Review of Converter Optimization Techniques for Harmonic Mitigation in DC Nanogrids with Variable Loads

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Abstract: *The DC nanogrids have emerged as a promising solution for integrating distributed energy resources and enhancing power quality in localized energy systems. However, the presence of variable loads introduces significant harmonic distortion, which can degrade system efficiency and reliability. This paper presents a comprehensive review of optimization techniques applied to power electronic converters for harmonic mitigation in DC nanogrids under variable load conditions. The study categorizes existing methods into passive, active, and hybrid approaches, with a particular focus on control-based and algorithmic optimization strategies such as particle swarm optimization (PSO), genetic algorithms (GA), model predictive control (MPC), and artificial intelligence (AI)-based methods. Key performance metrics including total harmonic distortion (THD), dynamic response, and computational efficiency are analyzed.*

Keywords: *DC nanogrids, Harmonic mitigation, Converter optimization, Variable loads, Power quality.*

I. INTRODUCTION

This paper focuses on the performance analysis of various DC-DC converter topologies employed in DC nanogrids, specifically assessing their impact on Total Harmonic Distortion (THD). A DC nanogrid is a localized, self-regulating energy system capable of operating in both grid-connected and islanded modes. It enables seamless integration of distributed energy resources (DERs)—such as solar photovoltaic (PV) systems and energy storage devices—with local DC loads [1].

DC nanogrids offer several advantages over traditional AC systems, including improved efficiency, reduced power conversion stages, and greater compatibility with DC-based DERs and loads. The inherent islanding capability of nanogrid architectures enhances system reliability and resilience, particularly in residential and remote-area applications, by allowing continuous operation during grid outages [2].

This study evaluates the performance of three fundamental DC-DC converter topologies—buck, boost, and buck-boost converters—focusing on their roles in voltage regulation and power flow control within the nanogrid. These converters are responsible for adjusting the output voltage of PV modules to meet the varying demands of connected loads. Particular attention is given to the buck-boost converter, due to its versatility in stepping voltage both up and down based on load requirements [3].

The performance of each converter topology is analyzed using MATLAB/Simulink simulations, with an emphasis on THD levels, voltage stability, and overall system efficiency under dynamic load conditions. The objective is to determine which converter configuration most effectively minimizes harmonics while ensuring stable and efficient nanogrid operation [4].

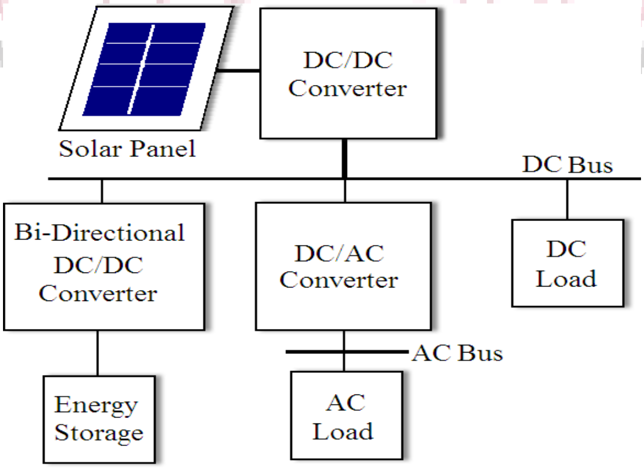

Figure 1.1: General architecture of DC Nano-grid

Figure 1.1 illustrates the schematic diagram of a DC nanogrid. The system comprises solar photovoltaic (PV) panels as the primary energy source, power electronic converters, energy storage elements, and local AC and DC loads. The energy required by the loads is primarily supplied by the solar PV panels, while the storage elements help maintain power balance and enhance system stability. As shown in Figure 1.1, the energy sources, storage units, and various types of loads are interconnected through a common DC bus via dedicated power electronic converters. These converters play a critical role in regulating voltage levels and managing power flow within the nanogrid.

II. LITERATURE REVIEW

Weimin et al, in 2016 in their work proposed the modelling and designing of a dual buck-boost converter used in DC Nano-Grid. Due to the lower voltage generation and excessive low DC voltage requirement of the electronic gadgets, the author proposed the designing of the buck-boost converter through which the output of the solar PV can be converted to desired level of voltage as per the load.

Nelson et al, IN 2019 in their work showed the designing and operation of boost converter which is used for stepping up the output voltage of the solar PV output. The boost converter is basically used for maintaining the DC bus voltage in DC Nano-grid system. In their work they also showed that the boost converter has two semiconductors like an SMPS with an energy source like L or C or L-C.

Sudev V. et al,. in 2014 in their work found that to reduce voltage ripple, filters made of capacitors or combination of both inductor and capacitor both are normally added to such converter’s output and input since the power for the boost converter can come from any suitable DC source such as batteries, solar PV, rectifiers etc in a hybrid system.

A.Safariet al, in April 2011 in his work gave the basic idea for solar PV array while working on MPPT controlled solar PV module. The PV array is built of strings of modules connected in parallel, each string consisting of modules connected in series. The PV array is a five parameter model using a current source IL (light-generated current), diode (I0 and parameters), series resistance Rs, and shunt resistance Rsh to represent the irradiance and temperature-dependent I-V characteristics of the module.

Prof. Koshti et al, in 2017 in their work they reviewed the various topologies of the boost converter for various application and proposed the design of the boost converter which is efficient, reliable, self-sufficient and fault tolerant for a DC Nano- grid and will be compared for their operation and performance for the wide varying input.

Mammaon et al, in 2001 in their work showed the SMPS class of the buck converter and comparison of topologies between voltage and current mode. In this the voltage is stepped down by stepping up the current of the output of solar PV and therefore the buck converter is used for low voltage applications.

Chierchie et al, in 2009 in their work found that the buck converter can also be operated in discrete time for which they designed and did modelling and controlling of a buck converter which can be used for both Micro-grids and Nano- grids. The low voltage problem of the solar PV used in the DC Nano-grid system can be solved using the various DC-DC converters and use of various topologies as per the requirement of the load. The DC Nano-grid uses converters for improving the power quality, maintaining the continuous power supply and maintaining the DC bus voltage so that there is smooth functioning of the system.

Nag et al, in 2013 gave a brief idea of Nano-Grid system. According to them, Nano-grid is the low power renewable energy based on distribution system suitable for residential power applications. Nano-grid is meant for supplying domestic loads of the order of few hundred watts to 5kW generated from renewable energy sources like roof-top solar photovoltaic, fuel cells or wind farms etc. There are certain problems in Nano-grid system which has a major impact on the power quality and performance of the system. The major problem is about harmonics on AC load side, low voltage generation through solar PV, battery management and high installation cost.

III. DISCUSSION AND FINDINGS

The reviewed literature underscores the critical role of converter optimization in enhancing harmonic performance within DC nanogrids, particularly under variable load conditions. Harmonics, predominantly caused by nonlinear switching behavior in power electronic converters, significantly affect power quality, voltage stability, and efficiency in nanogrid systems. This section discusses key observations, comparative insights, and implications derived from the analysis of various converter optimization techniques.

Comparative Performance of Converter Topologies

Buck, boost, and buck-boost converters are the most commonly employed DC-DC converter topologies in nanogrids. Each exhibits unique voltage regulation capabilities under dynamic load conditions. Among these, the buck-boost converter stands out for its bidirectional voltage control, making it especially suitable in applications where load or source conditions vary significantly. However, its complex control structure often introduces higher harmonic distortion unless effectively optimized.

Harmonic Mitigation Techniques

Various techniques have been proposed for harmonic mitigation, ranging from passive filtering and hardware-based solutions to advanced control and software optimization approaches. While passive methods offer simplicity, they often lack adaptability under changing loads. Active and intelligent control strategies—such as Proportional-Integral (PI) control, Model Predictive Control (MPC), and Sliding Mode Control (SMC)—demonstrate better harmonic suppression and dynamic performance. However, these techniques often require precise system modeling and can be computationally intensive.

Optimization Algorithms

Metaheuristic optimization algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Artificial Neural Networks (ANNs) have gained attention for tuning converter control parameters. These algorithms enhance converter response by minimizing Total Harmonic Distortion (THD) and improving voltage stability under variable loads. Hybrid optimization strategies, which combine heuristic and deterministic methods, have also shown promise in balancing accuracy and computational overhead.

Impact of Load Variability

Converter performance is highly sensitive to load fluctuations. Many traditional control schemes demonstrate reduced effectiveness when subjected to rapid load changes. Adaptive control methods, which dynamically adjust control parameters based on real-time load profiles, show improved harmonic mitigation but may introduce complexity in implementation.

Simulation and Experimental Findings

Most studies validate their findings through MATLAB/Simulink-based simulations. Simulation results consistently indicate that optimized converter designs lead to significant THD reduction—often by 30–50% compared to unoptimized systems. However, there is a notable lack of real-time hardware-in-the-loop (HIL) implementations or field testing in many cases, limiting practical validation.

IV. CONCLUSION

This review has examined various converter optimization techniques aimed at mitigating harmonic distortion in DC nanogrids operating under variable load conditions. The analysis reveals that the performance of DC-DC converters—particularly buck, boost, and buck-boost topologies—significantly influences total harmonic distortion (THD), voltage stability, and overall system efficiency.

Among the converter types, the buck-boost converter demonstrates superior adaptability to dynamic voltage requirements, though it demands more sophisticated control strategies to manage harmonics effectively. Advanced control approaches such as Model Predictive Control (MPC), Sliding Mode Control (SMC), and intelligent methods including Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have shown substantial improvements in THD reduction and dynamic response. However, these techniques also introduce challenges in terms of computational complexity and implementation cost.

The findings suggest that no single optimization method is universally superior; rather, the effectiveness depends on system requirements, computational constraints, and real-time adaptability. While simulation-based results indicate promising reductions in THD, the lack of real-world experimental validation remains a key limitation across many studies.

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