/Simulink simulation model of the DPFC

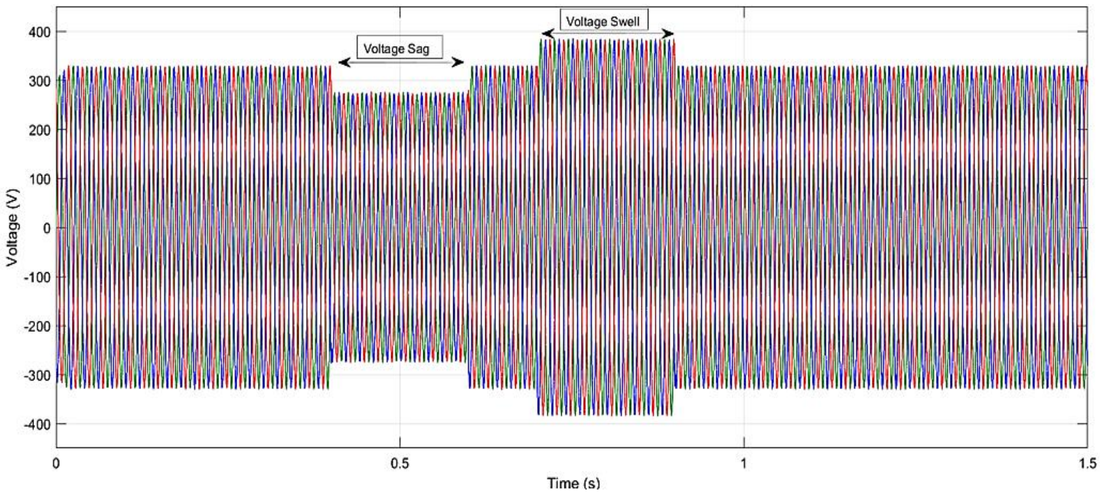

Figure 7. Grid voltage waveform without the DPFC

The shunt converters regulate the flow of reactive power, ensuring a stable DC capacitor voltage during operation, while the series converters enhance the system's voltage profile. Figure 9 presents the per-unit active power response of the DPFC, demonstrating how the coordinated power injection from the shunt and series converters contributes to the mitigation of voltage sags and swells within the system. Figure 10 displays the per-unit real load power response of the DPFC, where the consistent real power output waveform is achieved through the voltage compensation supplied by the shunt and series converters.

Figure 11 demonstrates a significant reduction in third harmonic distortion, bringing it down to a low value of 0.063%, well below the acceptable threshold of 5%. This underscores the effective suppression of power quality disturbances, such as voltage sags, voltage swells, and total harmonic distortion (THD). Figure 12 presents the DC waveform of the DC voltage V_{dc}, which closely follows the reference voltage V_{dc-ref} set at 720 V. This behavior demonstrates the effectiveness of the control strategy in maintaining a stable and regulated DC voltage. The minimal deviation between V_{dc} and V_{dc-ref} confirms the robustness of the system in handling disturbances and ensuring reliable steady state performance.

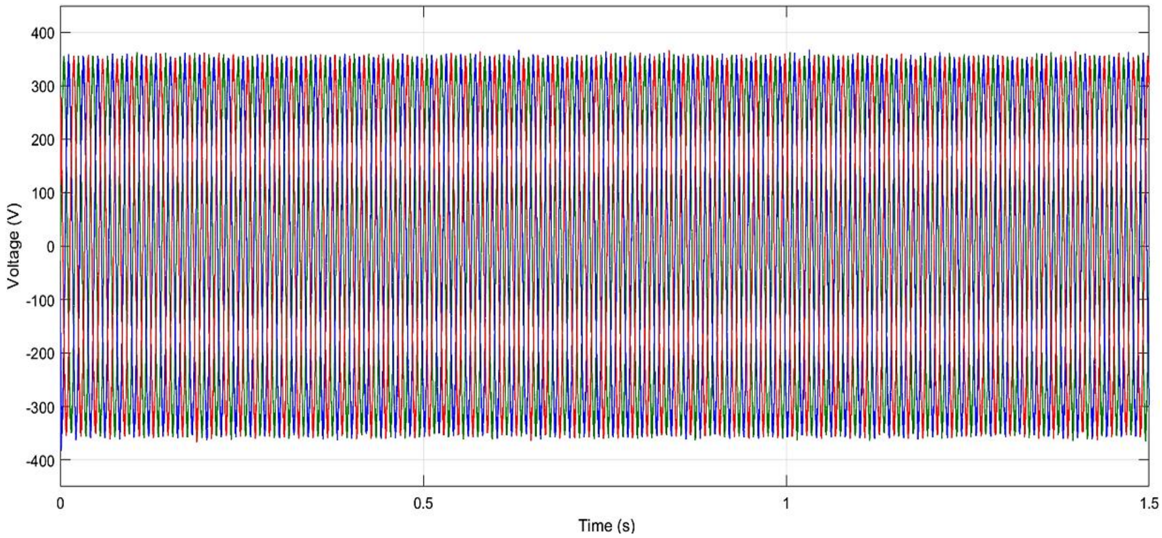

Figure 8. Grid voltage waveform with the DPFC in operation

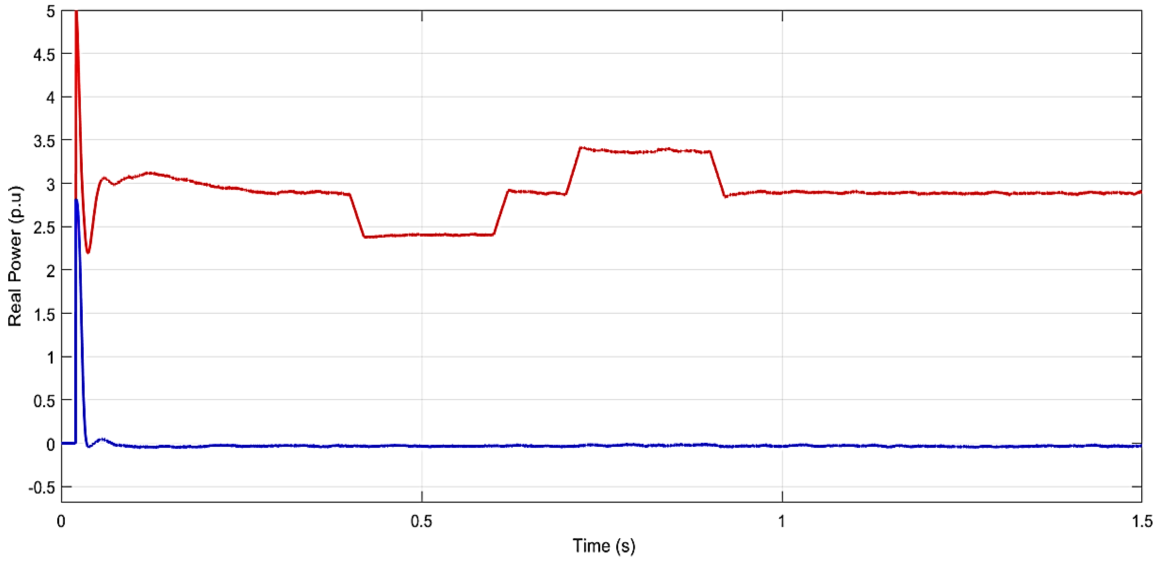

Figure 9. Real power source response per unit of DPFC

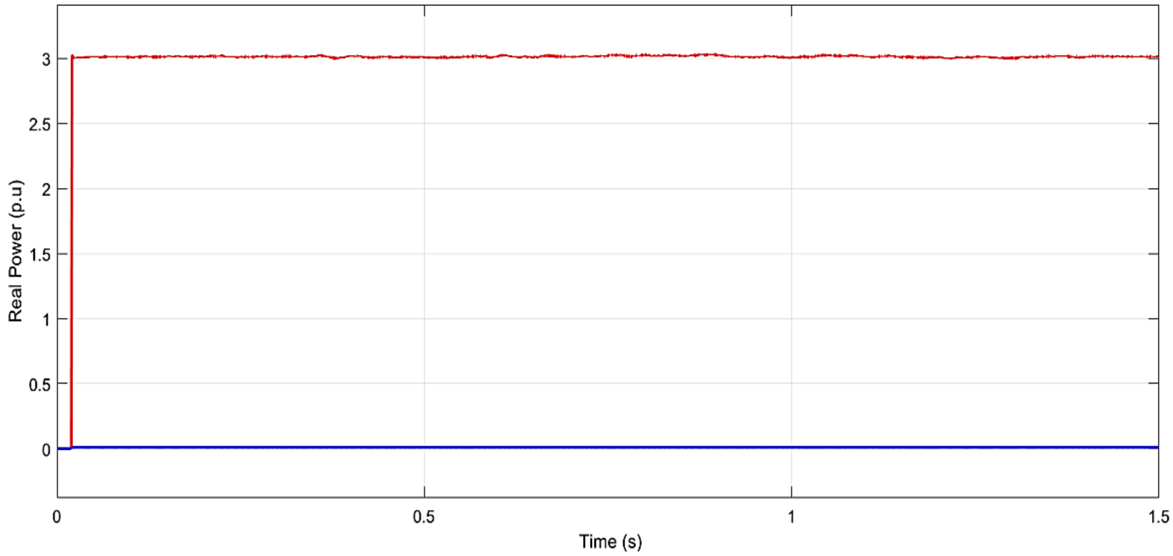

Figure 10. Real power load response per unit of DPFC

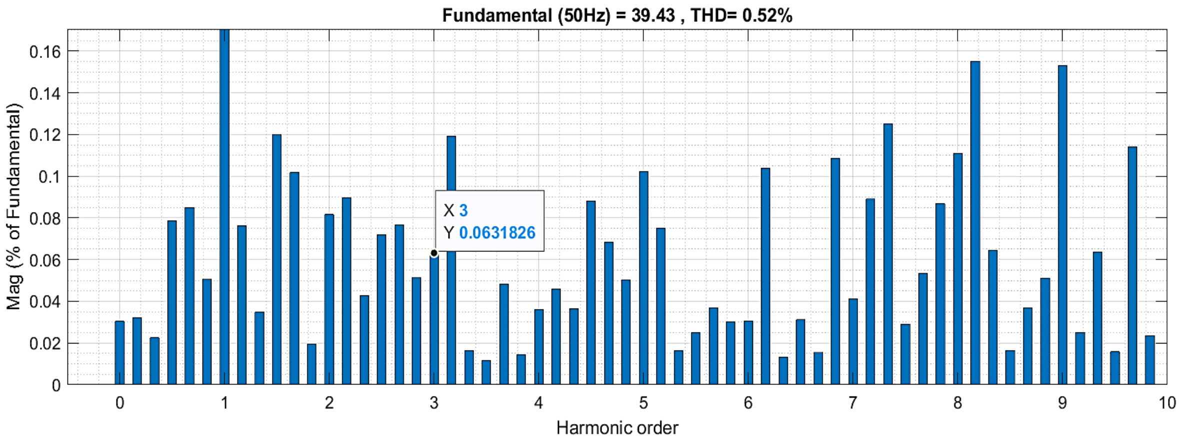

Figure 11. Third harmonic distortion in DPFC load current

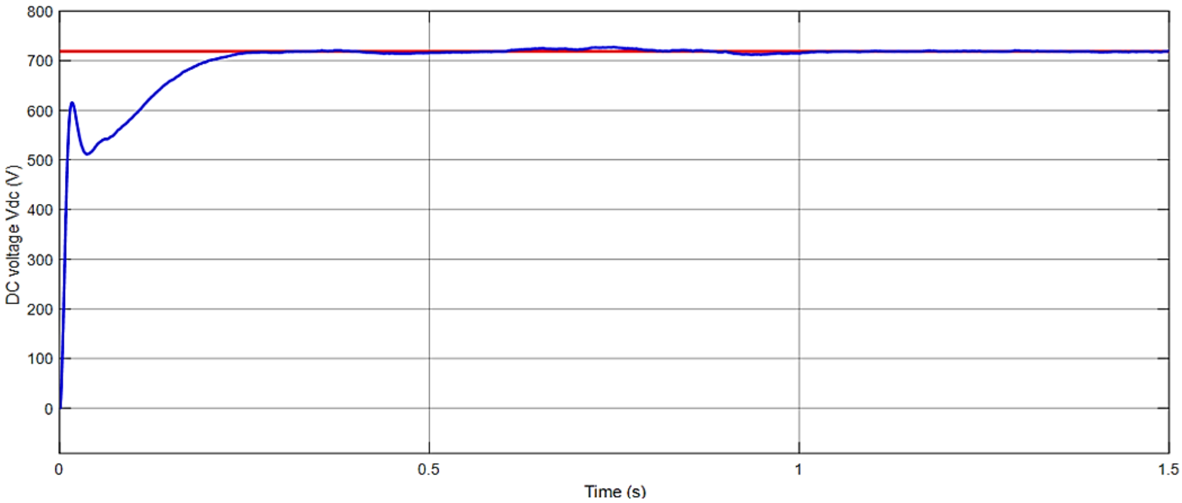

Figure 12. DC voltage V_{dc}

5. CONCLUSION

This study introduces an advanced implementation of the distributed power flow controller (DPFC), representing a significant evolution of the unified power flow controller (UPFC). While preserving the UPFC’s core functionalities, such as the coordinated control of transmission line impedance, power flow angle, and bus voltage magnitude, the DPFC eliminates the conventional DC link used for active power exchange. Instead, it facilitates power transfer through third harmonic components propagated along the transmission line, thereby improving system efficiency and operational flexibility.

The DPFC employs the distributed flexible AC transmission systems (D-FACTS) concept in its series converter architecture by replacing a centralized, high-capacity converter with multiple smaller, single-phase units. This decentralized configuration enhances system reliability through redundancy and reduces implementation costs by eliminating the need for high-voltage isolation in the series converter modules. Simulation results validate the performance of the proposed DPFC model, demonstrating its ability to mitigate voltage sags and swells and to suppress third harmonic distortions. These improvements contribute to enhanced power quality and system stability. Future research directions may include hardware prototyping, real-time system testing, and the integration of the DPFC with renewable energy sources and smart grid infrastructures to assess its dynamic performance in practical environments.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Fayçal Mehedi		✓	✓	✓		✓	✓			✓	✓	✓		
Khelifa Khelifi Otmane	✓		✓	✓		✓	✓			✓				✓
Youcef Bot				✓		✓	✓			✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

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

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