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Implementation Of Conjugate Gradient Backpropagation Neural Network Control Algorithm for Single-Phase Grid Tied SPV-DSTATCOM System

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ABSTRACT

Power quality is important for distribution system as it may have negative impact for both the utility company and consumer if it has a power quality issues such as harmonic current distortion. This issue may result in a breakdown of equipment of both the consumer and the utility company. Thus, it is important to solve the power quality issue. Therefore, this research was conducted in order to overcome the power quality issues that is faced by the distribution system by adding DSTATCOM to the system as it can compensate harmonic current distortion at the point of common coupling (PCC). Conjugate gradient back-propagation neural network (GCBPNN) based PQ theory is chosen as the controller for this research as the effectiveness of DSTATCOM performance is depending on its controller. GCBPNN would reduce the time taken to compensate the harmonic. All the simulations for this research have achieved THD below 8% after adding DSTATCOM where the simulation that added GCBPNN achieved the lowest THD at 5.35%. These simulations are performed by using MATLAB/Simulink.

1. Introduction

Power quality holds significant importance in the electrical power industry due to its potential negative impact on both power system equipment and the load. When power quality is poor, it will directly affect both the electrical system and the connected loads. The most common type of power quality issues are overvoltage, undervoltage, voltage sags, voltage swells (surges), harmonics distortion, noise, and voltage flicker. The sources of power quality issues in GCPV usually from the usage of non-linear load [1–5] and the photovoltaic penetration level of GCPV [6,7] which effect the waveform of the source current.

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The distortion of the waveform is the major problem cause by harmonic current to the mains feeding industrial and commercial buildings. The combined effect of all voltage drops leads to a high total harmonic distortion factor (THD Voltage), which significantly degrades power quality. This, in turn, adversely affects the operational efficiency of devices connected to the same point of common coupling (PCC) for various customers sharing the utility power supply. It is important to note that the propagation of harmonic currents through the finite system impedance at the PCC is responsible for this phenomenon [8].

The presence of current harmonics results in an increase in the root mean square (rms) current within the circuit, leading to higher power losses. These current harmonics affect the entire distribution system, impacting it all the way down to the connected loads [9]. This can cause various issues such as increased eddy current and hysteresis losses in motors and transformers, resulting in overheating, overloading of the neutral conductor, nuisance tripping of circuit breakers, and numerous other complications [10]. Hence, the installation of distribution static synchronous compensator (DSTATCOM) with appropriate control algorithm can help improving the power quality at the distribution system which will act as an active filter to mitigate the harmonic current distortion [11–13].

This project focuses on the design of a single-phase of grid-connected solar PV system-based distribution static synchronous compensator (GCPV based DSTATCOM). Single-phase PQ theory is used as DSTATCOM control algorithm as the effectiveness of DSTATCOM is depending on its control algorithm. Single-phase PQ theory will then be trained by CGBPNN. This training process aims to minimize the time required for mitigating power quality concerns associated with GCPV systems at the PCC.

The GCPV system was simulated using MATLAB/SIMULINK in three different configurations which are before DSTATCOM compensation, after DSTATCOM compensation and after been trained by CGBPNN to evaluate the performance and total harmonic distortion of GCPV based DSTACOM so that its performance can be analysed. Following the successful execution of the simulation, the project was integrated into a hardware-in-the-loop (HIL) configuration. For this purpose, the Texas instruments real-time control C2000 microcontroller was chosen due to its suitability for real-time closed-loop control applications, specifically for grid-connected solar PV systems. The microcontroller was selected as it offers the necessary capabilities and features required for effective control and operation in such systems.

2. Methodology

In order to design DSTATCOM, there are system parameters need to be calculated, which is DC bus voltage, DC bus capacitor and AC inductors [14].

2.1 DSTATCOM System Configuration
2.1.1 DC bus voltage

The value of the PCC voltage has a direct impact on the DC bus voltage (V_{dc}) in order to achieve successful pulse width modulation (PWM) control of the Voltage Source Converter (V_{SC}) in a DSTATCOM. Specifically, the DC bus voltage needs to be greater than the amplitude of the AC mains voltage. Eq. (1) defines the DC bus voltage for a single-phase Voltage Source Converter (V_{SC}).

$$V_{dc} = \frac{\sqrt{2}V}{m} \tag{1}$$

Where *m* is the modulation index and is considered as 1, while V is the AC line output voltage of DSTATCOM which is 230V. The value of V_{dc} is obtained as 339V using Eq. (1) and was picked as 360V.

2.1.2 DC bus capacitor

The value of DC bus capacitor is dependent on the instantaneous energy available to DSTATCOM and on second harmonic or ripple voltage in the DC bus voltage. For a single-phase V_{SC}, the DC bus capacitor is defined as Eq. (2).

$$C_{dc} = \frac{I_o}{2\omega\Delta V dc_{rip}} \tag{2}$$

Where I_0 is the capacitor current, ω is the angular frequency and V_{dcrip} is the ripple in capacitor voltage. Considering I_o is 138.88A, ω is 100π and V_{dcrip} is 18V, using Eq. (2), the value obtained for C_{dc} is 12279µF. Hence, the chosen capacitor value is 13000 µF.

2.1.3 AC inductors

The value of the AC inductance depends on the ripple current, I_{crpp} and switching frequency, f_s. AC inductor will remove the current ripple produced. The value of AC inductor, L_f is defined as Eq. (3).

$$L_f = \frac{mV_{dc}}{4 \times a \times f_s \times I_{crpp}} \tag{3}$$

Where *m* is the modulation index and is considered as 1, switching frequency, f_s is 1.8kHz, DC bus voltage, V_{dc} is 360V, overload factor, *a* is equal to 1.2 and I_{crpp} is 20.83A. Using Eq. (3), the value obtained for AC inductor, L_f is 2mH.

2.2 Design of GCPV

In order to design a solar PV panel, we need to calculate its series and parallel array using Eq. (4) and (5) respectively. The values of the parameters of PV module are listed in Table 1. The series and parallel PV array used after the calculations have been done is 13 series and 2 parallel panels with rated power 10784.83W.

$$N_{s\_oc\_max} = round\ down \left[\frac{V_{max\_inv\_abs} \times k_3}{V_{oc\_max}}\right] \tag{4}$$

$$N_{p\_max} = round\ down \left[\frac{I_{\mathrm{dc\_max\_inv}} \times k_7}{I_{\mathrm{sc\_string\_stc}}}\right] \tag{5}$$

Table 1
The value of the parameter of PV module type Q. Peak Duo-G5 315-335

Parameter	Value
IMPP	5.69 A
VMPP	72.9 V
VOC	85.3 V
ISC	6.09 A
Max. Power	414.801 W

2.3 Single-Phase PQ Theory-Based Control Algorithm of DSTATCOM

PQ theory, also known as the Instantaneous Reactive Power Theory, is a mathematical framework used to analyze and control the power quality issues in electrical systems. It focuses on maintaining the desired power factor (P) and regulating the voltage magnitude (Q) in the system [15]. This method involves the estimation of reference signals, which are subsequently utilized to generate pulses for switching purposes. To process the 3-phase signals effectively, the Clarke transform is employed, enabling the conversion of these signals into 2-phase components. The resulting 2-phase current and voltage components are then utilized for estimating the active power (P) and reactive power (Q) components. Subsequently, the inverse Clarke transform is applied to obtain the reference signal [16]. This process allows for accurate estimation and control of power components using the transformed signals. As part of the feedback control system, various parameters are sensed to monitor and regulate the V_{SC} of the DSTATCOM. These parameters include the load currents (i_{LA}, i_{LB}, i_{LC}), PCC voltages ($V_{SA}, V_{SB,} V_{SC}$), supply currents, and DC bus voltage (V_{DC}). These sensed signals provide crucial feedback information to ensure accurate control and operation of the DSTATCOM.

2.4 Conjugate Gradient Back-Propagation Neural Network

Conjugate gradient has a better performance than the other two optimization techniques of back-propagation algorithm, Levenberg–Marquardt and the resilient back-propagation algorithm as it training time is faster and requires less memory [17]. Training will automatically conclude when generalization ceases to improve, which is indicated by an increase in the mean square error of the validation samples. This mechanism ensures that the training process stops once further iterations no longer contribute to enhancing the model's ability to generalize and make accurate predictions. Mean squared error is known as the average squared discrepancy between outputs and targets. The lower the value, the better if the value is zero, it means there is no error. Number of neurons can be changed if the network does not perform well after training. Conjugate gradient Back-propagation can improved the training time taken for a system and has ability to deal with complex nonlinear problems [17]. It can have as many inputs, however, there will only be one output from it.

2.4 Circuit Design

Circuit was designed in 3 topologies, which are single-phase system without DSTATCOM, single-phase system based DSTATCOM using PQ theory control algorithm and single-phase system based DSTATCOM using PQ theory control algorithm with CGBPNN.

2.4.1 Single-phase system without DSTATCOM compensation

Figure 1 illustrate the basic block diagram of the single-phase system under non-linear load without DSTATCOM compensation. It only consists of voltage source and non-linear load. The source current will follow the waveform of load current as there is no compensation added to the PCC.

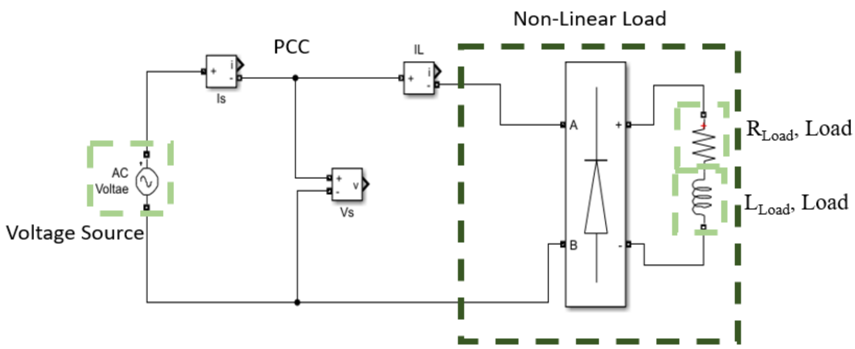


Fig. 1. Basic block diagram of the single-phase system under non-linear load without DSTATCOM compensation

2.4.2 Single-phase system with DSTATCOM compensation using PQ theory control algorithm

Figure 2 shows the basic block diagram of single-phase system with DSTATCOM compensation using PQ theory control algorithm. DSTATCOM is added at the PCC in order to compensate the harmonic current.

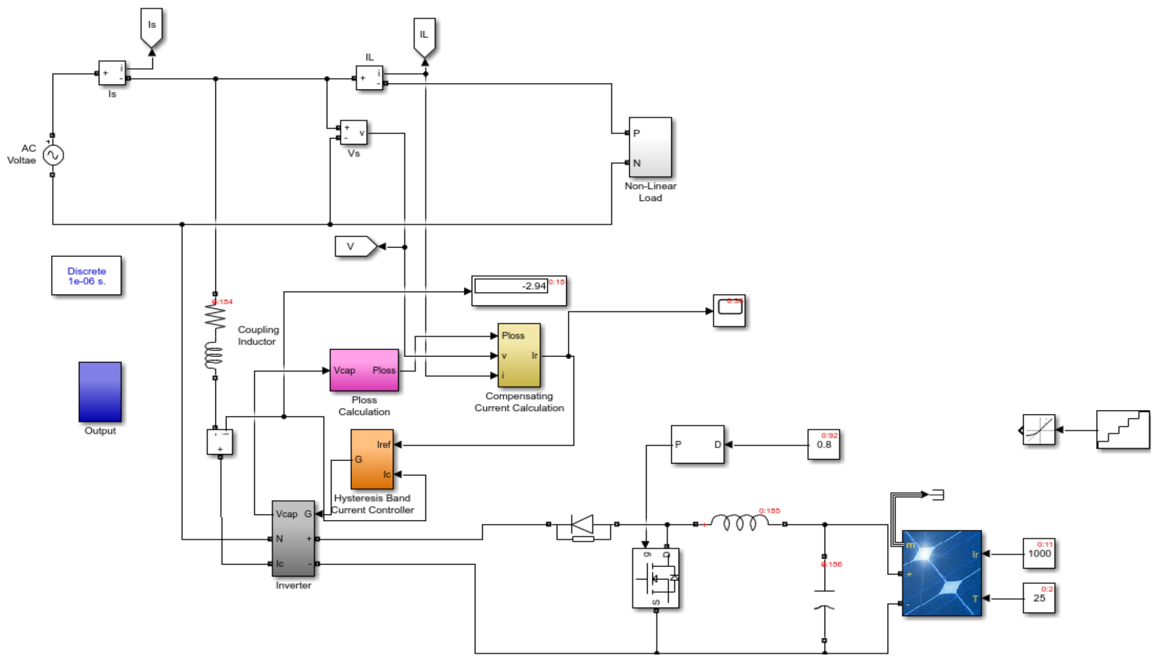


Fig. 2. Basic block diagram of the system with DSTATCOM and PQ theory control algorithm

Figure 3 shows the inverter diagram. The inverter in a DSTATCOM is typically based on power electronic devices such as insulated gate bipolar transistors (IGBTs). It generates compensating currents or voltages to mitigate power quality issues and provide reactive power support to the distribution system. Figure 4 shows the hysteresis band current controller diagram. It is utilized to control the voltage source converter (VSC) in the system. The reference voltage signal for the VSC is derived using the principles of PQ theory [18]. Figure 5 shows power losses diagram. The calculation of power losses involves analysing the power flow and evaluating the active power (P) and reactive power (Q) components. Power losses can be determined by considering both the resistive losses and the losses due to reactive power flow. Figure 6 shows the compensating currents diagram. It is generated based on the analysis of voltage and current waveforms using the principles of PQ theory.

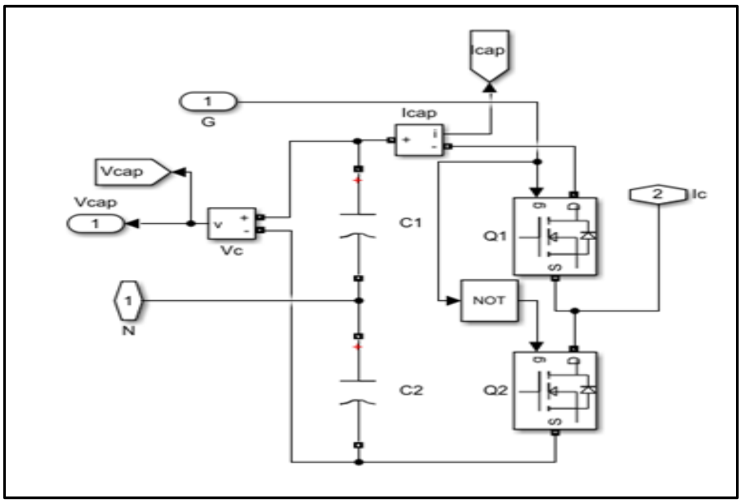


Fig. 3. Inverter block diagram

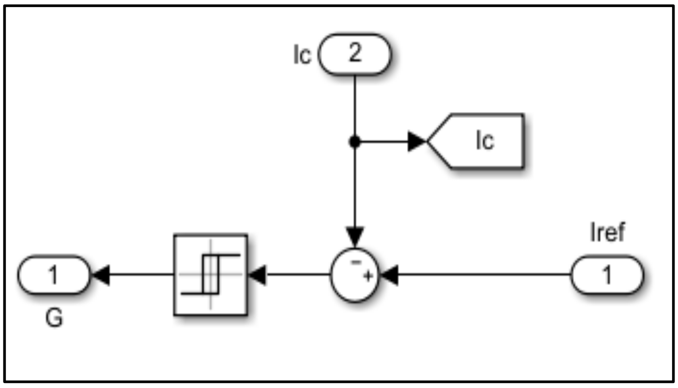


Fig. 4. Hysteresis band current controller block diagram

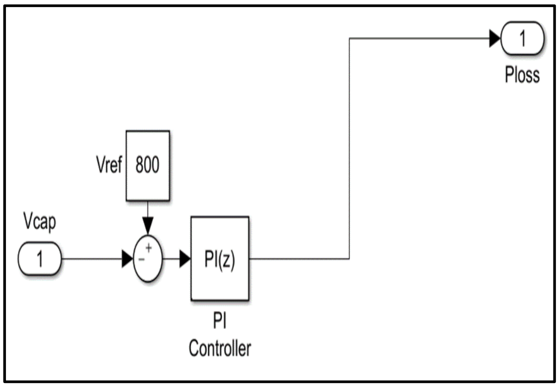


Fig. 5. Power losses block diagram

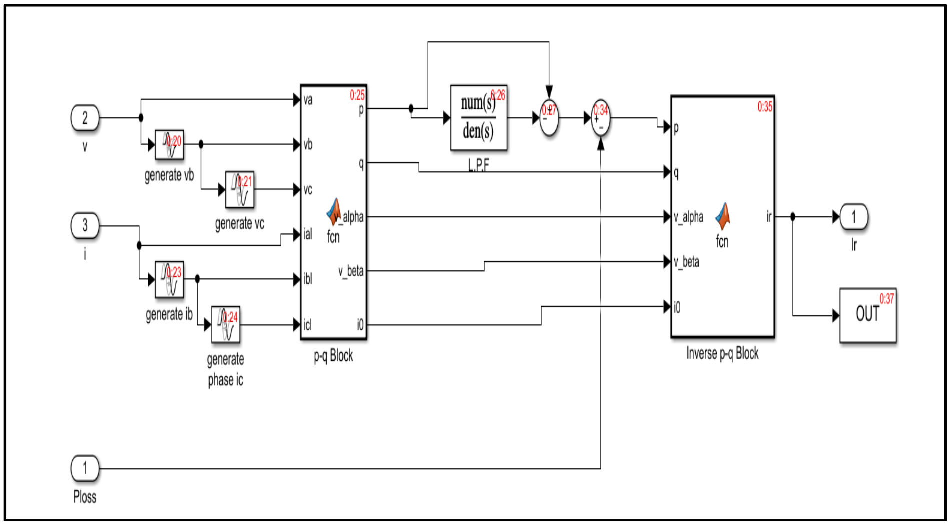


Fig. 6. Compensating currents block diagram

2.4.3 Single-phase system with conjugate gradient back-propagation neural network-based PQ theory.

The basic block diagram of single-phase system with conjugate gradient back-propagation neural network-based PQ theory is the same as in Figure 2. It only differs at compensating current diagram. Neural network is only added at the compensating current diagram as it involves complex mathematical calculation. By incorporating neural network, the time required to generate the reference current is significantly reduced. Figure 7 illustrates the compensating current diagram, enhanced with the integration of a neural network.

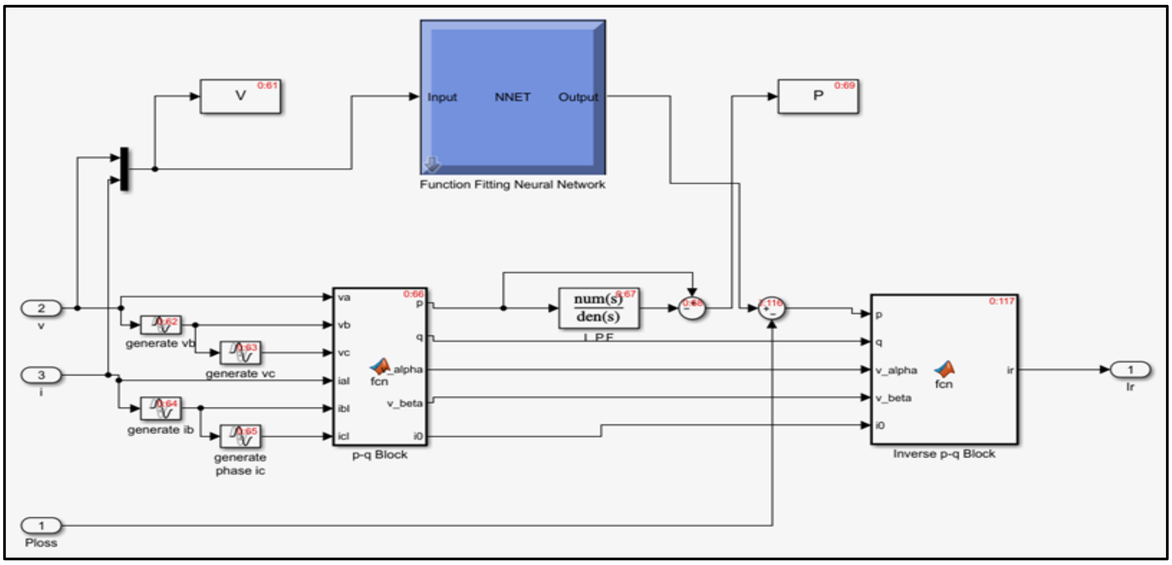


Fig. 7. Compensating currents diagram with neural network

2.5 Hardware-in-the-loop (HIL) Simulation

Hardware-in-the-loop (HIL) is a process that involves connecting actual controller signals to a test system designed to replicate real-world conditions. This setup creates an environment where the controller operates as if it were integrated into the final product. By simulating real-world interactions, the HIL process provides a comprehensive testing platform for evaluating the controller's performance and functionality in a realistic context. Iterative testing and design occur as if the real-world system is being used. By using HIL for testing, it can reduce testing infrastructure requirements, testing time, and there is no chance of equipment damage while running the test. It will also provide the versatility to execute a range of systems such as single-phase and three-phase, various rated power, and advanced grid support capabilities [19]. The analog-to-digital converter (ADC) plays a crucial role in converting the signals received from the analog input/output into digital signals. These digital input signals, represented as *v* and *i*, are then used to generate an appropriate C-code using MATLAB/Simulink's code generation capabilities and the Code Composer Studio (CCS) software. The resulting code output corresponds to the duty cycle, which serves as the input for the enhanced pulse width modulator (PWM) module [20]. This process ensures accurate conversion and utilization of the analog signals for efficient PWM control.

3. Discussion

This section discusses the performance of single-phase system with DSTATCOM compensation using PQ theory control algorithm.

3.1. Performance of Single-Phase System without DSTATCOM Compensation

3.1.1 Performance of single-phase system without DSTATCOM compensation under non-linear load in steady state condition

The performance of single-phase system under non-linear load without DSTATCOM was evaluated based on its load voltage, load current and source current. Its waveform and THD value were analysed to see the impact of non-linear load on it. Figure 8 shows the total harmonic distortion of source current and load current. When electrical equipment converts from AC to DC, current is drawn in pulses. These pulses produce distorted current waveforms with a lot of harmonics hence resulting in high THD for source current as in Figure 8(b) where it exceeds the recommended value of harmonic distortion by IEEE STD 519-2022 for source current at PCC.

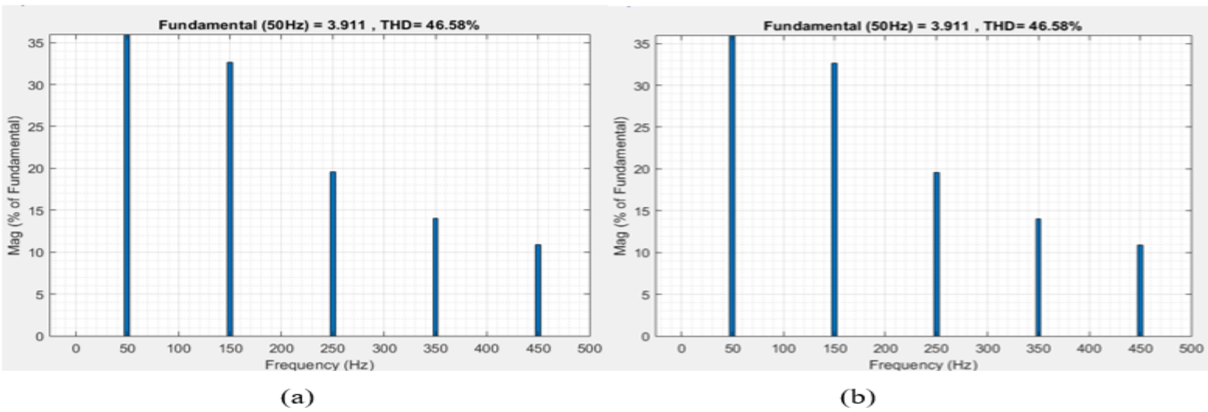
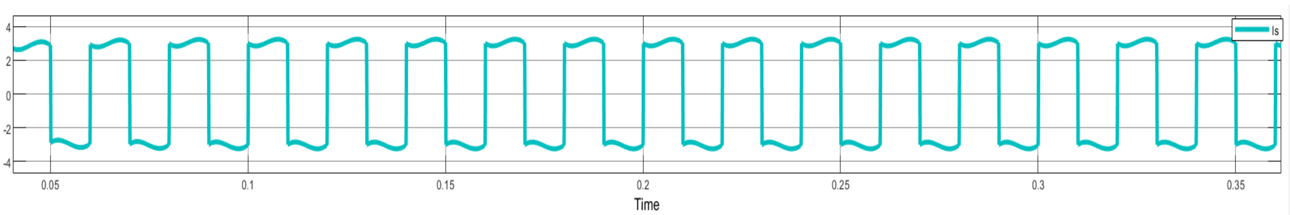
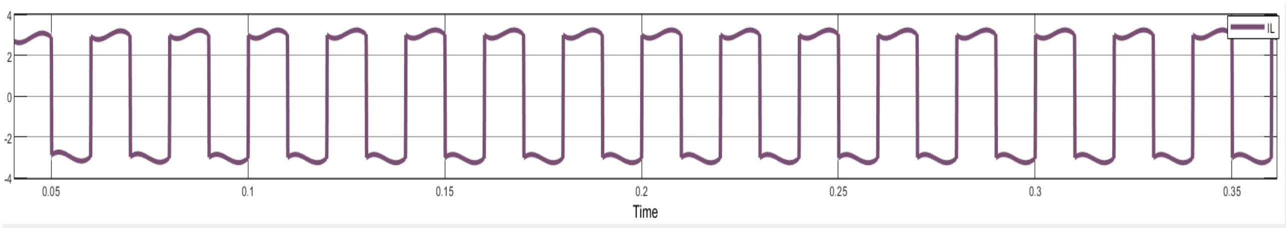


Fig. 8. (a) THD of load current, iL under non-linear load in steady state without DSTATCOM compensation (b) THD of source current iS under non-linear load in steady state without DSTATCOM compensation

Figure 9 shows the distorted waveform of load and source current as a result from the non-linear load. The distorted waveform of current source will affect the source current. This distorted waveform occurs because of the high amount of total harmonic present in the circuit from the non-linear load used by consumer. The source current will follow the waveform of load current as nothing is injected at PCC. Figure 9 (a) and (b) show the distorted waveform of source current and load current respectively.



(a)



(b)

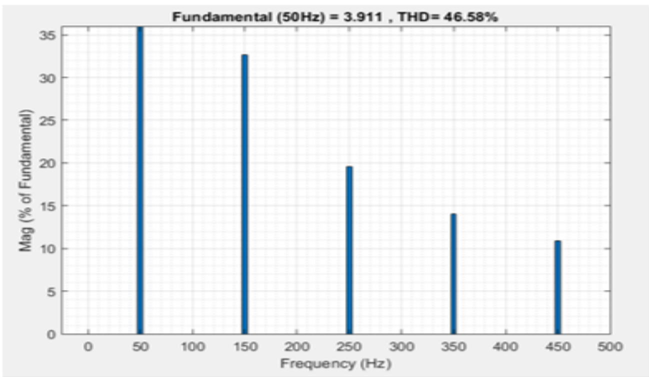
Fig. 9. (a) Waveform of source current, i_S under non-linear load in steady state without DSTATCOM compensation (b) Waveform of load current, i_L under non-linear load in steady state without DSTATCOM compensation

3.2. Performance of Single-Phase System based DSTATCOM Compensation using PQ Theory Control Algorithm

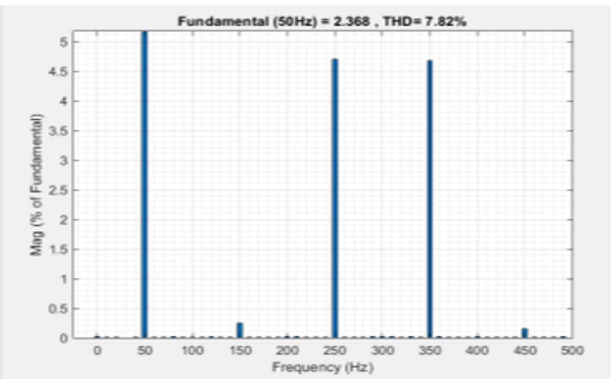
This section discusses the performance of single-phase system with DSTATCOM compensation using PQ theory control algorithm.

3.2.1 Performance of single-phase system with DSTATCOM compensation using PQ theory control under non-linear load in steady state condition

DSTATCOM is used to mitigate the harmonic current distortion of distribution system. The performance of DSTATCOM is analysed to see how it compensate the source current and total harmonic distortion of current source at PCC so that the voltage at PCC will be improved too. The value of total harmonic distortion is shown in Figure 10 where the harmonic has been reduced from 46.58% to 7.82%. This can be achieved due to DSTATCOM injecting compensating currents into the system to counterbalance the harmonic currents. By injecting compensating currents that are out of phase with the harmonic currents and synchronized with the system voltage waveform, DSTATCOM effectively mitigates harmonic currents at the PCC and improving the overall power quality.



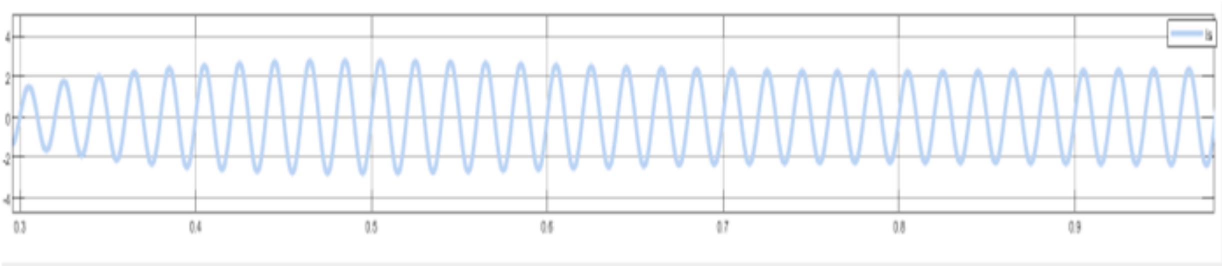
(a)



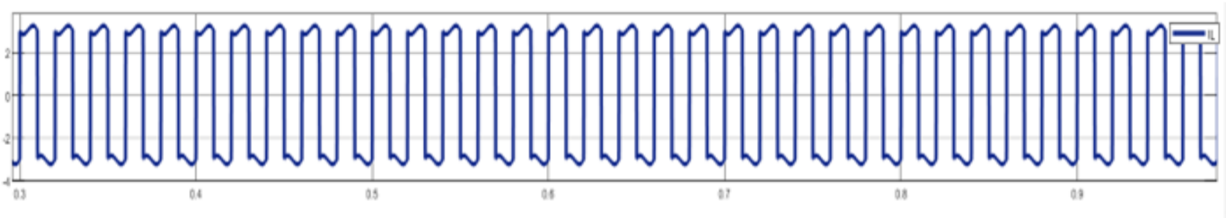
(b)

Fig. 10. (a) THD of load current, i_L under non-linear load in steady state with DSTATCOM compensation using PQ Theory (b) THD of source current, i_S under non-linear load in steady state with DSTATCOM compensation using PQ Theory

Figure 11 (a) and (b) shows the output waveform of the single-phase system based DSTATCOM compensation using PQ theory control algorithm circuit. The DSTATCOM has successfully compensated the source current as it achieved the desired sinusoidal waveform. This is because the THD has been reduced below the limit of harmonic current distortion.



(a)



(b)

Fig. 11. (a) Waveform of source current, i_S under non-linear load in steady state with DSTATCOM compensation using PQ Theory (b) Waveform of load current, i_L under non-linear load in steady state with DSTATCOM compensation using PQ Theory

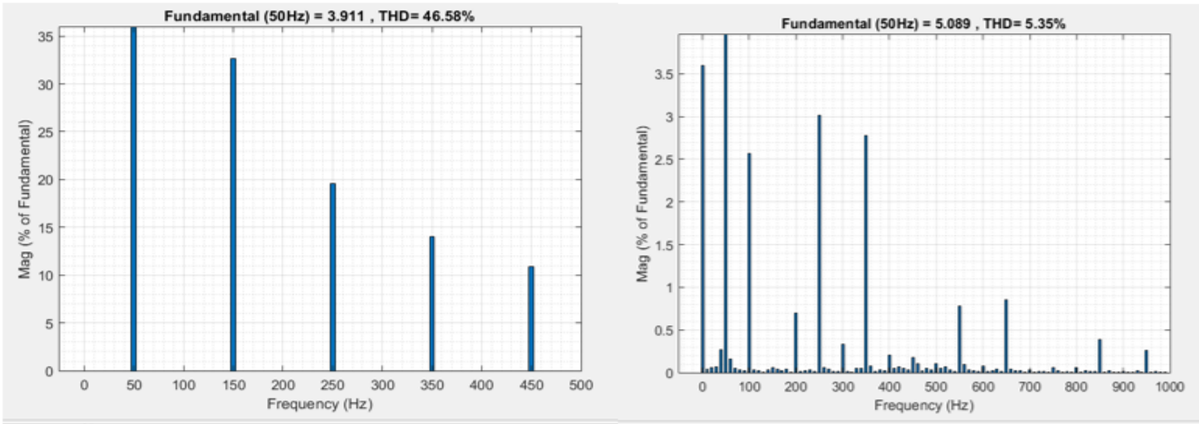
3.3. Performance of Single-Phase System with Conjugate Gradient Back-propagation Neural Network Based PQ Theory

This section discusses performance of single-phase system with conjugate gradient back-propagation neural network-based PQ theory.

3.3.1. Performance of single-phase system with conjugate gradient back-propagation neural network-based PQ theory under non-linear load in steady state condition

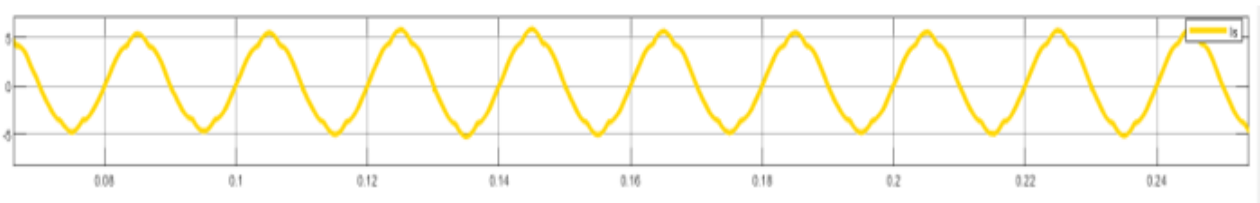
Conjugate Gradient Back-propagation Neural Network based PQ theory is added to the single-phase system to improve the training process of DSTATCOM. By adding Conjugate Gradient Back-propagation Neural Network, it will help to reduce the total harmonic distortion even more as it trains the DSTATCOM to get the desired output. Figure 12 show the total harmonic distortion of source current and load current. The THD has been reduced from 46.58% to 5.35%.

The waveform of the current source had greatly improved after adding DSTATCOM, but it takes quite a few times to stabilize the waveform into sinusoidal waveform. By adding CGBPNN to the single-phase system, it helped improving the training process of DSTATCOM. It shortened the time taken by DSTATCOM to stabilize the waveform where it took less than 1 cycle to become stable. Figure 13 shows the waveform of source current.

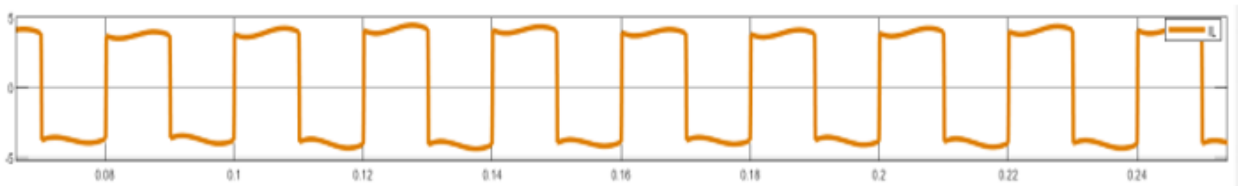


(a) (b)

Fig. 12. (a) THD of load current, i_L under non-linear load in steady state with DSTATCOM compensation using CGBPNN-based PQ theory (b) THD of source current, i_S under non-linear load in steady state with DSTATCOM compensation using CGBPNN-based PQ theory



(a)



(b)

Fig. 13. (a) Waveform of source current, i_S under non-linear load in steady state with DSTATCOM compensation using CGBPNN-based PQ theory (b) Waveform of load current, i_L under non-linear load in steady state with DSTATCOM compensation using CGBPNN-based PQ theory

Table 2
Percentage of THD for the system for non-linear load under different topology

Analysis	System Study		THD (%)
Simulation	Before DSTATCOM compensation		46.58%
	After DSTATCOM compensation	PQ	7.82%
		CGBPNN	5.35%

4. Conclusions

As a conclusion, power quality issues are a serious problem that cannot be ignored as it brings harm to both utility and user if it is ignored. It is important to identify the root of power quality issues so that the problem can be solved with an appropriate way. The utilization of DSTATCOM aims to address power quality concerns, specifically those associated with current issues. DSTATCOM serves as an effective solution for mitigating a wide range of problems related to current. Proper control algorithm of DSTATCOM need to be choose wisely, as performance of DSTATCOM is dependent on its control algorithm. For non-linear load condition, the system with DSTATCOM and conjugate gradient backpropagation neural network-based PQ theory proved to be the best system as it takes lesser time to stabilize the waveform. It also has the lowest amount of THD percentage. Overall, DSTATCOM excellency is proven for this project as it able to lower the total harmonic distortion to the permissible limit as stated by IEEE standard 519-2022 and maintain the waveform in sinusoidal waveform.

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