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Implementation of Grid Connected PV Inverter with AdaptiveNeuro Fuzzy Interface System

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ABSTRACT: The electricity can be considered as one of the primary needs for human beings. The demand for electricity is increasing day by day. Therefore, renewable energy based systems are getting importance. Solar thermal, SPV (Solar Photovoltaic), wind power generations are few such renewable energy systems. A grid supportive two-stage three-phase three-wire SPV (Solar Photovoltaic) system with ANFIS controller is presented in this paper, wherein a boost converter is used as a first stage to serve the function of MPPT (Maximum Power Point Tracking) and a 3-leg VSC (Voltage Source Converter) is used to feed the extracted SPV energy along with supporting distribution system for improvement in the power quality. The harmonics elimination, grid currents balancing and compensation for non-active part of the load currents are extra features offered by proposed system other than conventional features of the solar inverter. The true power reflecting part of load current is estimated using an improved adjustable step adaptive neuron based control approach. The output of which is current component reflected on grid side to instantaneously regulate the DC link voltage. In the proposed approach, the load, PV array and loss contributions are kept decoupled. The feasibility of proposed control algorithm is confirmed via MATLAB/SIMULINK results.

Keywords— ANFIS, Solar PV; Two-stage; Power Quality; MPPT.

I INTRODUCTION

The electricity can be considered as one of the primary needs for human beings. The demand for electricity is increasing day by day. However, the conventional fuels for generation of electricity are getting depleted. Moreover, the environmental pollution is also a prime concern. Therefore, renewable energy based systems are getting importance. Solar thermal, SPV (Solar Photovoltaic), wind power generations are few such renewable energy systems. The SPV is gaining importance as it is reaching the grid parity [1]-[2].

Grid connected solar PV (Photovoltaic) systems do not require a battery energy storage hence these systems are gaining more popularity. Several researchers have proposed grid connected PV inverters [3]-[6]. These systems collect power from solar panel and feed that power into the grid without any big energy storage. A review of topologies for single phase converters is shown in [3]. A single stage topology based PV inverter for grid tied application is shown in [4]. A current source inverter based transformer less PV inverter is proposed in [5], wherein a 4-leg CSI (Current Source Inverter) is proposed for reduction of ground leakage current.

The solar PV characteristics are nonlinear due to which the peak power can be extracted only at a unique voltage from a given PV array. A classification of MPPT (Maximum Power Point Tracking) techniques is presented in [6]. An evaluation of P&O (Perturb and Observe) based MPPT technique is shown in [7]. The P&O based technique is simple and easy to implement, however, it has drawbacks of poor dynamic response and oscillation near MPP point in steady state conditions. An INC (Incremental Conductance) based MPPT technique is used in [8], which is used in here also, as it offers simple and easy to implement structure along with fast dynamic response and high steady state accuracy.
The nonlinear loads using power electronic converter at front-end are getting popular day by day as they offer high efficiency and occupy comparatively low space. However, the harmonics drawn by these systems cause several problems in the distribution system such as derating of transformer, higher distribution losses and distortion of CCP (Common Connection Point) voltage. The D-STATCOM (Distribution Static Compensator) offers a retrofit solution for these power quality problems [9]-[10]. A peak detection and low pass filter based control algorithm is presented in [9]. An adaptive neural

network based technique is used in [10], wherein constant learning rate is used.

The grid supportive solar PV generation systems are demonstrated in [11]-[13]. An algorithm shifting true power component to DC for a multifunctional PV generation system is presented in [11]. However, no experimental results are shown in [11]. The grid tied PV generation system under voltage power quality disturbances is shown in [12]-[15]. An ILST (Improved Linear Sinusoidal Tracer) based control approach for single-stage dual functional system is presented in [16]. However, the frequency response for ILST approach shows that the performance of the control approach deviates under frequency disturbances. Considering this nonstationary behavior with respect to frequency variations an adaptive frequency based approach is presented in [17]. However, in proposed approach, separate frequency estimation is avoided by use of grid voltage unit vectors.

A survey for application of neural network based technique for active filtering is shown in [18]. A variable step size based adaptive harmonics detecting algorithm is used for shuntactive filter in [19]-[20]. A control of DSTATCOM with adjustable step least mean square based algorithm is shown in [21]. However, in this paper an improved adjustable step adaptive neuron based control approach is used for grid supportive PV generation system. The proposed control algorithm is called an improved adjustable step neuron adaptive approach as it gives a decoupled estimation of load, loss and solar power contribution. Moreover, the quick response to sudden variation in insolation is managed via a feed-forward term considering active power changes from PV array which ensures a relieved burden on DC link PIC (Proportional Integral Controller). Therefore, the scope of the presented work are as follows.

1. A decoupled estimation of salient true power reflective components of grid current.
2. A suitable improvement is proposed in the exiting D-STATCOM algorithm to make it suitable for combined operation of distributed generation and power quality improvements.
3. Demonstration of effect of separate PV power contribution.
4. A case study for reduction in distribution losses via such multifunctional system.

II SYSTEM ARCHITECTURE

The power architecture of suggested grid supportive SPV system is demonstrated in Fig. 1. It consists of two power stages, which are the boost converter for MPPT and a three-leg grid tied VSC to transfer active power to a distribution system and to support it by providing harmonics mitigation, reactive power compensation and grid currents balancing. The connections of VSC and the distribution system are established via current smoothening inductors. The grid, smoothening inductors and shunt high pass filter are connected at a CCP. The shunt high pass filter absorbs the switching noise generated because of VSC.

CONTROL APPROACH

The control of proposed system in terms of block diagram is presented in Fig. 2. The control approach consists of two main parts corresponding to two power converters. The control approach for boost converter generates duty ration such that the voltage across PV array reaches MPPT. The control approach for grid interfaced VSC maintains the balance of true power among the grid, load and VSC. The VSC acts as a three phase currents source in which currents for all the phases are adjusted such that the overall load reflection at CCP is a resistive. In order to achieve

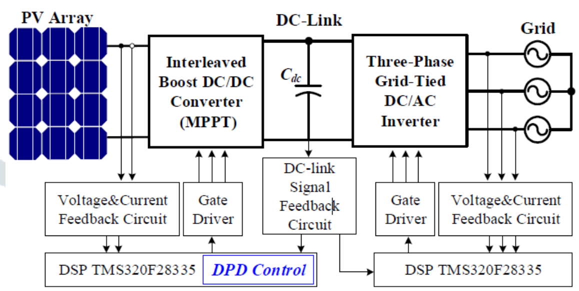

Fig: 1 System configuration

This objective, the VSC circulates the unbalanced currents to achieve grid currents balancing feature along with supplying inactive part of load currents. The control approach for both power converters are discussed here.

A. Control Approach for Boost Converter

An InC MPPT approach is used here [8]. The InC provides PV array voltage reference which finally generates reference duty cycle, using MPPT output and sensed output voltages of boost converter. The duty ratio to perform MPPT is as,

$$d_r(k) = 1 - \frac{V_{pvref}(k)}{V_{DC}(k)}$$

This duty ratio is used for calculation of pulse width for controlled switch of the boost converter.

B. Control Approach of Grid Connected VSC

The VSC is controlled as per block diagram shown in Fig. 2 (a). The CCP voltages (v_{sab}, v_{sbc}), grid currents (i_{ga}, i_{gb}), load currents (i_{La}, i_{Lb}), DC bus voltage (v_{DC}), solar voltage (v_{pv}) and current (i_{pv}) are sensed and processed according to block diagram shown in Fig. 2. The overall control approach for complete system is shown in Fig. 2 (a). The phase voltages are estimated using sensed line voltages [22]-[23], which are then used to calculate the peak value using formula as follows,

$$\begin{bmatrix} v_{sa} \\ v_{sb} \\ v_{sc} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & 1 \\ -1 & 1 \\ -1 & -2 \end{bmatrix}\begin{bmatrix} v_{sab} \\ v_{sbc} \end{bmatrix}$$

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

The PV power contribution is incorporated in reference grid currents using feed forward term. The feed-forward term is based on PV array power and amplitude of CCP voltage. The simulation study for effect of PVFF term is shown in Appendix B. The reflection of PV array power on grid current is estimated in form of a feed-forward (IPVFF) term given as,

$$u_{spa} = \frac{v_{sa}}{V_z}, u_{spb} = \frac{v_{sb}}{V_z}, u_{spc} = \frac{v_{sc}}{V_z}$$

$$I_{PVFF} = I_{pvg} = \frac{2P_{pv}}{3V_z}$$

An improved adjustable step adaptive neuron based approach is used to estimate the contribution of load current in the gridcurrents. In the proposed approach, three neurons are used, one for each phase current. The three neurons are cross coupled to estimate average true power reflective part of load current. The governing equations are,

$$w_{pa}(n+1) = w_{pA}(n) + 2\sigma_p e(n) u_{spa}$$
$$w_{pb}(n+1) = w_{pA}(n) + 2\sigma_p e(n) u_{spb}$$

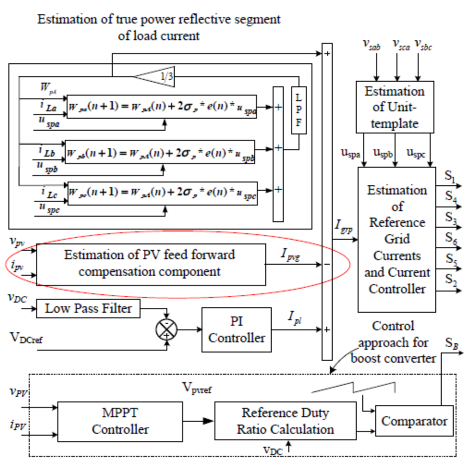

Fig 2 (a) Block diagram for control approach of the system

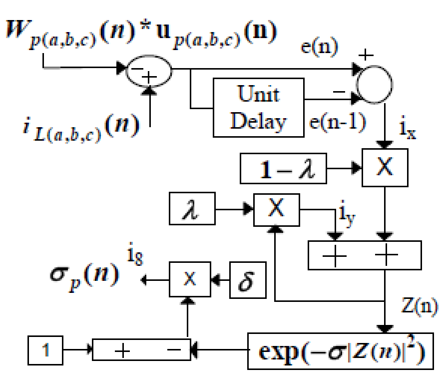

Fig 2 (b) Estimation of adaptive learning rate.

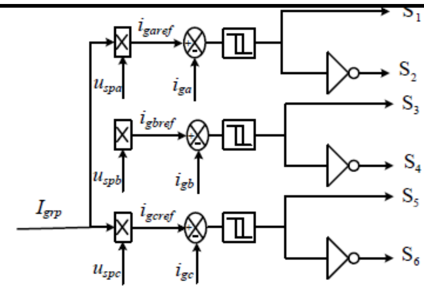

Fig 2. (c) Current controller

$$w_{pc}(n+1) = w_{pA}(n) + 2\sigma_p e(n) u_{spc}$$

whereσp is the learning rate for the phase neurons. The learning rate for phase neurons is kept adjustable. The relation for keeping adjustable learning rate is as,

$$\sigma_p(n) = \delta(1 - \exp\{1 - \mu |z(n)|^2\})$$

$$z(n) = \lambda z(n-1) + (1-\lambda)\{e(n) - e(n-1)\}$$

where e(n) and e(n-1) are difference between sensed and estimated output for corresponding phase. δ, λ and μ are constants, which are selected as 0.4, 0.3, 0.5 respectively. The complete update law is shown in Fig. 2(b). The σp is adjusted according to load currents in order to keep the step size adjustable.

An average weight for cross coupling of neurons is estimated as,

$$w_{pA} = \frac{w_{pa} + w_{pb} + w_{pc}}{3}$$

The neurons are called cross coupled as the average neuron weight is used to estimate weight for each phase.

The loss fraction of the grid current is estimated by the help of a PIC (Proportional Integral Controller) on the DC link voltage of VSC. The output of PIC (*Ipl*) is assumed as a loss component of the system as other two components are already estimated in feed-forward manner. Considering all three components, the amplitude of reference grid currents is estimated as,

$$I_{grp} = w_{pA} + I_{pl} - I_{pvg}$$

This Igrp is estimated amplitude true power part of uniformly distributed of grid currents. The three phase load power is distributed equally in three phases of grid while estimating amplitude of reference grid currents. Hence, reference grid currents estimated in this fashion are always balanced even in case when load draws unequal power from the three phases. The reference grid currents are estimated as,

The hysteresis current controller for grid currents decides the switching pattern for the VSC as shown in Fig. 2 (c).

C. Approximate Model and Assessment of Improvements

A general representation of a conventional PV inverter with its control approach is shown in Fig. 3, wherein the sensed load currents are processed with the adjustable step neuron based technique. In this conventional approach, a PI controller is used to maintain the DC link voltage to the desired value. A close observation reveals that in this case, the output of PI controller consists of loss component of VSC and contribution of solar power in the grid current. Therefore, while setting the gains of the PIC there is a coupling in loss and solar power component. Since the contribution of the solar power changes throughout the day, the output of the PI controller varies in a wide rage. Moreover, due to sudden cloud or change in climatic condition, the solar power contribution changes rapidly. Therefore, it is difficult to tune the DC link PIC to provide good steady state and dynamic performances under all operating condition. Therefore, in the proposed system, an extra term for contribution from solar array is derived using PV array power and sensed grid voltages. It should be noted here that no extra sensor is used to deduce this information. The PV array voltage and current are being already sensed forMPPT operation and the grid voltage for grid synchronization. The model for DC link voltage control loop is shown in Fig. 4, where the PIC bears the burden for loss and solar power contribution. However, the model for DC link voltage control for the proposed approach is shown in Fig. 5. It is clearly visible from the overall control loop in the Fig. 5 that the extra added solar array contribution cancels the PV array input power and the load term cancels the power drawn by the loads. Therefore, the feed-forward term instantaneously cancels effect of changes in the PV array power and the load power which leads to fast dynamic response and limited DC link voltage overshoot. These feed-forward terms also relieve the burden on the PIC such that the changes in the PV array power and load power are not dealt with the PI controller. Therefore, from DC link voltage control point of view, the burden on the PIC is reduced and it has to bear only the loss component of the power.

VI. DESIGN OF ADAPTIVE NEURO-FUZZY CONTROLLER

Adaptive neuro fuzzy inference system (ANFIS) integrates the best features of fuzzy systems and neural networks, and it has potential to capture the benefits of both in a single frame work. ANFIS is a kind of artificial neural network that is based on Takagi-sugeno fuzzy inference system, which is having one input an done output. Using a given data set, the toolbox function of ANFIS constructs a fuzzy inference system (FIS) where as the membership function parameters are tuned (adjusted) using a back propagation algorithm. In order to have an idea of optimized ANFIS architecture for proposed control, an initial data is generated from normal *PI* regulator and the data is saved in workspace of MATLAB. Then the ANFIS command window is opened by typing anfis editorin the main MATLAB window. Then the data previously saved in workspace is loaded in the ANFIS command window to generate an optimized ANFIS architecture as shown in Fig.3.

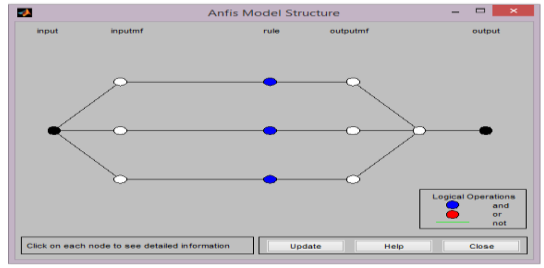

Figure. 3 Optimized ANFIS architecture suggested by MATLAB/anfiseditor.

In Fig.4 shows schematic of the proposed ANFIS based control architecture. The node functions of each layer in the ANFIS architecture are described as follows:

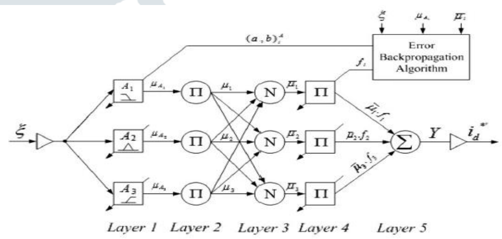

Figure. 4 Schematic of the proposed ANFIS-based control architecture.

The error between reference dc-link voltage and actual dc-link voltage ($\xi=V_{dc}*-V_{dc}$) is given to the neuro-fuzzy controller and the same error is used to tune the precondition and consequent parameters [10]. The control of dc-link voltage gives the active power current component (i_d *'), which is further modified to take in account of active current component injected from RES (i_{Ren}).The node functions of each layer in ANFIS architecture are as described below:

Layer 1: This layer is also known as fuzzification layer where each node is represented by square. Here, three membership functions are assigned to each input. The trapezoidal and triangular membership functions are used to reduce the computation burden as shown in Fig. 5. And the corresponding node equations are as given below:

$$\mu_{A1}(\varepsilon)=\left.\begin{matrix}1 & \varepsilon\le b_1\\ \dfrac{\varepsilon-a_1}{b_1-a_1} & b_1<\varepsilon<a_1\\ 0 & \varepsilon\ge a_1\end{matrix}\right\}\mu_{A2}(\varepsilon)$$

$$=\left.\begin{matrix}1-\dfrac{\varepsilon-a_1}{0.5b_2} & |\varepsilon-a_2|\le 0.5b_2\\ 0 & |\varepsilon-a_2|\ge 0.5b_2\end{matrix}\right\}$$

$$\mu_{A3}(\varepsilon)=\left.\begin{matrix}0 & \varepsilon\le a_3\\ \dfrac{\varepsilon-a_1}{b_1-a_1} & a_3<\varepsilon<b_3\\ 1 & \varepsilon\ge b_3\end{matrix}\right\}\qquad(12)$$

where the value of parameters (a_i, b_i) changes with the change in error and accordingly generates the linguistic value of each membership function. Parameters in this layer are referred as premise parameters or precondition parameters.

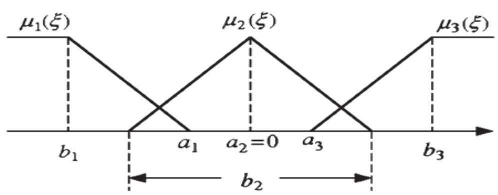

Figure. 5 Fuzzy membership functions.

Layer 2: Every node in this layer is a circle labelled as Π. which multiplies the incoming signals and forwards it to next layer

$\mu_i = \mu_{Ai}(\varepsilon_1).\mu_{Bi}(\varepsilon_2)$ ... ...i=1,2,3,... But in our case there is only one input, so this layer can be ignored and the output of first layer will directly pass to the third layer. Here, the output of each node represents the firing strength of a rule.

Layer 3: Every node in this layer is represented as circle. This layer calculates the normalized firing strength of each rule as given below:

$$\overline{\mu_i}=\frac{\mu_i}{\mu_1+\mu_2+\mu_3} \qquad (13)$$

Layer 4: Every node in this layer is a node function

$O_i = \overline{\mu_i}\ .f_i = \overline{\mu_i}(a_0^i + a_1^i\varepsilon)$i=1,2,3.

where the parameters $(a_0^i, a_1^i\ )$are tuned as the function of input (ξ). The parameters inthis layer are also referred as consequent parameters.

Layer 5: This layer is also called output layer which computes the output as given below: The output from this layer is multiplied with the normalizing factor to obtain the active power current component.

V MATLAB SIMULATION RESULTS

The proposed ANFIS based DPD strategy is verified via the computer simulation software, MATLAB/Simulink, first. Fig. 7, Fig. 8 and Fig. 9,Fig 10 show simulation comparisons of the three-phase grid voltages, V_{abc}, the PV current, I_{PV}, the PV power, P_{PV}, the output power, P_{out}, the dc-link voltage, V_{DC}, and the threephase output currents, I_{abc}under 5kW operation. First, normal circuit operation waveforms with 5kW are shown in Fig. 6. It can be seem that three-phase grid voltages and currents, $V_{abc}$and I_{abc}, shown in Fig. 6(a) and Fig. 6(f) are balanced and there is no ripple on P_{out} and V_{DC}, as shown in Fig. 6(d) and Fig. 6(e). In the meantime, the I_{PV} and P_{PV} shown in Fig. 6(b) and Fig. 6(c) are controlled by the MPPT algorithm and remain constant values.

In order to demonstrate the unbalanced voltage fault scenario, one phase voltage of $V_{abc}$is decreased to 0.5p.u. in both of the two simulations, as shown in Fig. 7(a) and Fig. 8(a). Therefore, a 120Hz ripple will be occurred on the P_{out}shown in Fig. 7(d) and Fig. 8(d). Without the proposed DPD strategy, the PV current and power shown in Fig. 7(b) and (c) are controlled by the MPPT and remains a constant value. In the meantime, due to the input-output power imbalance, V_{DC} shown in Fig. 7(e) is oscillated between 392V and 408V while the $I_{abc}$are distorted because of the fluctuation of the dc-link voltage, as shown in Fig. 7(f). n the other hand, with the proposed DPD, I_{PV} and P_{PV} are regulated as a sinusoidal waveform to decouple the dc-link voltage ripple, as shown in Fig. 8(b) and (c). The magnitude and phase of I_{PV} are determined by Eq. (6) and (7).

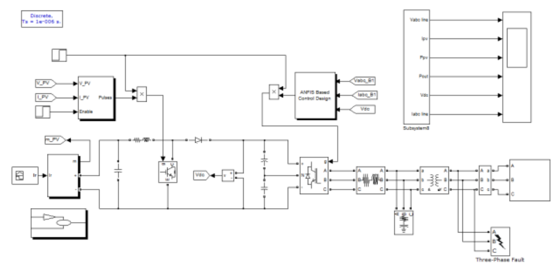

Fig.6 MATLAB SIMULINK model for the Proposed Grid Connected PV System with ANFIS

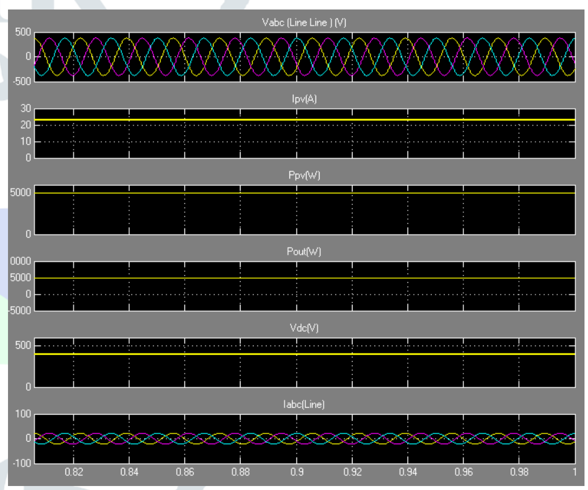

Fig 7 Simulation waveforms with 5kW normal operation (a) *Vabc*(b) *IPV* (c) *PPV* (d) *Pout* (e) *VDC* and (f) *Iabc*.

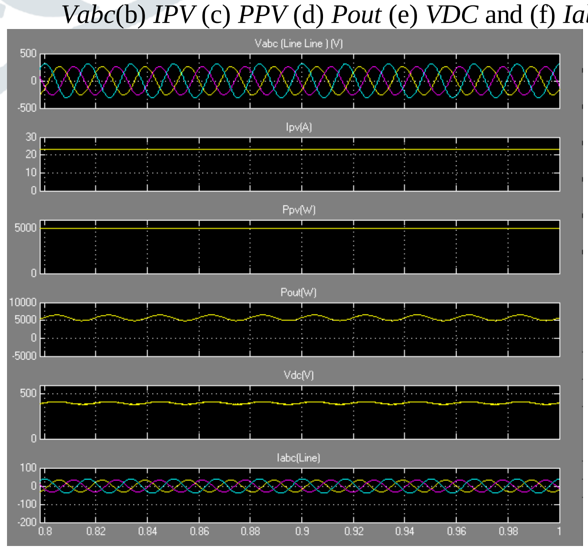

Fig 8 Simulation waveforms without the DPD under 5kW operation (a) *Vabc*(b) *IPV* (c) *PPV* (d) *Pout* (e) *VDC* and (f) *Iabc*.

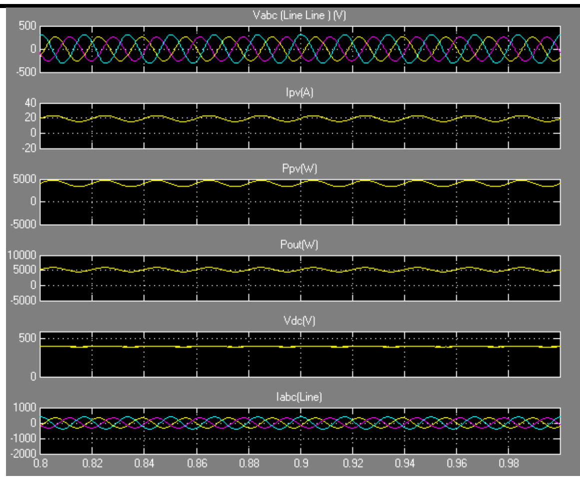

Fig 9 Simulation waveforms with the DPD under 5kW operation (a) *Vabc*(b) *IPV* (c) *PPV* (d) *Pout* (e) *VDC* and (f) *Iabc*.

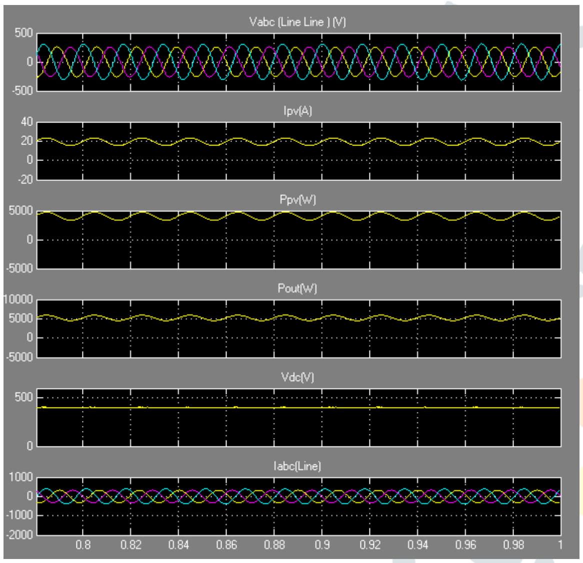

Fig 10 Simulation waveforms with the ANFIS Based DPD under 5kW operation (a) *Vabc*(b) *IPV* (c) *PPV* (d) *Pout* (e) *VDC* and (f) *Iabc*.

It can be confirmed that under the unbalanced grid fault, the dc-link voltage ripple can be effectively eliminated by the proposed DPD, as Fig. 8(e) shows. Moreover, there will be less distortion of I_{abc}shown in Fig. 8(f) because of the stable and constant dc-link voltage with the DPD. As a result, the total harmonic distortion (THD) of output currents of the inverter can be decreased.

It should be mentioned that the generated PV power will change under different weather conditions and the dc-link voltage ripple might be changed, too. However, the compensated current magnitude and phase angle calculated via Eq. (6) and (16) will be well determined. In other words, the proposed DPD can be applied to different power level and different voltage fault scenarios.

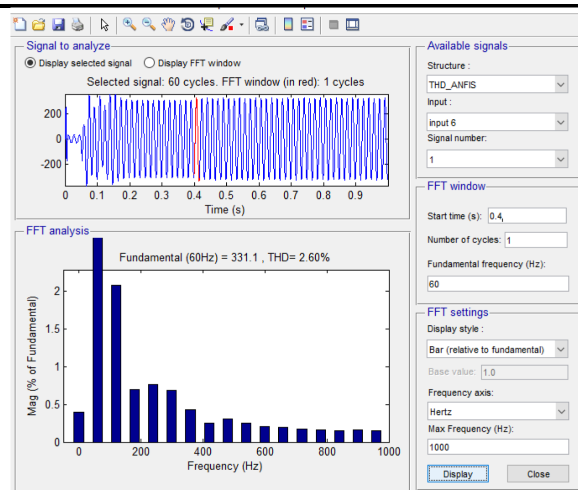

Fig 11 Source current THD (%) of the proposed SPV with ANFIS Controller

CONCLUSIONS

A grid supportive SPV generation system with Adaptive Neuro Fuzzy Interface System (ANFIS) has been proposed for combined aim of distributed SPV generation and power quality improvement. An ANFIS approach has been proposed for control and verified by MATLAB/SIMULINK environment. A reduction in distribution losses canbe achieved using these grid supportive PV systems on account of improved power quality. A corresponding case study for reduction in distribution losses is shown in sectionV. The prototype model is tested at Matlab Simulationwith considerable power handling advocating the feasibility of proposed grid supportive distributed generation system.

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