

Power Quality Improvement in PV Flyback Microinverter using Adaptive Fuzzy-PR Controller

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Abstract—this project presents an power quality improvement in PV Flyback microinverter using adaptive fuzzy-PR controller. The proposed control strategy consists of the proportional-resonant (PR) controller with fuzzy logic controller. Compared to the conventional control strategy using the proportional-integral controller, the PR controller with HC and fuzzy logic controller provides a higher system gain at the fundamental and harmonic frequencies of the grid without using a high gain in both operation modes. Then, it enhances the tracking speed and disturbance rejection performances satisfied, By applying fuzzy logic controller yielded from the proposed operation mode selection, the disturbance rejection is achieved more effectively, and the control burden is reduced. Finally, the simulation and experimental results were shown to verify the tracking speed and disturbance rejection performances of the proposed control strategy.

Index Terms—Current control scheme, photovoltaic (PV) module, single-stage inverter, Fuzzy logic control scheme, Proportional resonant (PR)controller .

I.INTRODUCTION

The renewable-energy sources, the photovoltaic (PV) energy have been widely utilized in various industrial fields. The PV power systems can be classified into centralized, string, and ac module systems [1]. The ac module system, a low-power grid connected inverter called as the micro-inverter is mounted on a single PV module; it can track the individual maximum power point, and so, it reduces power losses by PV module mismatch and partial shading [2]–[4]. Moreover, the ac module system has higher reliability and easier maintenance than those of the other PV systems [5]. Thus, with these advantages, the ac module PV system has been recently considered as a trend of the future PV power systems. The worth of the micro-inverter is evaluated by its power conversion efficiency, shape of the output current, power density, reliability, and cost [6]–[8]. To meet these requirements, a single-stage flyback inverter topology has been adopted due to its simple circuit structure and potential for high efficiency and reliability. Moreover, the flyback inverter topology has both step-down and step-up functions; this characteristic is suitable for the PV applications where the inverter should operate in a wide voltage range. When the flyback inverter operates under the constant switching frequency, the operation modes can be classified as the discontinuous current mode (DCM) [9]–[14] and continuous current mode (CCM) [15]–[17]. The PV inverter called as the CCM flyback inverter has both operation modes; it inevitably operates in DCM at the low instantaneous power level or low solar irradiation level, although it operates in CCM at all instantaneous power levels for rated average power. Then, it can be regarded that the flyback inverter has a hybrid operation mode over the whole ac line period. Compared to a flyback inverter only with DCM, the flyback inverter with hybrid mode has numerous merits such as higher efficiency with lower current stress, higher power capability, and easier filter design. However, the control input-to-output current transfer function of the flyback inverter in the CCM region has a right-half plane (RHP) zero which results in the limitations of increasing the system gain and controller bandwidth. Since the operating point varies widely in the PV inverter applications, in particular, the controller should cover the minimum RHP zero. When a conventional proportional-integral (PI) controller is applied to the flyback inverter with hybrid mode, the proportional gain is designed to be relatively low for ensuring stability in all operating points [17]. The system gain of the flyback inverter in the DCM region is inherently much low. To achieve fast reference tracking and disturbance rejection performances, the high-gain feedback controller is required in the DCM operation. However, when the conventional PI controller is applied, the control gain is limited by the RHP zero in CCM. As a result, it causes unacceptable power quality and high total harmonic distortion (THD) by the poor control performance in DCM [15]. This is the reason why the use of the flyback inverter with hybrid mode is limited despite its many advantages. To avoid the aforementioned problem, some previous studies in [15] and [16] control the primary current instead of controlling the output current because there is no RHP zero in the transfer function for the control input to the primary current. The control approach bypasses the difficulties posed by the RHP zero. However, the power quality is low because this approach controls the output current indirectly. The proportional-resonant (PR) controller is an alternative of the PI controller. It provides an infinite gain at a selected resonant frequency without using high proportional gain [18]–[20]. Moreover, because the controller has flexibility of selecting the resonant frequency, adding multiple PR controllers such as the harmonic compensator (HC) is possible for compensating the harmonics of the selected fundamental frequency. In

this paper, the current control strategy of the flyback micro-inverter with hybrid mode is proposed. The proposed control strategy consists of two components: the PR controller HC with fuzzy logic controller and the hybrid nominal duty ratio.

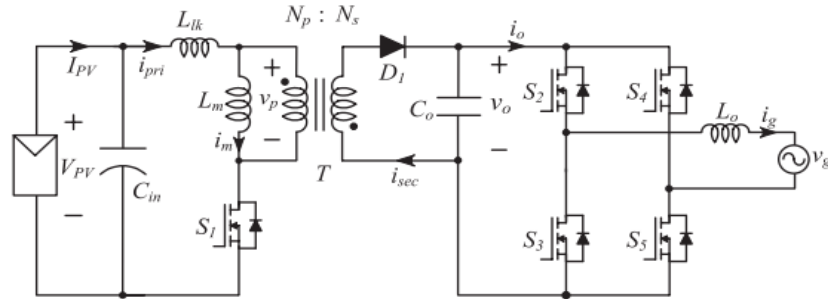


Fig. 1. Circuit diagram of the flyback micro-inverter.

The PR controller with HC and fuzzy logic controller provides a high gain at the fundamental and harmonic frequencies of the grid and achieves the zero tracking error in both operation modes. The hybrid nominal duty ratio performs as a feed_forward control input and is determined by the proposed operation mode selection. By applying the hybrid nominal duty ratio according to the proper operation region, it can achieve more effective disturbance rejection and faster dynamics. Thus, the proposed control strategy gives a higher tracking performance and a better disturbance rejection in both operation modes and strengthens the many advantages of the flyback inverter with hybrid mode. In Section II, the basic operation of the flyback inverter for each mode is introduced. Section III represents the system dynamic characteristic according to each operation mode and handles the problems on the conventional current control with the PI controller. Then, the proposed control strategy is introduced, and its superiority and validity are represented from theoretical analysis. Finally, the simulation and experimental results are shown in Section IV.

II. OPERATION OF FLYBACK INVERTER WITH HYBRID MODE

Fig. 1 shows a circuit diagram of the flyback micro-inverter; it consists of an input capacitor C_{in} , a flyback converter with turn ratio $n(N_s/N_p)$, a full-bridge-type unfolding circuit (S2 – S5), and an output filter. The flyback converter operates under the high switching frequency to convert PV power into rectified sinusoidal waveform. The unfolding circuit works under the grid frequency f to inject sinusoidal ac current into the grid; switches S2 and S5 are turned on during the positive half-cycle of the grid voltage v_g , while S3 and S4 are turned on during the negative half-cycle.

A. Steady-State Analysis of DCM and CCM Operations

Under the constant switching frequency f_s , the operation modes are classified into DCM and CCM. In DCM, the magnetizing current i_m becomes zero within each switching period T_s , and the transformer T is completely demagnetized as shown in Fig. 2. When S1 is turned on, the primary current i_{pri} is

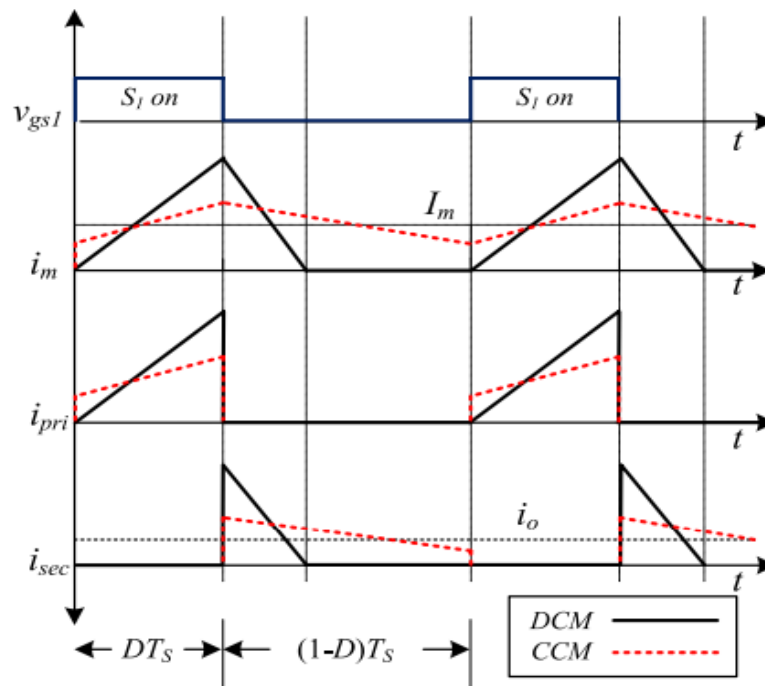


Fig. 2. Key waveforms in DCM and CCM.

stored in the magnetizing inductance L_m , and its peak value is expressed as follows:

$$I_{Pri,pk-DCM}(t) = \frac{V_{PV}}{L_m} D_{DCM}(t) T_s \quad (1)$$

where D_{dcm} is the duty ratio in DCM. The energy E_{lm} stored in L_m is expressed as

$$E_{lm} = \frac{1}{2} L_m I_{Pri,pk}^2(t) = \frac{(V_{PV} D_{DCM}(T) T_s)^2}{2 L_m} \quad (2)$$

Assuming lossless operation in the inverter, the power balance equations can be obtained as

$$V_{PV} I_{PV} = \frac{V_g I_g}{2} = P_o \quad (3)$$

$$V_{PV} I_{Pri}(t) = v_g(t) i_g(t) = V_g I_g \sin^2 \omega t \quad (4)$$

where V_{pv} and I_{pv} are the average values of the voltage and current for a PV module. V_g and I_g are the grid voltage and grid current, respectively; V_g and I_g are the peak values of V_g and I_g , respectively. P_o is the average output power. I_{pri} is the average primary current. ω is the angular frequency of the grid voltage. If there is no loss, the energy stored in L_m is equal to the energy transferred to the grid. Assuming $|v_g| \approx v_o$, from (2)–(4), DDCM can be derived as

$$D_{DCM}(t) = \frac{2}{V_{PV}} \sqrt{P_o L_m F_s} |\sin \omega t| \\ = d_{DCM,pk} |\sin \omega t| \quad (5)$$

where $D_{dcm,pk}$ is the peak value of D_{dcm} . In CCM, L_m is applied to V_{PV} during the turn-on time of S_1 , while the voltage across L_m is reflected the output voltage during the turn-off time. Using the voltage-seconds law for L_m , the duty ratio D_{ccm} in CCM is calculated as

$$D_{DCM}(t) = \frac{V_g |\sin \omega t|}{n V_{PV} + V_g |\sin \omega t|} \quad (6)$$

The duties D_{dcm} and D_{ccm} determine the relationship between the input voltage V_{pv} and output voltage v_o . As mentioned previously, the peak value of the primary current in DCM is expressed as (1). In case of CCM, as shown in Fig.2, the peak value of the primary current $I_{ipkpr-CCM}$ is equal to the sum of the average magnetizing current I_m and the ripple component. Because the magnetizing current is the same as the primary current when S_1 is turned on, its average value can be expressed using the average value of the primary current I_{pri} and the duty ratio D_{ccm} as

$$I_m(t) = \frac{I_{pri}(t)}{D_{CCM}(t)} \quad (7)$$

Thus, from Fig.2 and the power relationship in (2), the peak value of the primary current $I_{pri,pk-CCM}$ is calculated as

$$I_{pri,pk-ccm}(t) = \frac{I_{pri}(t)}{D_{CCM}(t)} + \frac{V_{pv} D_{CCM}(t) T_s}{2 L_m} \\ = \frac{i_o}{V_{pv}} (n V_{PV} + |v_g(t)|) + \frac{1}{2 L_m f_s} V_{PV} \frac{|v_g(t)|}{n V_{PV} + |v_g(t)|} \quad (8)$$

The peak value of the secondary current is the same as the peak value of i_{pri} for each mode divided by the turn ratio n .

B. Flyback Microinverter With Hybrid Mode

Under the DCM operation, the turn-off time T_{off} is divided into the falling time T_f and the zero time Δt . The time T_f is constant and is given by [6]

$$t_f = \frac{n V_{PV} d_{DCM,pk}}{v_g} T_s = n \lambda d_{DCM,pk} T_s \quad (9)$$

where V_{pv}/V_g is denoted as λ . Because i_m is zero before the end of each switching period T_s , the following condition (10) is satisfied in DCM:

$$t_{on}(t) + t_f = d_{DCM,pk} (|\sin \omega t| + n \lambda) T_s \leq T_s \quad (10)$$

With an increase of the output power, D_{dcm} also increases, and the sum of the turn-on time and falling time becomes T_s . Thus, from (5) and (10), the critical duty ratio D_{cri} can be obtained as follows:

$$D_{cri}(t) = \frac{t_{on}(t)}{T_s} = \frac{d_{DCM,pk} T_s |\sin \omega t|}{d_{DCM,pk} (|\sin \omega t| + n \lambda) T_s} \\ = \frac{V_g |\sin \omega t|}{n V_{PV} + V_g |\sin \omega t|} \quad (11)$$

From (11), the fact that the duty ratio D_{dcm} is equal to D_{ccm} under boundary condition is verified, and the flyback operates in the DCM region when D_{dcm} is smaller than D_{ccm} . Fig. 3 shows the operation regions of the flyback inverter in a half-cycle of the grid under the conditions given in Table I. As shown in Fig. 3, the flyback inverter operates in DCM at the low instantaneous power level or low solar irradiation level, although it operates in the CCM region above a certain power level in the ac line period. Because the flyback inverter has both operation modes over the whole ac line period, it performs as the flyback inverter with hybrid mode. The boundary between the DCM and CCM regions varies according to the magnetizing inductance L_m . A lower L_m results in a larger DCM region at the given output power. To make the flyback inverter only operate in the DCM region, L_m should be lower than $L_{m,cri}$ at a certain output power. The flyback inverter only with the DCM region suffers from the high current stress which causes high power losses and limits the increase of the power capacity. As L_m increases, the CCM region increases, and the maximum current stress gradually decreases. Thus, the high L_m enhances the efficiency and power capacity. However, when setting the value of L_m , there is a trade off between the efficiency and transformer size; a higher L_m gives the lower current stress but a larger transformer size. Thus, the design of L_m for the flyback inverter with hybrid mode should be above $L_{m,cri}$ and consider the acceptable current stress and transformer size.

Table.1: Parameters and Components

Parameters	Symbols	Value
PV voltage	V_{pv}	(40-80) V
Grid voltage	V_g	210 Vrms
Rated average output power	F	60 Hz
Switching frequency	P_o	200 W
Primary winding turns	N_p	14 turns
Secondary winding turns	N_s	51 turns
Magnetizing inductance	L_m	$50 \mu H$
Leakage inductance	L_{lk}	$0.6 \mu H$
Input capacitor	C_{in}	6.6 MF
Output capacitor	C_o	$0.68 \mu F$
Output inductor	L_o	$400 \mu H$

III. THE CONTROL STRATEGY OF THE FLYBACK MICROINVERTER WITH HYBRID MODE

A. Control Issues In the flyback micro-inverter with hybrid mode, the current controller should ensure the reference tracking and disturbance rejection performances in both operation regions.

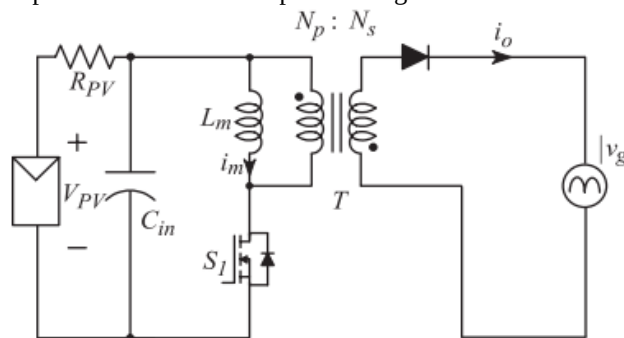


Fig. 4. Equivalent circuit of the grid-connected flyback microinverter.

Fig. 4 shows the equivalent circuit of the grid-connected flyback micro-inverter. The control input-to-output current transfer function in CCM has an RHP zero. The RHP zero varies according to the operating points, and its minimum value is at the peak of the grid voltage under maximum output power. Thus, the minimum RHP zero should be considered when the controller for the flyback inverter with hybrid mode is designed. In the conventional control system [17], the PI controller is used to ensure the reference tracking and disturbance rejection performances. The parameters used are listed in Table I. The operating point in DCM is at the instantaneous power of 25 W under the rated average output power, while the point in the CCM is the peak of V_g under the rated average output power, where it is the minimum RHP zero. The proportional gain k_p of the PI controller is tuned to be low to ensure the stability in the operation point with the minimum RHP zero. Thus, the gains of the conventional PI controller are set as follows: the PI gain $k_p = 0.08$ and $k_i = 64$. This makes the flyback inverter in the DCM region unable to ensure tracking the reference and rejecting disturbances by the PV and grid voltage effect. To increase the system gain at those frequencies, a high proportional gain is required. However, it raises the system gain at all frequencies, and so, it could make the flyback inverter in the CCM region become unstable. Consequently, when applying. The overall proposed control system for the flyback inverter with hybrid mode is shown in Fig. 4.3; it consists of the PR controller with HC and the nominal duty ratio D_n . $I^* g$ is the peak value of the reference grid current (or output current). As a kind of the feedforward control inputs, the nominal duty ratio D_n eliminates the disturbance effects and reduces the burden of the feedback controller. In [17], only the duty ratio D_{ccm} in (6) is applied to the whole ac line period. In this case, the duty ratio D_{ccm} causes the voltage mismatch in the DCM region, which increases the burden of the feedback controller. Since the system gain in DCM is relatively lower, this burden becomes heavier. To overcome the mismatch in DCM, the duty ratio D_{dcm} should be applied when the flyback inverter operates in the DCM region; it means that the nominal duty ratio should be determined according to the operation region. To classify the section of operation modes without an additional current sensor, the critical duty ratio in (11) can be used; it is noted that the flyback inverter operates in the DCM region when the following condition is satisfied, the proposed hybrid nominal duty ratio can significantly reduce the disturbance effect in both operation modes, and so, it improves the performance of the feedback controller.

IV. SIMULATION AND EXPERIMENTAL RESULTS

To verify the feasibility and performance of the proposed control strategy, the simulation by a simulator P_{sim} and experiment using the prototype for the flyback micro inverter shown in Fig.6.1 were conducted. The nominal PV voltage and rated power were set up to 60V and 200W, respectively. Based on the analysis in the controller parameters are designed. Fig. shows the output current control performance when the conventional PI controller only with the duty ratio DCCM is used. The simulation circuit of the flyback is shown in below figure 6.1,

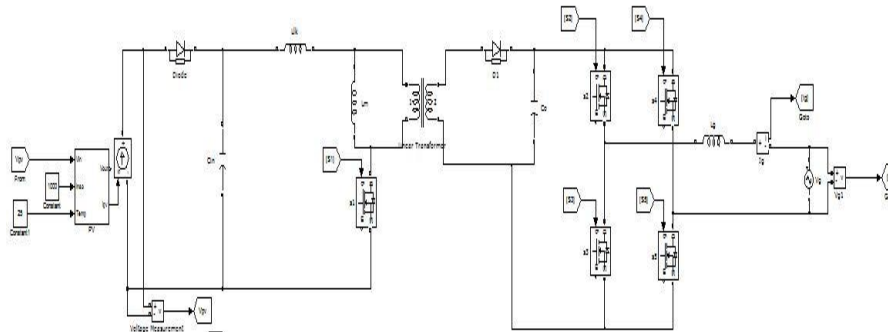


Fig.6.1: simulation circuit for the flyback microinverter

When the conventional control system is used, the grid current is distorted in the low power level. Especially, the output current is not regulated by the poor tracking and rejecting disturbance performances in the power level only with DCM region over whole ac line period. On the other hand, in the proposed control strategy, it is observed that the output current tracks the reference current and achieves the almost zero tracking error without high proportional gain. The output voltage of photovoltaic system as shown in Fig 6.2. The input voltage of the photovoltaic module will be the simulation output is shown in below figure.

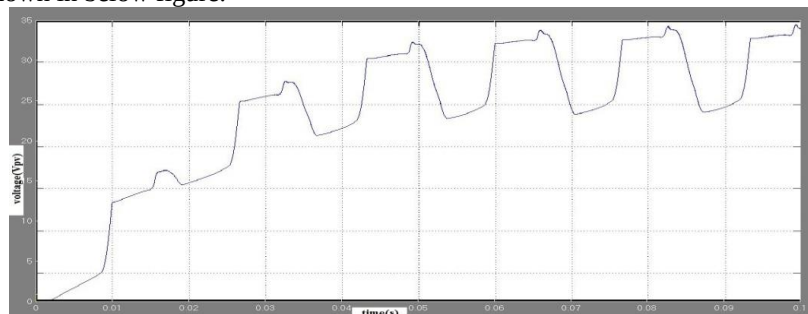


Fig.6.2: Simulation input voltage V_{pv}

CASE I: operation of photovoltaic fed flyback microinverter with hybrid mode under quarter load condition:

The simulation output current control performance when the conventional PI controller only with the duty ratio D_{ccm} . When the conventional control system is used, the grid current is distorted in the low power level. The output current is not regulated by the poor tracking and rejecting disturbance performances in the power level only with the DCM region over the whole ac line period.

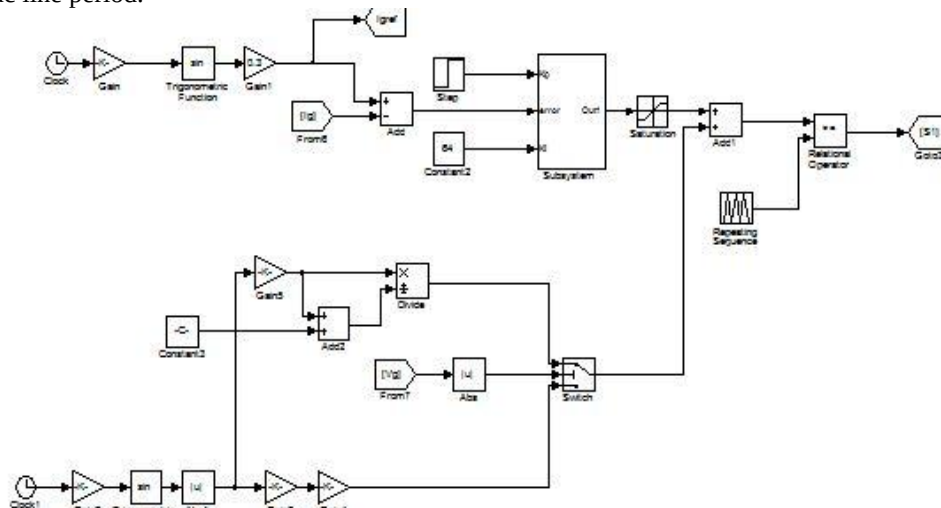


Fig.6.3: Subsystem of simulation circuit

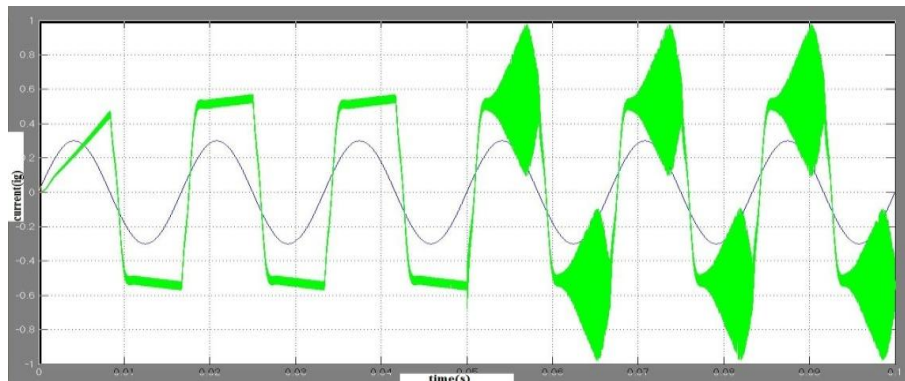


Fig.6.4: output of PI controller

The Total Harmonic distortion for the conventional control system by using PI controller is 40.78% to be calculated for the quarter load condition.

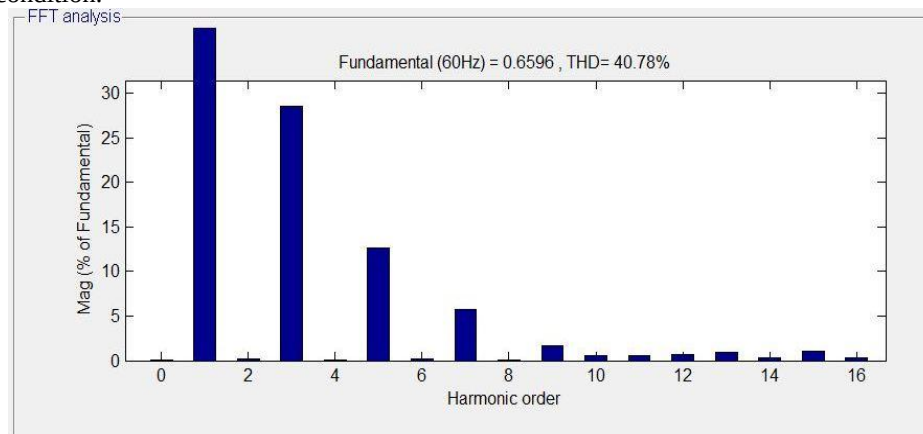


Fig.6.5: Graphical representation of THD at quarter load condition for the PI controller

The proportional integral control strategy, it is observed that the output current tracks the reference current and achieves almost zero tracking error without high proportional gain as shown in Fig.6.5 shows the simulation circuit, outputs are shown in below figures and also The THD calculations for the grid current.

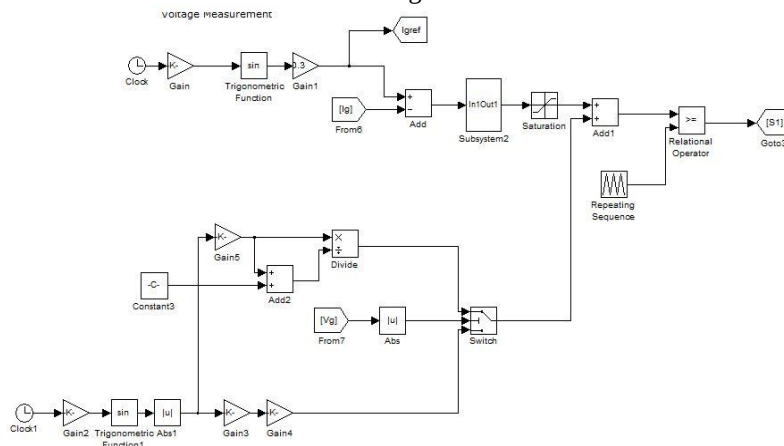


Fig.6.6: Subsystem of simulation circuit of PI controller

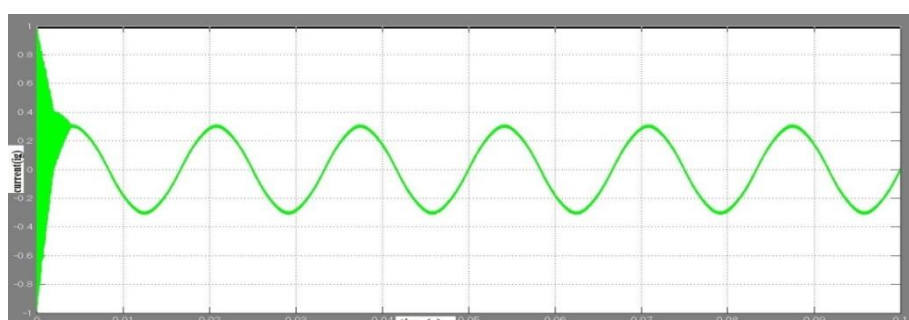


Fig.6.7: Grid current i_g and its reference i_{g-ref} with PR control system

The Total Harmonic distortion for the conventional control system by using PR controller is to be calculated 2.57% for the quarter load condition.

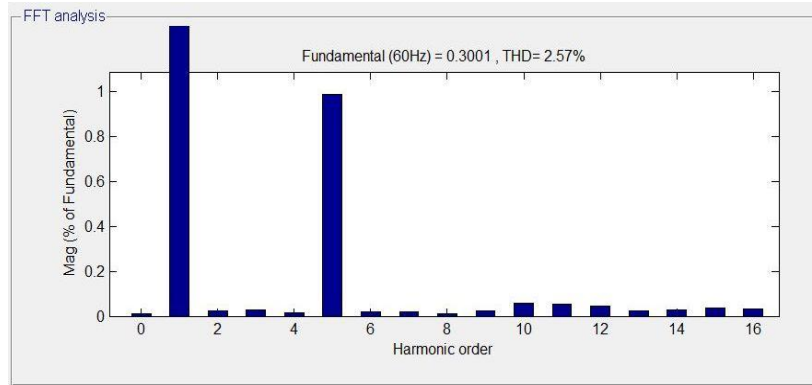


Fig.6.8: THD at quarter load condition for the PR controller

The proportional Resonance control strategy, it is observed that the output current tracks the reference current and achieves almost zero tracking error without high proportional gain as shown in Fig.6.8 shows the simulation circuit, outputs are shown in below figures and also The THD calculations for the grid current.

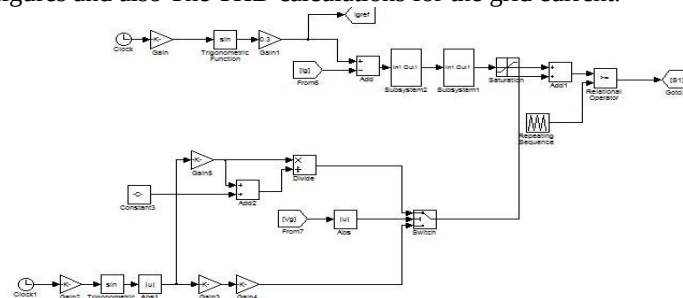


Fig.6.9: simulink diagram of proposed fuzzy-PR circuit

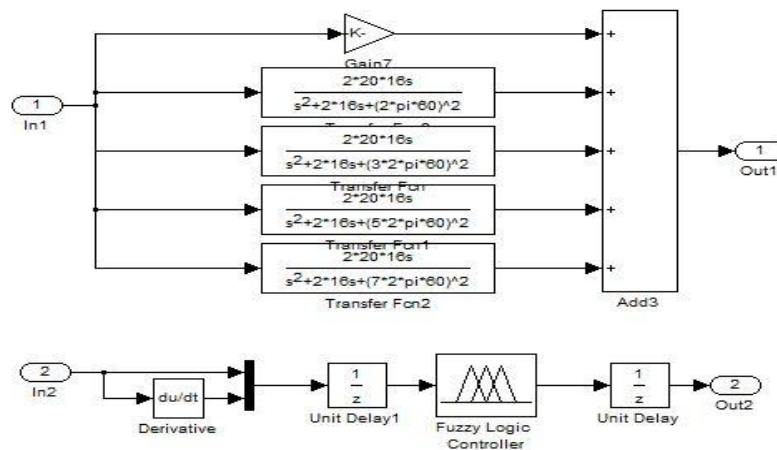


Fig.6.10: simulink of fuzzy-PR controller

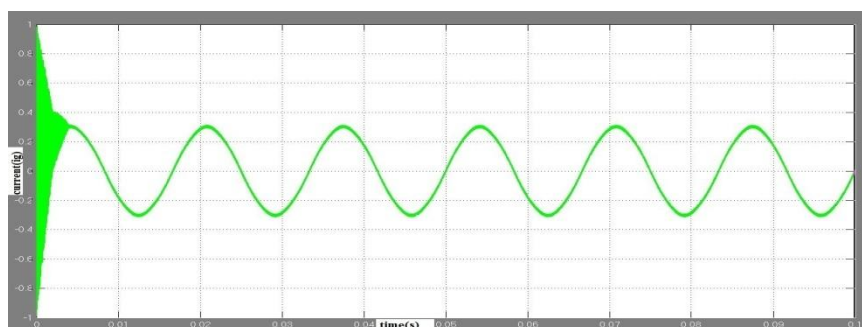


Fig.6.11: Grid current i_g and its reference i_{g-ref} with PR-FUZZY control system

The Total Harmonic distortion for the conventional control system by using FUZZY-PR controller is to be calculated 2.56% for the quarter load condition.

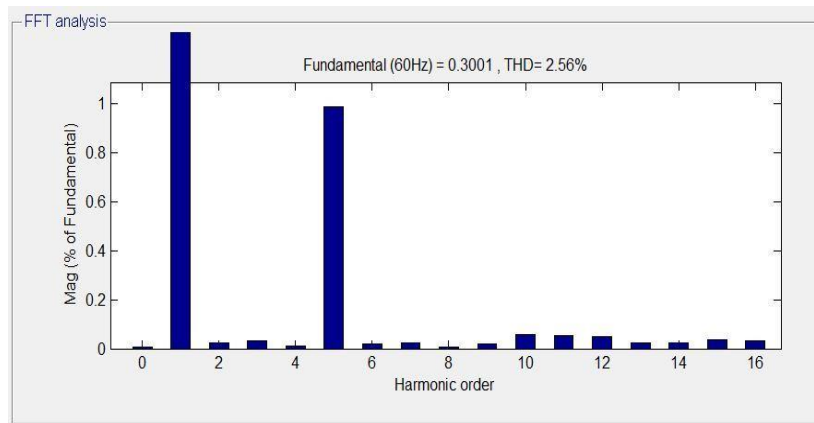


Fig.6.12: THD at quarter load condition for the FUZZY-PR controller

The Fuzzy-proportional Resonance control strategy, it is observed that the output current tracks the reference current and achieves almost zero tracking error without high proportional gain by using fuzzy logic controller as shown in Fig.6.12 shows the simulation circuit, outputs are shown in below figures and also THD calculations for the grid current.

Total harmonic distortion for the quarter load condition: The proposed control strategy is applied to we get THD on the grid current is measured as 2.56% under full-load condition and conventional condition the THD on the grid current is measured as reduced from 40.78% and 2.57%. The Total Harmonic distortion for the conventional control system by using PI controller, PR controller and PR-FUZZY logic controllers are to be calculated for the quarter load condition.

Table.6.1: Reduced THD calculation on the proposed controller system

ELEMENT	PI	PR	PR-FUZZY
T.H.D	40.78	17.64	2.56

CASE II: operation of photovoltaic fed flyback microinverter with hybrid mode under full load condition: The output current is not regulated by the poor tracking and rejecting disturbance performances in the power level only with the DCM region over the whole ac line period.

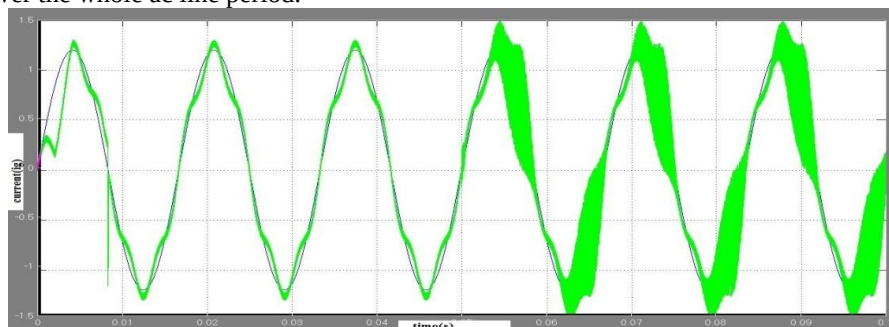


Fig.6.13: Grid current i_g and its reference i_{g-ref} with PI control system

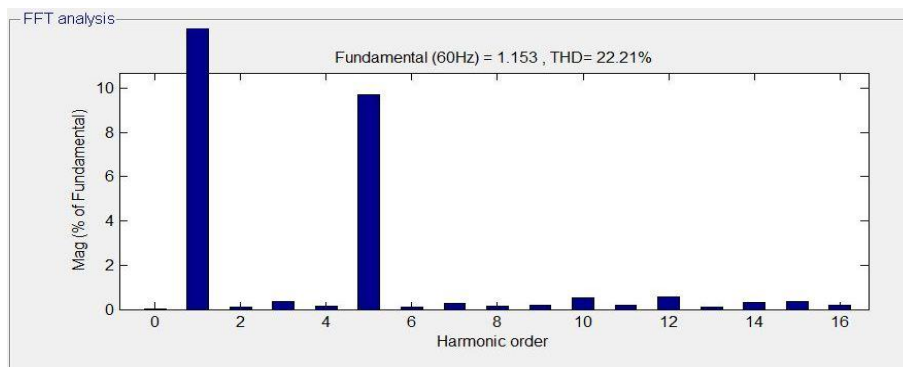


Fig.6.14: THD at full load condition for the PI controller

The proportional integral control strategy, it is observed that the output current tracks the reference current and achieves almost zero tracking error without high proportional gain as shown in Fig.6.14 shows the simulation circuit, outputs are shown in below figures and also The THD calculations for the grid current.

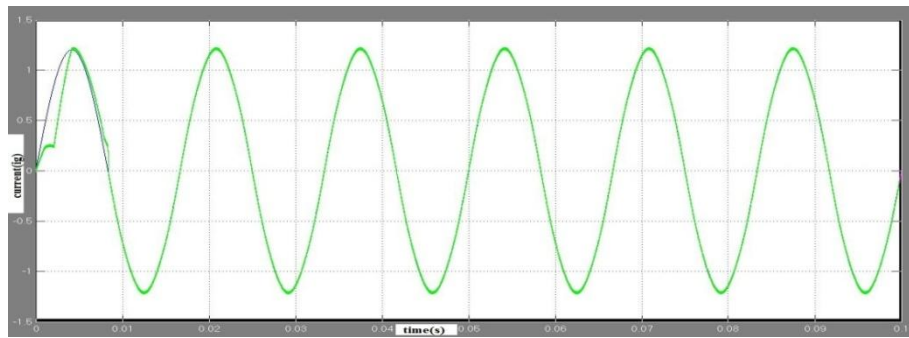


Fig 6.15: Grid current i_g and its reference i_{g-ref} when the PR system

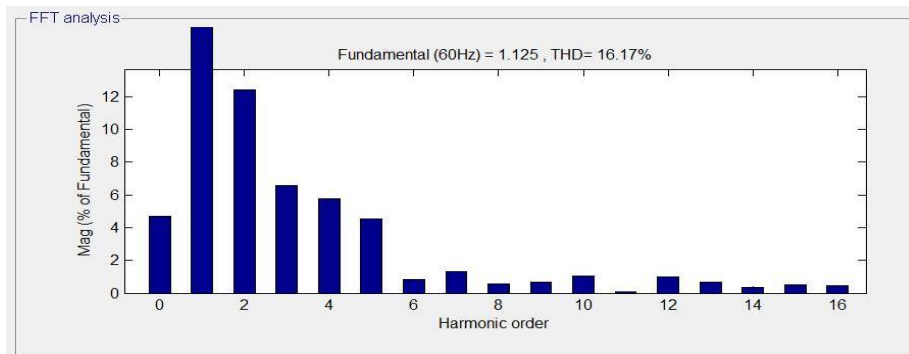


Fig.6.16: THD at full load condition for the PR controller

The proportional Resonance control strategy, it is observed that the output current tracks the reference current and achieves almost zero tracking error without high proportional gain as shown in Fig.6.16 shows the simulation circuit, outputs are shown in below figures and also The THD calculations for the grid current.



Fig.6.17: Grid current i_g and its reference i_{g-ref} when the PR controller with fuzzy logic controller is applied

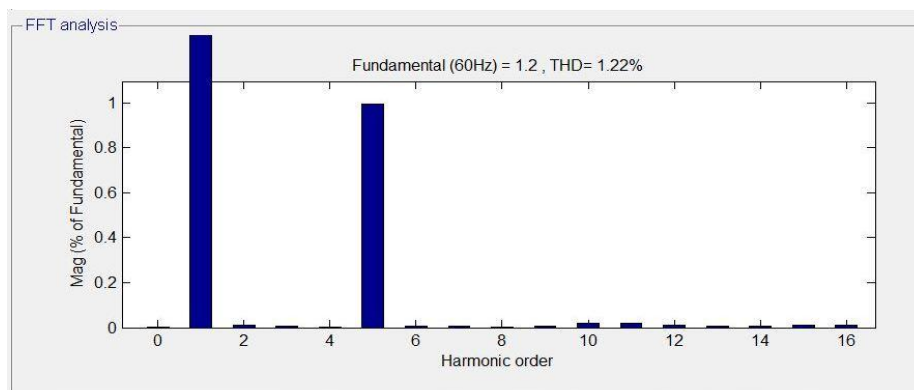


Fig.6.18: THD at full load condition for the FUZZY-PR controller

The Fuzzy with proportional Resonance control strategy, it is observed that the output current tracks the reference current and achieves almost zero tracking error without high proportional gain as shown in Fig.6.18 shows the simulation circuit, outputs are shown in below figures and also The THD calculations for the grid current.

Total harmonic distortion for the full load condition: The proposed control strategy is applied to we get THD on the grid current is measured as 1.22% under full-load condition and conventional condition the THD on the grid current is measured as reduced from 22.21% and 16.17%.

Table.6.2: THD calculation on the proposed controller system

ELEMENT	PI	PR	PR-FUZZY
T.H.D	22.21	16.17	1.22

The Total Harmonic distortion for the conventional control system by using PI, PR, PR-FUZZY controllers are to be calculated for the both full load condition. Table.6.2 shows the dynamic performance under the full load. From Fig. 6.17, Fig.6.18, it is verified that the proposed control system makes the output current track well its desired value under the load transient state. To ensure DCM operation for all operating points, the magnetizing inductance of the DCM flyback is set to 11 μ H. From Fig.6.17, it is observed that the flyback with hybrid mode has a much lower current stress in both primary and secondary sides than those of the DCM flyback inverter. Fig.6.17 shows the waveforms for the grid voltage and current when the proposed control strategy is applied. As shown in Fig.6.17, regardless of load conditions, the grid current has an almost perfect sinusoidal form and desired power level. The THD on the grid current is measured as 1.22% under full-load condition. Fig.6.13 to Fig.6.18 shows the dynamic performance under the full load. From Fig.6.18 it is verified that the proposed control system makes output current well track its desired value under the load transient state.

V. CONCLUSION

The current control strategy of the flyback micro-inverter with hybrid mode for the PV ac module has been introduced and verified by the analysis, simulation, and experimental results. In the proposed control strategy, the PR controller with fuzzy logic controller provides a high system gain at fundamental and harmonic frequencies in both operation modes. The proposed fuzzy logic controller yielded from the proposed operation mode selection eliminates the disturbance more effectively and reduces the burden. By using fuzzy logic system reduces the harmonic output results. From the simulation and experimental results, it is verified that the proposed control strategy fuzzy controller shows faster reference tracking than those of the conventional strategy.

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