CONTENT

KEYWORDS

- Battery
- DC-AC power Converters
- Distributed generation systems
- Floquet theory
- Frequency spectrum
- Harmonics
- Interharmonics
- Participation matrix
- Photovoltaic
- Power flow
- Stability
- Wind turbine

SUMMARY

1. Modeling techniques

Three approaches for transient simulation of time-periodic switched networks are outlined:

- Time-Domain (TD) Modeling**:** This mature technique effectively represents time-periodic systems by clearly defining and interpreting each part's behavior. TD methods can handle nonlinear elements and switching converters straightforwardly.
- Extended Harmonic Domain (EHD) Models: These models provide instantaneous time-variation harmonics, useful for calculating instantaneous power quality indices (e.g., ripple current/voltage) of switched networks. However, due to the high-frequency dynamics of switching converters, EHD models face the challenge of large dimensions, making transient simulation difficult.
- Flexible Extended Harmonic Domain (FEHD) Technique: FEHD generalizes EHD by involving distinct frequencies (not necessarily sequential integer multiples of the fundamental frequency) for each part of the switched network, allowing step-by-step analysis of interharmonics. FEHD does not depend on a sampling frequency and assumes time-varying dynamics of harmonics and interharmonics, avoiding errors like spectral leakage, Gibbs phenomenon, and aliasing that occur with PSCAD/EMTDC and TD-based models using FFT. Additionally, DFT-based methods require many samples over a long period when interharmonics are involved.

2. Floquet theory and participation matrix

This chapter introduces a methodology, combining Floquet theory and participation matrix, to characterize distributed generation systems in terms of pole locations in the complex plane. Participation factors identify which poles are most influenced by each state-variable, offering insight into modifying variables to stabilize unstable poles or vice versa. This methodology offers an effective tool for parameter design, stability assessment, and post-event analysis, particularly for closed-loop operation, in both linear-time-periodic and nonlinear systems. A key advantage is its potential implementation via parallel computing, alongside transient simulation using multiprocessor architecture, enhancing computational efficiency. However, a significant challenge arises when assessing stability in systems with multiple fundamental frequencies, such as wind-PV-battery systems, especially as the fundamental period increases, leading to substantial computational burden. Addressing this challenge remains an open area for further research.

3. Lumped-parameters equivalent using the FEHD

This section introduces a new method for integrating PV generators into a power flow algorithm using a π-shaped lumped-parameter circuit. The approach addresses the symmetry issue observed in previous methodologies applied to PV generators through a straightforward restructuring. This restructured approach allows for the incorporation of PV generator control variables into the power flow algorithm with ease. Additionally, the feasibility of using the HDAM concept for PV systems, despite their lack of symmetry and involvement of different source frequencies, is demonstrated. Notably, the proposed approach eliminates the need for calculating partial derivatives for power electronic devices within the power flow algorithm.

Validation of the π-equivalent was conducted using the widely-used power flow software tool PSS/E and, for verification purposes, with PSCAD/EMTDC, resulting in excellent agreement. Furthermore, it was shown that considering cross-coupling of harmonics leads to improved results compared to the Alternative Displacement Method (ADM), which accounts for DC and fundamental frequency only.

4. Dynamic FEHD. Analytic solution for time-periodic systems

This chapter introduces the Dynamic Extended Harmonic Domain (DFEHD) approach, enabling the computation of frequency evolution over time in Linear Time-Periodic (LTP) systems through a closed-form expression consisting of sinusoidal signals, both harmonically and interharmonically. The proposal offers the analytical solution for any LTP system represented as a sum of sinusoidal signals, with frequencies derived from pre-selected FEHD frequencies, natural frequencies, and their combinations. Consequently, switching frequencies can be directly integrated into the pre-selected set of frequencies within the DFEHD formulation.

DFEHD has been effectively validated through two case studies, demonstrating remarkable accuracy owing to its analytical nature. Its key features include: i) computation of dynamic harmonic/interharmonic transient solution via closed-form expression, ii) elimination of numerical integration methods and time-step dependency, and iii) provision of complete frequency spectrum dynamics.

Given these features, DFEHD serves as an alternative method for transient simulation of LTP systems and can be employed to assess power quality in modern systems. In contrast, PSCAD/EMTDC and TD-based models necessitate post-processing routines, leading to known errors, as evidenced in the case studies presented. Conventional FEHD models are limited by their fixed set of harmonic/interharmonic frequencies, thereby failing to incorporate natural frequencies of the system. The DFEHD approach overcomes this limitation by accounting for such frequencies, thereby enabling accurate initialization of FEHD models.

5. Correct initialization of EHD-based models

This chapter introduces a novel approach based on Dynamic Flexible Extended Harmonic Domain (DFEHD) for computing initial conditions of nonlinear systems. The implementation of this approach involves an initial conditions approximation method, which effectively reduces spurious oscillations at preselected frequencies caused by initialization or step changes, in comparison to traditional FEHD modeling. Moreover, the time required for implementing this approach is found to be negligible in comparison to the overall CPU-time simulation. The results obtained from the DFEHD-based approach were compared with traditional FEHD modeling, conducted without initial conditions computation, as well as with PSCAD/EMTDC. The comparison demonstrates excellent agreement in instantaneous values and an improved representation of frequency evolution.