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Enhanced Adaptive Harmonic Control for Efficient AC/DC Power Distribution

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Abstract: *This study presents an innovative adaptive algorithm for estimating fundamental power flow in hybrid AC/DC systems. The algorithm's efficacy was rigorously tested and validated against traditional methods, utilizing MATLAB/Simulink models for actual data generation and a conventional equivalent power grid for comparison purposes. The results, depicted in detailed comparative charts, unmistakably demonstrate that the proposed adaptive approach yields estimates that are significantly more accurate and closer to the actual data across all nodes in the system. This enhanced accuracy is indicative of the proposed algorithm's superior performance and reliability in representing power flow dynamics, making it a promising tool for future power system analysis and optimization endeavors.*

Keywords: *Voltage Source Converter (VSC), High Voltage Direct Current (HVDC), Harmonic Power Flow (HPF), Pulse Width Modulation (PWM), Hybrid AC/DC Systems.*

1. Introduction

The Adaptive Harmonic Power Flow Algorithm for hybrid AC/DC transmission systems is a computational approach used in power systems engineering to analyze and optimize the operation of electrical grids that combine both alternating current (AC) and direct current (DC) transmission lines. Hybrid AC/DC systems are becoming increasingly important in modern power grids as they offer benefits such as improved controllability, increased efficiency, and better integration of renewable energy sources. The Adaptive Harmonic Power Flow Algorithm is a cutting-edge computational tool revolutionizing power systems engineering. It addresses the complex challenges of modern electrical grids, particularly in hybrid AC/DC transmission systems. This algorithm enables precise analysis, control, and optimization of power flow, accounting for harmonics and transient conditions. Its adaptability allows for real-time adjustments, ensuring efficient and reliable energy transmission while accommodating renewable energy integration and maintaining power quality. As we navigate a changing energy landscape, the Adaptive Harmonic Power Flow Algorithm is instrumental in shaping the future of resilient, sustainable, and high-quality electrical grids [1][2].

The Adaptive Harmonic Power Flow Algorithm is a groundbreaking computational approach designed to handle the multifaceted challenges posed by hybrid AC/DC transmission systems. This algorithm not only performs traditional power flow analysis but also extends its capabilities to account for harmonic voltages and currents. By doing so, it helps ensure that the grid operates within acceptable harmonic distortion limits, thereby maintaining the quality of power supplied to consumers and safeguarding the integrity of connected equipment.

In addition to harmonic considerations, the Adaptive Harmonic Power Flow Algorithm is adept at addressing transient conditions in the grid. Transients, which represent abrupt changes in voltage or current caused by events like switching operations or system faults, necessitate thorough analysis to guarantee the safe and reliable operation of the network. This algorithm conducts transient simulations, providing insights into how the system responds to disturbances and enabling the design of protective mechanisms [3]-[10].

Furthermore, the "adaptive" nature of this algorithm signifies its ability to evolve and adjust to the ever-changing conditions of a dynamic grid. It can optimize control parameters, such as converter settings, in response to varying loads, generation patterns, or changes in the network topology. This adaptability ensures that the algorithm remains a robust and reliable tool for grid management in the face of evolving energy landscapes. As our society continues its transition toward cleaner and more sustainable energy sources, the Adaptive Harmonic Power Flow Algorithm emerges as a cornerstone technology that empowers power systems engineers to harness the full potential of hybrid AC/DC transmission systems. [4]. It enables the efficient integration of renewable energy, enhances grid stability, and ensures the delivery of high-quality electrical power to meet the needs of a modern and electrified world.

2. Literature Review

Li et al. [1] introduced a model particularly suitable for systems integrating voltage source converter (VSC) high-voltage direct current (HVDC) transmission lines. This multifaceted nonlinear model is versatile enough to be utilized in both primary and harmonic power flow examinations, especially at the convergence points. In order to validate the efficacy of their hybrid power flow method for intertwined AC/DC systems, a redesigned version of the IEEE 30-bus test system, which employs pulse width modulation (PWM)-controlled bi-terminal VSC-HVDC, serves as the experimental platform.

Both simulations and detailed computations affirm that this newly proposed method outperforms conventional strategies in terms of efficiency.

Becker et al. [2] introduced a Harmonic PowerFlow (HPF) technique designed to accurately depict AC power flows, taking into account the interplay among various harmonics. The conceptual foundation of the HPF approach is based on the discrepancies in the nodal equations linking the grid to resource models, and it's further resolved using the Newton Raphson technique. The current study takes the HPF approach a step further by incorporating models of hybrid AC/DC networks that interface through NICs. This adaptation ensures that harmonics either emerging from or traveling through the DC subsystems are duly represented. Consequently, the NICs' modeling and the inherent interaction between the AC and DC subsystems are integrated into the discrepancy equations and the Jacobian matrix. When applied to a representative hybrid AC/DC network, the refined HPF technique's precision is corroborated through exhaustive time-domain assessments using Simulink.

Lekić et al.[3] explored the analysis of systems using voltage source converter (VSC) high-voltage DC when varying VSC controls are implemented. The outcome of this power flow evaluation serves as a foundation for initializing the power converters.

Wang et al [4] introduced a technique where a harmonic signal is channeled into the IC using converters tied to a distributed generation linked to an AC bus. Through the use of a filter and a phase-locked-loop (PLL), the IC can pinpoint the AC bus voltage based on the signal's designated frequency. Subsequently, the IC is able to gauge line impedance using local data and counteract voltage drops, ensuring precise power transmission. Notably, this method is executed without the need for communication. When multiple ICs operate concurrently, this approach is easily adaptable, ensuring precise interplay between subgrids and equitable distribution of power across ICs, based on their stipulated capacities. Simulations and real-time tests validate the effectiveness of this approach.

Patel et al.[5] introduced a design for distributing photovoltaic (PV) distributed generations (DGs) within hybrid AC-DC setups. There's an observed average power loss enhancement of about 7.5% relative to previously reported outcomes. Additionally, there's nearly a 10% boost in the converter power factor and a significant 50% cutback in the ripple factor.

Sakinci et al.[6] introduced a methodology for analyzing the stability of comprehensive hybrid AC/DC power systems. This method distinctly considers the influences of both AC and DC systems without resorting to typical oversimplified assumptions. The AC system's portrayal is achieved through a transformation from three-phase ABC variables to a singular frame, ensuring a detailed representation of components like cables and overhead lines without compromising the intricacy of the model. This approach is elucidated further by showcasing models for passive network elements and the modular multilevel converter (MMC). The practicality of this method is highlighted using a point-to-point High-Voltage Direct Current (HVDC) link as an example.

Ortiz et al.[7] introduced a microgrid (MG) model that encompasses both DC and AC buses, integrating diverse load types and distributed generation across two voltage tiers. They utilized the MATLAB/Simulink platform to simulate the entirety of this MG. The outlined electrical framework is intended to serve as a foundational reference for subsequent research areas like reactive power offset, stability evaluations, inertia scrutiny, reliability checks, demand reaction explorations, layered control mechanisms, fault-resilient control measures, optimization techniques, and energy storage methodologies.

3. Research Methodology

A 3-phase Voltage Source Converter (VSC) that operates with a 2-level topology. The switching or carrier frequency (f_{sw}) is determined by the number of triangular wave repetitions within a sinusoidal fundamental frequency (f_1), and is calculated using the formula $f_{sw} = \omega_{sw}/2\pi$. The frequency modulation ratio (m_f), typically a multiple of 3, connects the switching frequency to the fundamental frequency through the equation $\omega_{sw}=m_f\omega_1$. The modulation index (m_a), which is the ratio of reference voltage to carrier wave voltage ($m_a=V_{carrier}/V_{reference}$), facilitates the independent transfer of active and reactive power through the converter, either from AC to DC or vice versa. Although the passage notes a relationship between the AC-side voltage and the DC circuit boost voltage (V_{dc}), it does not provide specific details about this relationship.

$$V_{iLL_{rms}}^{AC} = M_a K_{vsc} V_j^{DC} \quad (1)$$

The converter constant Kvsc is dependent on the type of Voltage Source Converter (VSC) and the Pulse Width Modulation (PWM) strategy used. For a 3-phase Sinusoidal PWM (SPWM) converter, Kvsc is computed as $\sqrt{3/2}*\sqrt{2}$. In contrast, for a 3-phase Space Vector PWM (SVPWM) converter, Kvsc is calculated as 1. The specific values of Kvsc are vital since they vary with the chosen converter and modulation strategy, influencing the efficiency and performance of the conversion process.

A. Switching Function

A 6-pulse IGBT converter with converter valves labelled Q1 to Q6. In a 2-level PWM system, a reference signal (Vref input) is compared to a symmetrical triangular wave carrier. With MATLAB Simulink, a 2-level PWM block utilizing natural sampling generates a unipolar switching function. The upper switching device receives a high pulse (1) when the reference signal is above the carrier, while the lower device receives a low pulse (0). Although the passage mentions identifying the switching function of phase p, it doesn't provide specific details or formulas related to this.

$$S_p = \begin{cases} 1, & where\ Q1\ close \\ 0, & where\ Q1\ open \end{cases} \quad (2)$$

The passage explains that in practical situations, the input reference signal, Vref, might not perfectly be sinusoidal due to the effects of LCL filter parameters and resonance characteristics, although the error is minimal at high switching frequencies. Vref can be approximated. However, in the overmodulation scenario (ma>1), this relationship becomes non-linear, resulting in increased side-band harmonics. In the overmodulation region, the traditional switching function, often expressed by a Bessel function, is no longer accurate.

B. Proposed Adaptive HVDC

The proposed model makes several basic assumptions for deriving a harmonic model, including a single slack bus in the hybrid power system, ideal valves with no internal losses, and converters operating with symmetrical sinusoidal voltage and balanced mode. It also assumes that VSCs are the sole sources of harmonics and that the upper switches in two phase legs undergo similar processes, with reference signals delayed by 120° and 240° respectively. A steady-state model of a VSC-HVDC station is presented with Y-Y winding transformer converters, where the rectifier is the master DC voltage regulator and the inverter is the power dispatcher. This model is used for transmission stations and operates similarly to the HVDC back-to-back configuration. VSCs in this model are connected through transmission DC lines with cable impedance Rd. The equivalent load, including resistances and filters, can be calculated, and is considered the primary non-linear load at the converter AC bus when calculating harmonics. The power compensates for phase shifting and adjusts the firing angle, functioning as a Power Factor Compensator (PFC). Properly selecting parameters of LC, phase reactors, and LCL filters allows the angles to ideally be set to 0°, even though adjustments to these angles don't affect the overall calculation procedure. Various aspects of power and voltage in the system are also discussed, including power delivered from node 12, voltages at nodes 4 and 12, and the DC transmission line resistance. The boost voltage of the DC circuit, Vd1, is essential for the PI controller parameters in the control scheme and is tested at 40 kV in the system. Manipulating the phase angle difference between the VSC output voltage and the Point of Common Coupling (PCC) voltage regulates the active power exchange between the AC and DC systems. The reactive power exchanged is controlled by adjusting the voltage magnitude difference across the coupling transformer.

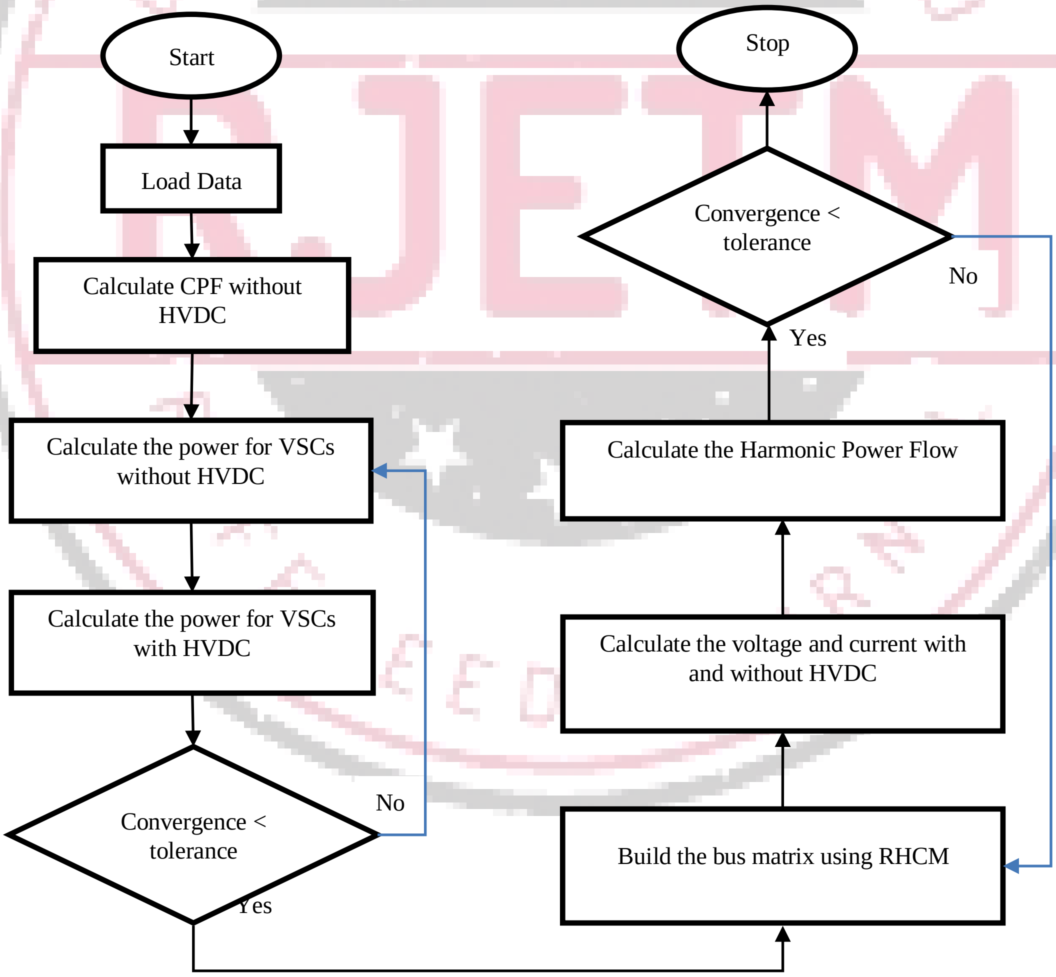

Figure 1: Flow of Adaptive HPF

The proposed adaptive Harmonic Power Flow (HPF) algorithm, visualized in a flowchart, consists of two loops and is related to the Continuation Power Flow (CPF). The algorithm uses the RHCM method to construct an admittance matrix for each harmonic order, determining the HPF for each. Initial variable values are crucial for the convergence of the Newton-Raphson (NR) method used in the algorithm. The text also outlines a procedure for validating the proposed framework's accuracy, where the hybrid AC/DC system is converted into an AC system for analysis. This conversion and subsequent power flow analysis provide a basis for comparing and verifying the accuracy of the proposed framework.

4. Result Analysis

The section presents a single-line diagram (Figure 2) of a developed 30-HVDC system. Parameters for this IEEE 30-bus transmission system are derived from the Illinois Center for a Smarter Electric Grid (ICSEG) power world model.

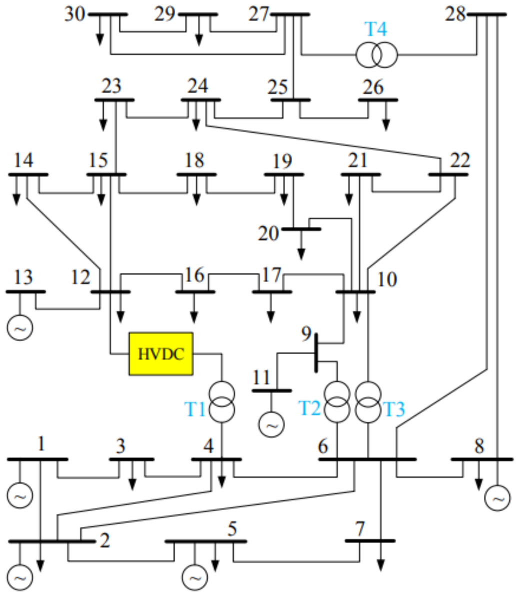

Figure 2: IEEE 30 Bus System Line Model

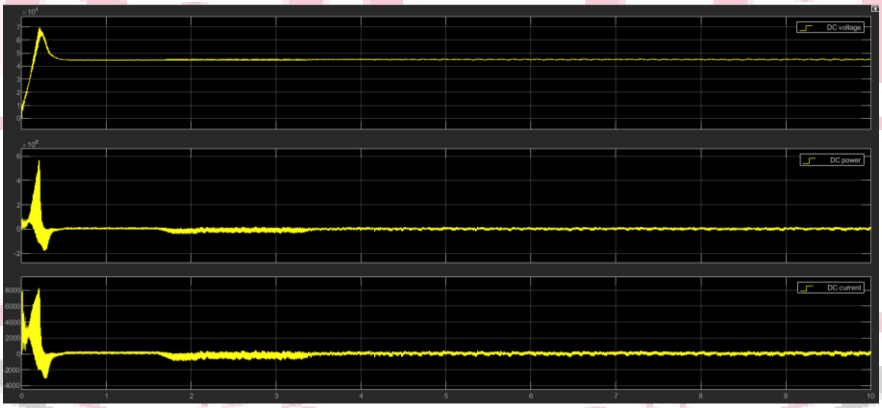

Figure 3: DC Voltage, Power and Current Output

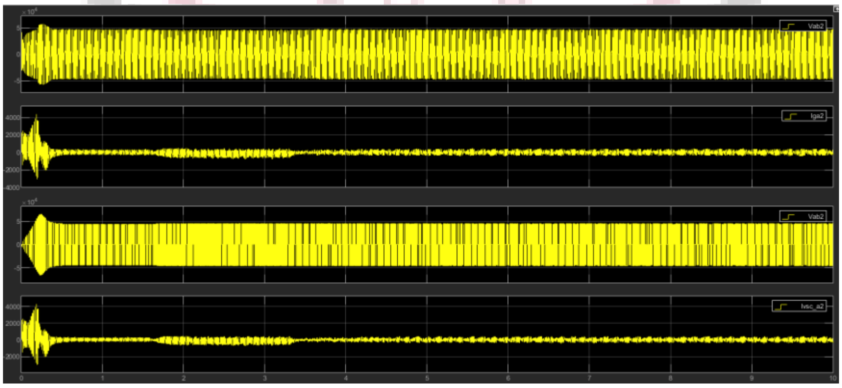

Figure 4: AC Voltage, Power and Current Output

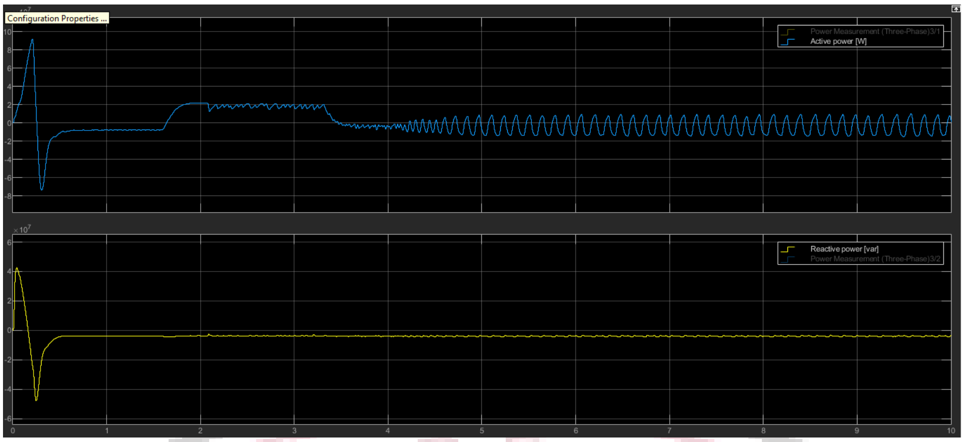

Figure 5: Active and Reactive Power

Based on the provided data in Figure 6 for Voltage Magnitude Comparison:

- The voltage magnitude at each node is higher when using the Proposed method compared to the Conventional method.
- The voltage magnitudes for the Proposed method range from 1.01 to 1.1, while those for the Conventional method range from 0.87 to 0.95.
- This suggests that the Proposed method results in higher voltage magnitudes across all nodes in comparison to the Conventional method.

This increase in voltage magnitude at each node might indicate a more robust or efficient system under the Proposed method, but the exact implications would depend on the specific requirements and constraints of the system being analyzed. For example, if the system requires higher voltage levels for optimal operation, the Proposed method may be more effective.

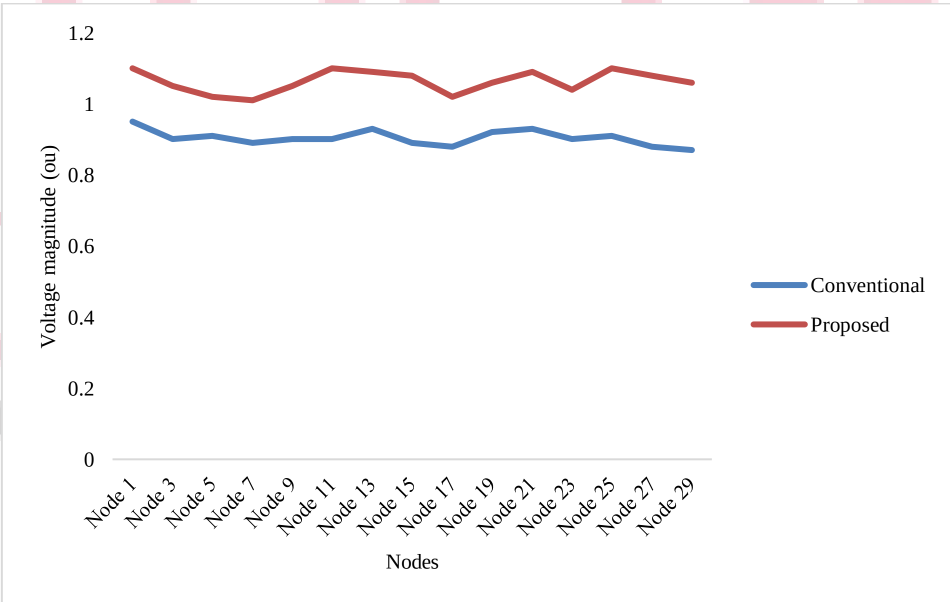

Figure 6: Voltage Magnitude Comparison

5. Conclusion

The research introduced and thoroughly evaluated a novel adaptive algorithm designed for the accurate estimation of fundamental power flow in complex hybrid AC/DC systems. Through meticulous comparison with conventional methodologies, the proposed algorithm exhibited commendable accuracy, consistently generating estimates closely aligned with actual data obtained from sophisticated MATLAB/Simulink models. This consistent accuracy highlights the algorithm's potential as an invaluable asset for engineers and researchers engaged in the analysis, design, and optimization of hybrid power systems. Future work should consider exploring the algorithm's applicability and performance in various real-world scenarios, as well as its integration with other analytical tools and platforms to further leverage its capabilities for advanced power system studies and applications.

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