A New Grid Synchronization Scheme for a Three Phase PV system employing Kalman Filtering

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Abstract—In this work, a new grid synchronization control strategy is developed for a single stage three phase grid coupled Photovoltaic (PV) system employing Kalman Filter Algorithm (KF) to estimate the fundamental sinusoidal components of the Point of common connection (PCC) voltage and load current respectively. The DC-link bus capacitor voltage is regulated employing a Proportional-Integral (PI) controller. KF effectively extracts the fundamental components by updating the Kalman gain such that it minimizes the estimation error variances. Simulation and experimental studies of the proposed KF-PI control strategy shows that it effectively extracts maximum PV power and mitigates load current harmonics reducing the Total Harmonic Distortion (THD) of the grid current and PCC voltage to a lower value which are within the limits presented by the IEEE 519 standards even distorted grid voltage condition.

Keywords—Photovoltaic (PV); Point of common connection (PCC); Kalman Filter (KF); Total Harmonic Distortion (THD).

I. INTRODUCTION

The Technological advancement in the stream of semiconductor devices have increased the efficiency of Photovoltaic (PV) modules with reduced cost [1]. From 2011-2013, PV modules cost has reduced by 60% and more than 40% reduction is forecasted by 2020 [2]. The reduced cost and environment friendly nature of PV module has given high impetus to inject PV power into the utility grid, to meet the increasing load demand.

Performance of the grid coupled PV system primarily depend on the effective control strategy adopted. So the control strategy for grid synchronization of PV system must be designed such that it extracts maximum PV power, injects active power into the grid, reactive power compensation and also mitigate load current harmonics so as to maintain the grid current sinusoidal in order to provide effective grid synchronization. Block diagram of a grid connected PV system is shown in Fig. 1. Local loads L_A and L_s are connected at PCC. Presence of nonlinear load L_A makes the grid current (i_P) distorted. i_P interacts with grid inductance (L_P) and makes the PCC voltage (v_P) distorted as given in eq (1)

\[ v_p = v_{pr} - L_P \frac{di_p}{dt} \]

(1)

where \( i_P = i_{1A} + i_{2A} - i_L \)

As \( v_P \) gets distorted it affect grid synchronization and further distorts other local loads connected at PCC.

Hence, to achieve effective grid synchronization it is essential to extract the fundamental current and voltage components of the distorted load current and the PCC voltage. The fundamental sinusoidal component of voltage or current are extracted conventional employing unit vector method, low-pass filter (LPF), positive sequence calculation and discrete Fourier transform (DFT). Conventional unit vector method [3] provides satisfactory steady-state performance but it yields incorrect reference currents under distorted grid voltage. A phase shift introduces in the output using LPF method [4] causing inaccurate compensation. In [5], the computation time more to determine the reference grid current which is evaluated by deriving the positive-sequence component of the unbalanced grid voltage and then extracting the fundamental component from it. DFT method [6] provides inaccurate estimate for variable grid frequency because of spectral leakage. Self-tuning filter (STF) has been applied with APFs [7] to improve PQ under distorted voltage conditions. Additional measurement noise at PCC voltage have not been considered to generate the reference current. In [8] Kalman filter based approach has been proposed for active power filters (APFs) to generate the reference current. Although KF has been used with APFs to improve PQ which provides excellent results. It is intended to extend the application of KF for a grid connected PV system under distorted grid voltage condition. In this work a KP-PI control scheme is proposed for a single stage three phase grid coupled PV system for effective grid synchronization. The contributions of the paper are as follows:

- Faster and accurate estimation of fundamental sinusoidal component of the distorted PCC voltage and the nonlinear

![Fig. 1. Block diagram of single stage grid coupled PV system with multiple loads connected at PCC](image-url)
load current using KF taking into account the measurement noise.

- Extraction of maximum PV power and simultaneously maintaining the grid current sinusoidal with unity power factor operation.
- Real time implementation of the proposed KF-PI scheme using dSPACE 1104.

This paper is prepared as follows. In Section 2, control strategy for grid connected PV system using KF-PI approach is presented. To authenticate the synchronization performance of the proposed KF-PI control approach, simulation and experimental study are performed using the developed prototype grid-connected PV system in Section 3. Finally, the paper is concluded in Section 4.

II. PROPOSED KF BASED CONTROL ALGORITHM GRID SYNCHRONIZATION OF PV SYSTEM

The basic configuration with the control strategy for the proposed single stage three phase grid coupled PV system is presented in Fig. 2. The proposed KF-PI control strategy is divided into three parts as:

A. Extraction of fundamental load currents:

A Kalman filter is a filter that minimize the mean square error of the states for a given state space system and perform well under noisy environment. It uses a linear regression method such that the estimation error variance for the states are minimized. The state space representation of a system is given as

\[ x_{k+1} = \Phi_k x_k + w_k \]  
\[ y_k = H_k x_k + v_k \]

where \(w_k\) is the process noise and \(v_k\) is the measurement noise. \(\Phi_k\) is the transition matrix and \(H_k\) is the observation matrix. Designating the estimate of \(x_{k+1}\) as \(\hat{x}_{k+1}\), the next estimate of the states are obtained using the following equations [9].

\[ \hat{x}_{k+1|k} = \Phi_k \hat{x}_{k|k-1} + K_k \left( y_k - H_k \hat{x}_{k|k-1} \right) \]  
\[ K_k = \Phi_k P_{k|k-1} H_k^T \left( H_k P_{k|k-1} H_k^T + R_k \right)^{-1} \]  
\[ P_{k+1|k} = \Phi_k P_{k|k-1} \Phi_k^T - K_k H_k P_{k|k-1} \Phi_k^T + Q_k \]

The Kalman gain \(K_k\) is updated such that it minimizes error variances i.e. each major diagonal terms of the error covariance matrix \(P_k, Q_k\) is the process error covariance matrix and \(R_k\) measurement error covariance matrix. The fundamental sinusoidal component of the nonlinear load current are estimated using the state space model of single sinusoid. Depending on the state model, the next state of the system is estimated. A single sinusoid signal \(z_k\) is represented as

\[ z_k = a_k \sin(k \omega T_s + \phi_k), \quad \omega_k = 2 \pi f_1, \quad k = 1, 2, 3, \ldots, N \]  

where \(N\) is a integer, \(T_s\) is the sampling time, parameters \(a_k\) and \(f_1\) are the fundamental amplitude and frequency respectively with initial phase \(\phi_k\). The orthogonal \(x_{1k}\) and the quadrature

![Fig.2. Block diagram of single stage three phase grid coupled PV system](image_url)
x₂ component of zₖ are represented as

\[ x₁ = aₖ \sin(k \omega Tₙ + \phi) \quad ; \quad x₂ = aₖ \cos(k \omega Tₙ + \phi) \] (8)

Hence \( x₁_{k+1} \) and \( x₂_{k+1} \) are given as

\[ x₁_{k+1} = x₁_k \cos(\alpha Tₙ) + x₂_k \sin(\alpha Tₙ) \] (9)

\[ x₂_{k+1} = -x₁_k \sin(\alpha Tₙ) + x₂_k \cos(\alpha Tₙ) \] (10)

Hence the values of \( \Phi_k \) and \( H_k \) in eq(2) and eq(3) are

\[ \Phi_k = \begin{bmatrix} \cos(\alpha Tₙ) & \sin(\alpha Tₙ) \\ -\sin(\alpha Tₙ) & \cos(\alpha Tₙ) \end{bmatrix}; H_k = [1 \quad 0] \] (11)

Using these estimates \( \hat{x}₁_{k-1} \) and \( \hat{x}₂_{k-1} \), the fundamental sinusoidal component of the load current are obtained as

\[ aₖ \sin(k \omega Tₙ + \phi) = \hat{x}₁_{k-1} \] (12)

### B. Estimation of unit vector:

To achieve effective grid synchronization under distorted grid voltage condition, accurate angular position of the PCC voltage is needed to be extracted for unity power factor operation (i.e. grid current is in phase with PCC voltage). The fundamental sinusoidal component of the PCC voltage \( \left( \overline{V}_{pa}, \overline{V}_{pb}, \overline{V}_{pc} \right) \) is extracted using KF algorithm. The quadrature-phase and in-phase unit vector templates of the fundamental PCC voltage are evaluated using eq (13) and eq (14) respectively.

\[ x_a = \frac{\overline{V}_{pa}}{V_E}; \quad x_b = \frac{\overline{V}_{pb}}{V_E}; \quad x_c = \frac{\overline{V}_{pc}}{V_E} \] (13)

\[ x_{a*} = -\frac{x_a}{\sqrt{3}} + \frac{x_b}{\sqrt{3}} + \frac{x_c}{\sqrt{3}}; \quad x_{b*} = \frac{x_a + \frac{x_b}{2} - x_c}{2 \sqrt{3}}; \quad x_{c*} = \frac{x_a - x_b}{2 \sqrt{3}} \] (14)

where \( V_E = \sqrt{\frac{2(\overline{V}_{pa}^2 + \overline{V}_{pb}^2 + \overline{V}_{pc}^2)}{3}} \)

### C. Estimation of Reference Grid Current:

The fundamental sinusoidal component of nonlinear load current \( (I_{ia}, I_{ib}, I_{ic}) \) are sampled and held at every zero crossing of the quadrature-phase unit vector templates of the PCC voltage \( (\overline{x}_{pa}, \overline{x}_{pb}, \overline{x}_{pc}) \) and its absolute value considered to evaluate the active current component of the nonlinear load current. Incremental conductance-based (Inc) maximum power point tracking (MPPT) is employed to track \( V_{mp} \) (voltage corresponding to maximum PV power), as it is simple, accurate, fast and feasible to practice in practical situation [10]. The capacitor voltage \( V_{dc} \) of VSI regulated using a PI controller, such that it follows \( V_{dc^*} \). \( I \) accounts for the switching loss in VSI and DC-link capacitor leakage loss, minus the real PV power extracted from PV array.

\[ I_s = K_{pV} V_{dc} + K_{dV} \int V_{dc} dt \] (20)

where \( V_{dc} = V_{dc^*} - V_d \).

The amplitude of the active reference grid current per phase per phase are given as:

\[ I_p = \frac{(I_s + I_a + I_b + I_c)}{3} \] (21)

The reference grid currents \( [i_{pa}^*, i_{pb}^*, i_{pc}^*] \) are then obtained by multiplication of \( I_p \) with in-phase unit vector template \( \left[ x_{a*}, x_{b*}, x_{c*} \right] \) as:

\[ i_{pa} = I_p \cdot x_{a*}; \quad i_{pb} = I_p \cdot x_{b*}; \quad i_{pc} = I_p \cdot x_{c*} \] (22)

Hysteresis band current controller is employed such that the actual grid current tracks the reference grid current.

### III. RESULTS AND DISCUSSION

To analyze the synchronization performance of the proposed KF-PI based control scheme for grid synchronization, simulation and experimental studies have been pursued using MATLAB/Simulink and dSPACE 1104 respectively in the following subsections.

#### A. Simulation Results

Simulink model of a single-stage three phase grid coupled PV system using the proposed KF-PI approach has been developed and results obtained are shown in Fig.3. For realizing a distorted grid condition, 3rd and 5th order voltage harmonics are introduced into the grid. A local nonlinear load connected at PCC comprises of an uncontrolled rectifier and series RL load in DC side. The load current and the grid voltage are both non-sinusoidal due to the presence of harmonics. All the parameters required for modelling the PV module are the same as used in [12]. A 5 kW PV array is used which consists of 26 PV modules, with irradiation of 700 W/m². The maximum Power Point (MPP) is at \( V_{mp} = 678.5 \text{ V} \) and \( P_{max} = 3.395 \text{ kW} \). The open circuit voltage is 840 V and short circuit current is 5.75 A. All the parameter for simulation study are given in Appendix I.

The responses after compensation using the proposed KF based approach are presented in Fig. 3. The control action is provided at time \( t = 0.3 \text{ s} \). The grid current \( (i_{pa}) \) reaches steady state at around time \( t = 0.35 \text{ s} \), and is almost sinusoidal with reduced harmonic content. InC based MPPT tracks the MPP and using the PI controller, Dc-link capacitor bus voltage \( (V_{dc}) \) is maintained constant at \( V_{mp} \) such that maximum PV power is
obtained. The nonlinear load of 1.6 kW is entirely fed from the PV array and the remaining PV power minus the losses in the system is sunk into the utility grid. Negative value of grid active power signifies that the surplus PV power is being injected into the utility grid. The FFT analysis of the PCC voltage ($v_{p}$) and grid current ($i_{g}$) using KF-PI control approaches are presented in Table 1. THD of the uncompensated $v_{g}$ and $i_{g}$ are 5.95% and 26.90% respectively. After compensation using KF-PI control approach the THD of $v_{g}$ and $i_{g}$ reduced to 2.82% and 3.72% respectively.

**B. Experimental Results**

The prototype of a three phase grid coupled single stage PV system is shown in Fig. 4 (a). A 600W, Agilent made solar array simulator (E4360A) is used as virtual PV array. The VSI is made up of three number of IGBT modules with two numbers of 4700 µF/450 V capacitors. The local nonlinear load consists of an uncontrolled rectifier and series RL load in DC side. dSPACE 1104 is employed to run the proposed KF-PI based control scheme in real-time. Hall Effect current sensor (LEM LA 55-P) and voltage sensor (LEM LV 25-P) are used to sense the three phase current and voltage signals that are necessary for generating the PWM signal. Control Desk developer version 3.5 is used to debug the proposed KF-PI based control scheme developed in Simulink into dSPACE 1104. The parameters used for the experimental study are presented in Appendix II. Fig. 4(b) shows MPP tracking performance obtained by using InC MPPT. The operating point is shifted to the MPP thus extracting maximum PV power which is 355.86 W.

Fig. 5(a) show the grid current waveforms after compensation using KF-PI control approach. The grid current waveform obtained after compensation using KF-PI are found to be sinusoidal with reduced harmonic content. The active power analysis of grid power and inverter power using KF-PI control scheme are shown in Fig. 5(c-d) respectively. Nonlinear load of 0.154 kW with 0.93 pf connected at PCC is entirely fed from PV array and the remaining PV power is sunk into the grid. Negative value of grid power signifies that the excess PV power is being injected into the utility grid at unity power factor. As the reactive power of the grid is almost

![Fig. 3. Waveforms after compensation using Kalman Filter under distorted grid voltage condition. [PCC voltage ($v_{p}$), Grid current ($i_{g}$), DC-link capacitor voltage ($V_{dc}$), Inverter active power ($P_{i}$), Grid active power ($P_{g}$)]](image)

![Table 1 FFT analysis of PCC Voltage and Grid Current](image)

![Fig. 4. (a) Experimental Set-Up of a single stage three phase Grid coupled PV system, (b) Power-Voltage and Current-Voltage Curves of PV array with InC MPPT performance](image)
zero i.e. the power is injected into grid at with unity power factor. FFT study of the grid current after compensation using KF-PI are shown in Fig. 5(b). THD of the grid current is reduced to a lower value of 3.8%.

CONCLUSIONS

In this work a KF-PI control strategy is developed for a single stage three phase grid coupled PV system. From the presented simulation and experimental studies, it is verified that the proposed KF-PI based control scheme provides effective grid synchronization of PV system i.e. extracting maximum PV power, active and reactive power compensation and also mitigates load current harmonics. KF accurately extracts the fundamental voltage and current component of the distorted PCC voltage and the nonlinear load current. The grid current becomes sinusoidal with reduced harmonic content and is in phase with the PCC voltage thus guaranteeing unity power factor operation. InC-based MPPT technique effectively tracks the MPP i.e. estimating the reference DC-link voltage corresponding to maximum PV power. The maximum PV Power is extracted by regulating the DC-link voltage using a PI controller, which effectively tracks the estimated reference value. The FFT analysis shows that by using the KF control approach, the grid current THD is reduced to 3.8% which are well with limits presented by the IEEE 519 standards.

REFERENCES


APPENDIX I

Simulation Parameters: PV array Power ($P_{pv}$) = 5 kW, Grid Voltage ($v_g$) = 230 V, System Frequency ($f$) = 50Hz, Load Impedance ($R_L$) = 200 $\Omega$, ($L_L$) = 25 mH, Grid Impedance: $R_g = 0.1$ $\Omega$, ($L_g$) = 1 mH, DC-link Capacitance ($C_{dc}$) = 1300 $\mu$F, Filter Impedance: $R_f = 0.1$ $\Omega$, ($L_f$) = 13 mH, Switching frequency ($f_s$) = 20 kHz, Proportional and Integral Gain to regulate Vdc: ($k_{pi}$) = 0.231, ($k_{pi}$) = 3.267. Process error covariance matrix ($Q_k$) = $[10$ $0$ $0$]. Measurement error covariance matrix ($R_k$) = 1.5, Initial error covariance matrix ($P_0$) = $[10$ $0$ $0$ $]$. Initial state variables ($x_0$) = $[1$ $0$ $0$ $1]$.

APPENDIX II

Experimental Parameters: PV array Power ($P_{pv}$) = 350 W, Grid Voltage ($v_g$) = 40 V, System Frequency ($f$) = 50Hz, Load Impedance ($R_L$) = 10 $\Omega$, ($L_L$) = 20 mH, Grid Impedance: ($R_g$) = 0.1 $\Omega$, ($L_g$) = 2 mH, DC-link Capacitance ($C_{dc}$) = 2350 $\mu$F, Filter Impedance: ($R_f$) = 0.1 $\Omega$, ($L_f$) = 10 mH, Switching frequency ($f_s$) = 20 kHz, Proportional and Integral Gain to regulate Vdc: ($K_{pi}$) = 0.417, ($K_{pi}$) = 5.906.