Research Article

International Journal of Advanced Technology and Engineering Exploration, Vol 11(114)
ISSN (Print): 2394-5443 ISSN (Online): 2394-7454
http://dx.doi.org/10.19101/IJATEE.2023.10102587

Total harmonic distortion mitigation and voltage control using distribution static synchronous compensator and hybrid active power filter

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Received: 12-December-2023; Revised: 25-May-2024; Accepted: 27-May-2024

Abstract

The incorporation of renewable energy sources (RESs) into power systems is now widely recognized as a crucial element of modern civilization. A significant obstacle in this situation is the reduction of voltage distortion and total harmonic distortion (THD), which can disrupt the smooth transfer of power and weaken the performance of electrical systems. When a power generation system integrates RESs, it results in the generation of both THD and voltage instability. Various types of active power filters (APFs), passive filters (PFs), compensators such as the synchronous condenser, static var compensator (SVC), static synchronous compensator (STATCOM), distribution static synchronous compensator (D-STATCOM), and hybrid active power filter (HAPF) have been developed in order to solve these problems. Along with those methods, various other techniques have been deployed to regulate voltage and minimize THD. However, this study involves a comparison of data between D-STATCOM and HAPF, with an emphasis on measurements of voltage waves, the 3rd and 5th harmonics, and THD. Three distinct capacitor banks, with capacities of 40-kilovolt ampere reactive (KVAR), 60 KVAR, and 80 KVAR, have been selected as references. All the relevant data for each of these referenced capacitor banks has been collected using MATLAB/Simulink software. HAPF outperforms D-STATCOM in every aspect of data analysis in this study. Although a simulation was conducted to determine if there would be any variations for different loads, no alterations were observed. This study aims to facilitate the selection of an appropriate device for industrialization, as failure to do so can have detrimental effects on the system.

Keywords

D-STATCOM, Hybrid active power filter, Total harmonic distortion, Voltage control, Renewable energy.

1.Introduction

Since electricity is essential to our modern lifestyle, it is crucial that effective regulations be put in place. At the same time, the global shift towards renewable energy sources (RESs) demonstrates a collective effort to address environmental concerns. The search for a mutually beneficial partnership between power and sustainability is still vital to determining our course as we go through this challenging landscape. Some studies were conducted whose purpose is to provide an introduction to the smart grid, including an explanation of its key components and functionality. The overarching goal of these studies is to illustrate how Smart system technologies have impacted the evolution of today's power system. These studies trace the origins of the smart grid with renewable energy [1–3].

Another study was conducted where both developed and developing nations can benefit from renewable energy's favorable and statistically significant impact on sustainable development [4]. An article by Li et al. [5] provides a concise overview of the current state of energy development on a global scale, specifically focusing on the following countries: Brazil, Australia, India, the United States, and the European Union. A pattern of growth power sources, including hydroelectric, wind, solar, biomass, and geothermal energy, have been studied. There is a great deal of untapped potential for electricity generation in Africa's abundant natural resources. Unfortunately, Africa is still in the midst of a crisis because it is unable to harness its vast renewable energy resources. Redesigning the electrical system, developing new energy storage technologies, and reducing environmental influences, along with changes in the seasons. The study and assessment that is being proposed would help improve the

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renewable energy position in Africa by addressing all concerns and finding sustainable solutions [6].

Multiple studies have been conducted previously, revealing a range of issues. However, one of the primary obstacles that arise when renewable energy is integrated is the issue of voltage instability and total harmonic distortion (THD). The sporadic nature of variable renewables, like wind and solar, presents obstacles to grid stability, resulting in voltage fluctuations and system instabilities.

RESs can introduce harmonic distortions into the power grid, which can have a negative impact on power quality and efficiency. A classification system in a paper improves visibility into the intricate process of renewable energy integration, which in turn aids in problem-solving and better specifies the need for targeted solution technologies [7]. Because wind and sunlight are intermittent, RESs like these are quite unpredictable. In the following paper, the main obstacles that high-level RESs face while trying to connect to the current grid have been taken. Each problem has its own set of answers, and those answers are showcased and analyzed [8]. The problems caused by greenhouse gases can be adequately addressed by RESs. The effects of flexible alternating current (AC) transmission system technology on power systems that rely on RESs and use flexible AC transmission system technology on power systems controllers, a sort of flexible AC transmission system, are also explored in this article [9]. Though renewable energies can be employed for sustainable development, certain challenges come with them. Both THD and voltage instability can be caused by them. However, it is important to note that these issues can be resolved. Various devices, such as active power filters (APFs), passive filters (PFs), hybrid filters, and compensators, are employed to alleviate these issues. The system mentioned in a study offers the added functionality of compensating for either harmonics exclusively or both harmonics and reactive power simultaneously [10]. The objective of another study is to outline the various uses, difficulties, and patterns associated with conventional active and passive harmonic filters. These filters are employed to minimize harmonic distortion and enhance power quality [11]. Semich et al. provided and discussed research on the effects of intermittent RESs on power systems' transient, small-signal, and frequency stability; the study also looked at flexibility measurements and approaches to make things more adaptive [12].

Previous studies have investigated the functionality of both distribution static synchronous compensator (D-STATCOM) and hybrid active power filter (HAPF) individually. However, a comparative analysis of these two technologies has not been undertaken in the manner demonstrated by this study, which aims to provide a comprehensive understanding of power systems that incorporate RESs. When it comes to RESs, THD, and voltage instability are significant challenges for a power system. This study was selected in order to lessen the impact of these damaging problems. If it is possible to do a comparison study between D-STATCOM and HAPF, then it will be simple to comprehend which device is superior to install in a power system in terms of the issues that it encounters. The utilization of a capacitor bank is essential in power systems to ensure stability because it is crucial to note that the selection of a capacitor bank value should not be arbitrary. In addition to the aforementioned, this study also assessed various load values that can be employed.

This study aims to evaluate the values that can be utilized for a specific power system operating at a frequency of 50 Hz. This paper presents an analysis of the control strategy employed by the D-STATCOM and HAPF. The results of this study assist power industries in making informed decisions regarding the selection of appropriate devices, capacitor banks, and loads. This proposal presents a viable approach for implementing a sustainable power system that harnesses RESs. In order to achieve this objective, various types of devices can be included in the power system. However, it is vital to figure out which equipment can yield superior outcomes. This objective is achieved by the utilization of this comparative analysis. Furthermore, because of these issues, there is no damage to any of the equipment.

Literature review is explored in Section 2. Methods are discussed in Section 3. Section 4 covers the results and experimentation. A discussion of the results is presented in Section 5. The conclusion is provided in Section 6.

2.Literature review

Liu et al. [13] proposed a real-time algorithm for computing switching angles in multilevel inverters, with the aim of minimizing THD. The algorithm is implemented on a digital signal processor and tested on a microprocessor. The algorithm's performance is validated by conducting rigorous mathematical analysis and evaluating the THD. The computational complexity is minimal, allowing for real-time handling. The performance of the proposed algorithm is confirmed through experimental results. However, the paper could not discuss the long-term stability and reliability of the proposed algorithm. It is crucial to examine if the algorithm can sustain its performance over extended periods without any decline or instability, as real-world systems often operate for long durations.

Biswas et al. [14] proposed a differential evolution algorithm called L-SHADE to optimize HAPF parameters. This algorithm enhances the efficiency of success history based parameter adaptation technique of differential evolution optimization process by gradually decreasing the population size in each subsequent generation. The study examines two frequently employed topologies of HAPF for parameter estimation, formulates a single objective function, and aims to minimize harmonic pollution in a system with non-linear source and loads. The L-SHADE algorithm demonstrates comparable performance to other algorithms and consistently achieves superior solutions compared to previously reported results. However, factors such as grid disturbances, voltage fluctuations, and environmental interference can impact the performance of the optimized HAPF parameters.

RESs, when integrated into the grid, can lessen our reliance on fossil fuels and help lower carbon footprint. There are a number of issues that require fixing, including power availability, quality, cost, power forecasting, generation unpredictability, speed variance, and accessibility. The promising alternative to non-RESs such as coal and fossil fuels is wind power, which is experiencing tremendous expansion in New Zealand due to the government's aim of achieving zero carbon emissions by 2050. It is projected that by 2030, wind power will generate 20% or more of New Zealand's electricity. An impressive compound annual growth rate of 15.51% has been recorded in India's renewable energy sector during the past five years. Ensuring widespread access to energy and massive deployment of renewable sources, especially solar and wind, are part of the government's efforts to build a secure, affordable, and long-term energy system. Discontinuation of incentives, land acquisition, changes in bidding procedures, and obsolete wind sites are only a few of the obstacles that the wind sector must overcome. In order to make wind energy investments that are more effective in terms of sustainable development, the article lays out three criteria: project, firm, and market. Among the important elements that were identified using the hesitant interval-valued intuitionistic fuzzy Decision Making Trial and Evaluation Laboratory, the most important of these were firm-based factors. In order to predict electrical energy consumption in the future, both industrialized and developing economies have undergone research on sustainable development using RESs. The results demonstrate that this model can reduce electrical energy consumption and CO2 emissions in accordance with the Paris Agreement goals. It was created by analyzing scenarios based on solar and wind energy sources using artificial neural network modeling. One way to lessen the impact of renewable energy's intermittent nature is via a hybrid wind-solar energy system [15–22].

A research work introduces a simplified control approach for the parallel APFs. The approach effectively removes harmonic and reactive components from the load current, leading to source currents that are sinusoidal and have a unity power factor (PF). This improves system efficiency by preventing the source from handling harmonic and reactive power. The proposed theory for three-phase power systems offers a solution to the limitations of traditional theories by allowing for the extraction of harmonic current. It also provides a compensator for three-phase power systems with harmonic distortion and zero-sequence components. Capacitor compensation can improve voltage at the point of common coupling, which in turn enhances the torque-speed capability of an induction generator. Static var compensators (SVC) are commonly employed for parallel compensation, whereas series compensation helps to counteract voltage drop caused by line impedance. Fixed capacitors can be used for both types if they are the appropriate size. Optimal compensation of reactive power is crucial for maintaining power quality and voltage stability. Thyristor-controlled reactors and thyristor-switched capacitors can be utilized in conjunction with the grid. Solving the issue of optimal reactive power compensation in smart microgrids can be achieved through the utilization of quadratic optimization frameworks and a distributed algorithm. A distributed algorithm is designed, which operates without a central leader and incorporates randomization. It relies on local communication and knowledge of the network topology. A performance metric is suggested, enabling the optimal clustering choice [23–26]. Lam et al. [27] presented an innovative approach to address power quality issues in a three-phase four-wire system. The proposed solution is an adaptive direct-current (DC) -link voltage-controlled inductor-capacitor coupling HAPF with dynamic reactive power compensation capability. The simulation and experimental results demonstrate that the proposed algorithm delivers excellent performance in dynamic reactive power compensation. It also effectively minimizes switching loss and noise, outperforming traditional fixed DC-link voltage-controlled inductor-capacitor coupling hybrid APFs. Zhang et al. [28] proposed reactive power planning, which is a method that aims to minimize costs and technical merits in power systems. Alzakkar et al. [29] other methods employ sensitivity analysis to simplify optimization formulations and minimize compromises in accuracy. MATLAB is commonly employed to model and calculate transformer and filter parameters to manage reactive power in electrical grids effectively. Mohseni-bonab et al. [30] examined current research on the optimal reactive power dispatch problem, with a particular emphasis on the growing adoption of stochastic multi-objective optimal reactive power dispatch methods and the challenges posed by resource uncertainties. Introducing a new objective function, the variable cost of wind farms, is crucial for maintaining voltage stability.

Research on reactive power compensation systems by Igbinovia et al. [31] shows that control coordination is an important issue in static synchronous compensator (STATCOM) and SVC situations. The ability to generate harmonics is a key feature that sets synchronous condensers apart from SVC and STATCOM. On the other hand, synchronous condensers might be more attractive than SVC. These devices can endure low-voltage conditions and are dependable reactive power sources. Both performance and cost are positively affected by technical developments and the accessibility of replacement parts.

Nuhin et al. [32] exhibited a simulation of a power monitoring system for a grid-connected solar photovoltaic system with an energy storage system. The system operates with a peak capacity of 2.091 kW and is designed to seamlessly integrate with both the utility grid and solar plant. An energy storage system utilizing lithium-ion batteries is incorporated to provide power in the event of grid failure or load-shading situations. The simulation study showcases the system's functionality, measuring power consumption, export of surplus power, and power generation during grid outages. Surender et al. sought to optimize the allocation of distributed generation and D-STATCOMs in a radial distribution system using the gravitational search algorithm to improve system voltage and reduce power losses. The approach is expanded to address the network reconfiguration problem and allocate distributed generation and D-STATCOM with a focus on minimizing losses. The proposed approach is being tested on a standard 33-bus radial distribution system to analyze its long-term viability. Seven cases were simulated, and the minimum loss was reported to be 202.68 kW. Additionally, the minimum bus voltage showed an improvement from 0.9131 p.u. to 0.9412 p.u. The voltage has increased from 0.9131 p.u. to 0.9692 p.u. The optimization results revealed a significant 61.44% decrease in power loss when compared to the base case [33]. Salkuti et al. presented a method for minimizing power losses in radial distribution systems through the use of network reconfiguration and distributed generation. An algorithm called differential evolution is utilized to solve the problem. Simulations indicate that the combined use of distributed generation and D-STATCOM units significantly decreases power losses by 82.92% and raises the minimum voltage to 0.9805 p.u [34]. Goyal and Birla examined the performance of the Yd11 transformer in a traction power substation, showcasing its advantages over Scott and V/V transformers. When comparing it with an existing fuzzy logic controller and a proportional-integral controller integrated with a type-2 fuzzy logic controller, it is able to find results under both balanced and unbalanced conditions [35].

Rajalingam et al. conveyed a pure wave distribution static compensator for solar power interconnection, ensuring power quality remains uncompromised. It utilizes a seven-level inverter for solar energy conversion and an inductor-capacitor inductor filter for active damping, just like an electrical engineer would. This configuration minimizes THD and improves the stability of the system's voltage. Simulation results indicate a THD of 3.00% and a current of 2.26% using the proposed method, resulting in reduced costs and sizing for the filter. MATLAB Simulation software is utilized for the development and simulation [36].

THD is a technique used to measure the extent of distortion in a wave derived from the voltages and currents at the common coupling point for distribution systems and clients. It varies based on the source of distortion and can be achieved through a straightforward algorithm. Inter-harmonics in signals can pose challenges in analysis and measurement because of variations in waveform periodicity and low amplitudes. There are certain sources of inter-harmonics that arise from devices that connect two frequencies of AC and direct current (DC). Applying Hanning windowing can enhance the accuracy of the results, whereas techniques such as phase-locked loop, which involve synchronized processes, can be affected by uncertainties when estimating fundamental frequencies. Utilizing desynchronized process techniques and harmonic filtering ensures precise and consistent results without the need for re-sampling. Non-stationary signals may result in non-integral bins. However, these bins should not be considered genuine interharmonics. For accurate identification of inter-harmonics, it is important to carefully choose the window size so that the frequency resolution is a shared factor among all signal components. By utilizing voltage-current correlation, wave shape check, and zero-padding techniques, one can effectively identify real inter-harmonics. Solar photovoltaic energy is receiving more and more attention worldwide, but it does come with some drawbacks, including PF and THD issues. These problems may result in excessive heat and potential harm to the components of the power system. This study examined PF and THD values under cloudy conditions using a MATLAB/simulation program. It derived analytical expressions for these factors based on the level of irradiation. The findings make a valuable contribution to the field of science by conducting a thorough comparison with existing literature. They offer insights that can be utilized to mitigate issues related to low power quality in situations with limited solar irradiation [37–39].

Bilgin et al. [40] explored the application of MATLAB in mitigating current harmonics generated by current-source converters, resulting in a switching frequency of 500 Hz. This approach can be utilized for transmission and D-STATCOMs, broadening its range of possible applications beyond generation. Awasth and Huchche [41] also presented a versatile control scheme for D-STATCOM utilization. It utilizes instantaneous symmetrical component theory to calculate reference source currents, ensures the minimum allowable PF at the point at common coupling, enhances PF if the reference load voltage drops below the lowest permissible operating voltage, and keeps the load voltage stable during voltage disturbances while protecting delicate loads. Simulation results demonstrate the effective management of energy and the successful resolution of current and voltage-related power quality issues. An article by Qi et al. [42] demonstrated a comparison of SVC and STATCOM performance using simulation tests and introduces a novel coordination method for reactive power control of doubly fed induction generator and STATCOM. The proposed control method is thoroughly tested under various working conditions to assess its effectiveness. Additionally, the advantages of this control method are carefully analyzed and verified in different system short-circuit fault scenarios. An approach for improving the settings of HAPF based on differential evolution is presented: the L-SHADE optimization algorithm by Biswas et al. [14]. The aforementioned paper explores its application in HAPF parameter design and evaluates its performance in comparison to other similar algorithms. The L-SHADE technique is straightforward yet powerful, assisting in the initial selection of HAPF parameters prior to field experiment validation. This study investigates the application of finite control set model predictive control in a HAPF. It aims to enhance reactive power control, dynamic response, and the separation of active and reactive power control. Various wind speeds are utilized for the purpose of comparing maximum power point tracking algorithms. Additionally, a simulation model with a capacity of 2 mega-watt is developed and analyzed using MATLAB/Simulink [43, 22].

Another HAPF provides a range of benefits, including a low DC-link operating voltage, a wider operational range, and the ability to simultaneously compensate for reactive, harmonic, and unbalanced powers. This paper explores linear control aspects and presents a multi-quasi-proportional-resonant controller with gain scheduling for a thyristor-controlled LC-coupling HAPF. The proposed controller effectively minimizes steady-state current tracking errors and output current ripple and can be compared to hysteresis current and quasi-proportional-resonant controllers [44].

Lee et al. developed a technique to monitor AC capacitor voltage in a grid-connected HAPF without the need for extra voltage sensors. This method effectively safeguards against the burnout of AC capacitors caused by harmonic current and inverter voltage. Simulations and experiments have successfully validated the sensorless AC capacitor voltage monitoring method, showing a small average difference of 0.526[%] between the measured and predicted voltages [45].

Long-term stability and reliability of the real-time algorithm for multilayer inverters are the main challenges. Grid interruptions, voltage variations, and environmental interference can affect optimal HAPF parameters, according to certain authors. Wind energy faces challenges that include incentive discontinuance, land acquisition concerns, bidding changes, and outmoded wind sites. Optimization and control methods address reactive power compensation and voltage stability, although STATCOM and SVC coordination and synchronous condenser robustness remain important. HAPF and hybrid energy system control methods and algorithms must also be tested under various scenarios to assure reliability and efficiency.

3.Methods

For an optimal simulation, MATLAB/Simulink software was selected. Next, the main or core circuit was drawn in the Simulink section, incorporating components such as step-up and step-down transformers, a three-phase power source, resistive and resistive-inductive-capacitive loads, RESs, two busbars, and two scopes. Two separate main circuits were added to the system, with the inclusion of D-STATCOM and HAPF in each circuit. These circuits were then connected in parallel. A capacitor bank has been added to each circuit. Next, the primary data collection involved measuring the three-phase voltage at busbars 1 and 2, as well as the THD of each voltage for both busbars. This was achieved by adjusting the capacitor values. If the results fell within the stable and accepted range, then the analysis was conducted. If the values were not ideal, the process would return to the step where the capacitor bank was selected. *Figure 1* shows how the methodology proceeded.

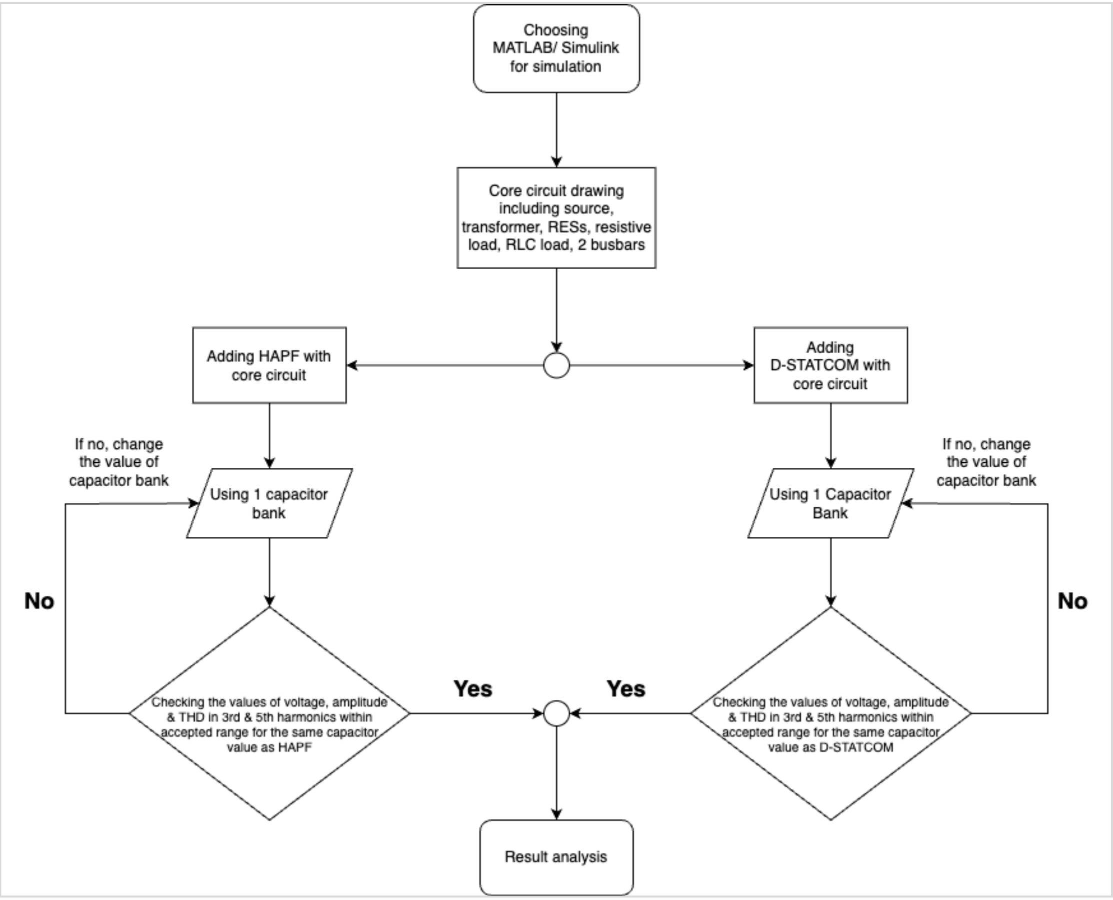


Figure 1 Flow diagram of methodology

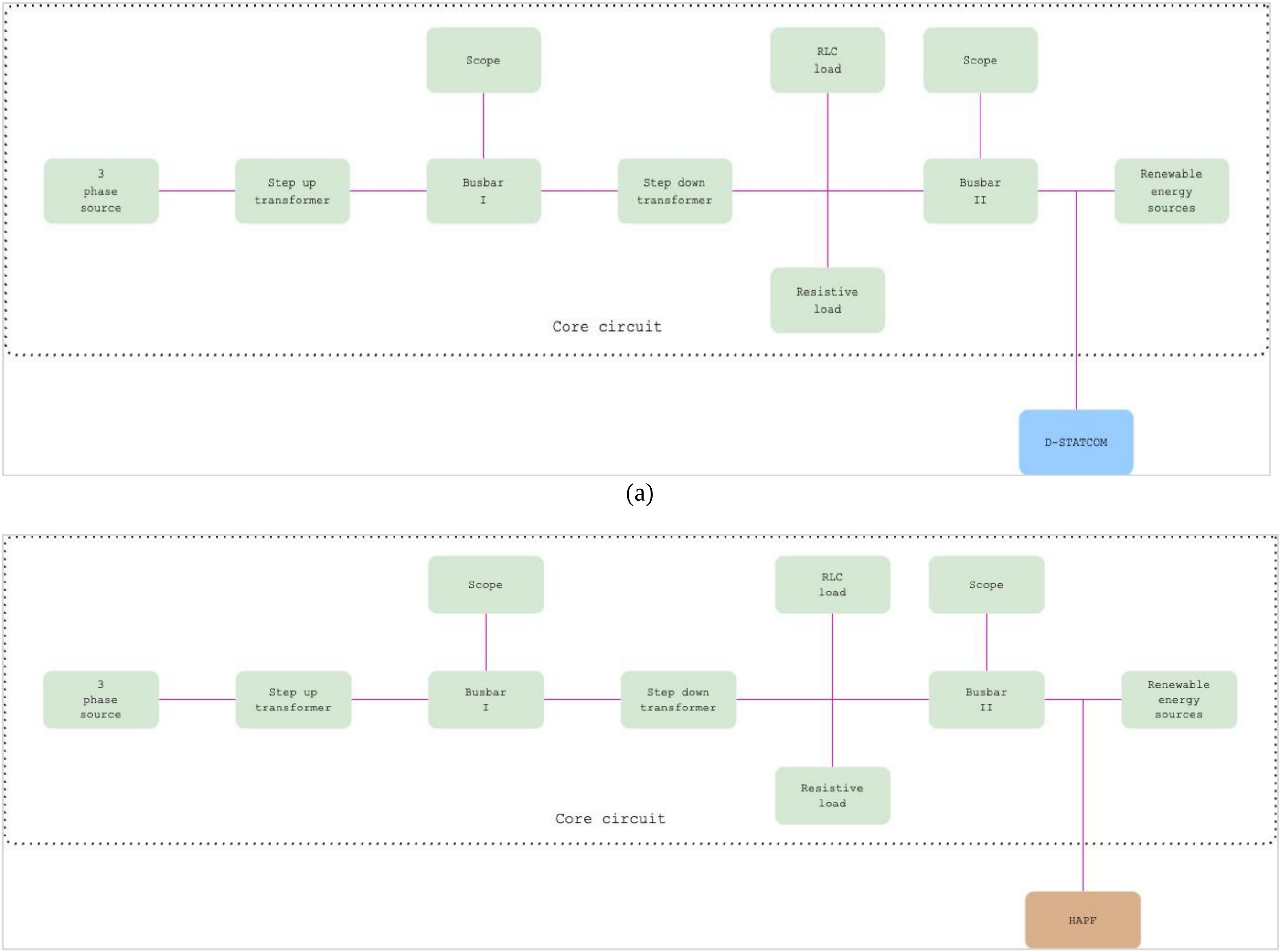
3.1D-STATCOM and HAPF

Figure 2(a) and *Figure 2(b)* depict the fundamental block diagram of the power system, illustrating the integration of power derived from RESs into the preexisting grid. The implementation of D-

STATCOM and HAPF has been undertaken as a means to achieve sustainable grid synchronization.

The regulation of voltage at the point of connection to the power grid can be achieved through the utilization of a D-STATCOM. The D-STATCOM device has been implemented in this study which generates reactive power in instances where the voltage of the system is low. When the voltage is high, the D-STATCOM causes the system to draw reactive power, which reduces THD. The D-STATCOM is installed parallel to the power system [46].

The principal purpose of a HAPF is to mitigate and regulate load harmonics [47]. The design of the harmonic filter is innovative as it incorporates the advantages of both active and PFs types. APFs, PFs, a proportional-integral controller, a hysteresis current controller, and a three-phase voltage source inverter are all part of the system as a whole. The instantaneous space vector values can be conveyed by observing the waveforms of the current and voltage in three-phase circuits, which do not change in real time. Thus, using Clark's transformation matrix, a b c coordinates with a 2Pi/3 phase difference between each axis can be transformed into alpha-beta coordinates [2, 3, 8].



(a)

(b)

Figure 2 Block diagram of the **(a)** D-STATCOM connected **(b)** HAPF connected with the main grid

3.2THD

THD is a quantitative measure used to assess the extent to which a signal deviates from its ideal sinusoidal form. The purpose of this analysis is to measure the extent to which harmonic components, which are frequencies that are integer multiples of the fundamental frequency, are present in the signal. The calculation of THD commonly involves determining the ratio between the root mean square amplitudes of all harmonic components and the root mean square amplitude of the fundamental frequency [13].

In Equation 1, where V_1, V_2, V_3, and V_n are the voltage amplitudes of the first, second, third, and nth harmonics, respectively.

$$\mathrm{THD} = \frac{\sqrt{V_2^2+V_3^2+\cdots+V_n^2}}{V_1} \times 100\% \qquad (1)$$

4.Results

Two different models have been implemented for the comparative analysis, and one of them has shown better results. A D-STATCOM and HAPF have been implemented on a power system with RESs.

4.1Simulation models

This study aims to assess and compare the performance of D-STATCOM [46] and a HAPF [47], which have been added in parallel to the power system. The results have been taken for busbar 1 and then for busbar 2, respectively. Every simulation was carried out at a frequency of 50 Hz in every element and device. Three distinct capacitor banks have been implemented (40-kilovolt ampere reactive (KVAR), 60 KVAR, and 80 KVAR), and all of the analyses have been completed for each capacitor bank.

Table 1 is provided, which contains the main components of D-STATCOM and HAPF. *Table 1* does not give specifications for capacitor banks. *Figure 3* shows the D-STATCOM and HAPF models, which are included in the D-STATCOM and HAPF as a rectangle-shaped box. Which one has shown better results between D-STATCOM, which is shown in *Figure 3(a)*, and the HAPF, which is shown in *Figure 3(b)*, is analyzed in this study. The external part is the main grid where these two models have been implemented. The values of resistors, inductors, and capacitors have been changed, but the results were always indifferent to each value of the capacitor bank. This analysis is also important for the simulation of these models.

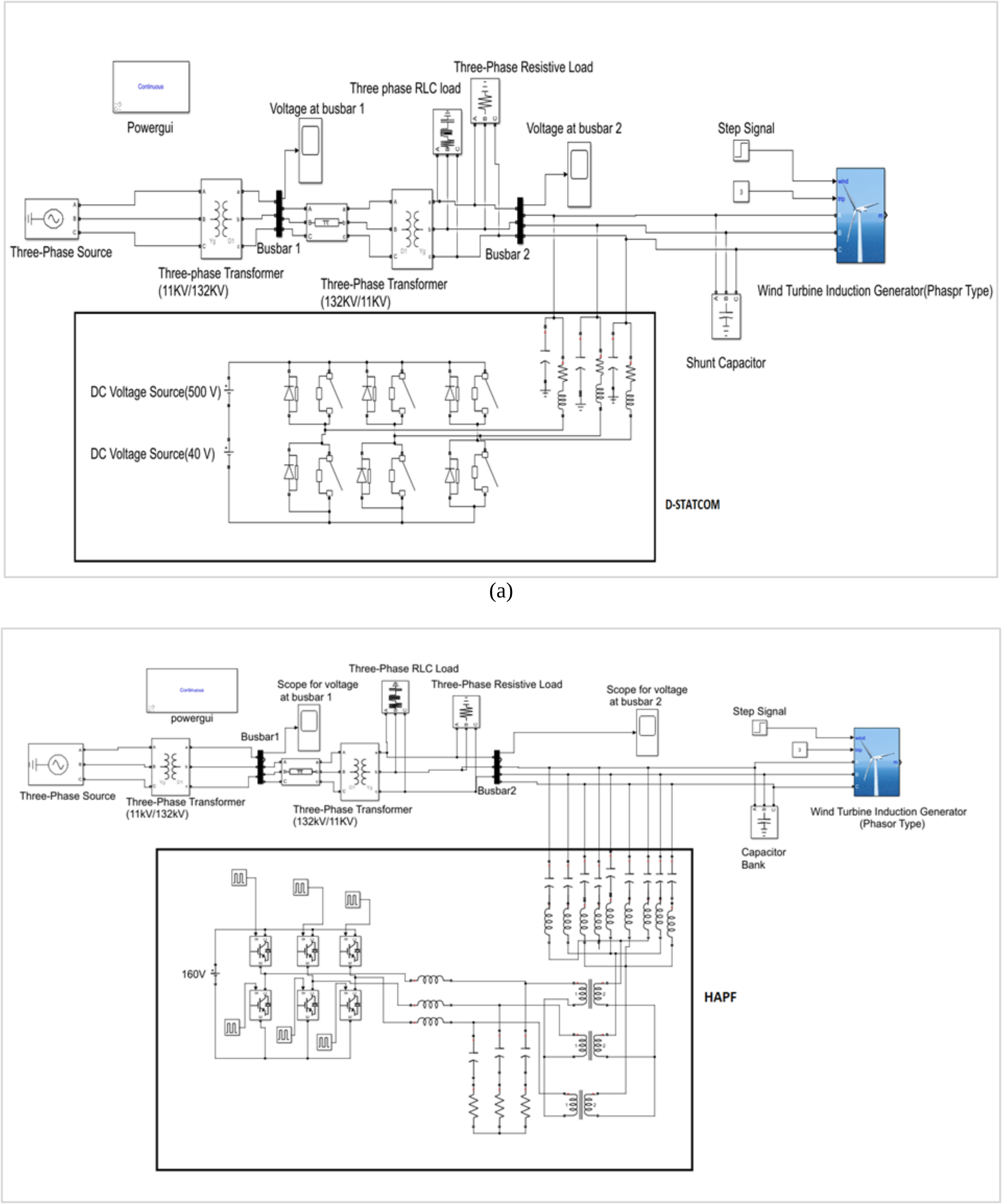
Table 1 The main components of the major blocks

Main Grid	**D-STATCOM**	**HAPF**
Source (11 kilovolts (KV))	Two DC voltage sources (500 V and 40 V) 1.	One DC voltage source (160 V)
Two three-phase transformers (11KV/132KV and 132KV/11KV)	Six diodes	Six IGBTs
One wind turbine induction generator (11KV and 12 MW)	Three resistors (1K ohm at each), three capacitors (470 mF at each), and three inductors (200mH at each)	Twelve resistors (5 ohms), twelve capacitors (47 uF), and twelve inductors (10 uH)
One capacitor bank	-	Three transformers
Two loads	-	

4.2Simulation results

The duration of voltage stability in each scenario, considering various capacitor banks, has been modeled in this study. The present study examines the THD values in relation to various capacitor banks and loads. The simulation outcomes are obtained using the MATLAB/Simulink software. The simulation results of the three-phase voltage at busbar 1 are shown in *Figures 4 to 6* for the main circuit with D-STATCOM, and the main circuit with HAPF with different capacitor bank values. *Figures 4 to 9* clearly show that the D-STATCOM stabilizes after 0.5 seconds, and the HAPF achieves stability after 0.1 seconds. The results in *Figures 4 to 9* indicate that the HAPF demonstrates enhanced voltage stability, which has significant implications for a range of applications, such as the integration of RESs and industrial operations. Gaining comprehension of the transitory dynamics of these technologies and the corresponding duration of instability is crucial for making informed decisions.

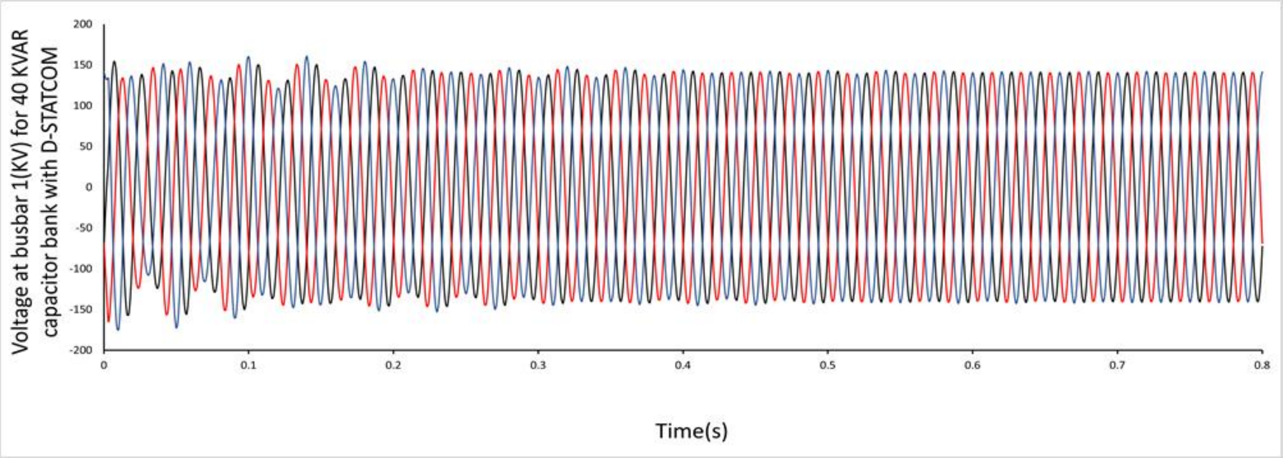
The simulation results for the three-phase voltage at busbar 2 are displayed in *Figures 7 to 9*. These figures illustrate the basic model with D-STATCOM and the basic model with HAPF, each incorporating different capacitor bank values.



(a)

(b)

Figure 3 Simulation models (a) the model including D-STATCOM (b) the model integrating a HAPF



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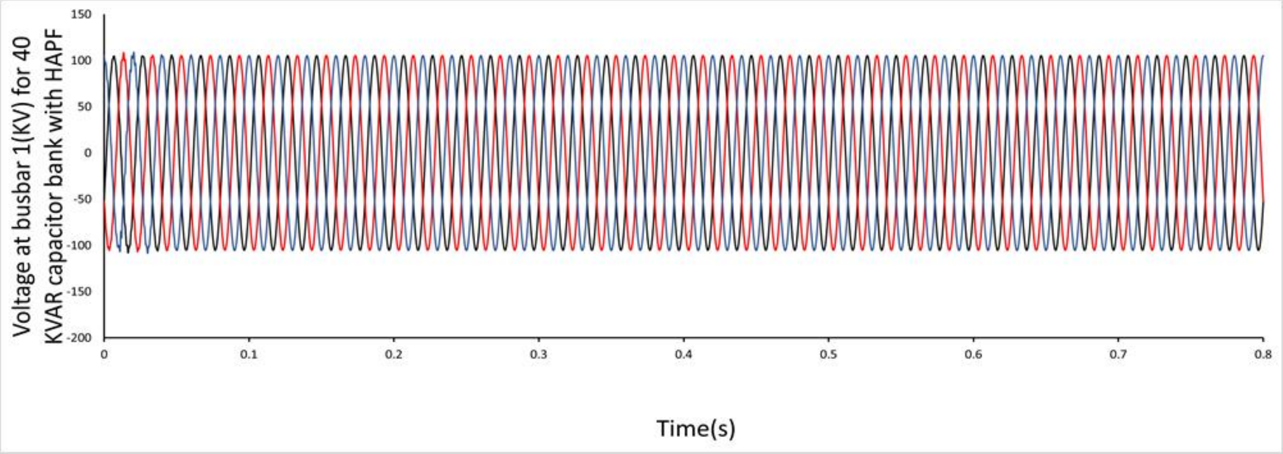
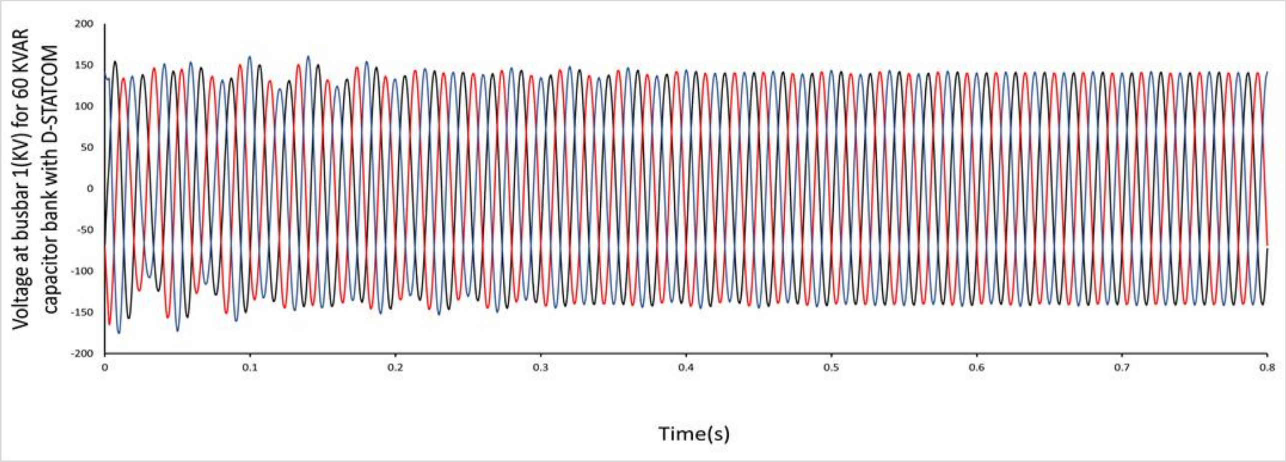


(b)

Figure 4 Simulation results for D-STATCOM and HAPF at busbar 1 **(a)** For D-STATCOM at 40 KVAR **(b)** For HAPF at 40 KVAR



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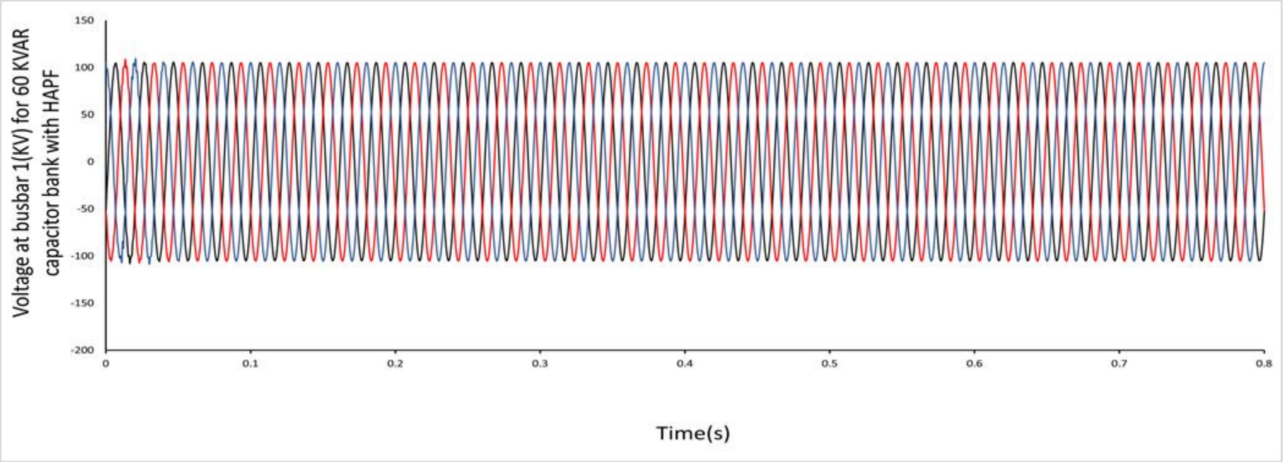
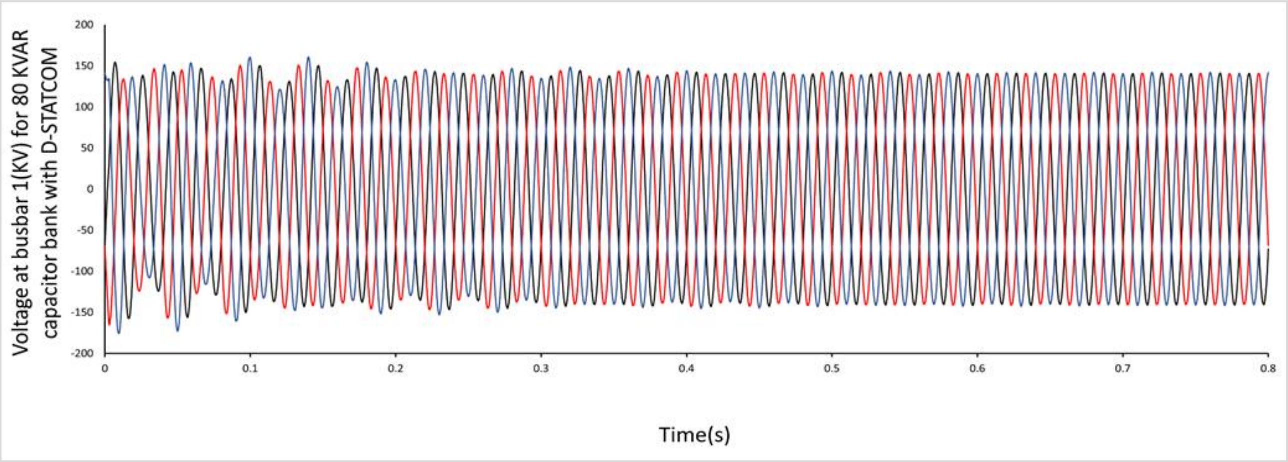


(b)

Figure 5 Simulation results for D-STATCOM and HAPF at busbar 1 **(a)** For D-STATCOM at 60 KVAR **(b)** For HAPF at 60 KVAR



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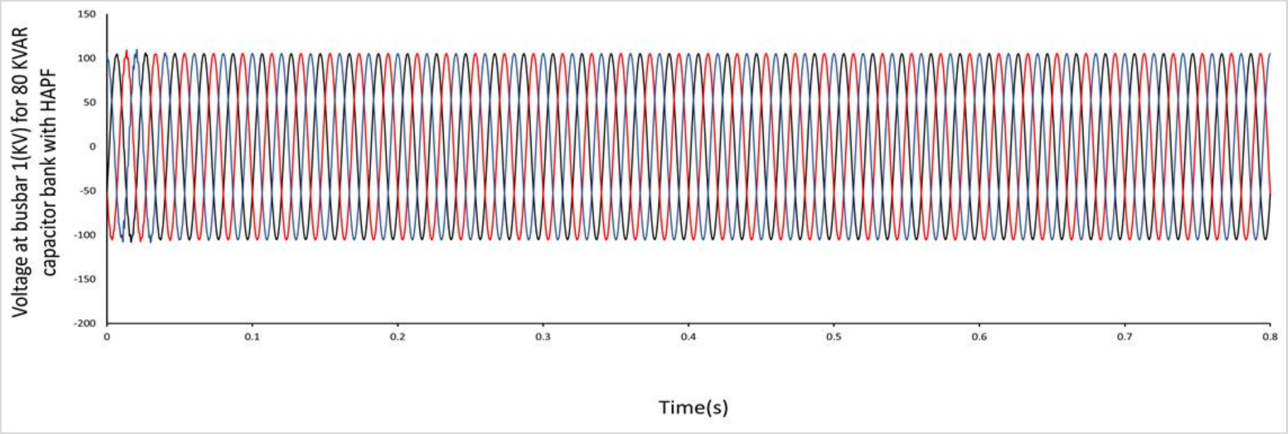
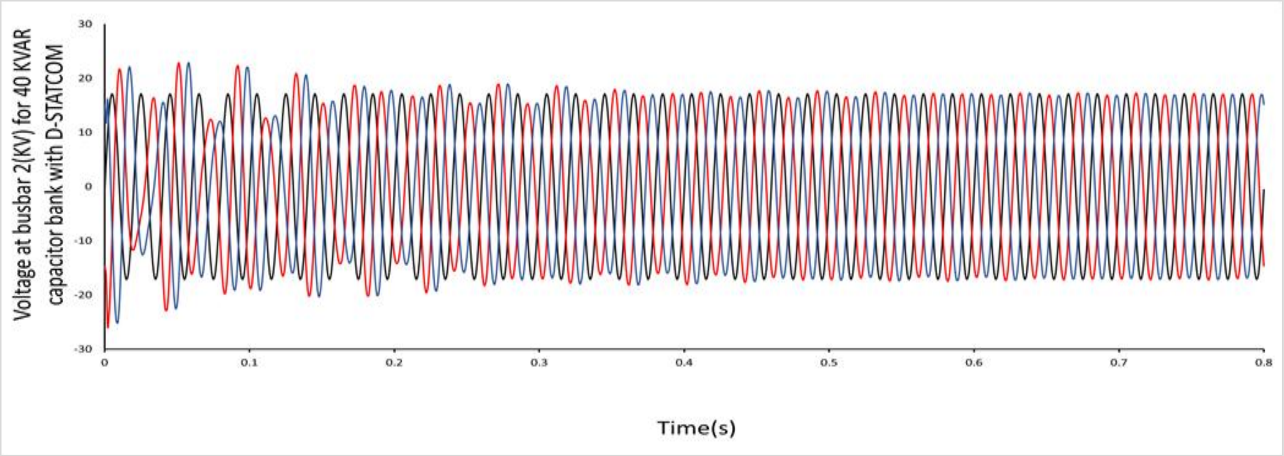


(b)

Figure 6 Simulation results for D-STATCOM and HAPF at busbar 1 **(a)** For D-STATCOM at 80 KVAR **(b)** For HAPF at 80 KVAR



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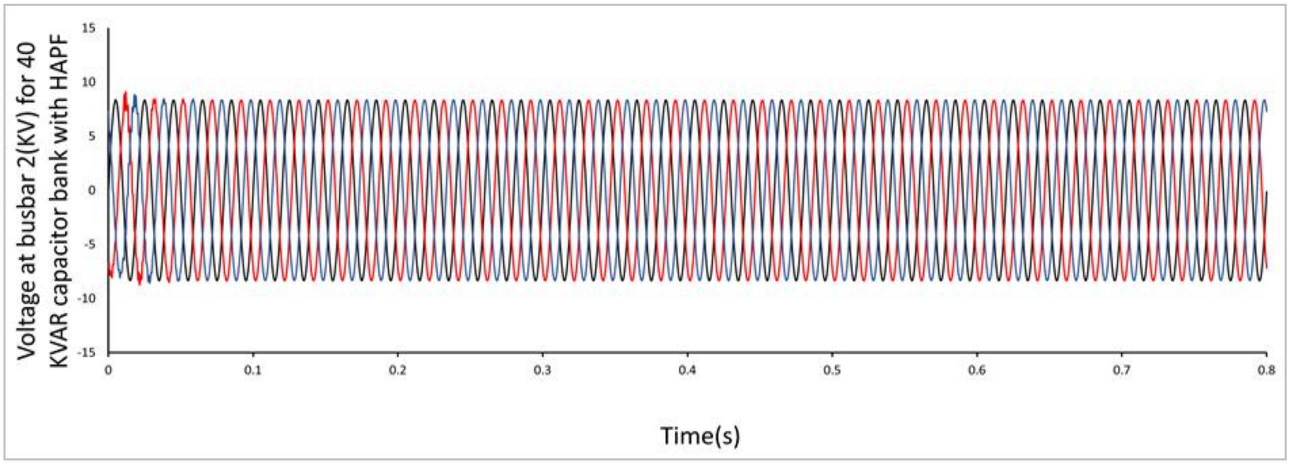
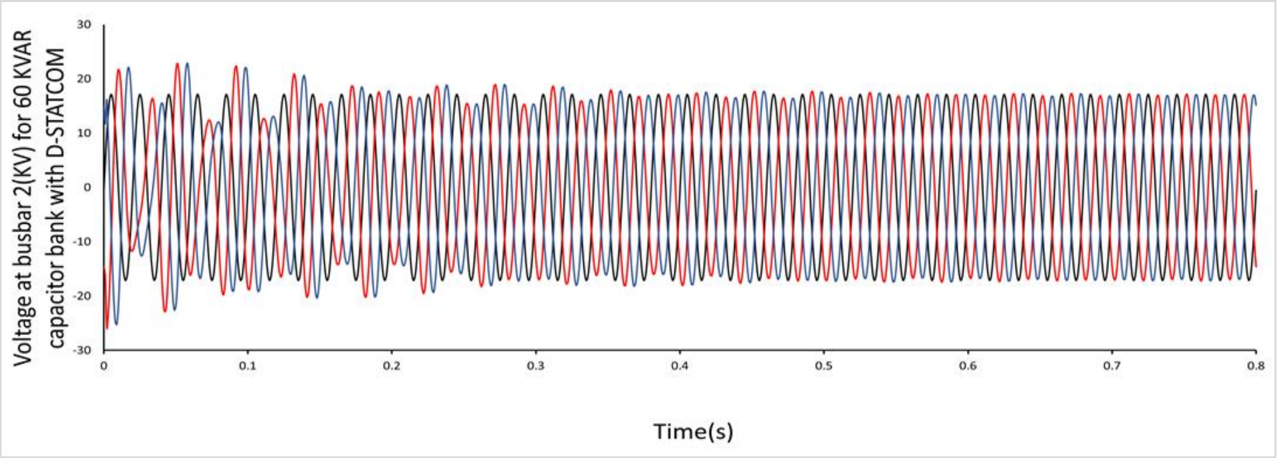
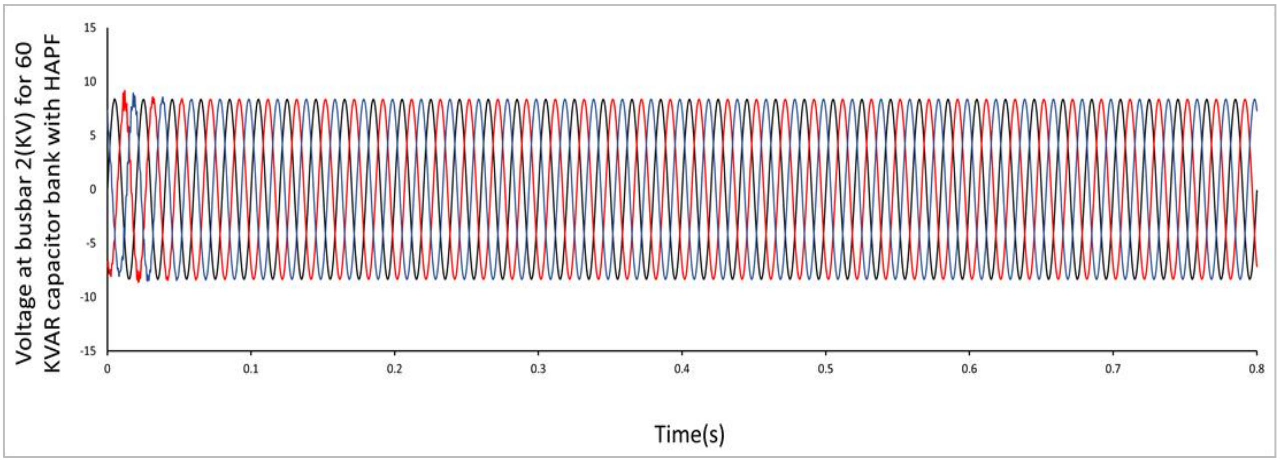


(b)

Figure 7 Simulation results for D-STATCOM and HAPF at busbar 2 **(a)** For D-STATCOM at 40 KVAR **(b)** For HAPF at 40 KVAR

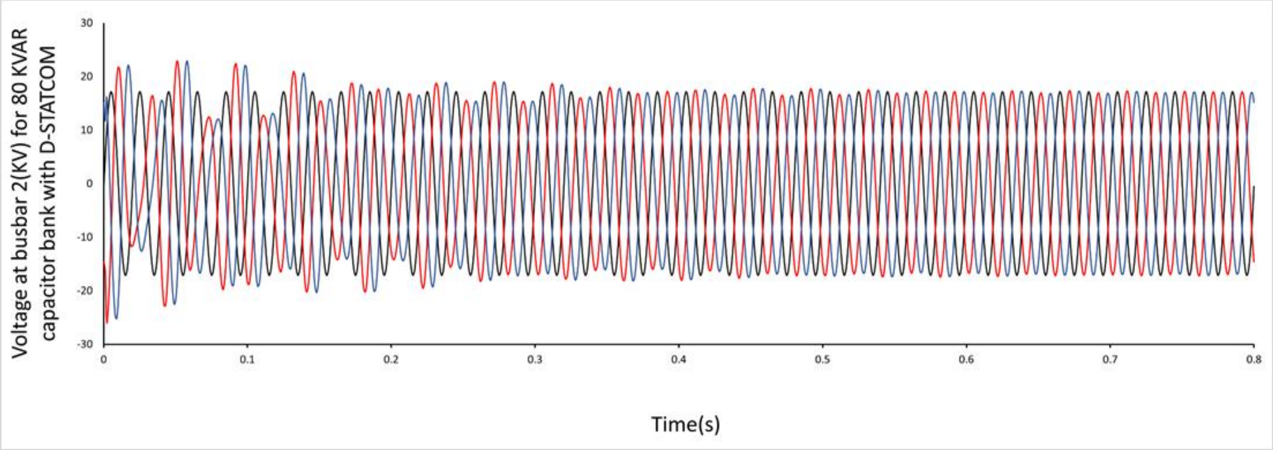


(a)

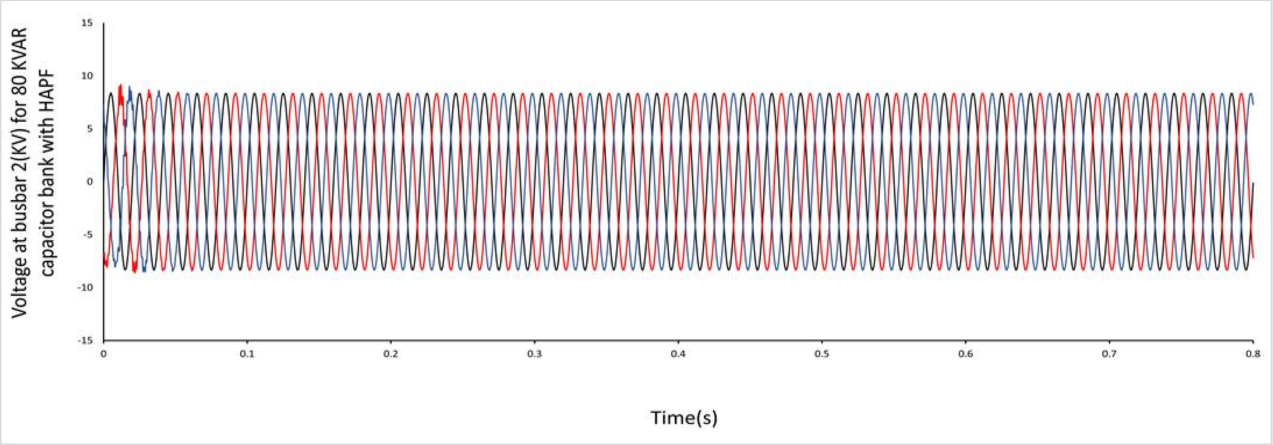


(b)

Figure 8 Simulation results for D-STATCOM and HAPF at busbar 2 (a) For D-STATCOM at 60 KVAR (b) For HAPF at 60 KVAR



(a)



(b)

Figure 9 Simulation results for D-STATCOM and HAPF at busbar 2 **(a)** For D-STATCOM at 80 KVAR **(b)** For HAPF at 80 KVAR

Nevertheless, it is imperative to recognize that any technology possesses inherent limitations. The D-STATCOM, despite its initial instability, ultimately achieves voltage stabilization. Furthermore, as further investigation of this topic, additional variables, including the levels of THD and the 3rd and 5th harmonics of each phase of voltages have been discussed. Various measurements offer a more holistic comprehension of the performance of various technologies and their influence on the quality of power provision. *Figure 10* displays the comparative bar chart of THD at busbar 1 and for 0.8 seconds between D-STATCOM and HAPF.

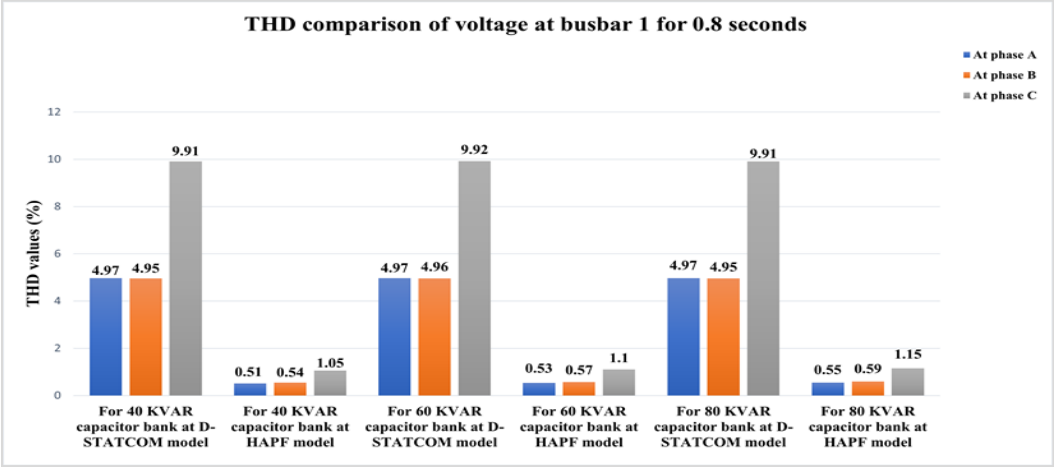


Figure 10 Bar chart between D-STATCOM and HAPF of THD (%) of voltage at busbar 1 for 0.8 seconds

The THD values of the D-STATCOM model's voltages in *Figure 10* are observed to be higher than those of the HAPF model, specifically for a specific capacitor bank. Three capacitor banks were chosen for the THD comparison of both models. The capacitor banks used in the analysis are 40 KVAR, 60 KVAR, and 80 KVAR for both busbars 1 and 2. The HAPF demonstrates the accepted THD of voltage at busbar 1. The voltage of busbar 1 is 132 kV, and the voltage of busbar 2 is 11 KV. Nevertheless, the D-STATCOM does not provide the accepted voltage THD values for individual capacitor banks. Therefore, it is crucial to implement the D-STATCOM in a planned manner while also minimizing the potential risk associated with unacceptable THD values in this grid. The repetition of the conclusion stated in *Figure 10* becomes almost apparent in *Figure 11*. The HAPF has demonstrated acceptable THD values, as opposed to the D-STATCOM. The variations in voltage levels between phases A, B, and C are large. In certain instances, this occurrence can have negative consequences. Based on an analysis of the voltage graph and the THD values, it is evident that the HAPF outperforms the D-STATCOM. Another analysis was conducted to examine various load values. However, no noticeable modifications were observed in either the D-STATCOM or the HAPF. Based on the available evidence, it can be assumed that the load variable does not have any noticeable influence on the models under consideration. The THD values remained consistent across different load variations for both D-STATCOM and HAPF. The last analysis has been conducted with regard to the 3^{rd} and 5^{th} harmonics for every phase. This analysis might also serve to illustrate which model is superior. *Figures 12* and *13* present bar charts illustrating the 3rd and 5th harmonics observed at busbar 1 and busbar 2. *Figure 12* and *Figure 13* demonstrate that the D-STATCOM model exhibits higher harmonics than the HAPF model. The voltage harmonics at busbar 1 exhibit zero values, whereas at busbar 2, they do not exceed values bigger than 0.01 in the context of the HAPF model. However, the D-STATCOM model has significantly higher values compared to the HAPF model. Based on the present data, it is evident that HAPF has exhibited superior outcomes in comparison to D-STATCOM. Based on the data, it is evident that HAPF has exhibited more favorable results in comparison to D-STATCOM.

Numerous prior studies have been conducted. However, the methodology employed for comparison in this particular study is unique. A concise overview of the THD and the fundamental model is provided to enhance comprehension. The simulation was performed using MATLAB/Simulink software, and the corresponding simulation models and results are presented. The practical implications of these findings are examined. The output has been measured and compared by varying the values of the capacitor bank and load in order to determine which configuration yields superior results across multiple criteria.

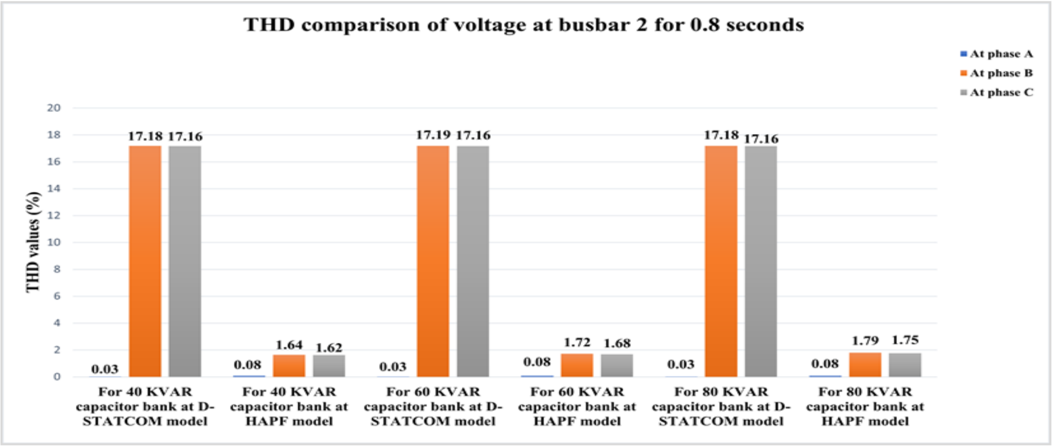
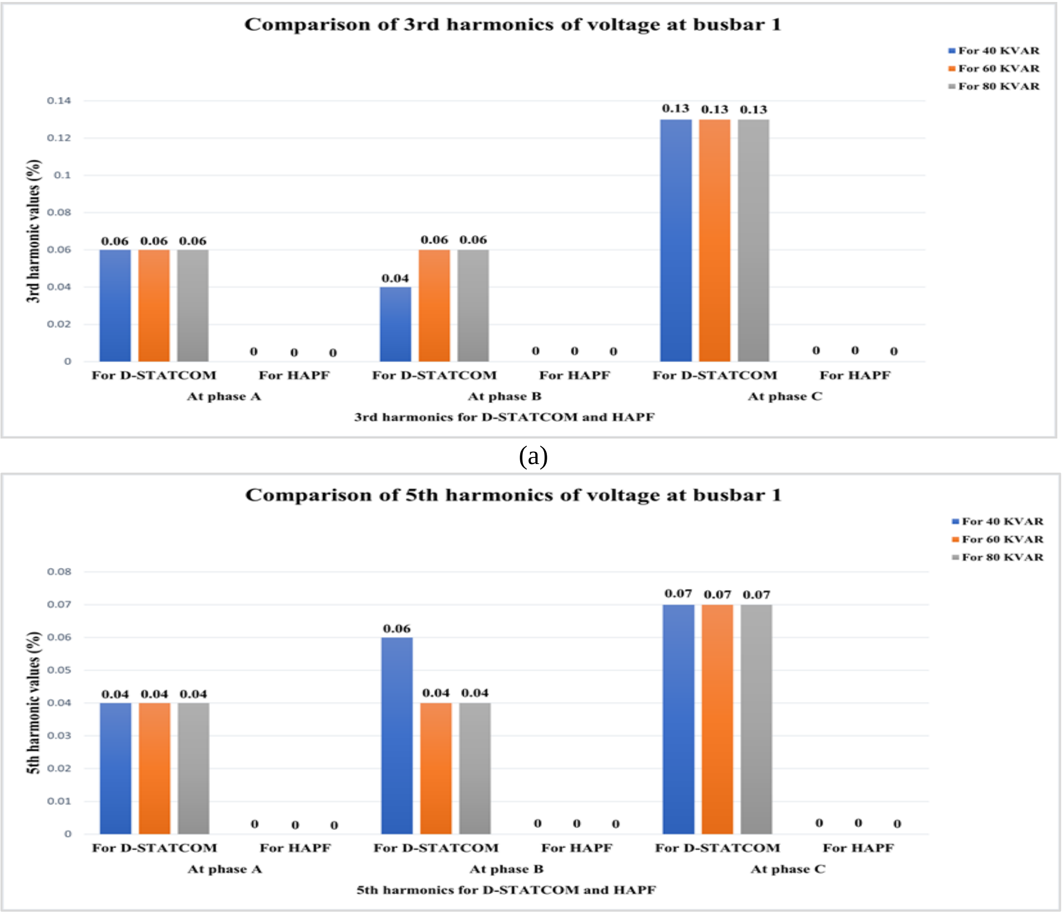
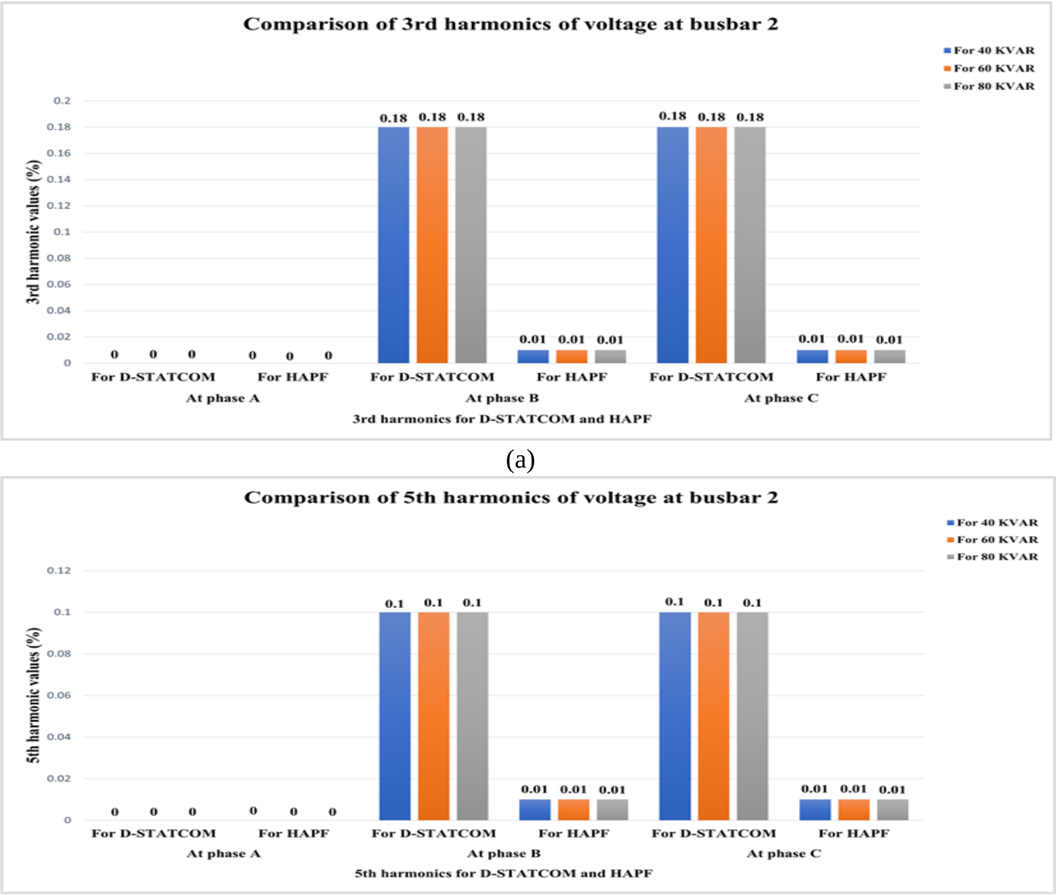


Figure 11 Bar chart between D-STATCOM and HAPF of THD (%) of voltage at busbar 2 for 0.8 seconds



(b)

Figure 12 Bar chart between D-STATCOM and HAPF of harmonics of voltage at busbar 1 for 0.8 seconds (a) Data of 3rd harmonic (%) (b) Data of 5th harmonic (%)



(a)

(b)

Figure 13 Bar chart between D-STATCOM and HAPF of harmonics of voltage at busbar 2 for 0.8 seconds (a) Data of 3^{rd} harmonic (%) (b) Data of 5^{th} harmonic (%)

5.Discussion

The analysis presented in this input focuses on the performance comparison between the D-STATCOM and HAPF technologies. *Figures 4 to 9* provided the stability of both technologies over time, with the D-STATCOM achieving stability after 0.5 s and the HAPF after 0.1 s. The results indicate that the HAPF demonstrates enhanced voltage stability, which has significant implications for various applications, including renewable energy integration and industrial operations. While the D-STATCOM initially experiences instability, it eventually achieves voltage stabilization. To gain a comprehensive understanding of their performance, additional variables such as THD and the 3rd and 5th harmonics of each phase of voltages need to be examined. These measurements provide a more holistic view of the technologies' impact on power quality. The THD values comparison between the D-STATCOM and HAPF models reveals that the HAPF consistently demonstrates acceptable THD values, while the D-STATCOM does not meet the accepted voltage THD values for individual capacitor banks. This highlights the need for careful implementation of the D-STATCOM to minimize the risk associated with unacceptable THD values in the grid. Further analysis of load variations shows no noticeable modifications in either technology, indicating that load does not significantly influence their performance. Additionally, the analysis of the 3rd and 5th harmonics demonstrates that the D-STATCOM model exhibits higher harmonics compared to the HAPF model. Based on these findings, it is evident that the HAPF outperforms the D-STATCOM in terms of THD and harmonics. The unique methodology employed in this study provides a concise overview of THD and the fundamental model, utilizing MATLAB/Simulink software for simulation. The practical implications of the findings are also examined, considering variations in capacitor bank and load values to determine the superior configuration based on multiple criteria.

The acquired output also references other studies that have explored power quality improvement and voltage stability in hybrid AC-DC microgrids and the performance of D-STATCOM integrated with a grid-tied solar photovoltaic array. The study by Nafeh et al. [48] covered topics related to improving power quality and voltage stability in hybrid AC-DC microgrids. The findings of the simulation are used in MATLAB/Simulink to simulate the microgrid that was tested with two controllers based on fuzzy logic. When utilizing fuzzy logic proportional-integral-derivative, the performance of the dynamic system is enhanced by 8.8%, while using fuzzy-PI improves it by 7.86%. Additionally, when comparing the controlled and uncontrolled systems, the voltage fluctuation at the D-STATCOM is reduced by 0.982% and 0.577%, respectively, and the performance of the dynamic system is enhanced by 6.67% and 5.71%, thanks to the fuzzy logic proportional-integral-derivative controller and fuzzy logic proportional-integral, respectively [48]. The work by Rastogi et al. [49] presents and investigates the performance of a D-STATCOM that is based on a two-level, three-phase, reduced-switch, voltage source converter and integrated with a grid-tied solar photovoltaic array. The size and cost of the converter have been minimized by using a three-phase, two-leg reduced-switch count D-STATCOM. Additionally, reducing the number of switches lowers the switching and conduction losses. The switching losses are cut in half compared to the old-fashioned 3-phase,3-leg voltage source inverter [49]. Compared to inductor-capacitor-inductor-capacitor coupling HAPF with proportional-derivative, the data show that active damping improves the performance of the former in an analysis [50].

Numerous studies have examined D-STATCOM and HAPF, but this study is the first to compare and contrast the two. In addition, the 3rd and 5th harmonics of the THD are hardly considered in the little research on these two devices. The outcomes have been outstanding and within the acceptable range. These studies highlight the benefits of using fuzzy logic controllers and reduced-switch converters to enhance system performance and reduce losses. Overall, this analysis contributes to the existing body of research by comparing and contrasting the D-STATCOM and HAPF technologies, considering various performance metrics such as stability, THD, and harmonics. The outcomes suggest that the HAPF exhibits more favorable results compared to the D-STATCOM, emphasizing the importance of selecting the appropriate technology for specific applications.

5.1Limitations

The analysis was successful, but it only considered one power system that used renewable energy, wind energy, in this instance. The study establishes the fixed specifications of this power system. Experimenting with various types of wind generators, solar energy generators, power systems, or combinations of these can reveal what works best. Another factor that can affect the stakeholders is the lack of a cost analysis in this study. Therefore, future studies could benefit from analyzing various power systems and costs in order to put these models into practice. However, it is important to acknowledge the limitations of this study, specifically regarding the disparity in THD and unstable time values between the voltages at busbar 1 and 2. This observation can provide valuable insights for future research works. The findings of this study are expected to have a substantial impact on future research and the practical application of power systems. A complete list of abbreviations is listed in *Appendix I.*

6.Conclusion and future work

This study conducts a comparative analysis between a D-STATCOM and a HAPF. The findings of this analysis indicate that the HAPF has demonstrated superior performance compared to the D-STATCOM in terms of stability, THD, and 3rd and 5th harmonics. The stability of the graphs, the THD values, and the 3rd and 5th harmonic values of the HAPF were found to be within the acceptable range, in contrast to the D-STATCOM. The motivation for conducting this study originated from the imperative to establish a secure and reliable infrastructure for a power system. In the event of power system instability, there exists the potential for detrimental effects on system components, with the most severe outcome being a complete system problem. Both D-STATCOM and HAPF have demonstrated outstanding performance in previous research studies. However, this particular analysis has not been previously conducted. The utilization of renewable energy in a power system necessitates an examination that can enhance comprehension regarding the appropriate selection and implementation of compensators or filters.

Acknowledgment

None.

Conflicts of interest

The authors have no conflicts of interest to declare.

Data availability

None.

Author's contribution statement

Bonolata Biswas Taya: Conceptualized, wrote, and edited the manuscript, conducted the study, and analyzed the results. **Arif Ahammad**: Conceptualized and revised the paper, supervised the conducted study, and checked the study results. **Fahmida Islam Jahin**: Conducted the study.

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Appendix I

S. No.	Abbreviation	Description
1	AC	Alternating Current
2	APFs	Active Power Filters
3	D-STATCOM	Distribution Static Synchronous Compensator
4	DC	Direct Current
5	HAPF	Hybrid Active Power Filter
6	KV	Kilovolts
7	KVAR	Kilovolt Ampere Reactive
8	PFs	Passive Filters
9	PF	Power Factor
10	RESs	Renewable Energy Sources
11	STATCOM	Static Synchronous Compensator
12	SVC	Static Var Compensator
13	THD	Total Harmonic Distortion