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RESEARCH ARTICLE

Investigation of power quality problems and harmonic exclusion in the power system using frequency estimation techniques

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Abstract

This work aims to investigate a problem with power quality and the exclusion of harmonics in the power system using a method called frequency estimation. This study aims to explore the performance of several strategies for estimating phase and frequency under a variety of less-than-ideal situations, such as voltage imbalance, harmonics, dc-offset, and so on. When the grid signals are characterized by dc-offset, it has been shown that most of the approaches are incapable of calculating the frequency of the grid signals. This article introduces a frequency estimation method known as Modified Dual Second Order Generalized Integrator (MDSOGI). This method accurately guesses the frequency under all of the unideal scenarios. Experiments have shown that the findings are accurate. In order to build a control scheme for a shunt active power filter that is able to function under such circumstances, the scheme is further integrated with the theory of instantaneous reactive power. In order to demonstrate enhanced performance, the experimental prototype is being created.

Keywords: DC-Offset, Frequency Estimation Method, Modified Dual Second Order Generalized Integrator, Power Quality.

Introduction

In the past, the majority of electricity was generated by massive centralized power plants. These facilities were often situated in close proximity to the primary source of energy (for example, coil mines), but were positioned a significant distance from load or consumer centres. Conventional fossil fuels like coal, gas, or oil were burned in thermal power plants equipped with enormous spinning generators. This was how the energy was generated. After the power has been created, it is sent out into the world through the lengthy transmission lines, which just so happen to be part of a passive network. In the last step, the power is distributed to the user via the use of the (radial) distribution network. In such a system, there was only one route that power could travel: from the producing station to the consumers.

The state maintained complete control over electricity production, transmission, and distribution (single player). In addition, the problem with the power quality (particularly the distortion of the voltages and currents) was not nearly as serious as it was made out to be since there were so few non-linear loads in the utility.

Over the course of the last few decades, there has been a discernible deviation from this tendency. The depletion of fossil resources, the decreased efficiency resulting from the transmission of information over vast distances, and the high expense involved in expanding the transmission capacity are the primary contributors to the drift. In addition, growing environmental concerns over the toxic and greenhouse gases emitted by centralized power plants have also played a crucial influence in this shift.

The use of renewable energy sources such as wind, solar, fuel cells, and other similar technologies for the creation of power may contribute to the solution of these problems. In contrast to centralized power plants, energy production may be decentralized and carried out in close proximity to various load centres. In addition, the producing unit's capacity may now range anywhere from a few kW to several MW, and

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the state no longer has a monopoly on the production of electricity (or a few power producers).

In addition to the effects of environmental policies and the progression of technology, deregulation has significantly impacted the overall structure of electricity generation, transmission, and distribution. This has led to the emergence of new conditions in the field of electricity generation. As was just indicated, the production of energy currently uses various technologies and takes place on a much larger scale.

Generating units may even be located on the distribution lines. The power flow is no longer unidirectional. All these raise certain challenges in the modern power system.

Literature Survey

For the study purpose, we have selected some important research articles which are as follows:

Abdoos, A. A., *et al.* (2016) "presented a new hybrid algorithm for PQ disturbances detection in electrical power systems. The proposed technique consists of four steps: simulation of PQ events, feature extraction, dominant feature selection, and feature categorization. Variational mode decomposition (VMD) and S-transform (ST) are used to extract possible features from PQ events. It decomposes signals into modes and examines them in time and frequency domains. Sequential forward selection (SFS) and sequential backward selection (SBS) as wrapper-based techniques and Gram–Schmidt orthogonalization (GSO) based feature selection method as a filter-based approach are used to eliminate duplicate features. SVMs are used as the classifier core to distinguish PQ events. The thorough experiments show that the suggested technique works well in terms of speed and accuracy even in noisy environments. PQ event start and endpoints may also be recognized precisely."

Abdullazyanov, E. Y., *et al.* (2015) "investigated the problem of developing mathematically rigorous methods for calculating the composition of higher harmonics. Higher harmonics are important in modern electrical grids of power systems because they increase accountability between power suppliers and their customers. The first and most important reason is that it provides a solution to the issue of energy conservation. In addition, the demarcation of responsibility for ensuring the appropriate power quality between the electrical supply business and its consumers is an important consideration."

Alfieri, L., *et al.* (2017) "developed new power quality (PQ) indices for the evaluation of waveform distortions in the frequency range of 0 kHz to 150 kHz. In particular, several already accessible indices have been correctly changed to allow them to be applied to waveforms with a broad range of frequency responses. As an example, numerical applications demonstrate that the proposed indices are effective tools for the identification of problems (e.g., overheating, equipment malfunctioning, losses due to skin effects or eddy currents) in the presence of both low-frequency and high-frequency distortions in the case of renewable energy generation sources."

Almutairi, M. S., & Hadjiloucas, S. (2019) "developed a novel approach for controlling distortions in non-sinusoidal power systems by utilizing the non-linearity current index (NLCI) to estimate the value of the shunt single-tuned passive filter (STPF) compensator, to keep the power factor within desirable limits. At the point of common coupling, the suggested technique seeks to reduce the nonlinear current generated by customers' loads in the power system to the greatest extent possible (PCC). The proposed design also considers other practical constraints for the total voltage and individual harmonic distortion limits, ensuring compliance with IEEE 519-2014 guidelines, and maintaining distortions at an acceptable level while also adhering to the capacitor loading constraints established by IEEE 18-2012. A well-documented IEEE standard is used to evaluate the performance of the ideally built compensator. This standard is based on numerical examples of nonlinear loads that were collected from prior publications."

Al-Ogaili, A. S., *et al.* (2020) "offered thorough research and analysis of the performance of two well-known time-domain harmonic extraction strategies, synchronous reference frame (SRF) theory, and instantaneous power (PQ) theory, respectively. The MATLAB-Simulink platform is used to undertake extensive simulation work under two circumstances, which are steady-state conditions and dynamical-state conditions, while considering a variety of highly nonlinear loads and parameters. Specifically, each control method is included in a three-phase SAPF controller that was constructed utilizing a three-level neutral point clamped (NPC) inverter to serve as an assessment platform. Comprehensive data are supplied to demonstrate the effectiveness of the SAPF's mitigation performance when each harmonic extraction method is used."

Askarian, I., *et al.* (2017) "centered on the development of a system for detecting and monitoring disruptions and oscillations in the electric power grid. They described a unique real-time harmonic estimation approach that is capable of swiftly and accurately estimating the dc component, as well as the synchronous and asynchronous harmonic contents of the grid voltage, even though the nature of the unknown harmonic contents is unknown. The suggested approach may be used in the control system of power converters, which has the potential to improve the dependability and resilience of future microgrid systems. The performance of the suggested harmonic estimator is tested in the context of power converter grid synchronization, which is used as a case study. The findings of the case study's simulations and experiments demonstrate that the converter can inject a smooth sinusoidal current even in the face of disturbances and variations in the grid's voltage. The obtained findings demonstrate that the suggested harmonic estimation approach is both dynamic and accurate in a short period."

Bajaj, M., *et al.* (2020) "proposed an analytic hierarchy process (AHP) inspired methodology for PQ assessment of distorted distribution power systems under the presence of renewable-based DGs. The suggested PQ evaluation technique considers four PQ phenomena: voltage harmonics, voltage sags, voltage imbalance, and steady-state voltage profile at each bus. t. The technique is shown on an IEEE 13 bus test distribution system modified with nonlinear loads and DG systems based on photovoltaic (PV), wind, and fuel cell RES in MATLAB/Simulink. The findings validated the approach's effectiveness in measuring each bus's total PQ performance and comparing it against the threshold level of unity. Based on the findings, a comparison of DN PQ performance with three RES-based DGs is made. The developed index is also used to study the influence of using custom power devices (CPDs) and excessive renewable energy penetration on distribution network PQ performance."

Baraniak, J., & Starzyński, J. *et al.* (2020) "produced simulation models based on measurements taken from the actual charger. Data provided by the equipment's producers, and simulation models that have been extensively described in the literature. It was determined, based on the study's findings, if electric car chargers had a negative influence on the quality of electric power, and consideration was given to the prospects presented by the development of charging systems that include vehicle-to-grid (V2G) capabilities. Proposed technical standard changes include considering the heating of power supply cables under the impact of increased current harmonics produced by converter systems while choosing power supply cables."

Blazek, V., *et al.* (2020) "presented an analysis of the influence of household appliances on the quality of the energy consumed by the end user. The study's findings affect the ultimate customer (the lowest level of the power grid). The study used 120 grid-connected electrical appliance combinations. Each combination has three devices in a microgrid. The gathered and statistically analysed data showed that certain kinds of appliances greatly impacted variations in power quality characteristics. The results of the trials show the devices that impacted the THDV, FREQ, and voltage fluctuation (V). The importance of certain device characteristics on the power quality deviation was investigated. This highlighted the key aspects to consider while building a prediction model. This is the future of smart grids. One of the important features is the reduction of energy usage from renewable sources. This phenomenon is detailed in their work. They studied the impact of smart home equipment on individual amounts on an actual model. They also looked at gadgets that had a big influence on power quality. To increase the prediction model's usefulness, they explain their distinctive behaviour and relevance to the occurrence."

Bottura, F. B., *et al.* (2019) "proposed an optimized allocation methodology of power quality (PQ) meters in a medium voltage (MV) distribution system (DS), considering the potential harmonic resonance conditions. The HRMA technique is used to compute critical modal impedances and detect harmonic resonance frequencies. Using the HRMA, one may create a binary observability matrix that includes node observability for hypothetical harmonic resonance frequencies. The allocation issue is modeled as a constraint integer linear programming to ensure comprehensive observation of the specified harmonic resonance frequencies. The final practicable solution specifies the ideal sites to put PQ meters, considering harmonic resonance situations, DS operating scenarios, and client capacitor banks for PFC. The allocation mechanism was tested in two CIGRÉ MV test DSs and an IEEE 34-node test feeder. To fully monitor the potential harmonic resonance frequencies in both test DSs requires four PQ meters. The final allocation solution is proven to be appropriate even when the capacitor banks are variable."

Brunoro, M., *et al.* (2017) "offered a novel idea for load modeling that incorporates the ZIP model and the admittance matrix across the board. As a result of this combination, the advantages of load characterization are combined with the classic ZIP model, which gives some physical information about the load as well as the frequency crossing provided by an admittance matrix. With this information, it can properly compute the harmonic power injection in the load bus, which is then used to calculate the harmonic voltage of the load bus. However, the current plan still contemplates a constraint for the ZIP coefficients to define the power ratio in terms of constant impedance, constant current, and constant power, as well as constant resistance. An electronic load case study is presented, which includes a discussion of the process for selecting the load model parameters, which includes exhaustive search and multiple linear regression. Data from a power quality meter is used to demonstrate the model's use in an electronic load. The findings reveal that the suggested harmonic model could accurately represent the load and that the parameters discovered could offer information about the sort of modeled load being represented."

Bubshait, A. S., *et al.* (2017) "studied a four-leg inverter linked to the grid side to inject the available energy, as well as operate as an active power filter minimizing load current disturbances and improving power quality. Three-phase and single-phase linear and nonlinear loads are examined. The utility-side controller compensates for disturbances induced by reactive, nonlinear, and/or unbalanced single- and intra-phase loads and delivers active and reactive power as needed. In the absence of wind power, the controller is designed to enhance power quality by utilizing a dc-link capacitor connected to the grid. The suggested control structure is based on conservative power theory decompositions, which is unique in the literature. This option gives decoupled power and current references for inverter control, allowing for more flexibility and power. Real-time software benchmarking was used to assess the suggested control algorithm's performance in full real-time. The use of a real-time simulator and a TMSF28335 DSP microcontroller allows the control methods to be tested in hardware-in-the-loop. Consequently, we eliminated passive filters from our smart-grid-based control, making it more compact, adaptable, and dependable."

Buzdugan, M. I., *et al.* (2017) "outlined a few challenges developed in low voltage distribution grids at the end-user level as a result of power system harmonics. The introduction part briefly discusses harmonics sources, their analysis, effects, and measuring techniques, with a strong emphasis on the limitations specified in the individual standards as the primary reference. The authors provided two case studies of power electronics equipment with highly distorted currents and, as a result, high harmonic content. One of the examples is a piece of household equipment that is powered by a switch-mode power supply and has been tested in a laboratory setting. The second kind of drive, a variable speed drive, has been tested in an industrial setting, i.e., under real-world circumstances. Finally, harmonic measurements and analysis enable the selection or creation of retrofitting mitigation countermeasures that are capable of alleviating the impacts of harmonics."

Cai, W., *et al.* (2020) "investigated the impact of the uncertainty principle on the power quality monitoring issue, and the problem has been solved using perfect atomic decomposition (IAD). Whereas the new approach detects the power quality waveform, it is done so using a pair of time and frequency bases. As a result, it is possible to decrease both temporal and frequency uncertainty simultaneously. The orthogonal matching pursuit method is used to implement the sensing process (OMP). According to the results of simulated and field power quality tests and comparisons of developed methods, the new method can provide faithful sensing and accurate analysis for a wide range of power qualities. The method has also been validated as an effective power quality monitoring method in smart substations."

Chokkalingham, B., (2018) "considered the two multilevel pulse width modulation (PWM) methods; multi-carrier sine PWM (MCSPWM) and space vector PWM (SVPWM) for NPC-MLI. Different restrictions, such as voltage profile, total harmonic distortion (THD), common-mode voltage (CMV), and neutral point fluctuation, are applied to both approaches and compared and assessed (NPF). When the SVPWM technique is compared to the MCSPWM methods, the findings show that the SVPWM approach is better. The

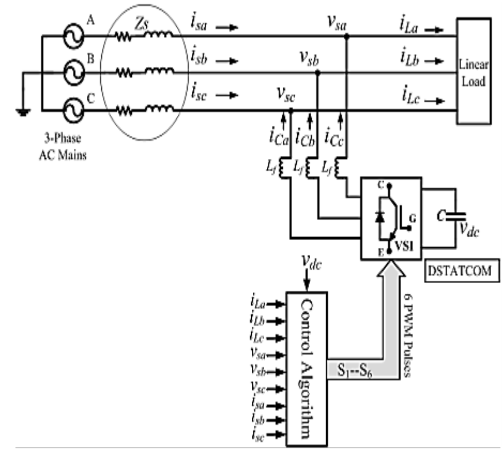

Figure 1: Schematic configuration of DSTATCOM

FPGA-SPARTAN – III generation – 3AN –XC3S400 with a 2KW NPC-MLI fed changeable speed–drive system is used to experimentally verify the analytical and simulation findings obtained by utilizing the MATLAB/Simulink for control systems."

Christe, A. J., (2020) "investigated the Open Power Quality (OPQ) project. Specifically, it aims to build and deploy a low-cost, distributed power quality sensor network that will offer producers, consumers, academics, and regulators meaningful new kinds of information about current electrical grids in real time. In 2019, they conducted a three-month pilot study at the University of Hawaii microgrid, which included the deployment of an OPQ sensor network. The findings of the pilot research confirm that the Open Power Quality (OPQ) system is capable of collecting reliable power quality data in a manner that delivers important new insights into electrical grids."

In the author's next work, the author will investigate the performance of DSOGI-FLL and the suggested MDSOGI-FLL based frequency estimation method for use in the DSTATCOM application in the presence of an idealized offset error. When using the MDSOGI-FLL method in the DSTATCOM program, the grid current will be free of dc offset, and the THD will be substantially below 5%, according to the simulation results derived from this algorithm.

Proposed Methodology

The methodology implemented during the research work is as follows:

- DSTATCOM implementation is based on the SRF

Table 1. Configuration of DSTATCOM.

Supply voltage (RMS)	415 (line-line voltage), 50 Hz
Linear load 1	3.2 kW,0.5kVAR
Linear load 1	0.7 kW,0.5kVAR
DC-link capacitor	C = 4000μF
DC-link voltage v_{dc}	700 V
Coupling inductor	Filter inductance L_f = 15 mH
Source impedance	Rs = 0.01 Ω, Ls = 1mH

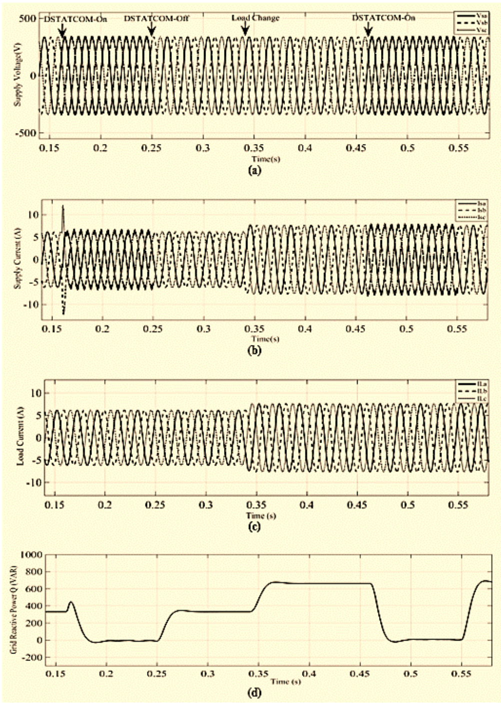

Figure 2: D-STATCOM results with DSOGI-FLL algorithm (without offset error in supply measurement) :(a)supply voltage (b) supply current (c) load current (d) grid side reactive power

theory, in which the production of reference current is mostly reliant on the phase information included in the grid signal. The switching pulses generated by this reference current are used to run DSTATCOM to meet the reactive power requirement of the load connected at PCC, as shown in Figure 1.

- The proposed (MDSOGI-FLL) and conventional (DSOGI-FLL) algorithms are used to calculate the DSTATCOM's performance under normal conditions and in the presence of an offset component in the utility signals. The phase (frequency) information is calculated by the proposed (MDSOGI-FLL) and conventional (DSOGI-FLL) algorithms.
- With the help of simulation findings, it is possible to compare the robust performance of the suggested MDSOGI-FLL for frequency estimation with that of the standard DSOGI-FLL for reference current generation.

In the author's next work, the author will investigate the performance of DSOGI-FLL and the suggested MDSOGI-FLL based frequency estimation method for use in the DSTATCOM application in the presence of an idealized offset error. When using the MDSOGI-FLL method in the DSTATCOM program, the grid current will be free of dc offset, and the THD will be substantially below 5%, according to the simulation results derived from this algorithm.

Figure 1 shows the connection diagram of a three-phase VSI-based DSTATCOM at the point of common coupling (PCC), where three-phase AC mains feed the linear load

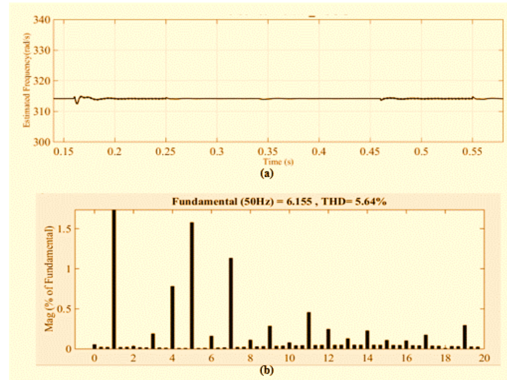

Figure 3: D-STATCOM results with DSOGI-FLL algorithm (without offset error in supply measurement): (a) estimated frequency (b) frequency spectrum supply current during D-STATCOM on

(R-L) with source impedance (Z_s). The various utility signals i.e. PCC voltage (v_{sa}, v_{sb}, v_{sl}), load currents (i_{La}, i_{Lb}, i_{Lc}), source currents (i_{sa}, i_{sb}, i_{sc}). DC bus voltage (v_{dc}) of VSI used in DSTATCOM are sensed and given to the control algorithm to generate pulse width modulation (PWM) switching pulses (S1—S6). These switching pulses will operate the VSI to inject the compensating current (i_{Cabc}) at PCC. The injection of compensating currents i_{Cabc} at the PCC through the coupling inductance Lf makes the supply current (i_{sabc}) in phase with supply voltage (v_{sabc}), which indicates the unity power factor operation by supplying the reactive power demand of the load (at the PCC). The parameters used in the implementation of VSI-based DSTATCOM are tabulated in Table 1.

Results And Discussion

The results of the simulation of DSTATCOM's performance are shown in this part. The simulation was run with the supply voltage in ideal condition and with an offset error present. When the phase-angle (frequency) information is received by the DSSOGI-FLL and the suggested MDSOGI-FLL, the performance analysis is carried out and compared. On the basis of the schematic-set up illustrated in Figure 2, the performance of both the DSOGI-FLL based DSTATCOM and the proposed MDSOGI-FLL based DSTATCOM for reference current extraction for load reactive power compensation is examined. All of the simulation results reported in this section were generated using the settings that are listed in Table 1.

Figure 2 illustrates the performance of a standard implementation of the DSOGI-FLL algorithm for the DSTATCOM application. In this example, the grid signal is analyzed without any measurement offset error being present. The DSTATCOM provides a consistent response to the linear load 1's need for reactive power. It may be seen in the outcomes for the time interval ranging from t=0.16s to t0.25s. In addition, the step change in linear load can be seen at time t=0.34s after the event. In addition to meeting the requirements of the earlier linear load 1, the D- STATCOM

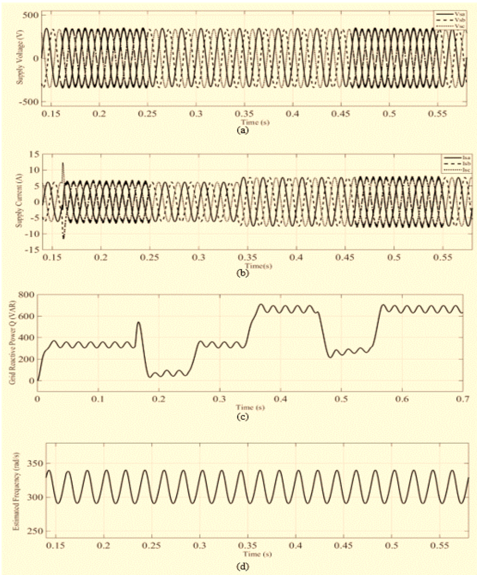

Figure 4: D-STATCOM results with DSOGI-FLL algorithm (with offset error in phase-a of supply measurement): (a) supply voltage (b) supply current (c) grid reactive power (d) estimated frequency

also fulfills the reactive power demand of linear load 2 when it is connected at time t=0.34s. At the time t=0.16s, the DSTATCOM is turned on, and at the time t=0.25s, it is turned off. As a direct consequence of this, it starts working at t=0.46s and stops working at 0.55s. It can be recognized that DSTATCOM is fulfilling the load reactive power demand (shown in Figure 2((a)-(d)) throughout this time period since Figure 2(a) and (b) show that the supply voltage and current are both in phase during the DSTATCOM activities. Even when there is a sudden shift in load, it reacts quite well. The estimated frequency information for the grid signals is shown in Figure 3(a). The traditional DSOGI-FLL precisely tracks the frequency in the optimal supply voltage.

Figure 4 represents the simulation results of DSTATCOM reactive power compensation when the supply voltage is affected by the measurement and data processing limitation. To carry out this analysis, the offset (4% of RMS phase voltage) is introduced in phase-a of the three-phase supply voltage. The results are represented in Figure 4 ((a)-(d)) with the conventional DSOGI-FLL frequency estimation algorithm. Figure4 (c) indicates the improper reactive power compensation as per the load demand. It is due to

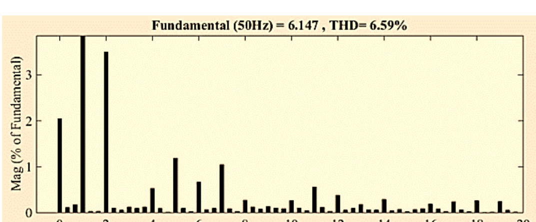

Figure 5: Frequency spectrum of supply current during D-STATCOM on

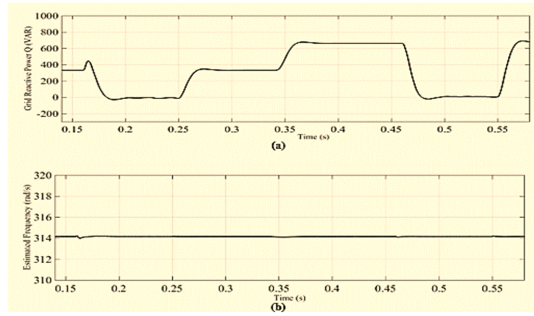

Figure 6: D-STATCOM results with MDSOGI-FLL algorithm (with offset error in phase-a of supply measurement): (a) grid reactive power (b) estimated frequency

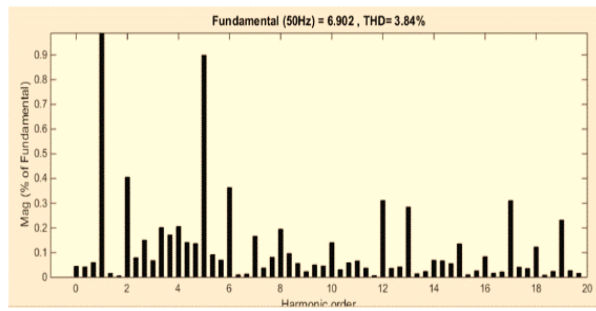

Figure 7: Frequency spectrum of supply current during D-STATCOM on

the oscillatoryresponse of frequency estimated through the DSOGI-FLL algorithm, which fails toestimate frequency accurately in case of offset error in the grid signal. Ultimately, the reference current extraction is inaccurate; hence, reactive power compensation passes on the offset error in the source current. The frequency spectrum in Figure5 proves the presence of an offset component in the source current during the DSTATCOM on period.

Figure6 represents the performance analysis of DSTATCOM, where the phase-angle information is extracted through the proposed MDSOGI-FLL algorithm discussed in this research work. The performance results are shown according to the previous supply voltage deviation. The DSTATCOM accurately does the reactive power compensation as the accurate generation of the reference current. The accurate frequency estimation is depicted in Figure6 ((a)-(b)). Figure 7 shows the frequency spectrum of the source current, which shows the elimination of the dc offset component.

Conclusion

From the above investigation, we can conclude that the performance of DSOGI-FLL and the proposed MDSOGI-FLL-based frequency estimation algorithm in the DSTATCOM application is analysed under ideal and the presence of offset error. Both the frequency estimation algorithm estimates the frequency correctly in absence of the offset error in supply voltage for DSTATCOM reactive power compensation. However, when the presence of a dc-offset characterizes the (sensed) grid voltage, DSOGI-FLL fails to estimate the frequency correctly resulting in the grid current with a dc offset and a higher THD. The MDSOGI-FLL correctly estimates the frequency and hence, an accurate compensating current can be generated. The simulation result shows that with MDSOGI-FLL based algorithm in the DSTATCOM application, the grid current is free of dc- offset and the THD is well below 5%.

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