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Power quality improvement in the cold store comprises voltage source inverters based on d-STATCOM with an LCL filter

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Abstract

LCL filter complicates the design of a hybrid power filter (HPF) and improves the power quality (PQ) better over the conventional one. In this research work, extensive approaches have been proposed to deal with the power quality (PQ) issues. Apart from these, effective and cost-efficient solutions play an important role for making distribution healthy. This paper presents a study of HPF technique, where a generalised approach to developing a volt-age source inverter (VSI) by implementing Deep Learning (DL) algorithm to the circuit is proposed. Based on this approach, source current harmonics reduction, power factor correction in the source side, load compensation, regulation of load voltage and upholding constant voltage across the Dc-link capacitor of these two models' results are achieved. Later on, the inductor and capacitor are effectively determined by means of mathematical analysis. Comparisons are then made between conventional and proposed HPF by considering the implementation procedure. Consequently, the HPF is realised as a best alternative for the PQ improvement over VSI using DL algorithm. Finally, the both topologies are ana-lysed using MATLAB/ Simulink with the help of Sim power system toolboxes.

Keywords: HPF,LCL,VSI,DL,PQ

1. Introduction

Recently, the design of the improved version of custom power devices is in the limelight. Many more attention and research work are focused for the operation of voltage source inverter-based distribution static compensator (d-STATCOM) (Bayu et al., 2020). Now a days, the distribution systems are upgraded for multifunction purposes. Hence in the recent research work the idea of multifunction d-STATCOM that contains both normal operation with additional power quality improvement functionalities is achieved. The multifunction system supports flexible way to maintain high performance and clean power transferring to the distribution. The main objective of such equipment is to eliminate the source current harmonics and ensure reliable as well as flexible operation.

In different previous research work (such as photovoltaic, wind turbine, etc.), the VSI is the significant part of the d-STATCOM. In addition to the state-of-the-art, the hysteresis current controller is provided with the interfaced inverter to perform the power quality duties using different control techniques. The conventional approaches, originating from switching signal principle, have been commonly adopted in the application of converters (Gałecki et al., 2016.) This control scheme offers superior tracking ability. Moreover, in recent work the execution in the real time for the prototype model development is potential advance. With these advantages like superior performance and easy implementation, the LCL d-STATCOM can be utilized to achieve PQ enhancement.
Additionally, to get better the compensator voltage and current, a LCL is incorporated in series with the interfacing inductances. The integration of LCL filter has been widely applied with the active filters (Pan et

al., 2017; Liu et al., 2018). It has been examined in previous research work that the LCL filter offers a better smoothing output current. Moreover, this filter uses smaller value of inductance that escorts to smaller harmonic voltage drop across the output. The VSI with output LCL filter has been first proposed in, which mainly focuses on the concept of providing non active power to compensate source current. Nevertheless, the in-depth study and design scenario for the LCL based multifunction grid inverter has been seldom involved in the literatures thereafter. Different from these previous literatures, this paper aims at exploring the inherent features of the LCL filter based multifunction grid inverters and offering generalized models as well as control design for this application.

Table.1 development trends of different adaptive controllers

Types of techniques proposed	**Year of publication**	**Merits**	**De-merits**	**Control flexibility**	**Power loss**	**cost**
ALMS	2017	Robustness, good tracking ability	Poor convergence	Low	Low	Low
HLMS	2021	Simple and intuitive, stable control	Dependent on associated weights & sparse constant	Medium	Medium	Medium
SLMS	2021	Fast convergence capability, better optimization	Sparse dependent	High	medium	medium
KHLMS	2019	Less static error, fast convergence	Highly dependent on system parameters	High	High	High
DRL	2018	Stabilizes high dimensional and infinite-state problems.	Computation delays.	High	medium	medium
DL[Proposed]	2018, 2022	Low rating of DSTATCOM is gained, good pf	Medium computational burdens	High	low	low

An exhaustive literature review on LMS based d-STATCOM for PQ analysis is made; based on merits, demerits, control flexibility, power loss and cost as listed in Table 1. In ALMS based d-STATCOM, the merits such as robustness and good tracking capability were found. But, power convergence characteristics, low control flexibility, low power loss and low cost were observed (Panda et al., 2017). Later to this, the performance was analysed by considering HLMS supported d-STATCOM. The simulation studies are reported for certain limitations for dependent parameters, medium flexibility, power loss and cost (Mangaraj et al., 2021). Similarly, SLMS technique is also presented certain drawbacks like sparse dependent, and high control flexibility, power loss and medium cost (Mangaraj et al., 2021). In this way, KHLMS (Mangaraj et al., 2019), ADALINE LMS [17], DRL (Zhang et al., 2018) and DL approach et al., 2018) studies on d-STATCOM have been put forwarded for the different features. With the growing interest in designing of d-STATCOM for the better features with PQ improvements is integrated with LCL filter.

The original aspects of this proposed d-STATCOM compared to the previously published d-STATCOM studies are analysed as follows:

(i) Implementation of LCL coupled d-STATCOM using DL approach is obtained.
(ii) Ensures the optimized active and reactive power flow between the distribution system and d-STATCOM.
(iii) Significant of current THD is achieved with better voltage regulation, voltage balancing with pf improvement.
(iv) The analysis is obtained by selecting stable parameter of LCL coupling to improve the control capability, flexibility and reliability.

The structure of this paper is as follows: Section 2 describes the design and modelling of LCL coupling with VSI. In Section 3, the DL-approach control algorithm mathematical analysis are described. In section 4, the MATLAB/ Simulation results are highlighted to showcase the performance in the present system. Finally, Section 5 concludes this paper.

2. Distribution System Design

The proposed LCL coupled d-STATCOM is designed to operate in three phase distribution system according to the system analysis and the data attained as a result of simulations performed by MATLAB/Simulink. The power circuit configuration of the LCL coupled d-STATCOM is illustrated in fig 1. As shown in the fig 1, d-STATCOM is coupled with the nonlinear load which is directly fed. The two level VSI with the compensator impedance as shown in the fig. 2. The supply current, the load current, and the compensator current are denoted by $\mathbf{i_s}, \mathbf{i_l}, \mathbf{i_c}$ respectively. Here, $\mathbf{z_s}$, $\&\mathbf{z_c}$ are represented as the source impedance and compensator impedance respectively. The Overall DL algorithm for LCL based d-STATCOM is shown in the fig. 3, whereas the Flowchart of DL control algorithm for LCL based d-STATCOM is presented in the fig.4.

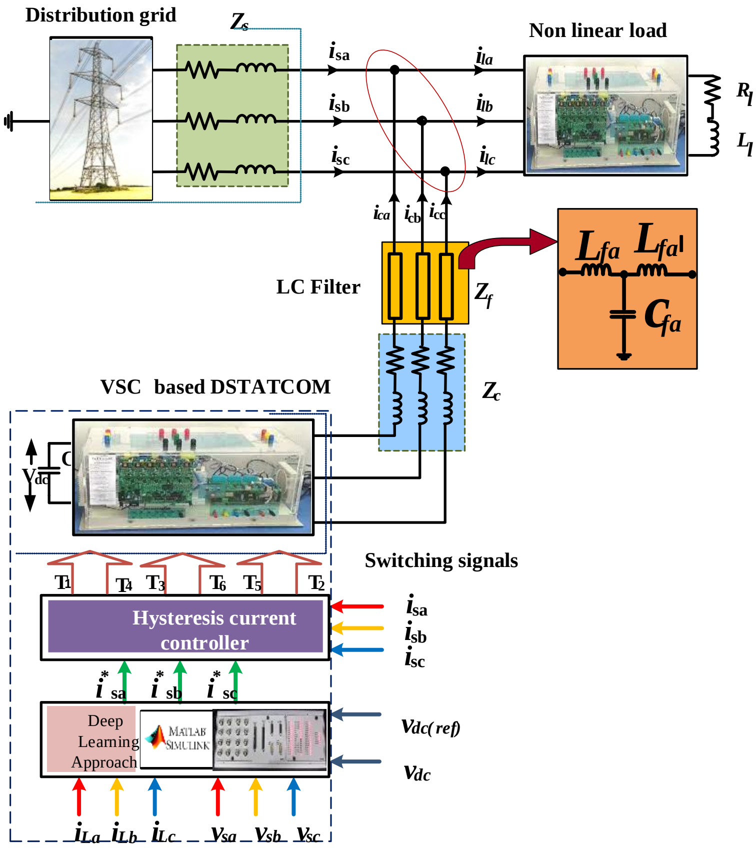

Fig. 1 Configuration of EDS with DSTATCOM

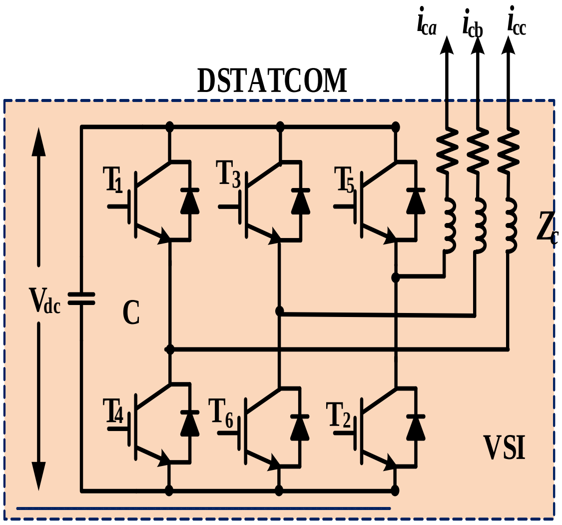

Fig. 2 Traditional d-STATCOM

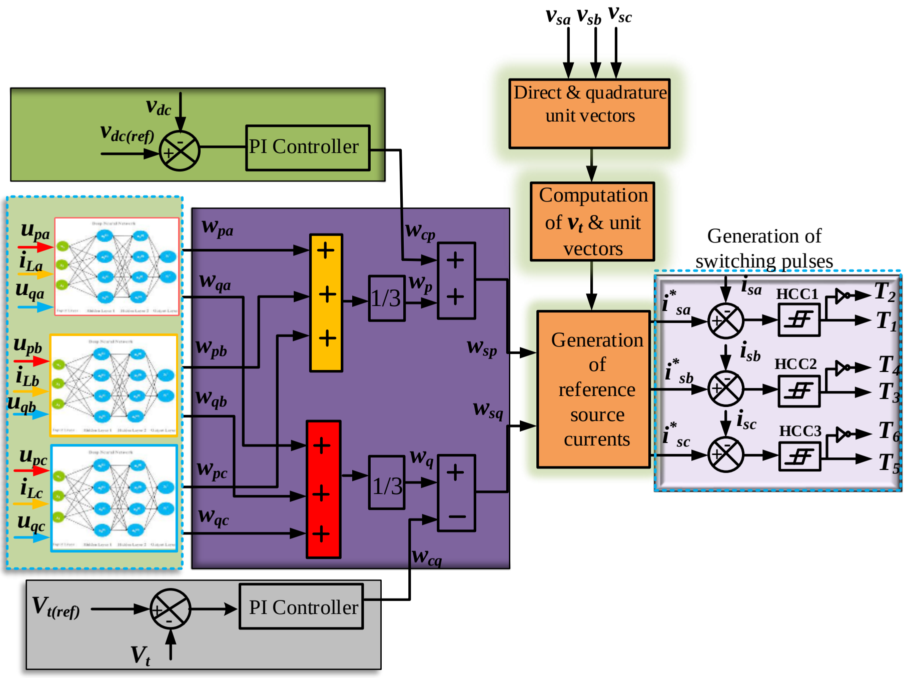

Fig. 3 DL algorithm for LCL based d-STATCOM

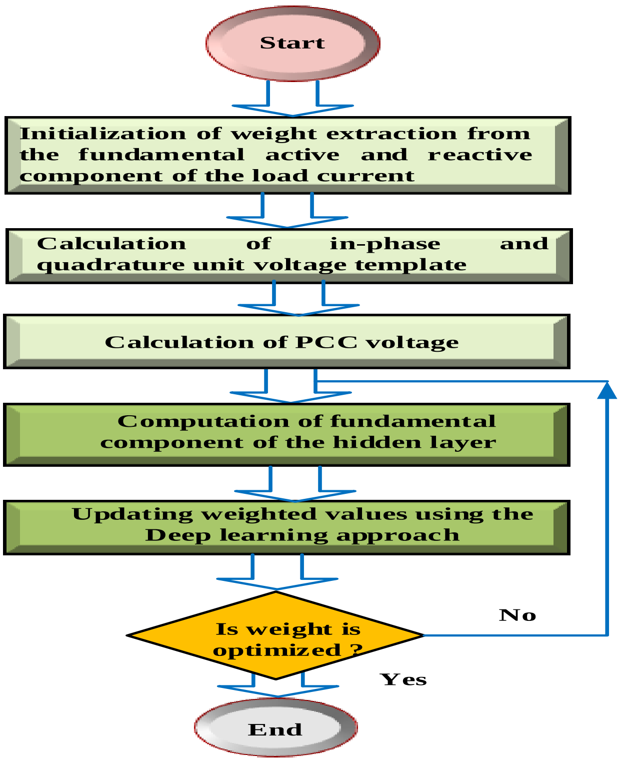

Fig. 4 Flowchart of DL algorithm for LCL based d-STATCOM

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3. mathematical Modelling of DL Algorithm

The structural diagram is developed by combining convergence factor & learning rate to accomplish the approximate tuned weight in suggested learning mechanism.

The following learning rules are represented to extract the reactive component of load current (w_{qa}, w_{qb}, w_{qc}) below:

$$W_{qa}^{n} = \sigma \sum_{k} W_{qa}^{i} \; h_{k}^{i-1} \; u_{qa}(n)(i_{la}(n) - w_{qa}(n-1) + b_{j}^{i} w_{qa}(n-1) \quad (1)$$

$$W_{qb}^{n} = \sigma \sum_{k} W_{qb}^{i} \; h_{k}^{i-1} u_{qb}(n)(i_{lb}(n) - w_{qb}(n-1) + b_{j}^{i} w_{qb}(n-1) \quad (2)$$

$$W_{qc}^{n} = \sigma \sum_{k} W_{qc}^{i} \; h_{k}^{i-1} \; u_{qc}(n)(i_{lc}(n) - w_{qc}(n-1) + b_{j}^{i} w_{qc}(n-1) \quad (3)$$

Likewise, the DL algorithm is used for extracting the active component for load current (w_{pa}, w_{pb}, w_{pc}) which are expressed by the following equation:

$$W_{pa}^{n} = \sigma \sum_{k} W_{pa}^{i} \; h_{k}^{i-1} \; u_{pa}(n)(i_{la}(n) - w_{pa}(n-1) + b_{j}^{i} w_{pa}(n-1) \quad (4)$$

$$W_{pb}^{n} = \sigma \sum_{k} W_{pb}^{i} \; h_{k}^{i-1} \; u_{pb}(n)(i_{lb}(n) - w_{pb}(n-1) + b_{j}^{i} w_{pb}(n-1) \quad (5)$$

$$W_{pc}^{n} = \sigma \sum_{k} W_{pc}^{i} \; h_{k}^{i-1} u_{pc}(n)(i_{lc}(n) - w_{pc}(n-1) + b_{j}^{i} w_{pc}(n-1) \quad (6)$$

Reactive average value is given as

$$w_{r} = \frac{w_{qa} + w_{qb} + w_{qc}}{3} \quad (7)$$

Similarly, active average value is calculated as

$$w_{a} = \frac{w_{pa} + w_{pb} + w_{pc}}{3} \quad (8)$$

Here, in-phase unit voltage templates (u_{pa}, u_{pb}, u_{pc}) are obtained from phase voltages (v_{sa} , v_{sb} , v_{sc}) & PCC voltage (v_t) which are given by:

$$u_{pa} = \frac{v_{sa}}{v_{t}}, \; u_{pb} = \frac{v_{sb}}{v_{t}}, \; u_{pc} = \frac{v_{sc}}{v_{t}} \quad (9)$$

Similarly, the quadrature unit voltage templates (u_{qa}, u_{qb}, u_{qc}) are expressed by:

$$u_{qa} = \frac{u_{pb} + u_{pc}}{\sqrt{3}}, \qquad u_{qb} = \frac{3u_{pa} + u_{pb} - u_{pc}}{2\sqrt{3}}, \qquad u_{qc} = \frac{-3u_{pa} + u_{pb} - u_{pc}}{2\sqrt{3}} \quad (10)$$

Where, v_t can be expressed as

$$v_t = \sqrt{\frac{2(v_{sa}^2 + v_{sb}^2 + v_{sc}^2)}{3}} \quad (11)$$

The constant dc bus voltage can be controlled processing the v_{de}signal using Proportional-Integral (PI) controller and can be expressed as

$$w_{cp} = k_{pa}v_{de} + k_{ia}\int v_{de}dt \quad (12)$$

Where, $v_{de} = v_{dc\,(ref)} - v_{dc}$; $v_{dc\,(ref)}$is the ref. voltage for DC link &$v_{dc}$is actual voltage for DC link

The total active weight of the reference source current can be given in the form.

$$w_{sp} = w_a + w_{cp} \quad (13)$$

The constant ac bus voltage can be controlled processing the v_{te}signal using Proportional-Integral (PI) controller and can be expressed as

$$w_{cq} = k_{pr}v_{te} + k_{ir}\int v_{te}dt \quad (14)$$

Where, $v_{te} = v_{t\,(ref)} - v_t$; $v_{t\,(ref)}$is ref. PCC voltage and v_t is actual PCC voltage.

Similarly, total active weight of the ref. source current can be specified in following form.

$$w_{sq} = w_r - w_{cq} \quad (15)$$

Multiplication of active power current component with in phase unit voltage template results the ref. source current active component as follows

By multiplying the active power current component by the in-phase unit voltage template, the reference source current active component is given as.

$$i_{aa} = w_{sp}u_{pa}, \quad i_{ab} = w_{sp}u_{pb}, \; i_{ac} = w_{sp}u_{pc} \quad (16)$$

Similarly, reference source reactive components are obtained as

$$i_{ra} = w_{sq}u_{qa}, \; i_{rb} = w_{sq}u_{qb}, \; i_{rc} = w_{sq}u_{qc} \quad (17)$$

The following equation formulates the reference source currents.

$$i_{sa}^* = i_{aa} + i_{ra}, \; i_{sb}^* = i_{ab} + i_{rb}, i_{sc}^* = i_{ac} + i_{rc} \quad (18)$$

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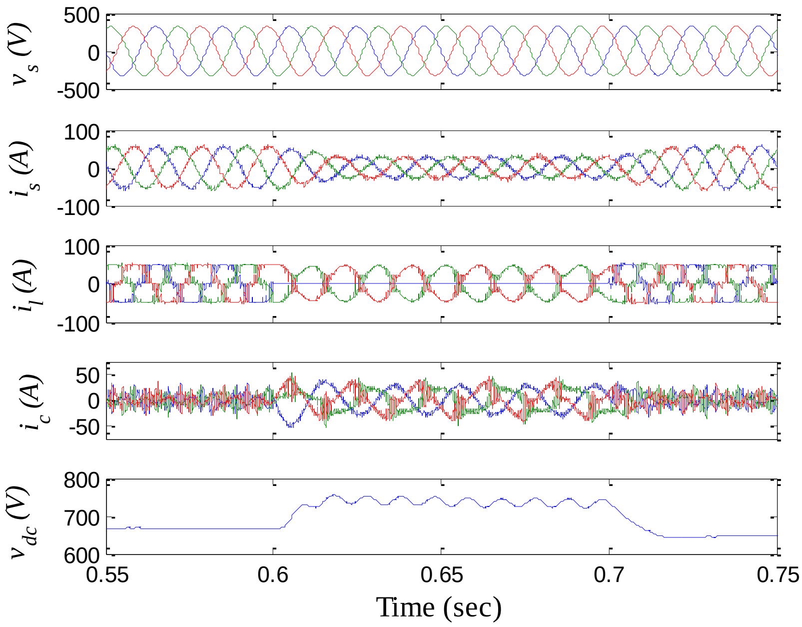
4. Results and discussion

The effective presentations of the premeditated distribution system comprise, VSI based d-STATCOM with LCL filter and 3-phase non-linear load controlled by the DL algorithm for power quality analysis, which will be validated in simulation set upsizing MATLAB/Simulink based Sim Power Systems toolbox. Appraised system parameters, which are used for improved Simulation results under IEEE standard grid-code are exposed in Table.2. In this research work, the LCL filter connected with VSI for power quality issues in the field of electrical utility system, compare with conventional VSI can be observed here with the simulation results, which are exhaustive below:

- Source side voltage and current are nearer to each phase, i.e. power factor improvement
- VAR control
- Source current harmonic reduction
- Constant voltage at PCC which upholding constant voltage across the Dc-link capacitor and improve the voltage regulation
- Increases the system reliability

3.4. Simulation study of d-STATCOM using DL mechanism

For the analysis of the power quality study, the simulation results are obtained from DL algorithm supported d-STATCOM in distribution. The group of simulation parameters are plotted on the common fig. 5 a. In this case, the power factor is obtained 0.95 which is shown in the Fig. 5 b which verifies improved. The source and load side THD are obtained 4.34 % and 21.03 % as shown in the fig. 5 c and 5 d respectively which verifies harmonic reduction at source side. Finally, voltage regulation and voltage balancing are realized as per theoretical studies aligned with IEEE guidelines.



5 (a) Simulation outcome for performance parameters of DL supported DSTATCOM in the distribution

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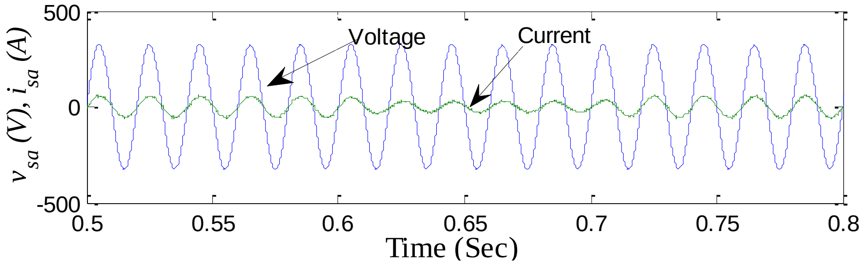
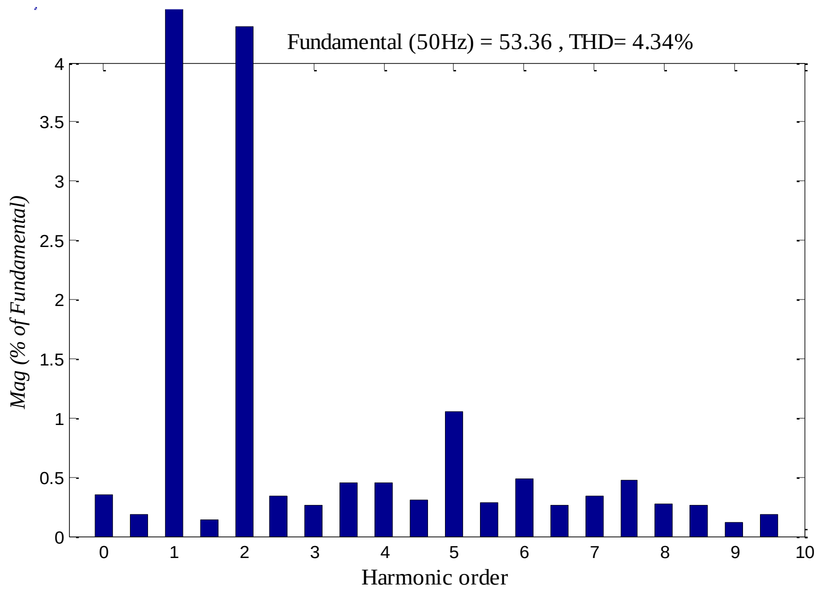
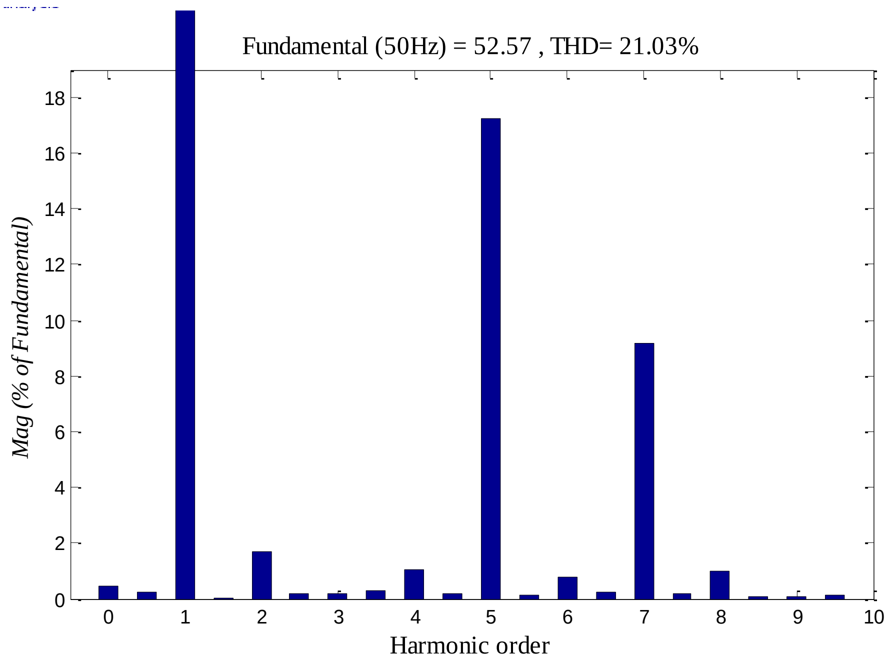


5 (b) source side power factor



5 (c) Source %THD



5 (d) Load % THD

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4.2. Simulation study of LCL based d-STATCOM using DL mechanism

For the analysis of the power quality study, the simulation results are obtained from DL algorithm supported d-STATCOM in distribution. The group of simulation parameters are plotted on the common fig. 5 a. In this case, the power factor is obtained 0.98 which is shown in the Fig. 5b which verifies improved. The source and load side THD are obtained 3.53 % and 20.76 % as shown in the fig. 5c and 5 d respectively which verifies harmonic reduction at source side. Finally, voltage regulation and voltage balancing are realized as per theoretical studies aligned with IEEE guidelines. The THD profile obtained from simulation study under (i) without DSTATCOM (Brown colour), (ii) DL supported DSTATCOM (orange colour), and (iii) DL supported LCL based DSTATCOM (grey colour) are shown in fig. 6. Including this, the comparative power quality studies are presented in the Table.3

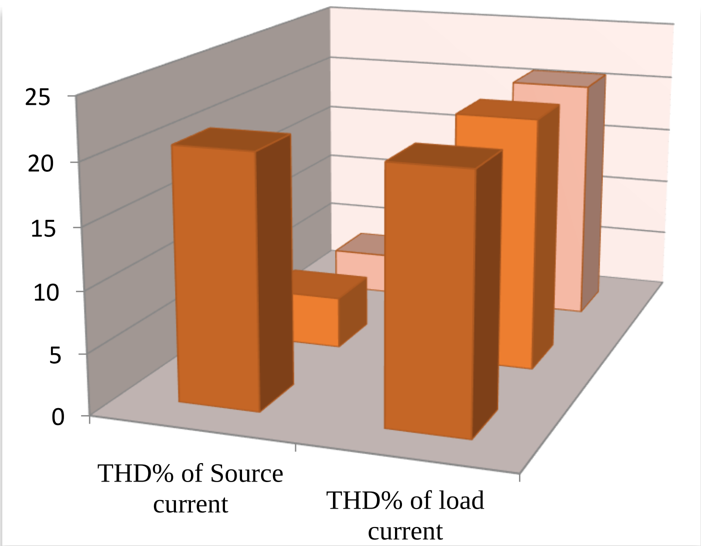

Fig. 6 THD profile obtained from simulation study under (i) without DSTATCOM (Brown color), (ii) DL supported DSTATCOM (orange color), and (iii) DL supported LCL based DSTATCOM (gray color)

Table 2. Simulation configuration parameters

Symbol	Definition	Value
v_s	3- phase source voltage	230V/phase
f_s	Frequency	50Hz
R_s	Source resistance	0.5Ω
L_s	Source inductance	2mH
K_{pr}	AC Proportional controller	0.2
C_{dc}	Capacitor	2000μF

K_{pa}	DC Proportional controller	0.01
K_{ia}	DC Integral controller	0.05
v_{dc}	DC link voltage	600V
R_c	VSC resistance	0.25Ω
L_c	VSC inductance	1.5mH
K_{ir}	AC Integral controller	1.1

Table 3. Simulated results of DSTATCOM and LCL coupled DSTATCOM using DL algorithm

Performance parameter	DSTATCOM	LCL coupled DSTATCOM
i_s(A), %THD	53.36, 4.34	52.87, 3.53
v_s (V), %THD	320.8, 1.83	321, 1.12
i_l (A), %THD	52.57, 21.03	52.84, 20.76
Power Factor	0.95	0.98
v_{dc} (V)	669.7	608.4

5. Conclusion

This paper presented a complete comparative analysis involving a d-STATCOM without LCL and with LCL coupled for different loading conditions using DL algorithm. Both balanced and unbalanced loading tests were performed to demonstrate and select the appropriate topology for the best performance. The following achievements are obtained from both the simulation and experimental studies by fulfilling the criteria of IEEE-519-2017 and EN-50160 standard which are summarized below:

1. The THD of source current 2.72% and 3.57 are achieved under balanced and unbalanced loading condition respectively.
2. The improvement of p.f leads the better source current and supply voltage behaviour.
3. The methodology proposed is successfully implemented for voltage stability and active damping.
4. The voltage balancing and voltage regulation established the viability and effectiveness of the DL controlled LCL based DSTATCOM.
5. After extensive experimental tests, it was possible to select that the proposed topology presents superior performance for balanced and unbalanced loading when compared to the other.

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