A Novel Modified-TOGI based PLL for the Three-Phase Unbalanced and Distorted Grid Conditions

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Keywords

≪Unbalanced Grid≫, ≪Asymmetric Grid≫,≪Decoupled-Double Synchronous Reference Frame (DDSRF)≫, ≪Modified Second-Order Generalized Integrator (MSOGI)≫, ≪Multi Second-Order Generalized Integrator (MSOGI)≫, ≪Second-Order Generalized Integrator≫

Abstract

This paper proposes a novel modified third-order generalized integrator phase-locked loop (TOGI-PLL) for balanced, unbalanced, and distorted grid conditions. This technique also eliminates the error factors that cause in experimental such as DC-offset and removing the second-order oscillation noise by adding the low-pass filter when generating the estimated filtered frequency. A step-by-step controller design procedure, system stability analysis, and comparison with the traditional second-order generalized integrator (SOGI), dual second-order generalized integrator (DSOGI), and decoupled double synchronous reference frame PLL (DDSRF-PLL) are carried out. The proposed PLL approach is simulated and experimentally implemented on a three-phase 7.5kW grid-connected inverter system.

Introduction

In grid-connected inverters, the phase and the amplitude of the grid voltage are extracted employing phase-locked-loop (PLL) techniques to synchronize the injected current into the grid voltage and must meet modern grid codes. Significantly, in an extensive control system, many control capabilities can burden the working of the microprocessor. It is necessary for the programmer to curtail and optimize the execution time as well as the code capacity in RAM or Flash of the DSP by simplifying the instructions to catch the results agile with the highest accuracy.
The unbalanced and distorted grid makes it difficult to extract the phase of the utility voltage for the generation of the references. Hence, the implementation of the exact phase-locking under unbalanced and distorted grid voltage conditions has recently been investigated [1]. A synchronous reference frame

PLL (SRF-PLL) has been extensively implemented in grid-connected systems due to its simplicity in structure, fast dynamic response, and can easily been implemented [2]. However, the SRF-PLL will result in inaccuracy if the harmonics and imbalance in the grid voltage presents, which results in an inexact tracking of the fundamental positive sequence component (FPSC) of the grid voltage and results in instability of the whole system. To overcome the drawbacks of the SRF-PLL, a decoupled double SRF-PLL (DDSRF-PLL) has been proposed in [3]. The DDSRF-PLL can decouple the positive and negative sequence components of the grid voltage by using a decoupling network to diminish the oscillations but the presence of the low-pass filter (LPF) introduces the time delay, which results in a slower dynamic response. A second-order generalized integrator (SOGI-PLL) has been widely implemented for the single and three-phase system due to its simplicity and has the capability of exact locking even under non-ideal grid conditions [4]. The SOGI-PLL produces errors in the extraction of the FPSC when the grid voltage contains the dc offset. A dual SOGI PLL (DSOGI-PLL) with frequency adaptive positive sequence detection technique based on the stationary reference frame ($\alpha\beta$) for the extraction of the positive sequence is proposed in [5, 6, 7, 8] for the unbalanced, and distorted grid conditions. The DSOGI-Frequency Locked Loop (DSOGI-FLL) was integrated in the DSOGI-PLL system to determine without any error the instantaneous positive- and negative-sequence components of the abnormal conditions grid voltage [9]. For A mixed second-and third-order generalized integrator PLL (MSTOGI-PLL) has been proposed in [10] to accurately lock the phase in the presence of the harmonics, dc offset elimination, and voltage imbalance. A frequency adaptive tracking block has also been implemented for the compensation of the grid frequency variations. In this paper, an extensive comparison, performance analysis of SOGI, DSOGI, and DDSRF with the proposed PLL technique for the three-phase balanced, asymmetric and distorted grid conditions are presented. The proposed modified-TOGI-PLL (MTOGI) structure is simple to implement and works better in performance than other PLLs for the unbalanced grid conditions. A step-by-step design procedure of the controller with the closed-loop stability analysis is presented. The traditional PLLs with the new PLL structure known as MSOGI is simulated in MATLAB/Simulink® and experimentally implemented on a 7.5 kW Three-phase grid-connected inverter system with the DSP from TI C2000 F28335 to verify the analytical results.

Controller design of the PLL

The controller design parameters play a vital role in achieving zero-steady state error. Proper selections of the PLL gains have always been a challenge for the exact tracking of the grid voltage. The traditional design of the controller parameters are given in [2], [5], and [11]. The problem with the design procedure explained in [2], [5], and [11] is the optimum tuning of the controller parameters and has to be redesigned depending on the type of the PLL and the operating conditions. This paper proposes a step-by-step design procedure of the controller parameters, which works well for balanced, unbalanced, and distorted grid conditions and satisfies the stability margins of the system. Taking the loop filter (LF) with the voltage-controlled oscillator (VCO) and considering the sampling delay, the open-loop transfer function $G_{OL}(s)$ is given as follows:

$$G_{OL}(s) = K_{pi}\left(\frac{1+sT_{ni}}{sT_{ni}}\right)\left(\frac{1}{1+sT_s}\right)\left(\frac{V_s}{s}\right) \tag{1}$$

where T_s is the sampling time, V_s is the peak grid voltage, K_{pi} is the proportional gain and T_{ni} is the time constant of the PI controller. The symmetrical optimum (SO) method in [12] was selected to calculate the controller gains. According to the SO method, the controller gains should be calculated in such manners that the amplitude and the phase plot of the $G_{OL}(s)$ are symmetrical about the crossover frequency (ω_c), which is the geometric mean of the two frequencies of the $G_{OL}(s)$ [13]. Considering a normalizing factor, alpha (α), the closed-loop transfer function $G_{CL}(s)$ is compared with the third-order standard equation, which yields to

$$G_{CL}(s) = \frac{\alpha\omega_c^2 s + \omega_c^3}{s^3 + \alpha\omega_c s^2 + \alpha\omega_c^2 s + \omega_c^3} \tag{2}$$

where $\omega_c = \omega_n$ and α is used to compensate the damping factor and the bandwidth (ω_c) of the system. The PLL controller gains can be then determined as [13],

$$\omega_c = \frac{1}{\alpha T_s}, \qquad T_n i = \alpha^2 T_s, \qquad K_p i = \frac{1}{\alpha V_s T_s} \tag{3}$$

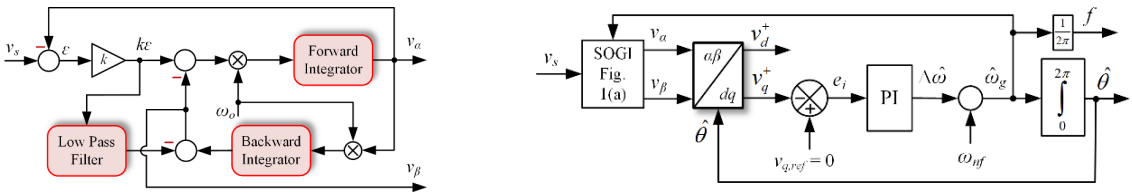
Substituting (3) into (2) results in the factor of α which is related to the damping factor (ξ) as:

$$\xi = \frac{\alpha - 1}{2} \tag{4}$$

By changing α the bandwidth of the system and damping can be controlled.

Second-Order Generalized Integrator (SOGI) PLL

Fig.1a shows the block diagram of the SOGI. The SOGI is responsible to generate the in-phase and in-quadrature signals from the grid voltage. The SOGI block uses the angular frequency (ω_g) before computing the integrators. The value of the SOGI gain (k) is important, which affects the bandwidth for the closed-loop system. The SOGI deteriorates the double frequency components in the measured fundamental frequency. The LPF is used to drop the noise, which may appear in the error signal [14]. The SOGI forward integrator and backward integrator need to be carefully discretized to avoid an algebraic loop as shown in Fig.1a. The discretization methods of forward and backward integrators can be found in [5]. The SOGI integrators have been discretized by with trapezoidal method and implemented as a third-order IIR filter. The simplest structure of the SOGI is shown in Fig.1b.



(a) Block diagram

(b) Simplified structure

Fig. 1: Second-Order Generalized Integrator (SOGI) PLL

The presented SOGI is based on the second-order integrator, which is defined as:

$$GI = \frac{\omega s}{s^2 + \omega^2} \tag{5}$$

where ω is the resonant frequency of the SOGI. The closed-loop transfer function of the α and β voltages are given as

$$H_\alpha = \frac{v_\alpha(s)}{v_\beta(s)} = \frac{k\omega s}{s^2 + k\omega s + \omega^2} \qquad H_\beta = \frac{v_\beta(s)}{v_\alpha(s)} = \frac{k\omega^2}{s^2 + k\omega s + \omega^2} \tag{6}$$

Dual Second Order Generalized Integrator (DSOGI) PLL

The DSOGI works in the SRF frame based on the instantaneous symmetrical component (ISC) method. Based on the SOGI given in Fig.2, the filtered outputs of two signals in SRF are obtained with 90° of phase shift are used to calculate the symmetrical components proposed given in [15]. The frequency adaptive positive sequence detection method is implemented on the SRF frame to extract the positive sequence for the unbalanced, and distorted grid conditions in DSOGI-PLL as given in Fig.2 [16]. The decomposition of the voltage vector into three symmetrical components as and the subscripts 0, 1, and 2

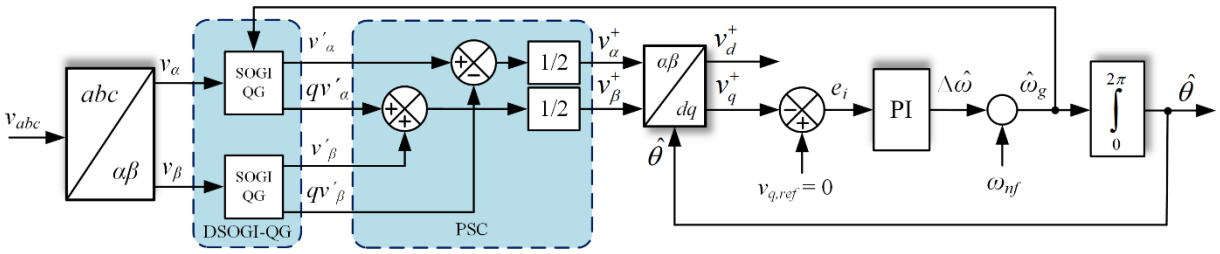


Fig. 2: Schematic diagram of the dual second-order generalized integrator (DSOGI) PLL

refers to the zero, positive and negative voltage sequence components respectively.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{a,0} \\ V_{b,0} \\ V_{c,0} \end{bmatrix} + \begin{bmatrix} V_{a,1} \\ V_{b,1} \\ V_{c,1} \end{bmatrix} + \begin{bmatrix} V_{a,2} \\ V_{b,2} \\ V_{c,2} \end{bmatrix} \tag{7}$$

$$V_{abc,1} = \begin{bmatrix} V_{a,1} \\ V_{b,1} \\ V_{c,1} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{bmatrix} \tag{8}$$

where $a = e^{j(-120^\circ)}$. The positive sequence in the orthogonal SRF can be determined as:

$$\begin{bmatrix} V_{\alpha,1} \\ V_{\beta,1} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \frac{1}{3} \begin{bmatrix} 1 & a^2 & a \\ a & 1 & a^2 \\ a^2 & a & 1 \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \qquad \begin{bmatrix} V_{\alpha,1} \\ V_{\beta,1} \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & -q \\ q & 1 \end{bmatrix} \begin{bmatrix} V_\alpha \\ V_\beta \end{bmatrix} \tag{9}$$

where $q = e^{-j\frac{\pi}{2}}$ is the phase shift operator and provides a 90° lagging phase voltage from the original phase.

Decoupled Double Synchronous Reference Frame (DDSRF) PLL

The DDSRF-PLL contributes a critical role in detecting the positive component of the fundamental frequency of the grid voltage under unbalanced and distorted grid conditions. The DDSRF-PLL is superior to the SRF-PLL because of the positive sequence detector, which cancels the detection error in the latter one. This is achieved by transforming both positive and negative sequence components of the grid voltage into the double synchronous reference frame (SRF). Then, a decoupling network is developed to extract clean and separate positive and negative sequence components [3]. The decoupling network cancels out the double frequency oscillations at 2ω in dq^{+1} and dq^{-1} reference frame signals. Therefore, there is no need to decline the bandwidth of the PLL to attenuate such oscillations and the real amplitude of the unbalanced input voltage sequence components are indeed exactly detected [5].

Modified TOGI (MTOGI) PLL

The third-order generalized integrator (TOGI) is added to the traditional SOGI structure given in Fig. 3. The TOGI eliminates the DC offset present in the utility grid. The symmetrical positive sequence in SRF is extracted by implementing two TOGI blocks for each sequence. The authors proposed a novel-based PLL technique known a modified-third-order generalized integrator (MTOGI), which is much easier to implement, does not need for transformations, less computational burden, and better transient response as compared to the traditional SOGI, TOGI, DDSRF-PLLs. The three-phase grid voltages in abc frame can be given to the MTOGI and directly extracts the symmetrical components as given in (8). The matrix A and B implemented in the MTOGI are given in (13). The V_{abc} are transformed to the Synchronous reference frame (SRF) and is given to the PI controller to generate the estimated theta $(\hat{\theta})$. A second-order LPF is used to attenuate the second-order oscillations to generate the estimated filtered frequency and is given back to the MTOGI as given in Fig.3. The 120° phase shift operator will be separated into

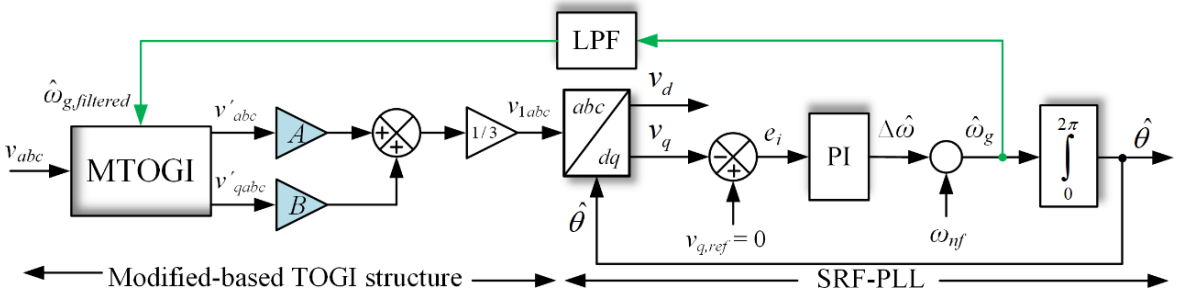


Fig. 3: The simplified structure of the modified-third-order generalized integrator (MTOGI) PLL

two parts as

$$a = e^{-j\frac{2\pi}{3}} = e^{-j(\frac{\pi}{2}+\frac{\pi}{6})} = -\sin(\frac{\pi}{6}) + \cos(\frac{\pi}{6})e^{-j\frac{\pi}{2}} = s_1 + c_1 q \tag{10}$$

$$a^2 = e^{-j\frac{4\pi}{3}} = e^{j(\frac{\pi}{2}+\frac{\pi}{6})} = -\sin(\frac{\pi}{6}) - \cos(\frac{\pi}{6})e^{-j\frac{\pi}{2}} = s_1 - c_1 q \tag{11}$$

where $s_1 = \sin(\frac{\pi}{6})$; $c_1 = \cos(\frac{\pi}{6})$

$$\begin{bmatrix} V_{a,1} \\ V_{b,1} \\ V_{c,1} \end{bmatrix} = (\frac{1}{3})(A.V'_{TOGI} + B.V'_{TOGI}) \tag{12}$$

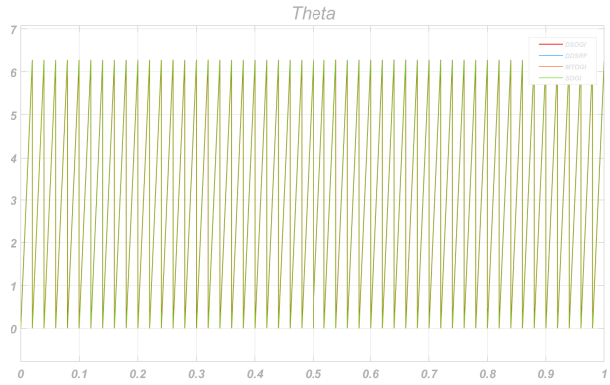
$$A = \begin{bmatrix} 1 & s_1 & s_1 \\ s_1 & 1 & s_1 \\ s_1 & s_1 & 1 \end{bmatrix}, \qquad B = \begin{bmatrix} 1 & -c_1 & c_1 \\ c_1 & 1 & -c_1 \\ -c_1 & c_1 & 1 \end{bmatrix}, \qquad LPF = \frac{w_c^2}{s^2 + 2\xi\omega_c s + \omega_c^2} \tag{13}$$

Simulation analysis

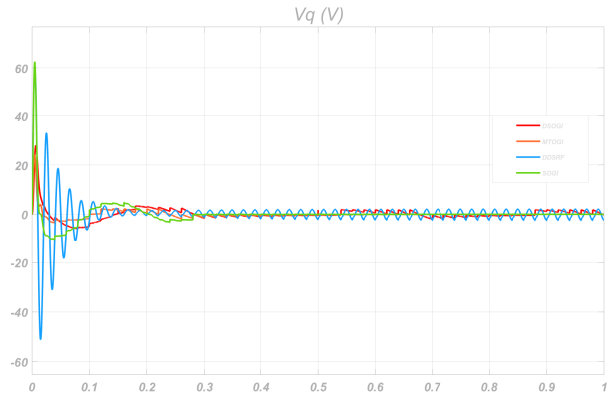
A simulation model was instituted to classify the performance and achievement of the new Modified TOGI (MTOGI) PLL. The simulation was established under these abnormal conditions namely: (1) in Fig.4, PLL is connected with distorted grid with 10% 17^{th} and 10% 23^{rd} harmonics at $t = 0.2s$; (2) the grid voltage has the frequency variations, changing from 50Hz to 55Hz at $t = 0.15s$ and coming back to 50Hz at $t = 1.5s$ in Fig.6; (3) the three-phase voltage becomes to asymmetric at $t = 0.5s$ with $V_A = 1.2V_m$, $V_B = V_m$, and $V_C = 0.7V_m$ is shown in Fig.7. The parameters of PI controller was determined from the symmetrical optimum (SO) that are presented in the above subsection "Controller design of PLL" are $k_p = 0.6505$, $k_i = 29.9248$, and $k_{sogi} = \sqrt{2}$.

Fig.4 demonstrates the comparative simulation results of our Modified-TOGI PLL against the others: SOGI, DSOGI, and DDSRF-PLL in the transient time. With the reasonable and satisfactory parameters controller design, the output theta (θ) is very accurate at zero-crossing in all cases as shown in Fig.4a. In regard to the q-sequence value in transient phase, it can be seen clearly that MTOGI PLL has the better response compared with DSOGI and DDSRF, and after approximately 0.3s, q-component becomes almost zero, the single SOGI has the best q value but the overshoot is very high. It could be not exceptional when implemented in an experimental setup. Concerning the output frequency, MTOGI and SOGI still have a very positive assessment, but SOGI has quite a high overshoot.

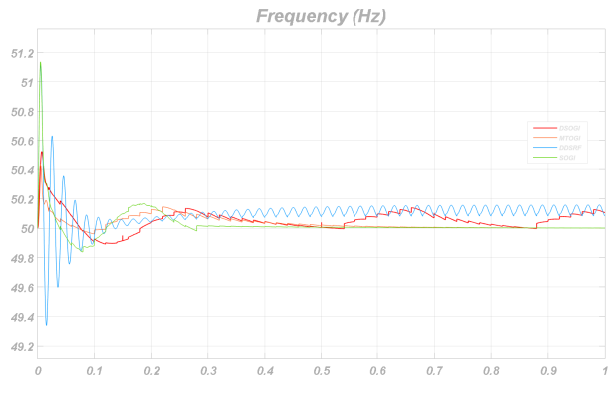
Fig.5 exhibits the operations of the PLL controller when the grid becomes too distorted with harmonics. Although MTOGI-PLL does not have the best output achievement, it, along with other PLLs, is also swift to stabilize the system and track to the set-point fundamental frequency of 50Hz precisely. This confirm that MTOGI-PLL can work very well in case of a distorted grid. Fig.6 expresses completion of PLLs during the frequency jump of three-phase voltage. At $t = 0.15$s it has a frequency change (from 50Hz to 55Hz), and $t = 1.5$s diminishes to 50Hz. After less than 1s, all of four PLL types can bring the system back to the desired frequency, but MTOGI-PLL and DDSRF-PLL have excellent results, with smaller overshoot in the transient phase and faster to the steady-state. We can see obviously here in this



(a) Output theta

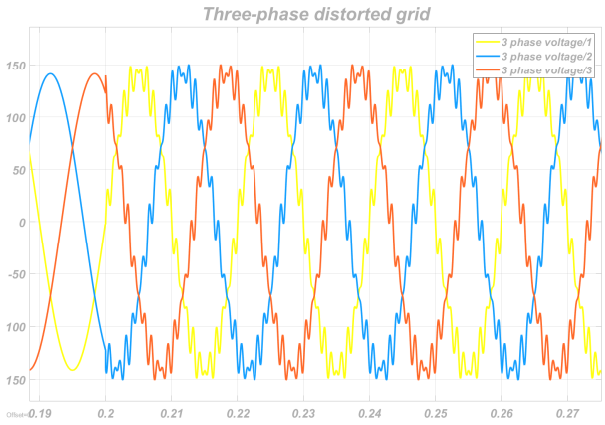


(b) q-component of instantaneous voltage

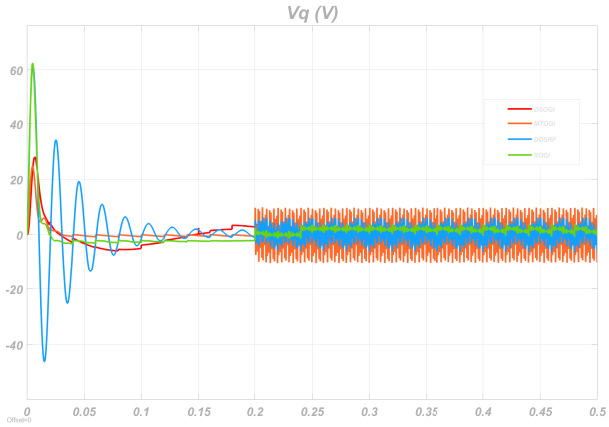


(c) Output frequency

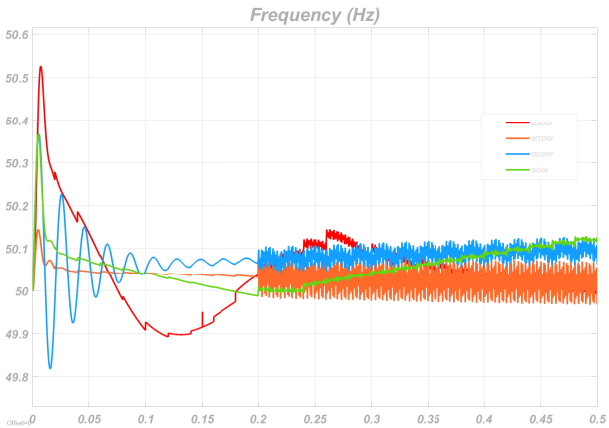
Fig. 4: Transient response comparison of every type of PLL



(a) Distorted grid voltages

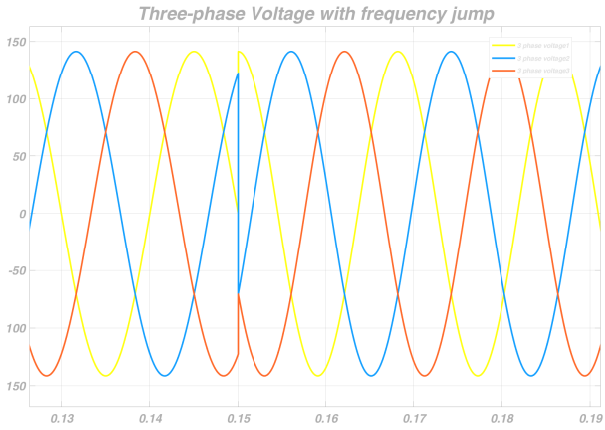


(b) q-component of instantaneous voltage

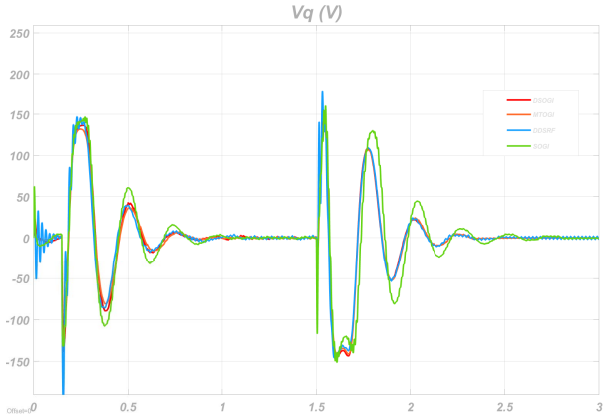


(c) Output frequency

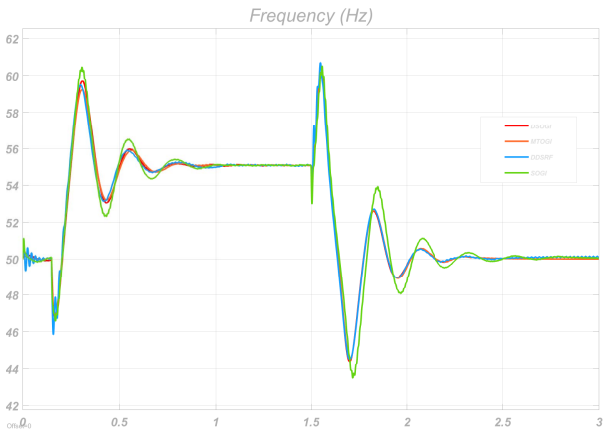
Fig. 5: Response when connecting with distorted grid



(a) Three-phase voltage with frequency jump

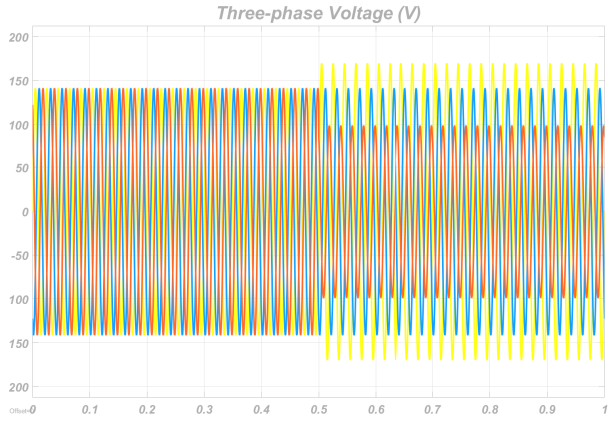


(b) q component of instantaneous voltage

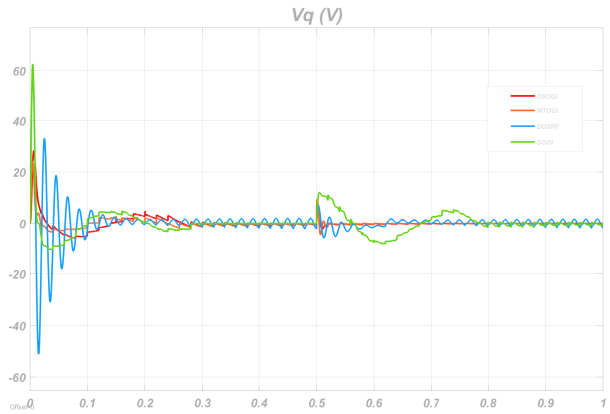


(c) Output Frequency

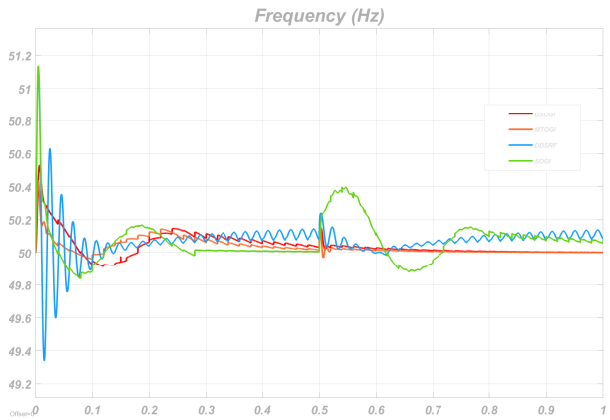
Fig. 6: PLL performance under frequency jump



(a) Three-phase grid voltage with amplitude jump



(b) q component of instantaneous voltage

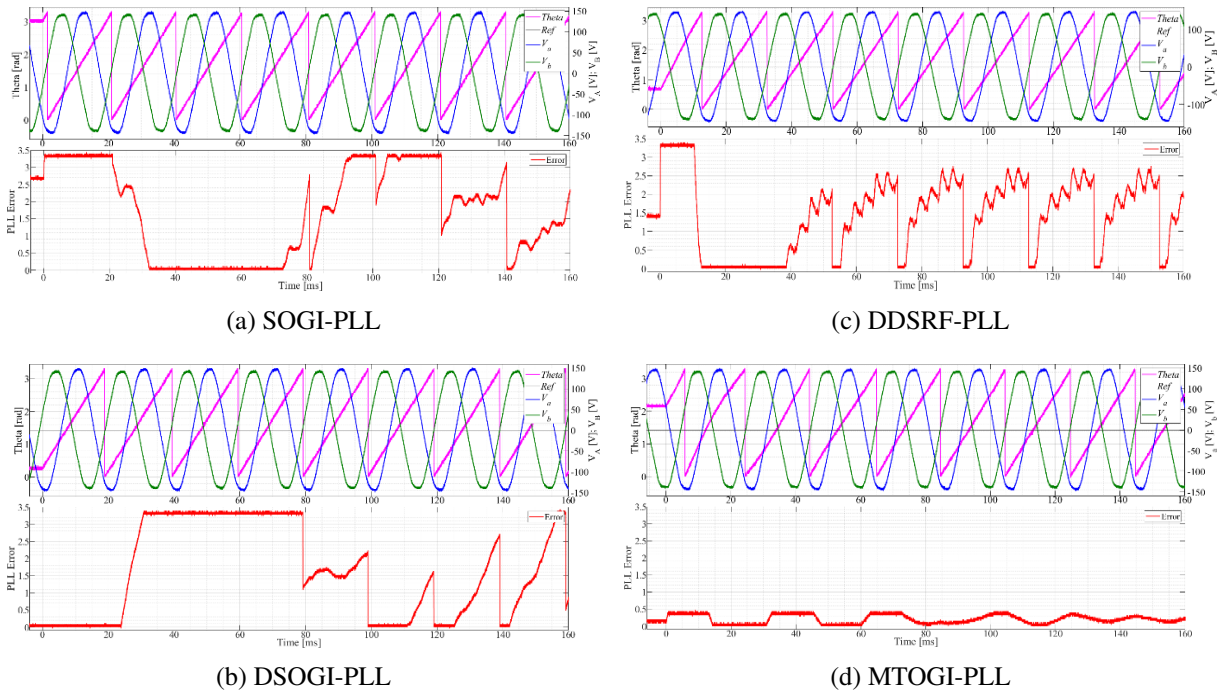


(c) Output Frequency

Fig. 7: PLL efficiency under amplitude and phase jump

circumstance that the overshoots of all PLL controllers are huge. It is necessary to identify and design the total system more precisely to have a very valuable development.
When the three-phase voltage has an amplitude jump at $t = 0.5s$ in Fig.7, the voltage of phase A boosts to $1.2V_m$ (V_m - peak value) and phase C declines to $0.7V_m$, MTOGI-PLL controller accomplishes extremely superb. MTOGI controller has the best performance (after a very short time it goes to the steady-state and lower overshoot). Therefore, MTOGI-PLL is absolutely suitable for the unbalanced and asymmetric condition grid.

Experimental Results



(a) SOGI-PLL

(c) DDSRF-PLL

(b) DSOGI-PLL

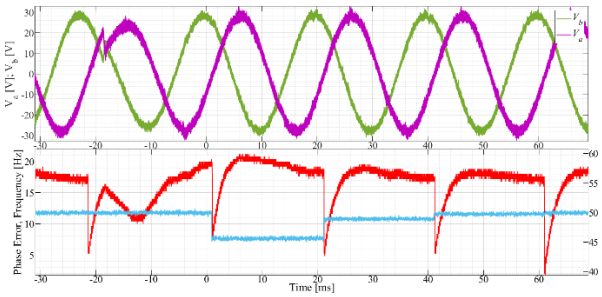
(d) MTOGI-PLL

Fig. 8: The transient response of the SOGI

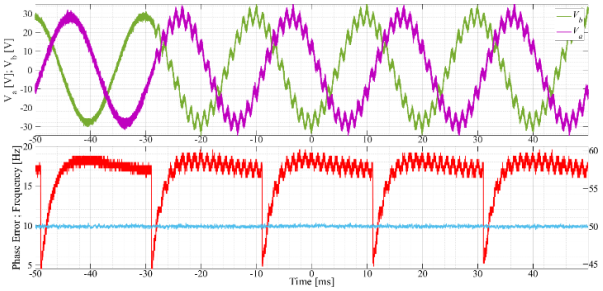
The proposed MTOGI PLL has been implemented on the experimental bench TMS320F28335 from TI that controlling a 7.5 kW grid-connected inverter and compared with the traditional PLLs for the balanced, distorted, and artificial unbalanced grid condition. Fig.8a and Fig.8b illustrate the transient response of the controller based on the SOGI and DSOGI-PLL respectively. The grid voltages V_a and V_b are depicted above with the controller error (red-line) below in Fig.8. It can be seen that the steady-state error in DSOGI is achieved in 100ms compared to the SOGI, which is around 140ms respectively. The PLL signal is synchronized in 3$\sim$4 cycles. Fig.8c and Fig.8d indicate the transient response of the controller based on the DDSRF and MTOGI-PLL respectively. The steady-state error of the controller in MTOGI is attained in 80ms where the DDSRF PLL takes 100ms. respectively The PLL signal is synchronized in around 1$\sim$2 cycle(s) in MTOGI where the DDSRF PLL takes 2$\sim$3 cycle(s). It can be noticed that the steady-state performance and dynamic response of the MTOGI are better than SOGI, DSOGI, and the DDSRF-PLL. Fig.9 presents the dynamic response of the MTOGI-based PLL for the (a) grid voltage amplitude and phase jump, where (b) outlines the frequency jump from 50Hz to 52Hz and (c) illustrates the distorted grid conditions. It can be observed that the dynamic response of the MTOGI shows superior performance under different grid conditions. The proposed MTOGI PLL has been implemented on a 7.5 kW grid-connected inverter and compared with the traditional PLLs for the balanced, distorted, and artificial unbalanced grid condition as shown in Fig.9d.

Conclusion

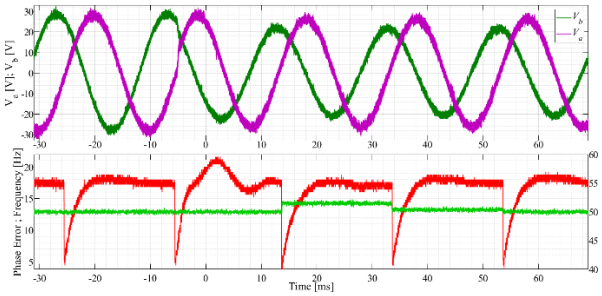
This paper proposes a novel MTOGI-PLL (Modified-Third Order Generalized Integrator PLL) for the balanced, unbalanced, and distorted grid conditions. The MTOGI-PLL has been compared with SOGI,



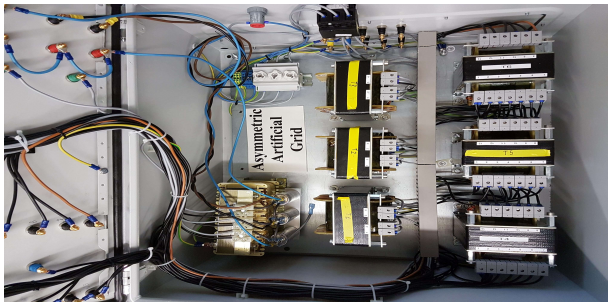
(a) amplitude and phase jump



(c) distorted grid condition



(b) frequency jump



(d) artificial unbalanced grid condition

Fig. 9: The dynamic response of the MTOGI

DSOGI, and DDSRF-PLL. The MTOGI based PLL is better in dynamic performance with faster locking of the fundamental frequency in $1 \sim 2$ cycle(s). Specially, the MTOGI-PLL is easy to implement, has no need for transformations, and has less computational burden. The simulation and experimental results verify the steady-state and dynamic performance of the proposed PLL for the unbalanced and distorted grid conditions.

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