Power quality monitoring for a solar PV grid controlled system at non-linear induction drives load

Akhil Gupta¹ and Saurabh Chanana²

¹ Assistant Professor, Department of Electrical Engineering,
I. K. Gujral Punjab Technical University, Batala Campus, District Gurdaspur Punjab India 143506
Email: akhilgupta1977@gmail.com, dr.akhilgupta@ptu.ac.in

² Associate Professor, Department of Electrical Engineering,
National Institute of Technology, Thanesar, Kurukshetra Haryana India 136119
Email: schanana75@gmail.com, s_chanan@rediffmail.com, saurabh@nitkkr.ac.in

Corresponding author: Akhil Gupta

Abstract—This paper unveils the impact of non-linear induction motor drives on operation of transformerless single-stage solar photovoltaic (SPV) grid tied inverter system. The system is controlled by an indirect type data-based maximum power point tracking (MPPT) technique. A fuzzy-logic controlled (FLC) dynamic voltage restorer (DVR) is operated coordinating two non-linear induction motor drives load: direct torque flux control (DTFC) and field-oriented control (FOC). Importantly, power quality (PQ) analysis for FOC induction motor drive is validated with DTFC induction motor drive. Results reveal mitigation of unbalanced voltage sag and voltage swell among the SPV converter, load and grid during transient conditions produced by fault. The effectiveness of FLC-DVR at FOC drive load is demonstrated over DTFC drive load and linear load for validation. It is worth mentioning that controlling action of FLC-DVR is implemented effectively at non-linear loads. As illustrated by IEEE-519/1547 standard, a reduction in total harmonic distortion (THD) and DC offset current is reported in grid voltage and current for accuracy. The proposed framework illustrates a comparative PQ study to justify satisfactory performance under varying environmental conditions.

Keywords: photovoltaic; power quality; induction motor drive; control; harmonic

1. Introduction

In weak residential and rural grids, the unpredictable variations in power and node voltages have been observed with solar photovoltaic (SPV) connections on the distribution low voltage grid side [1-4]. This phenomenon has greatly been increased during the operation of SPV systems at highly inductive loads and non-linear loads. The system reported in [5, 6] has been controlled for current harmonics, voltage sags, voltage swells, and compensation of reactive power has been highlighted by using converter as active series-shunt filter. Critical power quality (PQ) issues such as voltage flicker, harmonics, and transient voltage have been reported in [3-5]. The PQ performance of system with and without static compensator has been compared, and illustrated in [7-9]. The model, which analyses the behaviour of a SPV system using bond graph approach, has been reported in [10]. In recent times, the advancement taken place in the development of of power semiconductor devices, and the evolution of several control techniques for converter configurations have projected induction drives the first choice for numerous industrial applications [11, 12]. It has been found that the induction motor can compete with DC motor in high-performance applications on implementing with either field-oriented control (FOC) or direct torque flux control (DTFC) scheme [13]. An analysis on sine wave pump controller to drive SPV water pumping systems has been reported in [14]. Its efficiency with maximum power point tracking (MPPT) controller has been found to be 99.4%, with 3% harmonic distortion content. The dynamic performance of the FOC and DTFC system is mainly influenced by the type of pulse width modulation (PWM) method [15]. Many authors in [16-18] have proposed varied PWM techniques for dynamic performance improvement and
minimization of ripples in torque. Therefore, an important objective of the present study is to compare and address the various PQ concerns at PCCs for FOC and DTFC induction motor drives load. Additionally, the impact of fuzzy controlled dynamic voltage restorer (DVR) under single line to ground fault at changing levels of DC voltage study is highlighted.

This paper assesses the PQ performance of a SPV grid connected system using two induction motor drive connected loads [19-21] namely: DTFC and FOC. Literature survey reveals that data-based MPPT technique is implemented in conjunction with DVR controlled system at non-linear type induction motor driven loads. The scheme proposed is capable to perform during faulted conditions grid side under varying environmental conditions. Furthermore, since most of industrial load are non-linear, the preceding research has not addressed to solve PQ issues using any type of induction motor drive load. Because of these shortcomings, two types of controlling schemes for DVR are introduced in present work, namely: fuzzy-logic control (FLC) and a conventioned proportional integral (PI) control. A PQ comparison using each induction motor drive load at single line to ground fault is dynamically studied and analysed through simulations in MATLAB/SIMULINK. Values of total harmonic distortion (THD) and DC offset current for grid injected current and load current are calculated as specified by IEEE-519/1547 standard [22]. Using the fast fourier transform (FFT) algorithm the calculated THD values for grid current and load current are 3.36% and 0.89% respectively, for FOC drive load. The validation of results obtained for FOC drive is carried out by comparing computer simulations with DTFC drive and a linear RLC load. Finally, the performance of fuzzy-logic DVR-FOC drive in reducing distortion is satisfactory over DTFC controlled drive.

2. Configuration of solar photovoltaic grid connected system

The proposed system illustrated in Fig. 1 is composed of SPV arrays, and a voltage source converter (VSC) with reactor-capacitor-reactor (LCL) filter [23-26]. Capacitor in LCL-filter [27, 28] prevents the harmonics generated by inverter-based distributed generation system. A 50 kW three-phase induction motor connected as a non-linear load has been driven by two types of drives: DTFC and FOC. A non-linear drive load has been connected between utility and an insulated gate bipolar transistor (IGBT)-based VSC. A forced commutated VSC is implemented in DVR, along with energy storage to maintain the capacitor voltage. As depicted, the DVR consists of a VSC, a series connected linear injection transformer, a converter filter with an energy storage. As elaborated in [29], DVR injects a voltage component having controlled amplitude, phase and frequency between the points of common coupling (PCC) and utility. FLC is an active choice for VSC of DVR, where accurate formulations are not feasible. FLC has two crisp inputs: one is the difference between utility voltage and reference voltage $e$, while another is derivative of error $de$.

In this paper, FLC is based on mamdani’s system. The crisp variables $e$ and $de$ are converted into fuzzy variables $E$ and $dE$ using triangular and trapezoidal membership functions. The fuzzy variables are processed by an inference engine to execute control rules contained in 49 rule bases. The control rules are formulated using knowledge of DVR behaviour. The max-min type inference algorithm is implemented. The final membership degree is equal to maximum of product of membership degree. In defuzzification stage, the output variables are converted into crisp values. The crisp value is calculated through the centroid defuzzification algorithm, as the centre of gravity. The reference voltages for PWM generator are FLC crisp output commands.
3. Control system techniques

3.1 Maximum power point tracking

MPPT technique is a means to extract maximum energy from SPV panels under changing environmental conditions [23, 25, 30]. A crucial issue of this technique is development of an algorithm of MPP seeking. The important MPPT techniques are perturbation & observation or dithering-in [27], incremental conductance, constant voltage [31], FLC [32, 33], neural, and ripple correlation [5, 8]. Additionally, the highly converging type of MPPT techniques for SPV array are extremum seeking MPPT control [34], and sliding mode control [35] are reported. In case of uniform solar radiation levels, the characteristics of SPV array curve exhibit single MPP, which is being tracked through any of the existing MPPT techniques [36-40]. The research reappraises various techniques, which extracts maximum power SPV arrays. It is destined to bring many design engineers in global SPV-based distributed power systems.

Primarily, more stress has been put on the conventional MPPT algorithms under both uniform and non-uniform levels of solar radiation [41, 42]. Authors in [43] mainly accounted the various converter topologies, but a complete realization of all the recent advancements in MPPT for SPV generation systems has not been done. Additional MPPT techniques have been found to be metaheuristic-based MPPT, particle swarm optimization [44-47], genetic algorithm, and artificial bee colony [48-52]. Analysis on the laboratory implementation of SPV array using a FLC scheme has been done so that maximum SPV power is always tracked under stochastically changing levels [53-56]. In data-based MPPT technique, the data for SPV voltage at MPP is generated using 6 different SPV modules. SPV array has been validated through a prediction type MPPT technique at various values of series resistances \( R_s = 0.00011 \, \Omega, 0.00021 \, \Omega, 0.00031 \, \Omega, 0.00041 \, \Omega, 0.00051 \, \Omega \) and 0.00061 \, \Omega. It is pertinent to mention that each
module in SPV array has been simulated under varying levels of ambient temperature and solar radiation, keeping cell temperature constant.

3.2 Direct torque flux control drive

Introduced for voltage-fed PWM inverter drives [57, 58], this technique [19] involves the direct control of torque and stator flux of a drive by inverter voltage space vector selection through a look-up table. The torque expression as a function of the stator and rotor fluxes is expressed in Eq. (1):

$$ T_e = \frac{3}{2} P \frac{L_m}{L_s} |\psi_r| |\psi_s| \sin \gamma $$

(1)

Where $\gamma$ is the angle in degrees between the rotor flux $|\psi_r|$ and stator flux $|\psi_s|$, $P$ is the number of poles, $L_m$, $L_r$, and $L_s$ is the magnetizing inductance (H), rotor inductance (H), and constant inductance (H), respectively. The block diagram of control strategy for DTFC drive control has been depicted in Fig. 2 (a). The reference values of stator flux $\psi_{sr}$ and electromagnetic torque $T_{er}$ are compared with their actual values, and the errors are processed through hysteresis-band controllers. There are two levels of digital output of flux loop controller according to relations: $H_v = 0.005$ for $E_v > +HB_v$, $H_v = -0.005$ for $E_v < -HB_v$, where, $2HB_v$ = total hysteresis band width of flux controller. There are three levels of digital output for the torque control loop, which have the relations: $H_{T_e} = 1$ for $E_{T_e} > +HB_{T_e}$, $H_{T_e} = -1$ for $E_{T_e} < -HB_{T_e}$, $H_{T_e} = 0$ for $-HB_{T_e} < E_{T_e} < +HB_{T_e}$. Neglecting the stator resistance $R_s$ of the machine, the equation for stator voltage becomes, $\dot{\psi}_s = \frac{d(\psi_s)}{dt}$ or $\Delta \psi_s = \psi_s \Delta t$, which means that stator flux $\psi_s$ can be changed incrementally by applying stator voltage vector $V_s$ for time increment $\Delta t$. 

![Control diagram for DTFC drive](image-url)
3.3 Field-oriented control drive

The block diagram of a vector controlled three-phase induction motor drive is depicted in Fig. 2(b) [19]. In this drive, the machine control is considered in a synchronously rotating reference frame in which the sinusoidal variables are considered as DC quantities in steady state. In synchronously rotating reference frame, the input current controls and are direct axis and quadrature axis component of reference stator current, respectively. The total stator current $I_s$ is expressed as, $I_s = \sqrt{i_{ds}^2 + i_{qs}^2}$ A, where $i_{ds}$ is magnetizing component of stator current and $i_{qs}$ is torque component of stator current, flowing in the rotor circuit of drive. It is worth noting that a non-linear indirect or feed-forward vector control technique has been implemented in place of linear load with data-based MPPT technique in SPV grid connected system. This indirect vector control technique is easy to implement and popular in industrial applications.

As depicted in Fig. 2(b), the speed controller keeps the motor speed equals to reference speed input at steady state. The actual measured rotor speed and reference speed are compared; the error thus generated is processed through the PI controllers, which produces reference torque command. The reference flux signal is also generated, when the actual rotor speed is processed through hysteresis band controllers. Since the stator flux component of current $i_{ds}$ should be aligned on the $d$ axis, and the torque component of current $i_{qs}$ should be aligned on the $q$ axis, the reference flux signal is used to generate $i_{ds}^{*}$ signal, whereas the reference torque signal is used to generate the $i_{qs}^{*}$ signal. The components of reference
currents $i_{ds}$ and $i_{qs}$ are converted into three-phase currents $i_{abc}$ with the help of current regulators. Aiming to generate a three-phase current signal, hysteresis type current controllers have been used. In indirect or feed-forward vector control, the units control vectors $\cos \theta_e$ and $\sin \theta_e$ are generated in feed-forward manner. For decoupling feed forward vector control, the stator flux component of current $i_{ds}$ should be aligned on the $d'$ axis, and the torque component of current $i_{qs}$ should be aligned on the $q'$ axis. For decoupling control in order that total rotor flux $\psi_r$ is directed on the $d$ axis, it is essential that:

$$\psi_{r} = 0 \text{ or } \frac{d}{dt}\psi_{r} = 0 \text{ or } \psi_{r} = L_{w}i_{d}$$

(2)

It is evident from above that the rotor flux $\psi_{r}$ is directly proportional to steady state current $i_{ds}$.

The torque equation for vector control is expressed by Eq. (3):

$$T_{e} = \frac{3}{2} \Psi_{r}\Psi_{s}^{'}/L_{m}$$

(3)

which indicates that the developed electromagnetic torque responds with current components $i_{qs}$ and flux $\psi_{d}$.

4. Simulation, results and discussion

For observing the effectiveness of the proposed system under changing environmental conditions, the solver has been configured as follows: (simulation type: variable-step), (sample time: 1e-6) and (solver type: ode45: Dormand prince). The total simulation period is $t = 0.6$ s. The SPV array used in this paper has been tested by laboratory implementation by a DT2821 data acquisition board [59-63]. The photocurrent of each SPV cell is 5 A. Number of SPV cells connected in series and parallel are 3000 and 14, respectively. For IGBT control, the developed control system has three loops: outer MPPT control, DC link voltage control, and an inner current control loop. For DC voltage regulator, the chosen values of of proportional gain, and integral gain are $K_p=0.61$ and $K_i=9.1$, respectively. For current regulator, the chosen values of of proportional gain, and integral gain are $K_p=0.021$ and $K_i=4.2$, respectively. An indirect type data-based MPPT technique has been implemented [64], which has been validated through a prediction based technique [65-67]. Size of the DC link capacitor is 1500 $\mu$F. LCL filter connected between IGBT and grid has an inductance of $L=1500 \mu$H and capacitance of $C=30 \mu$F.

A single line to ground fault is introduced at phase $R$ on the grid side. The fault and ground resistance values are 0.066 $\Omega$ and 0.001 $\Omega$, respectively. The SPV grid connected system has been operated under faulted condition, which is tested at DTFC and FOC induction motor drive loads. Further investigation of the proposed system has been achieved through discrete PI and FLC-DVR systems. However, the discrete PI controller system has been presented for the critical review of THD analysis. For PI-DVR, the chosen values of proportional gain and integral gain are $K_p=5$ and $K_i=1000$, respectively. In the present section, the FLC-DVR aims to maintain normal voltage at grid side during faulted conditions, in each case. The response for data-based MPPT at 10 $\degree$C cell temperature has been presented, and discussed in the following sub-sections. The total torque hysteresis bandwidth and flux hysteresis bandwidth are 0.5 N-m, and 0.01 Wb, respectively for DTFC drive. The reference values of speed and torque of induction motor used as 500 rad/s, and 17.8 N-m, respectively for each drive.
4.1 Impact of single line to ground fault on DTC drive load

The parameters of DTFC drive for Matlab simulation [68] are illustrated in Table 1. From this table, it is noted that the initial stator flux of 0.01 Wb is established, after which the DTFC drive system begins to produce an electromagnetic torque. This value of small flux is produced by applying a constant voltage at the induction motor terminals.

Table 1. Simulation parameters of DTFC drive load

| System name and its components                                                                 |                                                                 |
|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------|
| Three-phase squirrel cage induction motor: nominal power: 50 kW, voltage (line to line): 440 V, frequency: 50 Hz, stator resistance, inductance: 0.435 Ω, 2×10^-3 H, rotor resistance, inductance: 0.816 Ω, 2×10^-3 H, mutual inductance: 69.31×10^-5 H |                                                                 |
| Direct torque flux control unit                                                             |                                                                 |
| Torque hysteresis bandwidth: 0.5 N-m; Flux hysteresis bandwidth: 0.01 Wb; Initial machine flux: 0.3 Wb; Number of pair of poles: 2; Maximum switching frequency: 2×10^4 Hz, Sampling time: 20 μs |                                                                 |
| Speed controller                                                                            |                                                                 |
| Machine nominal frequency: 50 Hz; Proportional gain: 100 Integral gain: 90; Controller output torque saturation [negative, positive]: -17.8 N-m to +17.8 N-m speed ramps (acceleration, deceleration): 500 rpm, -500 rpm |                                                                 |
| Flux controller                                                                            |                                                                 |
| Proportional gain: 45; Integral gain: 55; flux estimation low-pass filter cut-off frequency: 16 Hz; controller output flux saturation [negative, positive]: [-2, 2]; Sampling time: 20 μs |                                                                 |

As depicted in Fig. 3 (a-c) (the per unit responses), the fault in phase R between the time periods \( t = 0.1 \) s to \( t = 0.4 \) s is observed from distorted voltage waveforms of VSC, non-linear load and grid, respectively. From Fig. 3 (d), it is observed that the actual DC link voltage doesn’t track the reference MPPT voltage. Fig. 3 (e-g) depicts the distorted current waveforms of VSC, non-linear load and grid, respectively. Through close observation, the VSC current is distorted at \( t = 0.1 \) s. Note that due to the impact of fault, a short transient is visible at \( t = 0.01 \) s. From \( t = 0.02 \) s to \( t = 0.4 \) s, the amplitude of VSC current remains 0.25 per unit with no flow of current between \( t = 0.14 \) s to \( t = 0.22 \) s. At \( t = 0.4 \) s, the VSC current overshoots to 2.5 per unit for a short duration and maintains 1.8 per unit till \( t = 0.5 \) s. Between the time period \( t = 0.5 \) s to \( t = 0.6 \) s, the sinusoidal waveform is achieved in VSC current. Fig. 3 (f) depicts the sine wave shape of load current till \( t = 0.1 \) s, its behaviour becomes non-linear due to DTFC driven induction motor load till \( t = 0.4 \) s. Although, the SPV current flows through VSC, there is no injection of current into the grid during the faulted period as shown by Fig. 3 (g).
In this sub-section, an effort has been devoted to evaluate the performance of the system, when the DVR current transient around the reference torque voltage consumed as losses in the operation of non-linear semiconductor devices.

Figure 3. Between $t=0.1$ s to $t=0.4$ s, the impact of fault during with DTFC drive load for (a) VSC voltage (b) load voltage (c) grid voltage (d) MPPT voltage (e) VSC current (f) load current (g) grid current (h) real power (i) reactive power (j) torque (k) rotor speed (l) stator current.

Fig. 3 (h-i) depicts the response of real and reactive output power without the application of DVR during the faulted conditions, respectively. It is observed that the real power is being generated by SPV array under changing solar radiation and ambient temperature levels. However till $t = 0.1$ s, the SPV array generates real power of 52 kW through VSC. Due to occurrence of fault between $t = 0.1$ s to $t = 0.4$ s, there has been no flow of real output power from VSC and ultimately to grid. Also, the real output power generated by non-linear load becomes distorted during the period. Note that after $t = 0.4$ s, the real output power generated by VSC and grid shows the non-linear behaviour. However, the real output power of non-linear load has been maintained constant at around 45 kW. Real power of around 5 kW has been consumed as losses in the operation of non-linear semiconductor devices. Fig. 3 (j) shows the distortion in actual measured torque around the reference torque (17.8 N-m). From Fig. 3 (k), it is found that the induction motor attains the reference speed of 500 rad/s at $t = 0.277$ s. Fig. 3 (l) shows a small stator current transient at $t = 0.01$ s. The non-sinusoidal behaviour is observed from $t = 0.28$ s.

4.2 Behaviour of fuzzy controlled DVR at DTFC drive load

In this sub-section, an effort has been devoted to evaluate the performance of the system, when the DVR is controlled by FLC. Fig. 4 (a-c) depicts that the level of per unit voltage has been improved to 0.4 per unit at $t = 0.4$ s. From Fig. 4 (d), however, the actual DC link voltage tracks the reference MPPT voltage. Fig. 4 (e) depicts the VSC current response under the similar conditions. The VSC current is 1.0 per unit at $t = 0.22$ s. This value becomes 1.5 per unit at $t = 0.32$ s. Fig. 4 (f) depicts the flow of load current between the faulted period. The maximum value of load current flowing through phase R is around 40 A. Fig. 4 (g) depicts the grid current, where thin waveform is shown by red line for phase R. Per unit value of grid current becomes 1.0 per unit at $t = 0.2$ s. The maximum value of current is 1.6 per unit between $t = 0.24$ s to $t = 0.42$ s. As illustrated by Fig. 4 (h), there is more generation of real power by FLC-DVR due to more voltage injection by DVR. From Fig. 4 (i), it can be observed that there is an increase in the generation of reactive power. From Fig. 4 (j) depicts the tracking behaviour of actual measured torque. Fig. 4 (k) presents the tracking of actual rotor speed with reference speed. Fig. 4 (l) presents the less oscillatory stator current response between the period $t = 0.34$ s to $t = 0.5$ s. As evident, the transient behaviour of stator current is less oscillatory in the present case of fuzzy-logic control.
After that, the oscillatory response can be seen for the remaining period of the simulation. In this sub-section, an effort has been devoted to evaluate the capabilities of SPV grid connected system under the similar conditions, however, at FOC drive load. The simulation parameters of FOC drive are tabulated in Table 1.

From Fig. 5 (a-c), it has been observed that sine voltage is absent during the faulted period. Fig. 5 (d) shows the tracking behaviour of DC link voltage around the reference MPPT voltage. Fig. 5 (e) depicts the behaviour of VSC current. The steady-state analysis has been observed till \( t = 0.1 \) s. The value of current starts increasing from \( t = 0.1 \) s to 1 per unit at \( t = 0.24 \) s. From Fig. 5 (f), the load current less than 0.1 per unit flows till \( t = 0.4 \) s. After this time, the transients are observed from \( t = 0.4 \) s to \( t = 0.5 \) s. Fig. 5 (g) depicts the behaviour of grid current, however, notches can be seen during the steady-state behaviour till \( t = 0.1 \) s. Fig. 5 (h) depicts response of the real output power. The output power from grid becomes negative from \( t = 0.1 \) s to \( t = 0.4 \) s, therefore, the real power is generated by SPV through VSC during the same period. After \( t = 0.4 \) s, the response becomes non-uniform. Fig. 5 (i) depicts the reactive output power response. Fig. 5 (j) shows that the actual measured and reference torques are zero till \( t = 0.4 \) s. After this, it is revealed that its actual value doesn’t track the reference value closely. Fig. 5 (k) shows the zero speed of the FOC drive till \( t = 0.42 \) s. Fig. 5 (l) shows that the stator current is constant till \( t = 0.4 \) s, after that, the oscillatory response can be seen for the remaining period of the simulation.
Figure 5. Between $t=0.1$ s to $t=0.4$ s, the impact of fault during with FOC drive load for (a) VSC voltage (b) load voltage (c) grid voltage (d) MPPT voltage (e) VSC current (f) load current (g) grid current (h) real power (i) reactive power (j) torque (k) rotor speed (l) stator current.

4.4 Behaviour of fuzzy controlled DVR at FOC drive load

Fig. 6 (a-c) indicates per unit value of the voltage has been increased to 0.4 per unit. Fig. 6 (d) shows the tracking behaviour of DC link voltage around the reference MPPT voltage. Fig. 6 (e) depicts that per unit VSC current has been increased to 1.5. From Fig. 6 (f), oscillatory current flows till $t = 0.1$ s. The load of around 35 A flows till $t = 0.4$ s. Fig. 6 (g) depicts the transient behaviour in grid current till $t = 0.1$ s. Hence, the behaviour becomes sinusoidal from $t = 0.1$ s to $t = 0.6$ s.

According to Fig. 6 (h), there is smooth flow of real power output from grid to load at $t = 0.1$ s. The real power demand of load is met by both grid and SPV through VSC from $t = 0.1$ s to $t = 0.4$ s. Fig. 6 (i) depicts that the reactive power generated by grid and VSC is negative i.e. both absorb from $t = 0.03$ s to $t = 0.06$ s. As the load power becomes positive, there is reactive power compensation by SPV through VSC. The grid also aids the demand of power till $t = 0.4$ s. Thus, the tracking in demand of reactive power is accurate with FLC controller. Fig. 6 (j) shows the tracking of reference torque begins at $t = 0.1$ s, which follows till $t = 0.38$ s. After this, transients can be seen in actual tracking. These transients closely track the reference value, which reflects the ability of FLC controller. Fig. 6 (k) shows the tracking starts at $t = 0.14$ s which continues till $t = 0.5$ s. Fig. 6 (l) shows that there is the absence of notches which can be observed by using conventional PI controller. Moreover, the amount of the current being drawn is 78 A using FLC. Thus, there is the reduction in the power consumption by induction motor driven system using FLC.
In the present study, an effort has been made to control the grid voltage by DVR during the faulted conditions. According to Table 2, it is evident that the calculated value of THD for grid voltage is 8.24% at FOC drive using FLC-DVR. Also, the value of THD for grid current has been found to be 3.36% using FLC-DVR. It is apparent that the proposed system has been able to reduce the THD current according to IEEE-519/1547 standard. At DTFC drive load, the THD values for the grid voltage and grid injected current are 8.25% and 3.53%, respectively. The total harmonic content for load current, which has been controlled by FLC-DVR is 0.94% and 0.89% at DTFC drive and FOC drive load. It clearly indicates that the implementation of DVR has controlled the non-linear nature of operated drives, effectively. However, this study has also revealed that the discrete tuning of PI controller has also resulted in the reduction of harmonic content. From the harmonic analysis of current levels, it is revealed that the performance of DVR control at FOC drive load is effective over the DTFC drive.

Additionally, the performance of the proposed system has been compared with the results so obtained at linear load. The linear load is capable to generate the real power of 50 kW and reactive power of 22 kVAR. At linear load, the THD for VSC current is 12.07% and 10.93% using PI-DVR and FLC-DVR, respectively. It is also apparent that the calculated values of THD for VSC voltage, load voltage and grid voltage are 0.02%. However, the THD values for grid injected current are 5.62% and 5.61% using PI-DVR and FLC-DVR, respectively. The comparison between the application of non-linear and linear load reveals that controlling action of FLC-DVR is implemented effectively over PI controller, especially at non-linear loads.
Table 2. Comparative analysis of total harmonic distortion

| Parameter          | THD for non-linear induction motor drives load | THD for linear RLC load |
|--------------------|-----------------------------------------------|-------------------------|
|                    | DTFC drive | FOC drive | PI-DVR (%) | FLC-DVR (%) | PI-DVR (%) | FLC-DVR (%) | PI-DVR (%) | FLC-DVR (%) |
| VSC voltage        | 9.66%      | 8.25%     | 9.65%      | 8.24%       | 0.02%      | 0.02%       |
| VSC current        | 2.31%      | 5.33%     | 2.28%      | 5.29%       | 12.07%     | 10.93%      |
| Load voltage       | 9.66%      | 8.25%     | 9.65%      | 8.24%       | 0.02%      | 0.02%       |
| Load current       | 3.53%      | 0.94%     | 3.36%      | 0.89%       | 0.02%      | 0.01%       |
| Grid voltage       | 9.66%      | 8.25%     | 9.65%      | 8.24%       | 0.02%      | 0.02%       |
| Grid current       | 5.90%      | 3.53%     | 5.72%      | 3.36%       | 5.62%      | 5.61%       |

An active filter is employed for DC voltage compensation to reduce DC current in grid power lines [69-71]. At DTFC drive load, the various DC current component values at the PCC by using FLC-DVR are: VSC voltage=0.2083 A, VSC current=0.3198 A, grid voltage=0.2083 A, grid current=0.08128 A, load voltage=0.2083 A, and load current=0.401 A. At FOC drive load, the various DC current component values at the PCC by using FLC-DVR are: VSC voltage=0.1463 A, VSC current=0.2785 A, grid voltage=0.1463 A, grid current=0.07435 A, load voltage=0.1463 A, and load current=0.253 A. It is evident that the DC offset value has been maintained constant by FLC-DVR at all levels of voltage. However, the calculated value of DC offset for grid current and load current are found to be at reduced levels at FOC drive load, which is due to accurate implementation of synchronous reference frame algorithm with vectors control of input vectors.

5. Conclusion

PQ control requires urgent attention in distribution generation systems for SPV integration. To achieve this, a MPPT control coordinated FLC-DVR under non-linear loaded conditions is elaborated.

It is worth mentioning that the effectiveness of induction motor driven non-linear control systems is tested at unity power factor. It has revealed a remarkable coordination of VSC and data-based MPPT with FLC-DVR during a fault. Distortion-less real and reactive power with the distribution system is exchanged with mitigation of voltage sag during single line to ground fault. It is apparent that proposed MPPT technique has optimized SPV power generation, and improved PQ by reducing THD as mentioned in IEEE-519/1547 standard and DC offset current at PCC. In DTFC driven load, the direct control of torque and stator flux of drive is obtained by inverter voltage space vector selection. In FOC driven load, the vector control is considered in a synchronously rotating reference frame in which the sinusoidal variables are considered as DC quantities in steady state. In overall, it is concluded that the performance of fuzzy controlled vector controlled induction motor drive in reducing distortion is quite satisfactory over torque controlled induction motor drive.

The proposed model is validated for any SPV module and can be utilized to expedite research and development in distributed generation system.

Conflict of interest The authors declare that they have no conflict of interest

References

[1] Buresch M 1983 Photovoltaic energy systems design and installation. New York, McGraw-Hill
[2] Benner J P and Kazmerski L 1999 Photovoltaics gaining greater visibility. IEEE Spectrum, 29 (9): pp. 34-42

[3] Messenger R A and Ventre J 2004 Photovoltaic systems engineering, New York, CRC Press

[4] Sahoo S K 2016 Solar photovoltaic energy progress in India: a review. Renewable and Sustainable Energy Reviews 59: pp. 927-939

[5] Sinha A, Jana K C and Das M K 2018 An inclusive review on different multi-level inverter topologies, their modulation and control strategies for a grid connected photo-voltaic system. Solar Energy 170: pp. 633-657

[6] Woyte A, Thong V V, Belmans R and Nijs J 2006 Voltage fluctuations on distribution level introduced by photovoltaic systems. IEEE Transactions on Energy Conversion 21 (1): pp. 202-209

[7] Han J, Solanki S K, Solanki J and Schoene J 2012 Study of unified control of STATCOM to resolve the power quality issues of a grid-connected three phase PV system. In: Proceedings of the IEEE international conference on PES Innovative Smart Grid Technologies (ISGT), USA, 7

[8] Hamrouni N, Jraidi M, Dhouib A and Cherif A 2017 Design of a command scheme for grid connected PV systems using classical controllers. Electric Power Systems Research 143: pp. 503-512

[9] Xavier L S, Cupertino A F, Resendea J T, Mendes V F and Pereira H A 2017 Adaptive current control strategy for harmonic compensation in single-phase solar inverters. Electric Power Systems Research 142: pp. 84-95

[10] Mezghanni D, Andoulsi R, Mami A and Tanguy G D 2007 Bond graph modelling of a photovoltaic system feeding an induction motor-pump. Simulation Modeling Practice Theory 15 (10): pp. 1224-1238

[11] Panda A, Pathak M K and Srivastava S P 2013 Solar direct torque controlled induction motor drive for industrial applications. International Journal of Renewable Energy Research 3 (4): pp. 794-802

[12] Stonier A A 2017 Design and development of high performance solar photovoltaic inverter with advanced modulation techniques to improve power quality. International Journal of Electronics 104 (2): pp. 174-189

[13] Casadei D, Profumo F, Serra G and Tani A 2000 Implementation of a direct torque control algorithm for induction machines using space vector modulation. IEEE Transactions on Power Electronics 15 (4): pp. 769-777

[14] Habetler T G, Profumo F, Pastorelli M and Tolbert M 1992 Direct torque control of induction machines using space vector modulation. IEEE Transactions on Industrial Applications 28 (5): pp. 1045-1053

[15] Kang J K and Sul S K 1999 New direct torque control of induction motor for minimum torque ripple and constant switching frequency. IEEE Transactions on Industry Applications 35 (5): pp. 1076-1082

[16] Bose B K 2002 Modern power electronics and ac drives. Prentice-hall, USA

[17] Achour A et al. 2016 Application of direct torque control to a photovoltaic pumping system with sliding-mode control optimization. Electric Power Components and Systems 44 (2): pp. 172-184
[22] IEEE Std 519/1547-2003 IEEE standard for interconnecting distributed resources with electric power systems.

[23] Gupta A, Chanana S and Thakur T 2014 Power quality improvement of solar PV transformer-less grid connected system with maximum power point tracking control. *International Journal of Sustainable Energy* 33 (4): pp. 921-936

[24] Kang H, Hong T and Lee M 2019 Technical performance analysis of the smart solar photovoltaic blinds based on the solar tracking methods considering the climate factors. *Energy and Buildings* 190: pp. 34-48

[25] Altas I H and Sharaf A M 2007 A PV array simulation model for Matlab-Simulink GUI environment. In: Proceedings of the IEEE international conference on clean electrical power capri (ICCEP), Capri, pp. 345

[26] Prabaharan N, Campana P E, Jerin A R and Palaniswamy K 2019 A new approach for grid integration of solar photovoltaic system with maximum power point tracking using multi-output converter. *Energy Procedia* 159: pp. 521-526

[27] Adefarati T and Obikoya G D 2019 Techno-economic evaluation of a grid-connected microgrid system. *International Journal of Green Energy* 16 (15): pp. 1497-1517

[28] Moin H 2011 Investigation to improve the control and operation of a three-phase PV grid-tie inverter. Ph.D. Dissertation, Dublin Institute of Technology, Ireland

[29] Gupta A, Chanana S and Thakur T 2015 Power quality assessment of a solar photovoltaic two-stage grid connected system: Using fuzzy and proportional integral controlled dynamic voltage restorer approach. *Journal of Renewable and Sustainable Energy* 7: pp. 013113-18

[30] Molina M G and Juanico L E 2010 Dynamic modeling and control design of advanced PV solar system for distributed generation applications. *Journal of Electrical Engineering: Theory and Applications* 1 (3): pp. 141-150

[31] Marouani R and Mami A 2020 Voltage oriented control applied to a grid connected PV system with maximum power point tracking technique. *American Journal of Applied Sciences* 7 (8): pp. 1168-1173

[32] Ansari M F, Chatterji S and Iqbal A 2010 A fuzzy-logic control scheme for a solar photovoltaic system for a maximum power point tracker. *International Journal of Sustainable Energy* 29 (4): pp. 245-255

[33] Elamim A, Hartiti B, Haibaoui A, Lfakir A and Thevenin P 2019 Comparative study of photovoltaic solar systems connected to the grid: Performance evaluation and economic analysis. *Energy Procedia* 159: pp. 333-339

[34] Tsang K M, Chan W L and Tang X 2013 PLL-less single stage grid connected photovoltaic inverter with rapid maximum power point tracking. *Solar Energy* 97: pp. 285-292

[35] Montoyaa D G, Paja C A R and Giral R 2016 Maximum power point tracking of photovoltaic systems based on the sliding mode control of the module admittance. *Electric Power Systems and Research* 136: pp. 125-134

[36] Subudhi B and Pradhan R 2013 A comparative study on maximum power point tracking techniques for photovoltaic power systems. *IEEE Transactions on Sustainable Energy* 4 (1): pp. 89-98

[37] Javed K, Ashfaq H and Singh R 2020 A new simple MPPT algorithm to track MPP under partial shading for solar photovoltaic systems. *International Journal of Green Energy* 17 (1): pp. 48-61

[38] El-Khozondar H J, El-Khozondar R J, Matter K and Suntio T 2016 A review study of photovoltaic array maximum power tracking algorithms. *Renewables: Wind Water and Solar* 3 (3): pp. 1-8

[39] Vinifa R, Kavitha A and Selwynraj A I 2020 Control of power in the grid integrated solar photovoltaic system using linear quadratic regulator. *Proceedings of Materials Today*
Available online, https://doi.org/10.1016/j.matpr.2020.03.045

[40] Bidram A, Davoudi A and Balog R S 2012 Control and circuit techniques to mitigate partial shading effects in photovoltaic arrays. *IEEE Journal of Photovoltaics* 2 (4): pp. 532-54

[41] Weng X, Zhao Z M, He F B, Yuan L Q and Lu T 2015 Comparison of several MPPT methods for PV arrays under partially shaded conditions. In: Proceedings of the international conference on renewable power generation (RPG 2015), Beijing, China, pp. 6

[42] Borni A, Bouarroudj N, Bouchakour A and Zaghba L 2018 P&O PI and fuzzy-PI MPPT controllers and their time domain optimization using PSO and GA for grid-connected photovoltaic system: a comparative study. *International Journal of Power electronics* 8 (4): pp. 300-322

[43] Narasipuram R P 2018 Optimal design and analysis of hybrid photovoltaic-fuel cell power generation system for an advanced converter technologies. *International Journal of Mathematical Modelling and Numerical Optimization* 8 (3): pp. 245-276

[44] Shankar P U, Dhaneshwari S and Deepkiran T 2013 Maximum power point tracking using perturb and observe algorithm and compare with another algorithm. *International Journal of Digital Application and Contemporary Research* 2 (2): pp. 1-8

[45] Merabet A, Labib L, Ghias A M Y M, Aldurra A and Debbouza M 2019 Dual-mode operation based second-order sliding mode control for grid-connected solar photovoltaic energy system. *International Journal of Electrical Power & Energy Systems* 111: pp. 459-474

[46] Ishaque K, Salam Z and Lauss G 2014 The performance of perturb and observe and incremental conductance maximum power point tracking method under dynamic weather conditions. *Applied Energy* 119: pp. 228-236

[47] Singh P and Gaur P 2020 Grid interfaced solar water pumping system with improved space vector modulated direct torque control. *Ain Shams Engineering Journal* Available online. https://doi.org/10.1016/j.asej.2020.01.015

[48] Chahartaghi M and Jaloodar M H 2019 Mathematical modeling of direct-coupled photovoltaic solar pump system for small-scale irrigation. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects* Available online doi: 10.1080/15567036.2019.1685025

[49] Hilloowala R M and Sharaf A M 1996 A rule-based fuzzy logic controller for a PWM inverter in a stand alone wind energy conversion scheme. *IEEE Transactions on Industry Applications* 32 (1): pp. 57-65

[50] Yildiran N and Tacer E 2019 A new approach to H-infinity control for grid-connected inverters in photovoltaic generation systems. *Electric Power Components and Systems* 47 (14-15): pp. 1413-1422

[51] Kim H, Kim S, Kwon C K, Min Y J, Kim C and Kim S W 2013 An energy-efficient fast maximum power point tracking circuit in an 800-μW photovoltaic energy harvester. *IEEE Transactions on Power Electronics* 28: pp. 2927-2935

[52] Uprety S and Lee H 2016 A 0.4 W-to-21 W fast-transient global search-algorithm based integrated photovoltaic energy harvester with 99% GMPP efficiency and 94% power efficiency. *IEEE Journal of Solid-State Circuits* 51: pp. 2153-2167

[53] Mehmoood Z, Bilal Y, Bashir M and Asghar A 2016 Performance analysis of MPPT charge controller with single and series/parallel connected PV panels. In: Proceedings of the IEEE international conference on intelligent systems engineering (ICISE), Islamabad, Pakistan, pp. 282

[54] Jiang S, Cao D, Li Y and Peng F Z 2012 Grid-connected boost-half-bridge photovoltaic micro inverter system using repetitive current control and maximum power point tracking. *IEEE Transactions on Power Electronics* 27 (11): pp. 4711-4722
[55] Wu T F, Kuo C L, Sun K H, Chen Y K, Chang Y R and Lee Y D 2013 Integration and operation of a single-phase bidirectional inverter with two buck/boost MPPTs for DC distribution applications. IEEE Transactions on Power Electronics 28 (11): pp. 5098-5106

[56] Safari A and Mekhilef S 2011 Simulation and hardware implementation of incremental conductance MPPT with direct control method using cuk converter. IEEE Transactions on Industrial Electronics 58: pp. 1154-1161

[57] Hamrouni N, Jraidi M and Cherif A 2009 Theoretical and experimental analysis of the behavior of a photovoltaic pumping system. Solar Energy 83: pp. 1335-1344

[58] Kulaksız A A and Akkaya R 2012 A genetic algorithm optimized ANN-based MPPT algorithm for a stand-alone PV system with induction motor drive. Solar Energy 86: pp. 2366-2375

[59] Chahartahi M and Jaloodar M H 2019 Mathematical modeling of direct-coupled photovoltaic solar pump system for small-scale irrigation. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects Available online doi: 10.1080/15567036.2019.1685025.

[60] Sharma U, Singh B and Kumar S 2017 Intelligent grid interfaced solar water pumping system. IET Renewable Power Generation 11 (5): pp. 614-624

[61] Altas I H and Sharaf A M 1992 A fuzzy logic power tracking controller for a photovoltaic energy conversion scheme. Electric Power Systems Research 25: pp. 227-238

[62] Rathore N, Panwar N L, Yettou F and Gama A 2019 A comprehensive review of different types of solar photovoltaic cells and their applications. International Journal of Ambient Energy. Available online doi 10.1080/01430750.2019.1592774

[63] Altas I H and Sharaf A M 1991 A solar powered permanent magnet DC motor drive scheme. In: Proceedings of the 17th annual conference of solar energy society of Canada, Ontario, Canada, pp. 70

[64] Gupta A, Chanana S and Thakur T 2014 Power quality investigation of a solar PV transformer-less grid-connected system fed DVR. Frontiers in Energy 8 (2): pp. 240-253

[65] Patel N, Gupta N and Babu B C 2019 Design, development, and implementation of grid-connected solar photovoltaic power conversion system. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects Available online doi: 10.1080/15567036.2019.1668506

[66] Wang J C, Su Y L, Shieh J C and Jiang J A 2011 High-accuracy maximum power point estimation for photovoltaic arrays. Solar Energy Materials and Solar Cells 95 (3): pp. 843-851

[67] Coelho R F, Concer F M and Martins D C 2010 A MPPT approach based on temperature measurements applied in PV systems. In: Proceedings of the 9th IEEE International conference on industry applications (INDUSCON), Sao Paulo, pp. 6

[68] Matlab/Simulink, The Mathworks, Inc. 7.10.0.499 (R2010a)

[69] Menniti D and Pinnarelli A 2012 A novel compensation approach for DC current component in a grid-connected photovoltaic generation system. In: Proceedings of the IEEE international conference on power and energy society general meeting, San Diego, USA, pp. 6

[70] Infield D G, Onions P, Simmons A D and Smith G A 2004 Power quality from multiple grid-connected single-phase inverters. IEEE Transactions on Power Delivery 19 (4): pp. 1983-1989

[71] Gertmar L, Karlsson P and Samuelsson O 2005 On DC injection to AC grids from distributed generation. In: Proceedings of the IEEE international conference on power electronics and applications, Dresden, Germany, pp. 10