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An Advance Repetitive Control Scheme for Fuzzy Current Control Based Grid-Connected Inverter with Frequency-Adaptive Capability

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Abstract - ***In this paper, an advance repetitive control method (RCM) for fuzzy current control based grid connected inverter with a frequency adaptive capability is proposed. The main objective of the proposed scheme is to reduce total harmonic distortion (THD) such that by changing the FIR filter according to varied grid frequency and keeps the resonant frequencies fitting the grid fundamental and harmonic ones. The repetitive control scheme is adopted because it is very efficient in tracking periodic signals and low output total harmonic distortion (THD) where it is required that the ratio of sampling frequency be an integer. However, in real industrial application the ratio may be a non-integer then the resonant frequencies of RCM will diverts from the real grid fundamental and harmonic frequencies and this will take down the system performance. In order to establish the improvement of performance the proposed control scheme is compared with traditional repetitive control scheme based on PI controller. The control strategy is evaluated in grid -connected mode with experiments under different frequencies. The proposed controller effectively shows that it is better than the other control schemes in terms of the THD level and component harmonic of inverter systems .***

Index Terms---Finite impulse response (FIR) filter, gird-connected inverters, repetitive control method (RCM), total harmonic distortion (THD) frequency variation, proportional integral (PI) controller, fuzzy controller .

I. INTRODUCTION.

In the last few years along with contribution and share of renewable power source development, distributed power generation system (DPGS) has also drawn a lot of attention. Plusewidth modulation (PWM) voltage source inverter (VSI) is most normally used topology for interfacing this green power source to the utility grid. A micro-grid is generally functioned in the grid-connected mode and the power quality assessment is mainly based on THD in voltages and currents. THD for both photo voltaic arrays and wind turbines connected to grid is 5%.

To renumerate pollution to the grid, the grid connected VSI must had high output power factor and low output current THD . The operation of the VSI rely on the quality of the applied current control strategy and in order to meet power quality requirements, inverters in micro-grid must have good potentiality harmonic rejection .

Different methods for grid-connected inverters e.g. proportional integral (PI) control and proportional resonant (PR) control. The PI control schemes broadly used in synchronously rotating (d, q) reference frame and can work well with balanced systems, but it cannot deal with unbalanced disturbance currents, which are must usual in micro-grids. Due to its excellent potentiality to rule out the steady state error the PR control scheme in stationary (α β) reference frame is most usually adopted.

Repetitive control theory consider as a simple learning control method, allows a substitute to reduce the THD in voltages or currents. It is able to eliminate periodic errors in dynamic systems. There are different repetitive control techniques (RCT) present e.g. using internal model principle, applying a variable one- order low-pass filter and RCM with fictitious sampling points. The RCT using internal model principal can able to eradicate periodic errors in dynamic systems as it inserts high gains at the fundamental and all harmonic frequencies. The drawback is that there is auxiliary function cascaded with traditional delay function for generating the stabilization of the system will increase the steady state tracking errors and THD even the ratio is an

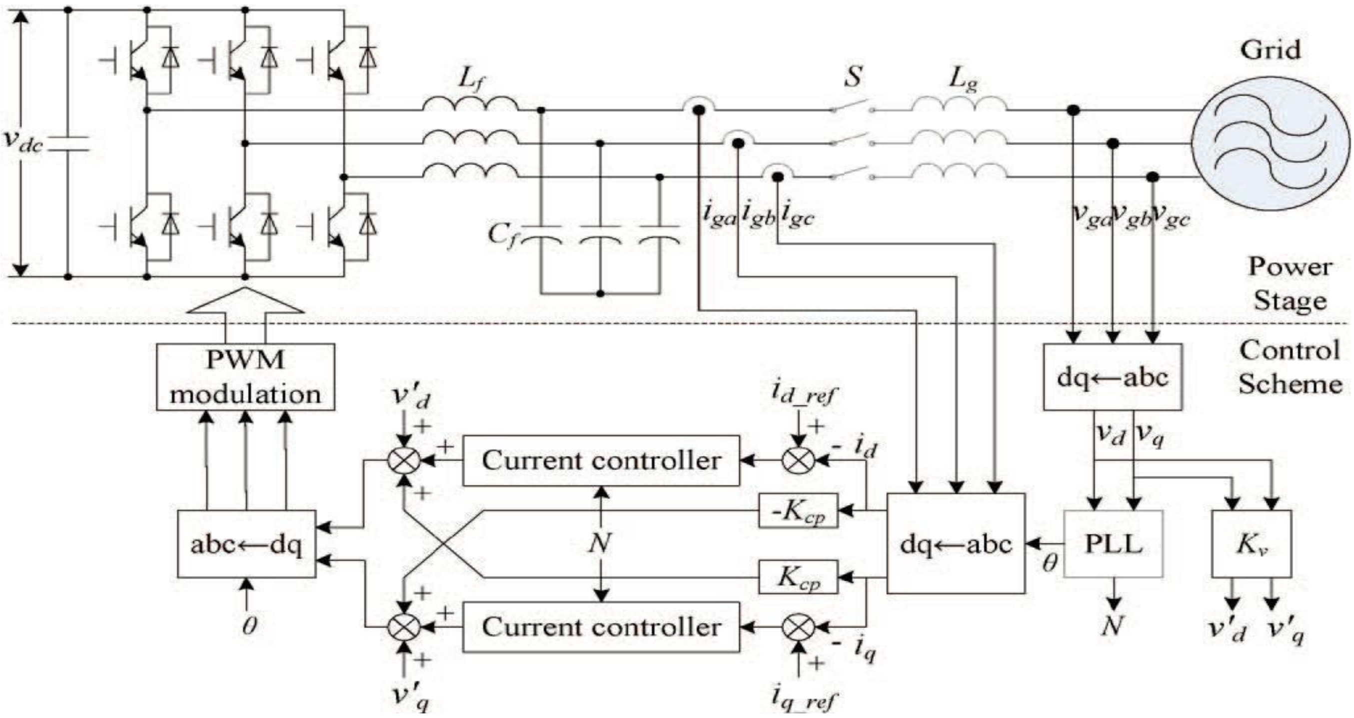


Fig-1: Block diagram of a three-phase grid-connected inverter with the improved repetitive control scheme

integer. The RCM using a Variable one-order low-pass filter can easily follows varied grid frequency but the limitation is that the resonant points and the fundamental frequency of the grid can be perfectly fits and the rest of the resonant points still deviate from the harmonic compensation performance. The RCM with fictitious sampling points can keep the ratio of sampling frequency to the grid frequency be an integer. But, fictitious sampling points are derives from the actual sampling points by linear calculation, and there are errors between them.

In this paper an advance RCM for Fuzzy current control based grid-connected inverter is proposed. This scheme innovates a special designed FIR filter which is cascaded along with a traditional delay function. The FIR filter substitutes the auxiliary function can estimate the ideal repetitive control function of any ratio. The advance scheme modifies the FIR filter according to the varied fundamental and harmonic frequencies. Thus, minimize the THD and tracking error.

This paper is organized as follows Section II briefly introduces the description of the system. Fuzzy current control based grid- connected VSI is analyzed in section III along with RCS is examined. In section IV, the simulation as well as experimental results, the comparison is also provided to demonstrate the improvement of performance of the proposed scheme over the existing schemes. The conclusions from the research are summarized in section V.

II. DESCRIPTION OF THE SYSTEM

Fig. 1 shows the block diagram of proposed control scheme i.e., an advance RCM for fuzzy current control based grid-connected inverters with frequency adaptive capability which consists of grid, insulated gate bipolar transistor (IGBT) inverter bridge, an LCL filter, PWM voltage source inverter(VSI), fuzzy based current controller, phase–locked loop (PLL), $dq \leftarrow abc$ and $abc \leftarrow dq$ converters. Where L_f and C_f are filter inductors and filter capacitors respectively, L_g is grid interface inductor; proportional regulator K_v and K_{cp} ; v_{dc} is voltage across DC supply ; i_{ga}, i_{gb} ,i_{gc} and v_{ga},v_{gb},v_{gc} grid currents and grid voltages respectively, which are transformed into i_d, i_q and v_d, v_q. A phase-locked loop (PLL) is uses to provide the phase information 'θ' of the grid voltages for dq/abc transformation and the ratio 'N' of the sampling frequency f_s to grid frequency f_o for the current controller. The circuit breaker S is needed during the synchronization and shutdown procedure. The circuit breakers could be closed at any time if the generated voltages should be equal to the grid voltages. In order to achieve this, the v_d and v_q are feed forwarded and injected to the output of the current controller via a proportional regulator K_v ; i_d and iq via $\pm K_{cp}$ are also added to the output of the current controller to decouple each other [24]. The inverter is assumed to be powered by a constant dc voltage source.

III. DESIGN OF THE IMPROVED REPETITIVE CURRENT CONTROLLER

The block diagram of the improved repetitive control is shown in Fig. 2. The current controller is accomplished based on the fuzzy controller and RCT after establishing the inverter model. The main objective of the fuzzy current controller is to infuse a clean and balanced current to the grid. G_p(s) is the transfer function of the VSI in the synchronous reference frame (SRF). G_c(s) is the transfer function of the fuzzy control for fundamental current regulation; Q(s), $e^{-sT}$and G_f(s) are the three factors. $I_{decouple}$(s) is the current-decoupling factor, and $v_{forward}$(s) is the grid voltage feedforward factors I_g(s) is the VSI output current inserted into the grid, I_{ref}(s) is reference current and I_D(s) is the disturbance of the grid current. When the inverter develops the power, the repetitive current controller makes appropriate contributions on the top of the feed forwarded grid voltages. The output current to the grid is used as feedback and the micro-grid voltage is maintained using the feed forwarded grid voltage .

A. Model of the Three-Phase Grid-Connected VSI in the SRF

Fig.1 shows a system having two stages i.e., power stage and control scheme. The power stage is a system topology of three-phase grid-connected insulated gate bipolar transistor and has a LCL filter connected the inverter output with the grid which converters a dc input voltage into an ac sinusoidal

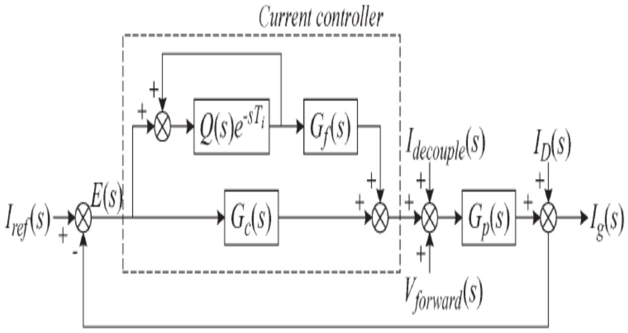


Fig-2: Block diagram of the improved repetitive control scheme.

voltage by means of appropriate switch signals to make the output current in phase with the utility voltage. Thus the current i_L and i_g and voltage of capacitor v_c are chosen as state variables ; then the model is given as

$$\frac{d}{dt}\begin{bmatrix} i_{Lab}(t) \\ i_{Lbc}(t) \\ i_{Lca}(t) \end{bmatrix} = -\frac{R_L + R_C}{L_f} \times \begin{bmatrix} i_{Lab}(t) \\ i_{Lbc}(t) \\ i_{Lca}(t) \end{bmatrix} + \frac{R_c}{L_f} \times \begin{bmatrix} i_{gab}(t) \\ i_{gbc}(t) \\ i_{gca}(t) \end{bmatrix} - \frac{1}{L_f} \times \begin{bmatrix} v_{Cab}(t) \\ v_{Cbc}(t) \\ v_{Cca}(t) \end{bmatrix} + \frac{v_{dc}}{L_f} \times \begin{bmatrix} d_{ab}(t) \\ d_{bc}(t) \\ d_{ca}(t) \end{bmatrix} \quad (1)$$

$$\frac{d}{dt}\begin{bmatrix} i_{gab}(t) \\ i_{gbc}(t) \\ i_{gca}(t) \end{bmatrix} = \frac{R_C}{L_g} \times \begin{bmatrix} i_{Lab}(t) \\ i_{Lbc}(t) \\ i_{Lca}(t) \end{bmatrix} - \frac{R_c + R_g}{L_f} \times \begin{bmatrix} i_{gab}(t) \\ i_{gbc}(t) \\ i_{gca}(t) \end{bmatrix} + \frac{1}{L_g} \times \begin{bmatrix} v_{Cab}(t) \\ v_{Cbc}(t) \\ v_{Cca}(t) \end{bmatrix} - \frac{1}{L_g} \times \begin{bmatrix} v_{gab}(t) \\ v_{gbc}(t) \\ v_{gca}(t) \end{bmatrix} \quad (2)$$

$$\frac{d}{dt}\begin{bmatrix} v_{Cab}(t) \\ v_{Cbc}(t) \\ v_{Cca}(t) \end{bmatrix} = \frac{1}{C_f} \times \begin{bmatrix} i_{Lab}(t) \\ i_{Lbc}(t) \\ i_{Lca}(t) \end{bmatrix} - \frac{1}{C_f} \times \begin{bmatrix} i_{gab}(t) \\ i_{gbc}(t) \\ i_{gca}(t) \end{bmatrix} \quad (3)$$

Here R_L is the parasitic resistance of filter inductor, R_c is the parasitic resistance of filter capacitor and R_g is the parasitic resistance of grid interface inductor and

and where i_{Lab} equals to i_{La} minus i_{Lb}, i_{gbc} equals to i_{gb} minus i_{gc} etc., d_{ab}, d_{bc} and d_{bc} the control signals.

The transformation matrix from the stationary reference frame to synchronous reference frame is

$$T = \sqrt{\frac{2}{3}}\begin{bmatrix} \sin\omega_0 t & \sin\left(\omega_0 t - \frac{2\pi}{3}\right) & \sin\left(\omega_0 t + \frac{2\pi}{3}\right) \\ -\cos\omega_0 t & -\cos\left(\omega_0 t - \frac{2\pi}{3}\right) & -\cos\left(\omega_0 t + \frac{2\pi}{3}\right) \end{bmatrix} \quad (4)$$

Where $\omega_0 = 2\pi f_0$, f_0= grid fundamental frequency. Thus, multiply the equations (1)—(3) with T^{-1} on both sides, then

$$\frac{d}{dt}\begin{bmatrix} i_{Ld}(t) \\ i_{Lq}(t) \end{bmatrix} = -\frac{R_L + R_C}{L_f} \times \begin{bmatrix} i_{Ld}(t) \\ i_{Lq}(t) \end{bmatrix} + \frac{R_c}{L_f} \times \begin{bmatrix} i_{gd}(t) \\ i_{gq}(t) \end{bmatrix}$$
$$-\frac{1}{L_f} \times \begin{bmatrix} v_{Cd}(t) \\ v_{Cq}(t) \end{bmatrix} + \frac{v_{dc}}{L_f} \times \begin{bmatrix} d_d(t) \\ d_q(t) \end{bmatrix} - X \times \begin{bmatrix} i_{Ld}(t) \\ i_{Lq}(t) \end{bmatrix} \quad (5)$$

$$\frac{d}{dt}\begin{bmatrix} i_{gd}(t) \\ i_{gq}(t) \end{bmatrix} = \frac{R_C}{L_g} \times \begin{bmatrix} i_{Ld}(t) \\ i_{Lq}(t) \end{bmatrix} - \frac{R_c + R_g}{L_f} \times \begin{bmatrix} i_{gd}(t) \\ i_{gq}(t) \end{bmatrix}$$
$$+\frac{1}{L_g} \times \begin{bmatrix} v_{Cd}(t) \\ v_{Cq}(t) \end{bmatrix} - \frac{1}{L_g} \times \begin{bmatrix} v_{gd}(t) \\ v_{gq}(t) \end{bmatrix} - X \times \begin{bmatrix} i_{gd}(t) \\ i_{gq}(t) \end{bmatrix} \quad (6)$$

$$\frac{d}{dt}\begin{bmatrix} v_{Cd}(t) \\ v_{Cq}(t) \end{bmatrix} = \frac{1}{C_f} \times \begin{bmatrix} i_{Ld}(t) \\ i_{Lq}(t) \end{bmatrix} - \frac{1}{C_f} \times \begin{bmatrix} i_{gd}(t) \\ i_{gq}(t) \end{bmatrix} - X \times \begin{bmatrix} v_{Cd}(t) \\ v_{Cq}(t) \end{bmatrix} \quad (7)$$

Where

$$X = T(dT^{-1}/dt) = \begin{bmatrix} 0 & \omega_0 \\ -\omega_0 & 0 \end{bmatrix} \quad (8)$$

In reality system are physically non – ideal; a completely accurate model could not be established. Therefore in this paper, the coupling capacitor voltage is neglected , which means the matrix X in (7) is zero. G_p(s), the transfer function of the voltage source invertor in the SRF present in equation (5A), shown at the bottom of the page, is directly derived from (5)—(7) by taking the laplace transform of equation(5)—(7) and neglecting the term whose coefficient is $\omega_0^2 L_g C_f L_f$. Moreover co-efficient of the current is

$$K_{cp} = \frac{\omega_0 * (L_f + L_g)}{v_{dc}} \quad (9)$$

B. Repetitive Controller Design

The block diagram of the improved repetitive control scheme is shown in Fig.2 the tracking error of the voltage source invertor without repetitive controller is

$$E_0(s) = \frac{I_{ref}(s) - I_D(s)}{1 + G_c(s)G_p(s)} \quad (10)$$

The RCS proposed in this paper is a plug-in type $I_{decouple}$(s) is the current-decoupling factor and $v_{forward}$(s) is the grid voltage feedforward factor. I_g(s) is the VSI output current inserted into the grid, I_{ref}(s) is its reference, and I_D(s) is the disturbance of the grid current. The tracking error of the VSI with repetitive controller in Fig.2. Equation (10) can be modified as

$$E(s) = E_0(s) \times \frac{1 - Q(s)e^{-sT_i}}{1 - [1 - G_f(s)H(s)]Q(s)e^{-sT_i}} \quad (11)$$

Here H(s) = G_p(s) / ($1 + G_c(s)G_p(s)$)

The closed system in Fig.2, is stable if it satisfy the following condition

$$|[1 - G_f(s)H(s)]Q(s)| < 1, \quad s = j\omega \qquad (12)$$

By using the Taylor progression, the equation (11) can be expressed as

$$E(s) = E_0(s) \times [1 - Q(s)e^{-sT_i}] \times \{1 - [1 - G_f(s)H(s)]Q(s)e^{-sT_i} + [1 - G_f(s)H(s)]^2 Q^2(s)e^{-2sT_i} + \dots\} \qquad (12)$$

$$E(s) = E_0(s) \times \{1 - G_f(s)H(s)Q(s)e^{-sT_i} - G_f(s)H(s)[1 - G_f(s)H(s)]Q^2(s)e^{-2sT_i} - G_f(s)H(s)[1 - G_f(s)H(s)]^2 Q^3(s)e^{-3sT_i} + \dots\} \qquad (13)$$

The equation (13) indicates that repetitive controller does not take effect on the first cycle if

$$1 - G_f(s)H(s) = 0 \qquad (14)$$

From the second cycle onward, the error can be simplified to $E(s) = E_0(s) \times [1 - Q(s)e^{-sT_i}]$ if equation (14) is possible When

$$1 - Q(jk\omega_0)e^{-jk\omega_0 T_i} = 0, \qquad k = 1,2,3, \dots \quad (15)$$

Because of the tolerance of the devices equation (14) and (15) cannot be ideally satisfied. At fundamental and all harmonic frequencies the tracking error in equation(11) can be zero. Q(s) is elected as a low order low pass filter, then

$G_f(s)$ is elected as

$$G_f(s) = \frac{1}{H(s)} \times \frac{p}{s + p} \qquad (16)$$

Here p is pole for robustness Then the stability condition of equation (12) would be satisfied too and the harmonic elimination requirements of equation (14) and equation (15) also almost quenched.

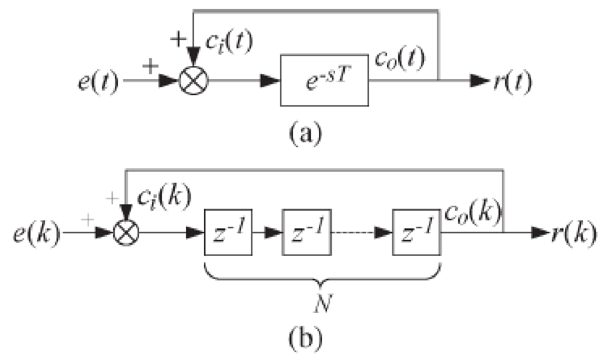


Fig-3: Block diagram of the repetitive control technique.
(a) Time domain.
(b) Discrete-time domain.

C. Improved Repetitive Control Scheme With Frequency- Adaptive Capability

The term adaptive repetitive control refers to algorithm which can be used to track or reject periodic signals under variations of the plant or the periodic signals. In this section we nominate an adaptive repetitive control that can hold the changes in reference period, and variable samples per period due to the fixed sampling rate. The design is based on the concept of multi-rate control. Fig. 3(a) shows the time-domain block diagram and Fig 3(b) shows the discrete time-domain block diagram which consists of N first-in-first-out (FIFO) cells , where N= $f_s/f_0 = T_0/T_s$ is the ratio of the sampling frequency to the grid frequency. When the grid frequency changes, the ratio cannot keep an integer, which is very natural in ideal DPGS. And which makes the Resonant frequencies of repetitive control technique to divert from the real grid fundamental and harmonic frequencies and system performance gradually degraded.

From Fig.2, the system performance shall be the same as that using the ideal repetitive controller, THD and the tracking error will be minimized if the auxiliary function $Q(s) \times e^{-sT_i}$ can reaches the ideal function e^{-sT_0}.

Let $N_i <$ N and $T_i = N_i T_s$, then it will be revised as that Q (S) must approach the function $e^{-s(N-N_i)T_s}$

Let D= N-Ni and the frequency characteristics of the delay function is

$$\angle e^{-sDT_s} = \angle e^{-j\omega DT_s} = -D\omega T_s \qquad (17)$$

However Q (s) must be a LPF which quenches the equation (15). Its normal transfer function in the dicrete- time domain is

$$F(z) = \sum_{i=0}^{M-1} a_i z^{-i} \qquad (18)$$

Here M is the Order of the FIR Filter

$$Q(z) = \sum_{i=0}^{M-1} q(k) z^{-k} \qquad (19)$$

Here Q(z) is the transfer function of the proposed FIR filter. The relationship of its coefficients is given as

$$q(M-1-k) = \frac{D-k}{(M-1-k)-D} q(k) \qquad (0 \le k \le M-1) \qquad (20)$$

Here the coefficients q(k)$[0 \le k \le \frac{(M-1)}{2}]$ are designed using rectangular window function and D is selected between $\frac{(M-3)}{2}$ and $\frac{(M-1)}{2}$.

With the given frequency characteristics in equation (17) FIR filter will be designed easily based on equation (19) and (20).

TABLE I
Parameters of VSI System

S.No	Symbol	Quantity	Value
1	L_f	Filter inductor	600μH
2	C_f	Filter capacitor	40μF
3	L_g	Grid interface inductor	40μH
4	R_L	Parasitic resistance of filter inductor	0.01Ω
5	R_C	Parasitic resistance of grid interface inductor	0.03Ω
6	R_g	Parasitic resistance of filter capacitor	0.001 Ω
7	v_g	Grid voltage	380V
8	v_{dc}	DC bus voltage	720V
9	P_o	Apparent power	30Kw

D. PLL Design

The phase-locked loop (PLL) system consists of two major parts, the phase detecting devices and loop filter. The phase detecting can be instantly carried out by using dq transform in the three phase system without additional phase detecting devices. In an advance repetitive control scheme, based on the real grid frequency, the coefficients of the FIR filter are estimated which is provided by phase-locked loop (PLL).

The output error of the PLL is large , then the performance of the system will be put down by the large frequency error and it should be as little as possible. Thus, the operation of the PLL will force the control system performance. In this paper, the method using abc/dq transformation of the grid voltages and currents is followed to figure the PLL and the output is computed at the sampling frequency. Therefore, for example if the PLL is computed at the sampling frequency 10 KHz then the coefficients of the proposed FIR filter can be forecasted at 10 KHz, 5KHz etc.,

IV. SIMULATION RESULTS

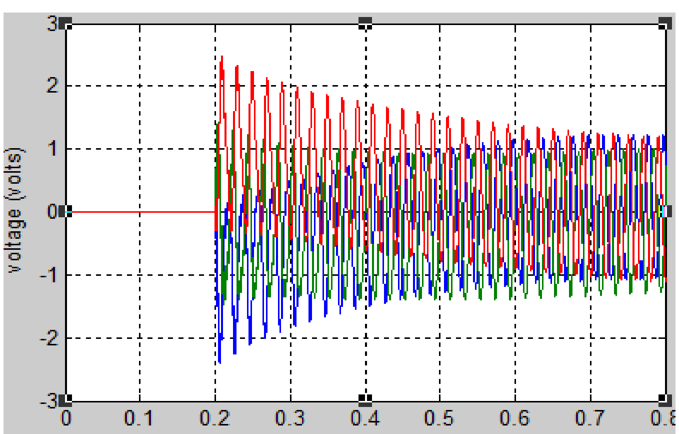
The system parameters of the VSI system are tabulated in table I. The grid voltage is 380V, DC bus voltage is 720V; the filter inductance, filter capacitance and grid interface inductance values are $600\mu H, 40\mu F, 40\mu H$ respectively. Both sampling frequency and PWM switching frequency are 10 Hz. The rated output power is 30KW and the output current of each phase is 45A at rms. By substitute the values in equation (8), we get the transfer function of VSI is

$$G_p(s) \approx \frac{9 \times 10^7 (s + 8.333 \times 10^6)}{(s + 17.187)(s^2 + 104.479s + 6.667 \times 10^8)} \quad (21)$$

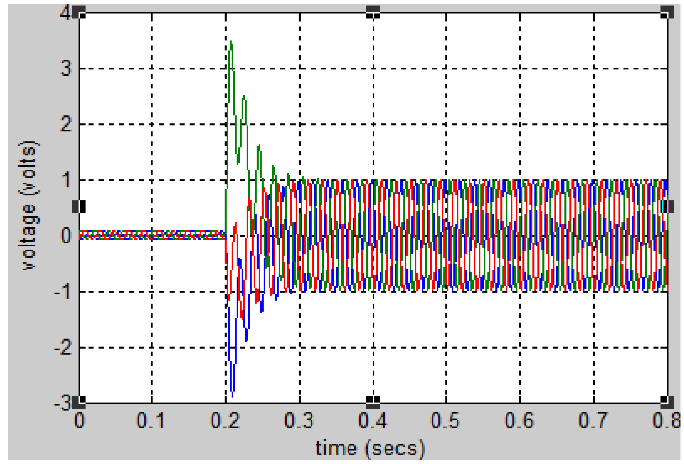
This section presents the simulation results of an advance repetitive control scheme for grid-connected inverters. The maximal step size is 500 ns and the sampling time is $100\mu s$.

(Test 1) Comparison of Controller Output :

Simulations using Simulink in MATLAB 2011a software are performed. The comparison is carried out between the outputs of the controllers i.e., the output of conventional repetitive control scheme with PI controller and the output of an advance RPM with fuzzy current controller to verify the potency of the proposed scheme is shown in Fig.4.Thus the diagram clearly shows that the waveforms in Fig.4(b) attains constancy at 0.3sec whereas conventional scheme in Fig.4(a) at 0.8 sec.



(a)



(b)

Fig-4: Simulation results at grid frequency. Output of controllers. (a)With PI controller. (b)With Fuzzy controller.

(Test 2) Effectiveness of proposed scheme (e_{ia} at different frequencies) :

In order to verify the effectiveness of the proposed scheme, the simulation results are also presented for comparison. The output current (i_{ga}) and the current tracking error (e_{ia}) at 49.9Hz, 50Hz and 50.1Hz grid frequencies are shown in Fig.5. This diagrams clearly shows that e_{ia} reaches zero at 1.5sec for synchronous frequency 50Hz, whereas for 49.9Hz it is about at 1.8sec and for 50.1Hz it is at around at 1.9sec. Above simulation results easily shows the effect of the proposed scheme on decreasing the steady-state tracing error and compensating the harmonics of the system.

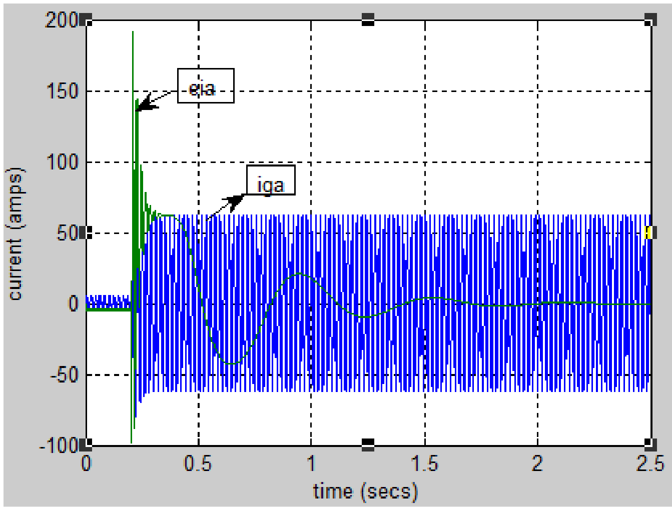


Fig-5(a): Simulation results of output current i_{ga} and current tracking error e_{ia} at 49.9Hz.

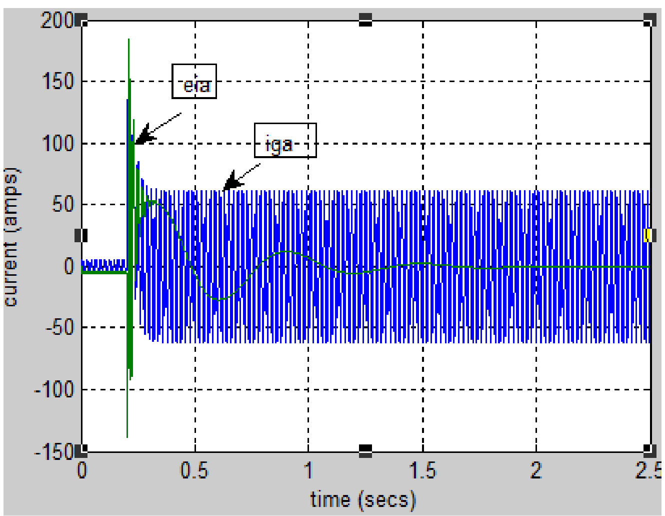


Fig-5(b): Simulation results of output current i_{ga} and current tracking error e_{ia} at 50Hz.

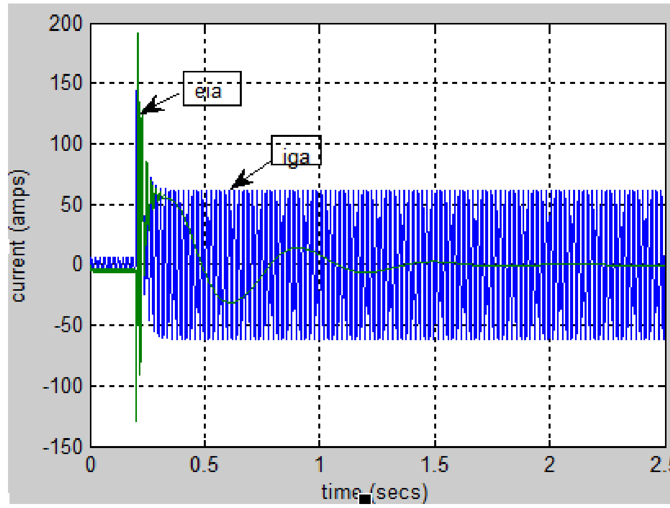
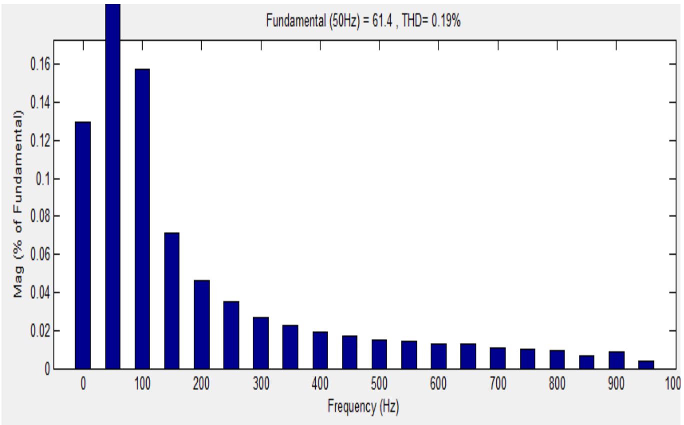


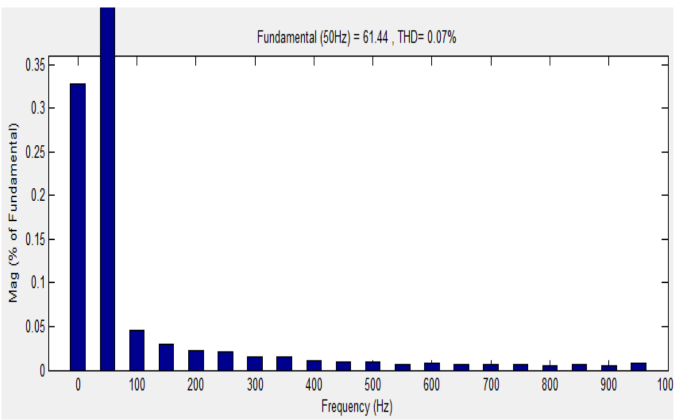
Fig-5(c): Simulation results of output current i_{ga} and current tracking error e_{ia} at 50.1Hz.

(Test 3) Comparison of spectrums of i_{ga} at different frequencies :

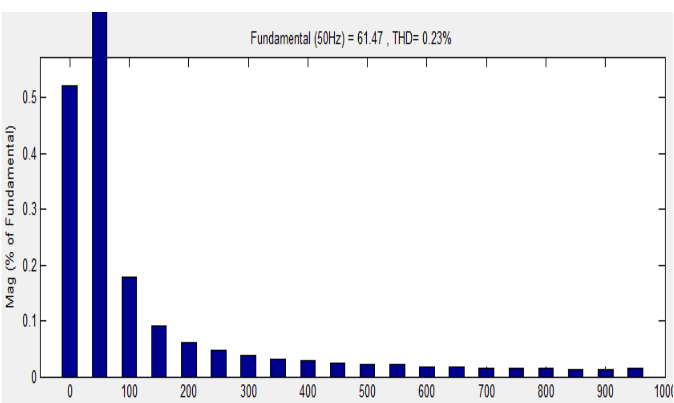
Fig.6 shows the spectrums of i_{ga} with two methods i.e., conventional RCM with PI regulator and an advance RCM with fuzzy current controller. This spectrums clears represents that with advance repetitive control scheme, the THD is reduced from 1.22% to 0.19%, at 49.9Hz. And at grid synchronous frequency 50Hz, the THD is deceases from 1.14% to 0.07%, and for 50.1Hz it is reduced from 1.20% to 0.27%.



(a)

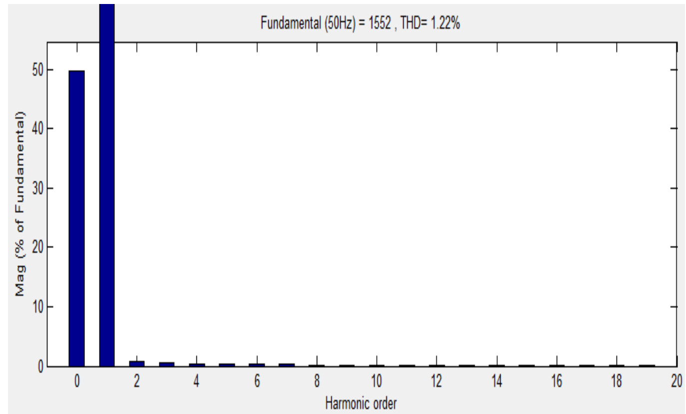


(b)

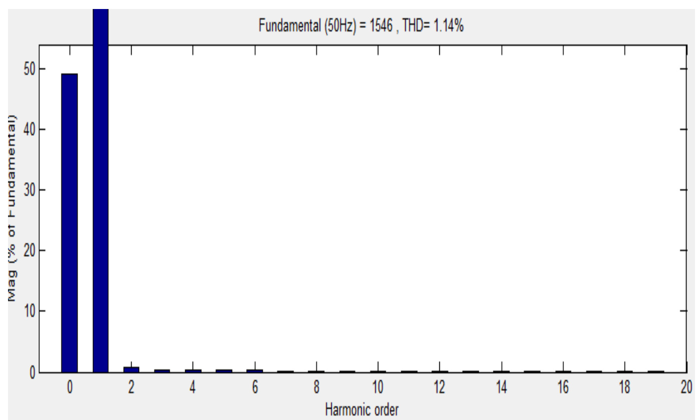


(c)

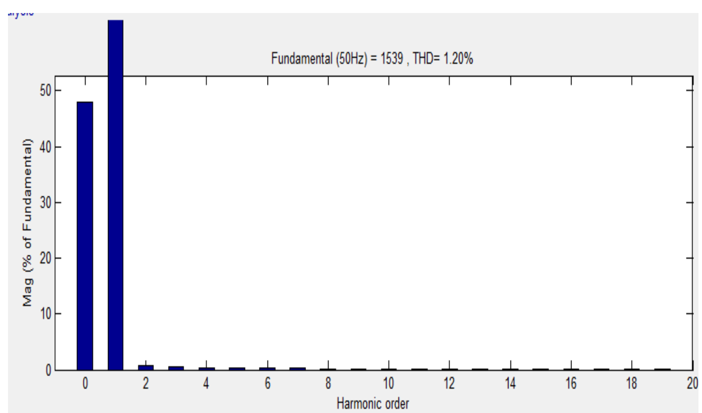
Fig-6(a): FFT Analysis of spectrums of i_{ga} with conventional repetitive Fuzzy control at different frequencies. (a)at 49.9Hz (b)at 50Hz and (c)at 50.1Hz.



(a)



(b)



(c)

Fig-6(b): FFT Analysis of spectrums of i_{ga} with conventional repetitive PI control at different frequencies. (a)at 49.9Hz (b)at 50Hz and (c)at 50.1Hz.

TABLE II :Comparison of THD at Different Frequencies

S.No	System	49.9Hz	50Hz	50.1Hz
1	With PI Controller	**1.22%**	**1.14%**	**1.20%**
2	With Fuzzy Controller	**0.19%**	**0.07%**	**0.20%**

V. CONCLUSION

The proposed advance repetitive control scheme for fuzzy current control based grid-connected inverter with frequency adaptability is subjected to different frequencies and at every point, the proposed scheme has shown better results than conventional scheme with PI controller. It also adopts a new FIR filter design method and can appropriate the ideal repetitive control when the ratio of the sampling frequency to the grid frequency varies. From simulations, it is demonstrated theoretically that by employing fuzzy logic controller it is even more accurate and reduce the steady state error and harmonic distortion than any other techniques and holds good performance.

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