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Experimental analysis of DI-ZSI based DSTATCOM

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ABSTRACT

This article presents the dual operation of distributed energy resources (DER) integrated impedance source inverter (DI-ZSI). The distribution grid, DER and variable nonlinear load are operating on two modes. In mode-1, power generated by the DER is zero or less then the load requirement and the inverter act as a voltage source inverter (VSI) for shunt compensation only. But, in mode-2, power generated by the DER greater than the load requirement and operates as a DI-ZSI based distributed static compensator (DSTATCOM). In this scenario, it not only acts as a shunt compensator but also inject active power to the distribution grid. An accurately tuned proportional integral with adaptive least mean square (ALMS) controller is used to generate the switching signals of inverter switches. The DI-ZSI performs stable operation in the distribution grid over a variable non-linear loading. A field programmable gate array (FPGA) SPARTAN-6 controller is used to develop the proposed system. Experimental results from DI-ZSI and VSI under variable loading highlighted the superiority of the DI-ZSI as per guidelines imposed by IEEE-2030-7-2017.

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1. INTRODUCTION

In recent years, quality of power delivered at rated parameters to the end users are the most important concerns in the distribution grid. At the same time the electrical energy dependency society engaged with more than ninety percent of the nonlinear loads, which degrades the whole system power quality (PQ) [1]. Harmonic distortion in source current is one of the major PQ issues for affecting the system rated parameters. The reason behind the issue occurred due to unmatched distribution transformer impedance, generation side and the end user side [2]–[4]. So, power electronics devices play a vital role for transferring electrical power from distributed energy resources (DER) to the distribution grid to fulfil the end user's electrical energy deficiency [5], [6].

The limited availability of fossil fuel and conventional energy affects the life of individuals and the growth of a nation. Distribution grid requires proper control and regulatory frameworks for reliable and flexible operation with enhanced PQ. The voltage source inverter (VSI) topology is generally used as a shunt compensator and now it has large area of applications such as, photovoltaic system [7], electric drives [8], microgrid [9]–[13], electric vehicle [14], and renewable energy integration [15], [16]. Nowadays VSI is playing a significant role in AC microgrids to provide reliable power with PQ improvement. The transformer less VSI is used in DER due to its low cost, high efficiency, reliable operation, small size, and simple design [16]. Keeping view of the previous research work on nonconventional energy generation integrations [16], this paper proposed DER integrated impedance source inverter (DI-ZSI) based distributed static compensator (DSTATCOM) with dual function ability over bounded VSI i.e., better reactive power compensation with active power injection.

Amalgamation of neural-network based control strategy and VSI are the best power flow architecture for the DER integration distribution grid. The control strategies such as, adaptive-control-based algorithm [17], Kernel Hebbian least mean square [17], [18], least mean fourth based neural network (NN) [19], Naïve back propagation control technique [20], gradient descent back propagation control algorithm [21], and power normalized Kernel least mean fourth (PNKLMF) based neural network control [22] are very complex due to adjustment of gains, less error reduction capability and unable to automatic adjustment. An accurately tuned adaptive least mean square (ALMS) controller has improved performance compared to the above controller [23]–[25]. The objectives of the proposed ALMS control technique are to inject active power as well as maintain the source current with sinusoidal profile. The ALMS control algorithm also supports the proposed system for stable operation in all scenarios. The innovation of this research approach is that the ALMS control technique is based upon the neural networks. Specifically, the proposed controller can abolish all the PQ issues with harmonic reduction, shunt compensation, power factor improvement, voltage balancing, and better voltage regulation. Previously, there was no work highlighting the integration of proposed topology and algorithm for power quality enhancement of distribution grids. Moreover, the IEEE grid code suggested a maximum 5% source current total harmonic distortion (THD) and these recommended values are achieved using DI-ZSI based DSTATCOM. Finally, a better sinusoidal profile waveform with improved filtering and active power feeding distribution grid is operated with better reliability and flexibility.

This article is organised as follows. In section 1, based on the concept of grid interface inverter, the basic operation DI-ZSI based DSTATCOM is introduced. Then, the DI-ZSI configuration and their novelty are explained in section 2. The control technique is derived and their ability is examined carefully in section 3. A hardware setup for a three phase three wire DI-ZSI based DSTATCOM is designed and examined under nonlinear loading which is discussed in section 4. Finally, the conclusion is careworn in section 5.

2. SYSTEM DESCRIPTION

In this section, DER connected to the DC link of the DI-ZSI is arranged in Figure 1 and the structure of ZSI is presented in Figure 2. The generated power from different energy sources to the distribution grid supplied through a DI-ZSI. The type of power generated in DER may be AC or DC, therefore the output of the DER needs rectifiers for AC sources before connecting input to the inverter. Both DER and distribution grid are independently controlled with common DC link capacitor.

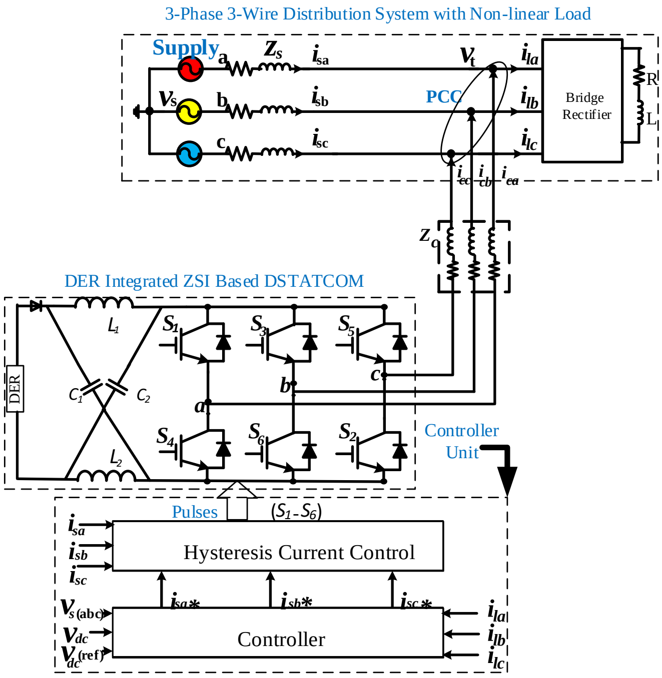

Figure 1. The general layout of distribution grid

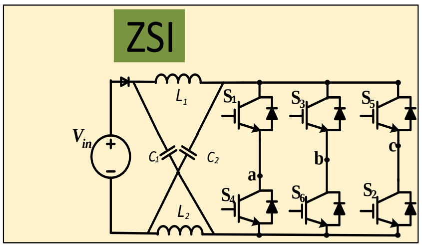

Figure 2. The general layout of ZSI configuration

2.1. Novelties of the DI-ZSI

There are different novelties of the DI-ZSI over traditional VSI are presented below:

- Better shunt compensator: the ZSI, referred to as DSTATCOM in this research work, provides increased flexibility in controlling the source current profile in the distribution grid.
- Better PQ issues abolished: previously, there was no work highlighting the the integration of proposed topology and algorithm for power quality enhancement of distribution grids. Specifically, the controller can abolish all the PQ issues with harmonic reduction, shunt compensation, improvement in power factor, voltage balancing, and enhanced voltage regulation.
- DC-link voltage decreased: the DI-ZSI DC-link voltage is decreased approximately 10% over VSI.
- Renewable energy resources integration facilities: as the DI-ZSI configuration integrated with DER, which facilitated the system with binary function capability i.e. active power injection and shunt compensation.

3. DESIGN OF ALMS CONTROL TECHNIQUE

The first step of control objective is to derive the average weight of both components, i.e. active and reactive components from fundamental load currents. Correspondingly, the second step of the control objective is derivation of the unit voltage template. The third and fourth control objective aims to computation of active and reactive components. Finally, the last step expresses the signal generation and control objective to reduce PQ problems with active power injection to the distribution grid. Here, the technique is briefly explained with the help of different parameters like input weights, bias, learning rate, and step size. The objective is to provide tuned weight corresponding to the real component of the connected load current. The structural representation of the algorithm is depicted in Figure 3 and the step by step switching signals generation is presented below:

- 3-phase load current's active part updated weights $'w_{pa}, w_{pb}, w_{pc}'$ are:

$$w_{pa}(n) = \alpha\gamma\{i_{la}(n) - w_{pa}(n-1)u_{pa}(n)\}u_{pa}(n) + w_{pa}(n-1) \tag{1}$$

$$w_{pb}(n) = \alpha\gamma\{i_{lb}(n) - w_{pb}(n-1)u_{pb}(n)\}u_{pb}(n) + w_{pb}(n-1) \tag{2}$$

$$w_{pc}(n) = \alpha\gamma\{i_{lc}(n) - w_{pc}(n-1)u_{pc}(n)\}u_{pc}(n) + w_{pc}(n-1) \tag{3}$$

- 3-phase load current's reactive part updated weights $'w_{pb}, w_{pc}'$ are:

$$w_{qa}(n) = \alpha\gamma\{i_{la}(n) - w_{qa}(n-1)u_{qa}(n)\}u_{qa}(n) + w_{qa}(n-1) \tag{4}$$

$$w_{qb}(n) = \alpha\gamma\{i_{lb}(n) - w_{qb}(n-1)u_{qb}(n)\}u_{qb}(n) + w_{qb}(n-1) \tag{5}$$

$$w_{qc}(n) = \alpha\gamma\{i_{lc}(n) - w_{qc}(n-1)u_{qc}(n)\}u_{qc}(n) + w_{qc}(n-1) \tag{6}$$

- Real component average weight $'w_a'$ is:

$$w_a = \frac{1}{3}\left(w_{pa} + w_{pb} + w_{pc}\right) \tag{7}$$

- In the same way, the reactive component average weight $'w_a'$ is:

$$w_r = \frac{w_{qa}+w_{qb}+w_{qc}}{3} \tag{8}$$

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

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

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

$$v_{de} = v_{dc\,(ref)} - v_{dc} \quad (12)$$

$$w_{cp} = k_{pa}v_{de} + k_{ia}\int v_{de}dt \quad (13)$$

$$w_{sp} = w_a + w_{cp} \quad (14)$$

$$v_{te} = v_{t\,(ref)} - v_t \quad (15)$$

$$w_{cq} = k_{pr}v_{te} + k_{ir}\int v_{te}dt \quad (16)$$

$$w_{sq} = w_r - w_{cq} \quad (17)$$

$$i_{aa} = w_{sp}u_{pa}, i_{ab} = w_{sp}u_{pb}, i_{ac} = w_{sp}u_{pc} \quad (18)$$

$$i_{ra} = w_{sq}u_{qa}, i_{rb} = w_{sq}u_{qb}, i_{rc} = w_{sq}u_{qc} \quad (19)$$

$$i_{sa}^* = i_{aa} + i_{ra}, i_{sb}^* = i_{ab} + i_{rb}, i_{sc}^* = i_{ac} + i_{rc} \quad (20)$$

The both actual source currents (i_{sa}, i_{sb}, i_{sc}) and the reference source currents ($i_{sa}^*, i_{sb}^*, i_{sc}^*$) of the respective phases are compared then current error signals are fed to a hysteresis current controller (HCC).

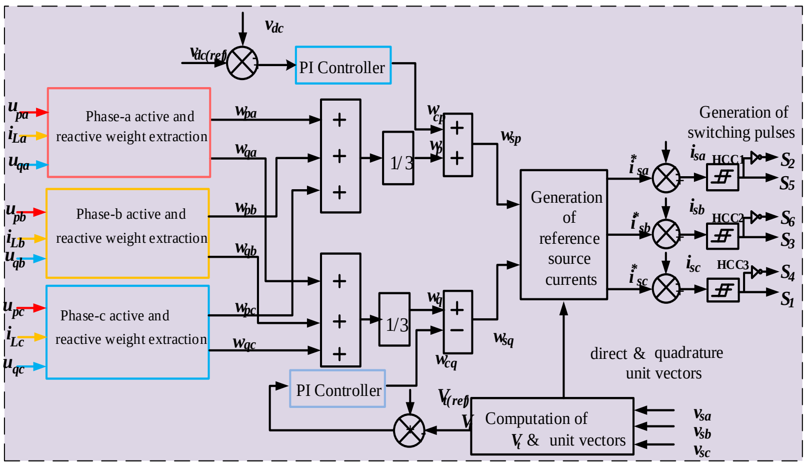

Figure 3. ALMS control structure

4. EXPERIMENTAL RESULTS AND DISCUSSION

As per the circuit diagram Figure 1, a hardware unit is designed. Experimental results are show the dynamic performance of the proposed system over the active and reactive power control with source waveform shaping. The DI-ZSI is designed using a three phase three wire VSI with impedance source, which contains six IGBT (SKM100GB12T4) and the rating of the both source inductor and filter inductor in hardware setup is (5-10 mH). The DER line voltage 415 V is achieved by using an auto transformer and RMS value of the phase voltage of the distribution grid is 230 V. The rating of capacitance in the experimental system is 2200 µF. The three-phase inverter rating is 2 kVA/415 V with switching frequency is 20 kHz. The ALMS control technique is implemented in a FPGA board using Xilinx software. The magnitude of the both topologies different parameters and their magnitudes are arranged in Table 1.

Table 1. Comparative analysis of VSI and DI-ZSI

S.L.	Parameters	VSI	DI-ZSI
1	Magnitude (V), THD (%) of source current	2.37 A, 3.6%	2.35 A, 1.8%
2	Magnitude (V), THD (%) of source voltage	218.5 V, 2%	217.6 V, 1.8%
3	Magnitude (A), THD (%) of load current	1.9 A, 29.9%	1.9 A, 29.9%
4	Power factor	0.982	0.985
5	v_{dc} DC link voltage "V"	620 V	570 V
6	Active power injection	No	Yes
7	Renewable source integration	No	Yes

4.1. Test procedure

The PQ issue is followed by connecting a three-phase bridge rectifier (6No diodes/MUR30120/1200 V) with external variable resistive (1 kW) and inductive load (60 mH). This nonlinear load injects harmonics to the distribution grid measured by two multifunction meters (MFM) connected at both source side MFM-1 and load side MFM-2. The motto of the proposed control technique is utilized to reduce the THD well below as recommended by IEEE standard grid code. The experiment was conducted on DI-ZSI based DSTATCOM in two test scenarios. In the first test scenario operation, power generated from DER is zero. In this mode the inverter acts as only conventional VSI and performs only to mitigate the PQ issues. In second test scenario, DER generates the active power and injects to the distribution grid through DI-ZSI and also incorporates the shunt compensation. All the experimental waveforms are recorded by a multi-channel digital storage oscilloscope (SIGLENT, SDS1104X-E-5100), while the active, reactive powers and THD are measured using MFM.

4.2. Experimental results of scenario 1 (VSI)

Power generated by the DER is zero. Source current, load current and compensating current shown with respective distribution grid source voltage of each phase a, b, and c respectively in Figures 4(a)-4(c). After VSI based DSTATCOM switched ON the phase angle between the phase-a supply voltage and current are presented in Figure 4(d). The VSI DC link voltage and current are presented in Figure 4(e). The source current profile becomes sinusoidal, when the shunt compensator switches on, distortion is reduced. The average source current THD is reduced to 3.5%. The experimental waveform and meter reading indicate better performance of VSI only as an active power filter. In this scenario, a very small amount of active power is consumed by the VSI to overcome the losses and maintain DC link voltage, whereas a large amount of reactive power is consumed to act as a shunt compensator. At DSTATCOM switched OFF, the THD value of source current and load current are measured by multi-function meter (MFM) 27.8% and 29.9% respectively. It indicated from the measured THD value that the distortions are present in both source and load current. But, when DSTATCOM switched ON the distortions are reduced in source current from 27.8% to 3.5% and also the power factor is improved from 0.966 to 0.982.

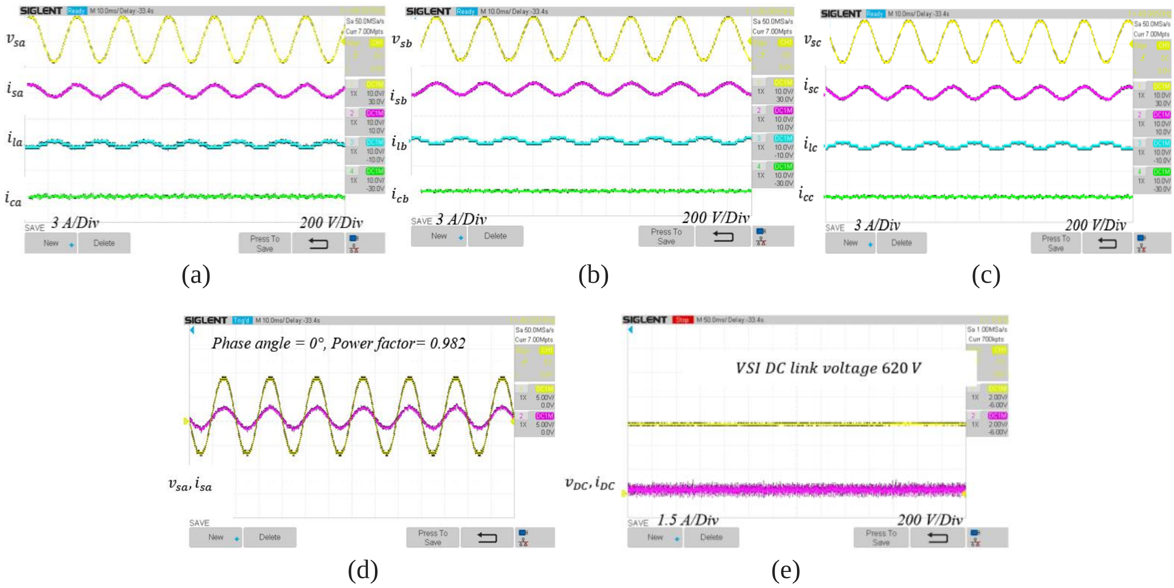

Figure 4. Experimental waveform of source voltage, source current, load current and compensating current of active power filtering scenario (a) phase-a, (b) phase-b, (c) phase-c, (d) after compensation phase angle between phase-a supply voltage and current, and (e) VSI DC link voltage and current

4.3. Experimental results of scenario 2 (DI-ZSI)

In this scenario, DER is generating active power. The experimental waveform of active power filtering and injection of phase-a, b, and c are shown in Figures 5(a)-5(c); phase-a, b, and c are 0.994. After DI-ZSI based DSTATCOM switched ON the phase angle between the phase-a supply voltage and current are presented in Figure 5(d). The DI-ZSI DC link voltage and current are presented in Figure 5(e). The phase relationship between source voltage and current is out of phase which indicates that the extra power supply to the distribution grid with improved power factor. The DI-ZSI current contains two component such as load current component and active power component. Hence, the proposed system supplies the surplus power to the distribution grid after providing the load demand. When DI-ZSI based DSTATCOM is switched ON the distortions are reduced in source current to 2.8% and also the power factor is improved to 0.982. The ALMS control technique accurately deals with the fluctuation in real power at DC link and supply to the distribution system. As an outline to this research, Table 1 provides a comparative performance.

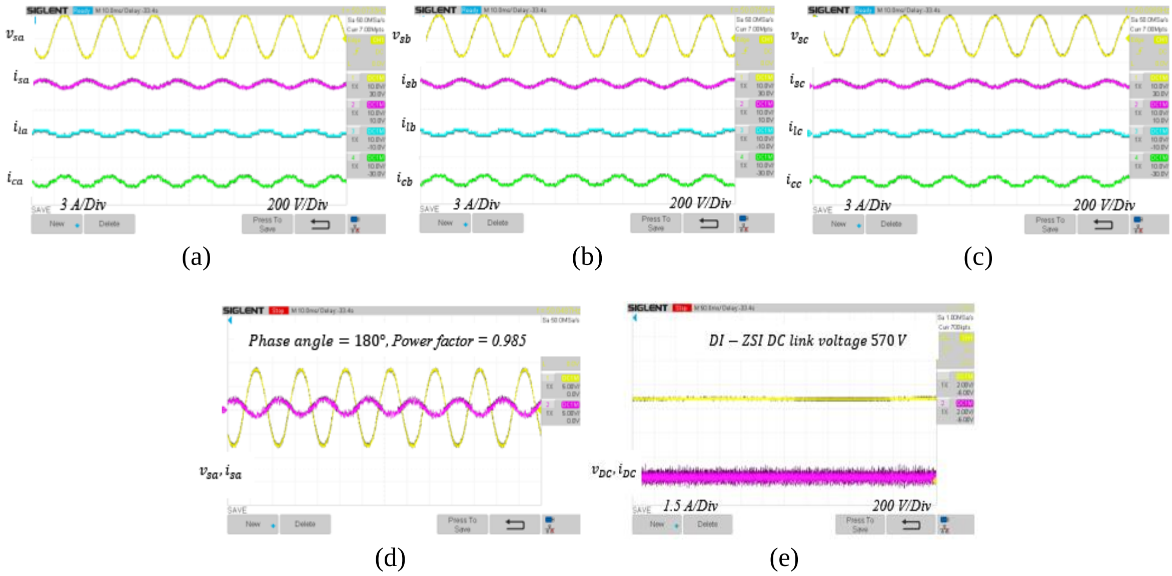

Figure 5. Experimental waveform of active power filtering and injecting scenario (a) phase-a, source voltage, source current, load current and compensating current; (b) phase-b, source voltage, source current, load current and compensating current; (c) phase-c, source voltage, source current, load current and compensating current; (d) after compensation phase angle between phase-a supply voltage and current; and (e) DI-ZSI DC link voltage and current

5. CONCLUSIONS

A neural-network based ALMS control technique implemented in DI-ZSI supported DSTATCOM for shunt compensation and real power injection in the distribution grid is proposed. The reference current estimation using ALMS control algorithm is made due to its faster speed and better convergence characteristics. The proposed controller also possesses simple to implement, automatic adjustment with greater performance and error free computation. The experimental waveform and meter readings indicated that the proposed topology with ALMS controllers is capable of controlling the flow of both active and reactive power from DER with minimizing the distortion of source current. The important merits of the proposed topology are utilized for the power control property which facilitates the utilization of maximum rating of inverter. Finally, point wise merits are provided for proposed topology over conventional VSI, and an efficiency performance of both topologies are compared on active power filtering capability and power flow control ability: i) the DI-ZSI with ALMS controller is engaged in a distribution grid not only to supply the active power generated from the DER but also function as a shunt compensator to enhance the PQ; ii) in this proposed topology the same rating of inverter is more utilized compared to conventional one, which further increases the efficiency of inverter; and iii) an external compensator is not required for the proposed system to inject active power.

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