Dynamic Stability of Three-Phase Grid-Connected Photovoltaic System Using Zero Dynamic Design Approach

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Dynamic Stability of Three-Phase Grid-Connected Photovoltaic System using Zero Dynamic Design Approach

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***Abstract*—This paper presents a new approach to control the grid current and dc link voltage to maximum power point tracking (MPPT) and dynamic stability of a three-phase grid-connected photovoltaic (PV) system. To control the grid current and dc link voltage, zero dynamic design approach of feedback linearization is used which linearizes the system partially and enables to design controller for reduced order photovoltaic systems. This paper also describes the zero dynamic stability of three-phase grid-connected PV system which is a key requirement for the implementation of such controller. Simulation results on a large-scale grid-connected PV system show the effectiveness of the proposed control scheme in terms of delivering maximum power into the grid.**

***Index Terms*—Dynamic stability, grid-connected PV system, maximum power point, zero dynamic controller**

I. Introduction

Due to global concern on climate change and sustainable electrical power supply, renewable energy is increasingly getting popular in the developed countries. Among different sources of renewable energy, PV system is a promising energy source in the recent years as PV installations are increasing due to their environment friendly operation [1]. Grid-connected PV system has gained popularity due to the feed-in-tariff and the reduction of battery cost. However, the intermittent PV generation varies with the change in atmospheric conditions. Maximum power point tacking (MPPT) techniques [2] are used to deliver maximum power into the grid. Efficient and advanced control schemes are essential to ensure maximum power output of a PV system at different operating conditions.

Implementation of proper controllers on a grid-connected PV system maintain the stable operation under disturbances like the change in atmospheric conditions, change in load demands, or an external fault within the system. This can be done by regulating the switching signal through the inverter, i.e., if a proper controller is applied through the inverter of the system, then the desired performances will be obtained. A number of techniques are available in the literature for designing the MPPT [3]. Perturb and observe (PO) [4], and incremental conductance method are commonly used techniques in the area of photovoltaic systems. In the PO method, the derivative of power (dp) and the derivative of voltage (dv) need to be measured to determine the movement of operating point. If the ratio of dp and dv is positive, the reference voltage is increased by a certain amount and vice versa [5]. A similar approach is followed for incremental conductance method by comparing incremental conductance and instantaneous conductance of the PV arrays [6].

The importance of DC voltage control for a grid-connected PV system can be found in [7]. In [7] a model prediction based voltage controller is proposed to improve the reliability and lifetime of the inverter and to enhance performance of the MPPT through the reduction of DC link capacitance. Recently, an improved MPPT based on voltage-oriented control is proposed in [8] by using a proportional-integral (PI) controller in the outer DC link voltage loop.

Current controllers are used to maintain stable operation of a grid-connected PV system as they can regulate the current to follow the reference current. There are several techniques to control the current such as PI controller, hysteresis controller, predictive controller, sliding mode controller, and so on. In [9], PI current control scheme is proposed to keep the output current sinusoidal and to have fast dynamic responses under rapidly changing atmospheric condition and to maintain the power factor at unity. The difficulty of using a PI controller is to tune the gain with the change in atmospheric conditions. The hysteresis controller as proposed in [10] has fast response by varying switching frequency. The predictive controller [11] overcomes the limitation of hysteresis controller as it has constant switching frequency but the main problem associated with this controller is that it cannot properly match with the existing problems related to the change in environmental factors.

Grid-connected PV systems are highly nonlinear systems where most of the nonlinearities occur due to the intermittency of the sunlight, the switching functions of the converters and inverters. The dynamic stability of a grid-connected PV system is analyzed in [12], [13] based on the eigenvalue analysis. In [12], [13], no controller is proposed to enhance the stability of PV system. However, the controllers proposed in [8-12] are mainly designed based on the linearized model of photovoltaic system which can provide satisfactory operation for a predefined set of changes. To ensure the operation of grid-connected photovoltaic systems over a wide range of operating points, the design and implementation of a nonlinear controller is important.

A sliding mode current controller for a three-phase grid-

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connected PV system is proposed in [14], [15] along with a new MPPT technique to provide robust tracking against the uncertainties within the system. In [14], [15], the controller is designed based on a time-varying sliding surface. However, the selection of a time-varying surface is difficult without prior knowledge of the system.

Exact linearization which is a straightforward way to design nonlinear controllers, transforms a nonlinear system into a fully linear system [16], [17] by canceling the inherent nonlinearities within the system. This linearization technique is independent of the operating point. Exact feedback linearization of grid-connected PV system is proposed in [18], [19] to enhance the dynamic stability. The control scheme proposed in [18], [19] is independent of environmental changes. However, in these papers [18], [19], the input DC current to the inverter is expressed in terms of the input and output power relation of the inverter to make the system exactly linearizable rather than using the nonlinear switching functions. Moreover, the inverter is considered as ideal and the resistances within the lines connected to the grid are neglected in [18], [19] and the calculation of reference values for the linear controllers are not discussed. But if the dynamics of the DC link capacitor are expressed in terms of switching function of the inverter, more accurate results can be obtained. In this case, the grid-connected photovoltaic system will be partially linearized rather than fully linearized. When the system is partially linearized, exact linearization is no more applicable.

Zero dynamic design approach of feedback linearization algebraically transforms nonlinear system dynamics into a partly linear one which is a reduced order linear system independent of operating points. Finally, linear controller can be designed for the reduced order system. Zero dynamic design approach also introduces the internal dynamics of the photovoltaic system which should be stable. Therefore, it is essential to ensure the stability of the internal dynamics before implementing zero dynamic design approach on a grid-connected photovoltaic system.

The aim of this paper is to design a new controller through zero dynamic design approach to control the DC link voltage and grid current using similar control algorithm. The partial linearizability of grid-connected photovoltaic systems are discussed along with the stability of internal dynamics of the systems. Finally, the stability of the system with the proposed control scheme is investigated by considering the environmental changes.

The rest of the paper is organized as follows. The mathematical model of a three-phase grid-connected PV system is shown in Section II. Section III presents the partial linearizability of PV system to prove the suitability of the proposed model for zero dynamic design approach. The controller design for a three-phase grid-connected photovoltaic system is shown in Section IV and relation of MPPT with the proposed control scheme is shown in Section V. Section VI shows the simulation results with the proposed controller under different circumstances. Finally, the paper is concluded with future trends and further recommendations in Section VII.

II. PV System Model

The schematic diagram of a three-phase grid-connected PV system which is main focus of this paper is shown in Fig. 1. The considered PV system consists of a PV array, a DC link capacitor C, a three-phase inverter, a filter inductor L and connected to the grid with voltage e_a, e_b, e_c. In this paper, the main target is to control the voltage v_{dc} across the capacitor C and to make the input current in phase with grid voltage for unity power factor by means of appropriate control signals through the switches of the inverter. The mathematical model of the system is presented in the next subsections.

A. PV Cell and Array Modeling

PV cell is a simple p-n junction diode which converts the irradiation into electricity. Fig. 2 shows an equivalent circuit diagram of a PV cell which consists of a light generated current source I_L, a parallel diode, shunt resistance R_{sh} and series resistance R_s. In Fig. 2, I_{ON} is the diode current which can be written as:

$$I_{ON} = I_s \left[\exp\left[\alpha\left(v_{pv} + R_s i_{pv}\right)\right] - 1\right] \quad (1)$$

where $\alpha = \frac{q}{AkT_C}$, $k = 1.3807 \times 10^{-23}\ JK^{-1}$ is the Boltzmann's constant, $q = 1.6022 \times 10^{-19}$ C is the charge of electron, T_C is the cell's absolute working temperature in Kelvin, A is the p-n junction ideality factor whose value is between 1 and 5, I_s is the saturation current, and v_{pv} is the output voltage of PV array which in this case is the voltage across C, i.e., v_{dc}. Now, by applying Kirchhoff's Current Law (KCL) in Fig. 1, the output current (i_{pv}) generated by PV cell can be written as,

$$i_{pv} = I_L - I_s \left[\exp\left[\alpha\left(v_{pv} + R_s i_{pv}\right)\right] - 1\right] - \frac{v_{pv} + R_s i_{pv}}{R_{sh}} \quad (2)$$

The light generated current I_L depends on the solar irradiation which can be related by the following equation:

$$I_L = \left[I_{sc} + k_i (T_C - T_{ref})\right] \frac{s}{1000} \quad (3)$$

where, I_{sc} is the short circuit current, s is the solar irradiation, k_i is the cell's short circuit current coefficient and T_{ref} is the reference temperature of the cell. The cell's saturation current I_s varies with the temperature according to the following equation [19]:

$$I_s = I_{RS} \left[\frac{T_C}{T_{ref}}\right]^3 \exp\left[\frac{qE_g}{Ak}\left(\frac{1}{T_{ref}} - \frac{1}{T_C}\right)\right] \quad (4)$$

where, E_g is the band-gap energy of the semiconductor used in the cell and I_{RS} is the reverse saturation current of the cell at reference temperature and solar irradiation.

Since the output voltage of PV cell is very low, a number of PV cells are connected together in series in order to obtain higher voltages. A number of PV cells are put together and encapsulated with glass, plastic, and other transparent materials to protect from harsh environment, to form a PV module. To obtain the required voltage and power, a number of modules are connected in parallel to form a PV array. Fig. 3 shows an electrical equivalent circuit diagram of a PV array

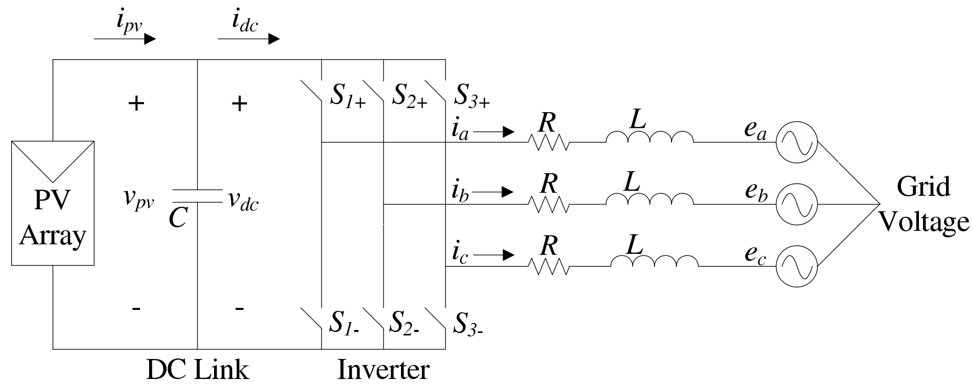

Fig. 1. Three-phase grid-connected PV system [15]

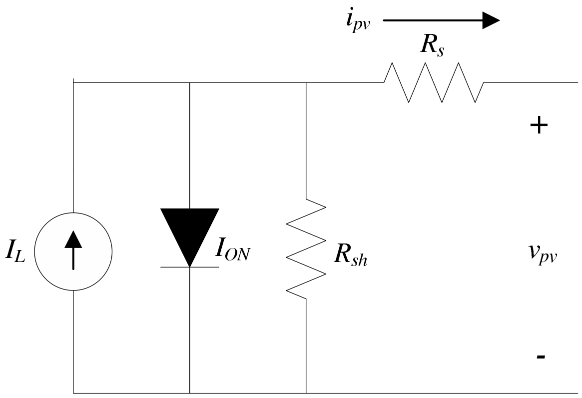

Fig. 2. Equivalent circuit diagram of PV cell [15]

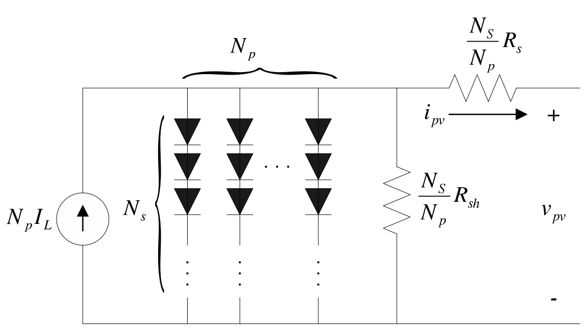

Fig. 3. Equivalent circuit diagram of PV array [15]

where N_s is the number of cells in series and N_p is the number of modules in parallel. In this case, the the array i_{pv} can be written as

$$\begin{aligned} i_{pv} = N_pI_L - N_pI_s\left[exp\left[\alpha\left(\frac{v_{pv}}{N_s} + \frac{R_si_{pv}}{N_p}\right)\right] - 1\right] \\ - \frac{N_p}{R_{sh}}\left(\frac{v_{pv}}{N_s} + \frac{R_si_{pv}}{N_p}\right) \end{aligned} \tag{5}$$

B. Three-Phase Grid-Connected PV System Modeling

For a control scheme to be effective for three-phase grid-connected PV system, some details of the system is essential. The details of any system can best be described by the mathematical model. In state-space form, Fig. 1 can be represented by the following equations [19], [20]:

$$\begin{aligned} \dot{i}_a &= -\frac{R}{L}i_a - \frac{1}{L}e_a + \frac{v_{pv}}{3L}(2K_a - K_b - K_c) \\ \dot{i}_b &= -\frac{R}{L}i_b - \frac{1}{L}e_b + \frac{v_{pv}}{3L}(-K_a + 2K_b - K_c) \\ \dot{i}_c &= -\frac{R}{L}i_c - \frac{1}{L}e_c + \frac{v_{pv}}{3L}(-K_a - K_b + 2K_c) \end{aligned} \tag{6}$$

where, K_a, K_b, and K_c are the input switching signals. Now, by applying KCL at the node where DC link is connected, we get

$$\dot{v}_{pv} = \tfrac{1}{C}\left(i_{pv} - i_{dc}\right) \tag{7}$$

But the input current of the inverter i_{dc} can be written as [15], [20]

$$i_{dc} = i_aK_a + i_bK_b + i_cK_c \tag{8}$$

which yields

$$\dot{v}_{pv} = \tfrac{1}{C}i_{pv} - \tfrac{1}{C}\left(i_aK_a + i_bK_b + i_cK_c\right) \tag{9}$$

The complete model of a three-phase grid-connected PV can be presented by equation (6) and (9) which are nonlinear and time variant. This time variant model can be converted into time invariant model by applying dq transformation [15] using the angular frequency ω of the grid, rotating reference frame synchronized with grid where the d component of the grid voltage E_d is zero [15], [19]. By using dq transformation, equation (6) and (9) can be written as

$$\begin{aligned} \dot{I}_d &= -\frac{R}{L}I_d + \omega I_q - \frac{E_d}{L} + \frac{v_{pv}}{L}K_d \\ \dot{I}_q &= -\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} + \frac{v_{pv}}{L}K_q \\ \dot{v}_{pv} &= \frac{1}{C}i_{pv} - \frac{1}{C}I_dK_d - \frac{1}{C}I_qK_q \end{aligned} \tag{10}$$

Equation (10) represents the complete mathematical model of the three-phase grid-connected PV system which is non-linear due to the switching functions and diode current. In equation (10), K_d and K_q are the control inputs and the output variables are I_q and v_{pv}. Since $E_d = 0$, the real power delivered to the grid can be written as

$$P = \frac{3}{2}E_qI_q \tag{11}$$

From the above equation, it is clear that by controlling I_q the active power P can be controlled.

III. Partial Feedback Linearization and Partial Linearizability of PV System

The mathematical model of three-phase grid-connected PV system can be expressed as the following form of multi-input multi-output (MIMO) nonlinear system:

$$\begin{aligned} \dot{x} &= f(x) + g_1(x)u_1 + g_2(x)u_2 \\ y_1 &= h_1(x) \\ y_2 &= h_2(x) \end{aligned} \tag{12}$$

where

$$x = \begin{bmatrix} I_d & I_q & v_{pv} \end{bmatrix}^T$$

$$f(x) = \begin{bmatrix} -\frac{R}{L}I_d + \omega I_q - \frac{E_d}{L} \\ -\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} \\ \frac{1}{C}i_{pv} \end{bmatrix}$$

$$g(x) = \begin{bmatrix} \frac{v_{pv}}{L} & 0 \\ 0 & \frac{v_{pv}}{L} \\ -\frac{I_d}{C} & -\frac{I_q}{C} \end{bmatrix}$$

$$u = \begin{bmatrix} K_d & K_q \end{bmatrix}^T$$

and

$$y = \begin{bmatrix} I_q & v_{pv} \end{bmatrix}^T$$

Consider, the following nonlinear coordinate transformation

$$z = [h_1 \quad L_f h_1 \cdots L_f^{r_1-1}h_1 \quad h_2 \quad L_f h_2 \cdots L_f^{r_2-1}h_2]^T \tag{13}$$

where, $L_f h_1(x) = \frac{\partial h_1}{\partial x} f(x)$ and $L_f h_2(x) = \frac{\partial h_2}{\partial x} f(x)$ are the Lie derivative [16] of $h_1(x)$ and $h_2(x)$ along $f(x)$, respectively. The above transformation transforms the nonlinear system (12) with state vector x into a linear dynamic system with state vector z, described as

$$\dot{z} = Az + Bv \tag{14}$$

provided that the following conditions

$$\begin{aligned} L_{g_1} L_f^k h_i(x) = 0 \\ L_{g_2} L_f^k h_i(x) = 0 \end{aligned} \tag{15}$$

where,$i = 1,\ 2,\ k < r_i - 1$ and

$$\begin{aligned} L_{g_1} L_f^{r_i-1} h_i(x) \neq 0 \\ L_{g_2} L_f^{r_i-1} h_i(x) \neq 0 \end{aligned} \tag{16}$$

are satisfied and $n = r_1 + r_2$ where r_1 and r_2 are the relative degree [16] of the system corresponding to output function $h_1(x)$ and $h_2(x)$, respectively. If these conditions are satisfied, the linear controller can be design for the linearized system (14) by using any linear controller design technique.

When $(r_1 + r_2) < n$, then we can do only partial linearization and this case, the transformed states z can be written as

$$z = \phi(x) = [\widetilde{z} \quad \hat{z}]^T \tag{17}$$

where, $\widetilde{z}$ represents the states obtained from nonlinear coordinate transformation up to the order $r_1 + r_2$ and $\hat{z}$ represents the states related to the remaining $n - (r_1 + r_2)$ order. The dynamics of $\hat{z}$ is called the internal dynamics whose stability need to be ensured before designing the linear controller for the following partially linearized system.

$$\dot{\widetilde{z}} = \widetilde{A}\widetilde{z} + \widetilde{B}\widetilde{v} \tag{18}$$

Now, the partial linearizability of the PV system represented in the form (12) can be obtained by calculating relative degree corresponding to the output functions. The relative degree corresponding to $h_1(x) = I_q$ can be calculated as

$$L_g h_1(x) = L_g L_f^{1-1} h_1(x) = \frac{v_{pv}}{L} K_q \tag{19}$$

where $r_1 = 1$. Similarly, the relative degree corresponding to $h_2(x) = v_{pv}$ can be calculated as follows:

$$L_g h_2(x) = -\frac{1}{C}(I_d K_d + I_q K_q) \neq 0 \tag{20}$$

which indicates $r_2 = 1$. Therefore, $r_1 + r_2 = 2$ which means that $(r_1 + r_2) < n$ as $n = 3$. Therefore, the system is partially linearized and exact linearizing controller is not possible for such system. In this case, the only way to implement feedback linearizing control is to implement the zero dynamic design approach provided that the zero dynamic of the system is stable which is shown in the following section.

IV. Controller Design

This section presents the controller design algorithm for a three-phase grid-connected PV system using the zero dynamic design approach as the system is partially linearized. The following steps needs to be followed to obtain the control law through zero dynamic design approach:

Step 1: Nonlinear coordinate transformation and formulation of partial linear system from state x to z

A nonlinear coordinate transformation can be written as:

$$\widetilde{z} \quad = \quad \widetilde{\phi}(x) \tag{21}$$

where, $\widetilde{\phi}$ is the function of x. For a three-phase grid-connected photovoltaic system, we choose

$$\widetilde{z}_1 = \widetilde{\phi}_1(x) = h_1(x) = I_q \tag{22}$$

and

$$\widetilde{z}_2 = \widetilde{\phi}_2(x) = h_2(x) = v_{pv} \tag{23}$$

Using the above transformation, the partially linearized system can be obtained as follows:

$$\begin{aligned} \dot{\widetilde{z}}_1 = \quad & \frac{\partial h_1(x)}{\partial x}\dot{x} = L_f h_1(x) + L_{g_1}h_1(x)u_1 + L_{g_2}h_1(x)u_2 \\ \dot{\widetilde{z}}_2 = \quad & \frac{\partial h_2(x)}{\partial x}\dot{x} = L_f h_2(x) + L_{g_1}h_2(x)u_1 + L_{g_2}h_2(x)u_2 \end{aligned} \tag{24}$$

For the photovoltaic system considered in this research, equation (24) can be rewritten as:

$$\begin{aligned} \dot{\widetilde{z}}_1 = \quad & -\omega I_d - \frac{R}{L}I_q - \frac{E_q}{L} + \frac{v_{pv}}{L}K_q \\ \dot{\widetilde{z}}_2 = \quad & \frac{1}{C}i_{pv} - \frac{1}{C}I_d K_d - \frac{1}{C}I_q K_q \end{aligned} \tag{25}$$

The above system can be written as the following linearized form:

$$\dot{\hat{z}}_1 = v_1 \quad \dot{\hat{z}}_2 = v_2 \tag{26}$$

where v_1 and v_2 are the linear control inputs expressed as

$$\begin{aligned} v_1 &= -\omega I_d - \frac{R}{L} I_q - \frac{E_q}{L} + \frac{v_{pv}}{L} K_q \\ v_2 &= \frac{1}{C} i_{pv} - \frac{1}{C} I_d K_d - \frac{1}{C} I_q K_q \end{aligned} \tag{27}$$

and which can be obtained by using a linear control techniques for the system (26). But before designing and implementing controller through zero dynamic design approach, it is essential to check the stability of zero dynamics which is presented in the next step.

Step 2: Zero dynamic stability of Grid-Connected PV system

In the previous step, the third-order PV system is transformed into a second order system which represents the external dynamics of the system. These external dynamics need both stability and good performance which can be obtained through the designed controller. To do this, the control law needs to be chosen in such a way that

$$\lim_{t\to\infty} h_i(x) \to 0$$

which implies $[z_1 \quad z_2 \cdots \quad z_r]^T = 0$ [16]. For the PV system considered in this work, this means that $z_1 = z_2 = 0$ which indicates

$$\dot{\hat{z}}_1 = 0 \quad \dot{\hat{z}}_2 = 0 \tag{28}$$

The remaining first order system needs to be determined to obtain the zero dynamics of the system for which it is essential to find out the rest state. Let, the remaining state is $\hat{z}_3 = \hat{\phi}(x)$. This needs to be selected in such a way that it must satisfy the following conditions [21]:

$$L_{g_1}\hat{\phi}(x) = 0 \quad L_{g_2}\hat{\phi}(x) = 0 \tag{29}$$

For a three-phase grid-connected PV system, equation (29) will be satisfied if we chose

$$\hat{\phi}(x) = \hat{z}_3 = \frac{1}{2} L I_d^2 + \frac{1}{2} L I_q^2 + \frac{1}{2} C v_{pv}^2 \tag{30}$$

By using $z_1 = I_q$ and $z_2 = v_{pv}$, equation (30) can be written as:

$$I_d^2 = \frac{2}{L}\hat{z}_3 - z_1^2 - \frac{C}{L} z_2^2 \tag{31}$$

Thus, the remaining dynamics of the system can be obtained as follows:

$$\dot{\hat{z}}_3 = L_f\hat{\phi}(x) = L I_d f_1 + L z_1 f_2 + C z_2 f_3 \tag{32}$$

For $z_1 = z_2 = 0$, equation (32) can be simplified as:

$$\dot{z}_3 = L I_d \left(-\frac{R}{L} I_d + \omega I_q - \frac{E_d}{L} \right) \tag{33}$$

Since $I_q = z_1 = 0$ and $E_d = 0$, equation (33) can be written as:

$$\dot{\hat{z}}_3 = -R I_d^2 \tag{34}$$

Substituting the value of I_d^2 from (31) into (34), it can be written as:

$$\dot{\hat{z}}_3 = -R \left(\frac{2}{L}\hat{z}_3 - z_1^2 - \frac{C}{L} z_2^2 \right) \tag{35}$$

Again, if we use $z_1 = z_2 = 0$, equation (35) can be written as

$$\dot{\hat{z}}_3 = -\frac{2R}{L}\hat{z}_3 \tag{36}$$

Equation (36) is the zero dynamic equation of the three-phase grid-connected photovoltaic system which is stable. Therefore, zero dynamic design approach can be implemented for three-phase grid-connected photovoltaic system. It is clear that the zero dynamic design approach divides the dynamics of a nonlinear system into two parts: one is external dynamics which needs both stability and good performance; and the other is internal dynamics which needs stability only. The derivation of the proposed control law is shown in the following steps.

Step 3: Derivation of Control Law for a Grid-Connected PV system

Using equation (25) and (26), the control law can be obtained as follows:

$$\begin{aligned} K_d &= \frac{L}{v_{pv}} \left(v_1 + \omega I_d + \frac{R}{L} I_q + \frac{E_q}{L} \right) \\ K_q &= -\frac{C}{I_q} \left[v_2 + \frac{i_{pv}}{C} - \frac{L I_d}{C v_{pv}} \left(v_1 + \omega I_d + \frac{R}{L} I_q + \frac{E_q}{L} \right) \right] \end{aligned} \tag{37}$$

Equation (37) is the final control law for a grid connected photovoltaic system. At this point, the only thing which needs to be designed is the new linear control input v_1 and v_2 by using any linear controller design technique. In this paper, proportional-integral (PI) controllers are used to track the reference outputs I_{qref} and v_{pvref}. Following two PI controllers are considered to track the output,

$$\begin{aligned} v_1 &= k_{1p}(I_{qref} - I_q) + k_{1i} \int_0^t (I_{qref} - I_q) dt \\ v_2 &= k_{2p}(v_{pvref} - v_{pv}) + k_{2i} \int_0^t (v_{pvref} - v_{pv}) dt \end{aligned} \tag{38}$$

Here, the gains need to be selected in such a way that the output follows the reference current to minimize the error. In this paper, the gains are considered as follows:

$$k_{1p} = 2 I_{qref}, \quad k_{1i} = I_{qref}^2$$

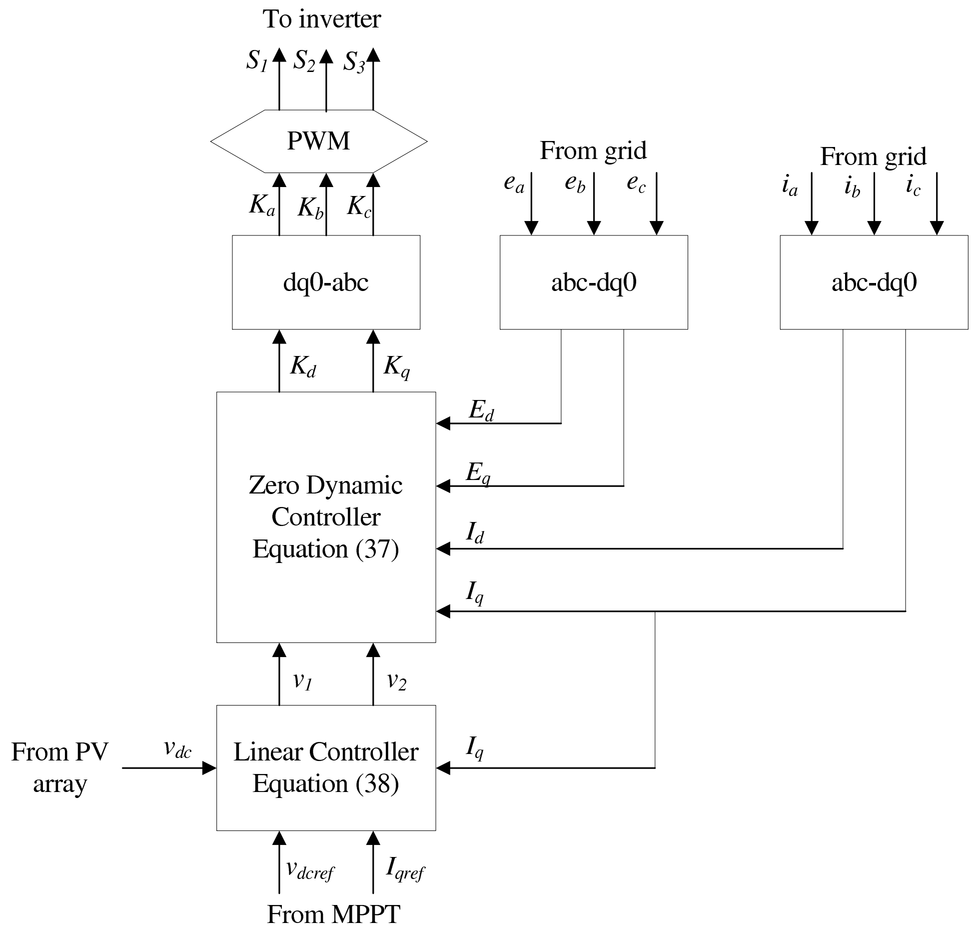

Fig. 4. Control block diagram.

and

$$k_{2p} = 2v_{pvref}, \quad k_{2i} = v_{pvref}^2$$

In this case, the gains of the PI controllers depend on the reference values of voltage and current. These reference values are calculated from MPPT as shown in the next section. Thus, the gain of PI controllers will be updated automatically with the change in atmospheric conditions.

V. MPPT ALGORITHM

MPPT technique adjust the PV array voltage in order to extract available maximum power under any atmospheric changes. MPPT uses v_{pv} and i_{pv} to detect the slope and generates P_{ref} to track the maximum power [15]. In this paper, incremental conductance method as presented in [19] is used to obtain the maximum power. At maximum power point,

$$\frac{dP_{pv}}{dv_{pv}} = 0 \tag{39}$$

where, $P_{pv} = v_{pv}i_{pv}$ and if we use this relation, then from (35)

$$\frac{\Delta i_{pv}}{\Delta v_{pv}} = -\frac{i_{pv}}{v_{pv}} \tag{40}$$

Here, $\frac{\Delta i_{pv}}{\Delta v_{pv}}$ is the incremental conductance, and $\frac{i_{pv}}{v_{pv}}$ is the instantaneous conductance. Maximum power point (MPP) can be obtained by considering the following conditions:

Condition 1: At MPP

$$\frac{\Delta i_{pv}}{\Delta v_{pv}} = -\frac{i_{pv}}{v_{pv}}$$

Condition 2: At left of MPP

$$\frac{\Delta i_{pv}}{\Delta v_{pv}} > -\frac{i_{pv}}{v_{pv}}$$

Condition 3: At right of MPP

$$\frac{\Delta i_{pv}}{\Delta v_{pv}} < -\frac{i_{pv}}{v_{pv}}$$

If a PV system satisfies condition 1, the voltage v_{pv} is ascertained at MPP voltage and fixed at this voltage until the MPPT encounters a change due to the change in atmospheric conditions. If the atmospheric conditions change in such a way that the PV system holds condition 2, then it is essential to increase the reference voltage to achieve MPPT and the opposite phenomena is true for condition 3.

At MPP, the reference output power generated by PV system is

$$P_{ref} = v_{pv}i_{pv} \tag{41}$$

Since P_{ref} is the maximum power which supplied to grid, therefore,

$$P_{ref} = P = \frac{3}{2}E_q I_{qref} \tag{42}$$

which implies that

$$I_{qref} = \frac{2}{3}\frac{P_{ref}}{E_q} \tag{43}$$

Since $v_{pvref} = v_{dcref}$, thus,

$$v_{dcref} = \frac{P_{ref}}{i_{pv}} \tag{44}$$

The reference values obtained in equation (39) and (40) are used for the reference values of linear controllers. The performances of the proposed controller are evaluated in the following section.

VI. Simulation Results

To simulate the performance of the grid-connected PV system with zero dynamic controller, a PV array consists of 20 strings, characterized by a rated current of 2.8735 A, are connected in parallel. Each string is subdivided into 20 modules, characterized by a rated voltage of 43.5 V and connected in series. Thus, the total output voltage of the PV array is 870 V and output current is 57.47 A. The value of DC link capacitor is 400 µF. The line resistance is considered as $0.1\ \Omega$ and the inductance is 10 mH. The grid voltage is 440 V and frequency is 50 Hz.

The block diagram representation of the zero dynamic design approach is shown in Fig. 4. From Fig. 4 it is shown that the three-phase grid voltages and currents are transformed into direct and quadrature axis components through $abc - dq0$ transformation which is done to match with the proposed modeling presented in Section II. The controller is the combination of linear controller and zero dynamic controller. Finally, the control inputs are again transformed into three-phase components using $dq0 - abc$ transformation to implement them through the inverter switches. To make the input signals suitable for switches a PWM is used. All the simulations are done in the widely used PSCAD environment.

In this case, the system is simulated at standard atmospheric condition where the value of solar irradiation is considered as $1\ \mathrm{kW\,m^{-2}}$ and the temperature as 298 K. At this condition, the output power of PV unit which is shown in Fig. 5 where there is some fluctuation due to the nonlinear characteristics of PV system. The main purpose of the control action is to extract 50 kW power from the PV unit through MPPT and supply this power to the grid. This can be done by regulating the inverter switches through the proper control scheme when the system is operated at unity power factor. Therefore, to evaluate the performance of the controller, it is essential to analyze the grid voltage and current. The grid voltage (solid line) and current (dotted line) of phase A are shown in Fig. 6 from 1.1 s to 1.15 s with the proposed control scheme. From Fig. 6, it is seen that the voltage and current are in phase which ensure the operation of grid-connected PV system at unity power factor.

In a practical PV system, the atmospheric condition changes continuously for which there exists variations in cell working temperature as well as in solar irradiance. Due to the change in atmospheric condition, the output voltage, current, and power of PV unit changes significantly. For example, if a single module of a series string is shaded partially, then its output current will be reduced which will dicate the operating point of whole string. Fig. 7 shows the performances of the proposed zero dynamic controller with the change in atmospheric conditions. From Fig. 7, it is seen that the PV system operates at standard atmospheric conditions from 1.05 s to 1.15 s. But the irradiance changes from $1000\ \mathrm{W\,m^{-2}}$ to $700\ \mathrm{W\,m^{-2}}$ at 1.15 s and the weather remains cloudy, i.e., the PV system is shaded until 1.25 s. At this stage, the amount of power delivered to the grid will be changed and MPPT will select a different MPP but the grid voltage will be the same. The change in grid current is also shown in Fig. 7. After 1.25 s the grid

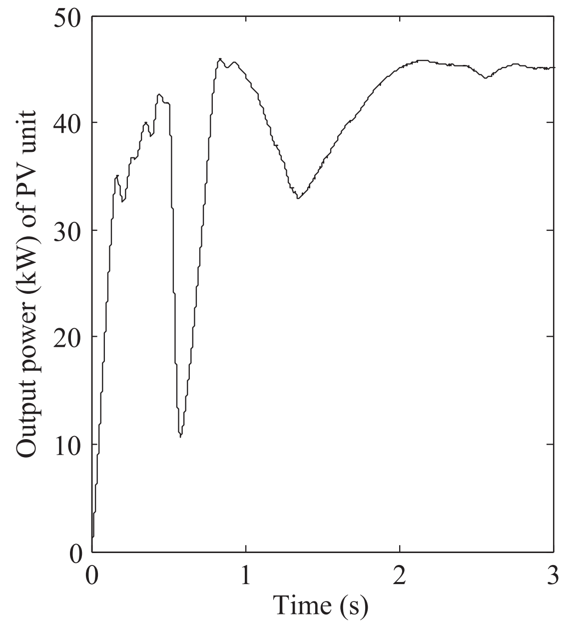

Fig. 5. Output DC power of PV Unit at standard atmospheric condition.

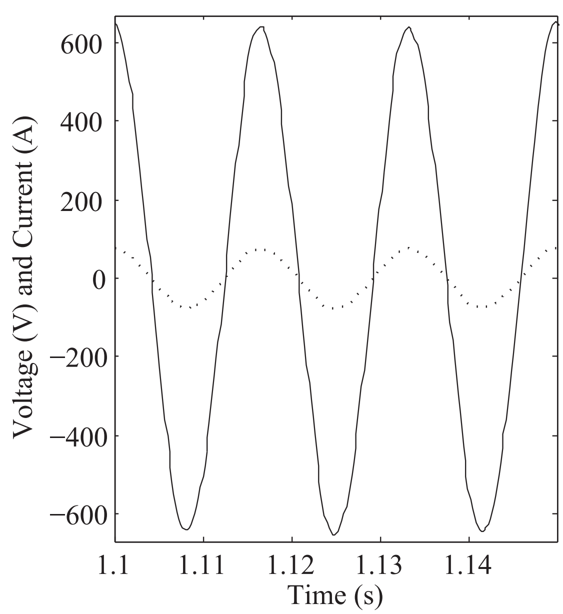

Fig. 6. Voltage (solid line) and current (dotted line) of phase A at standard operating condition.

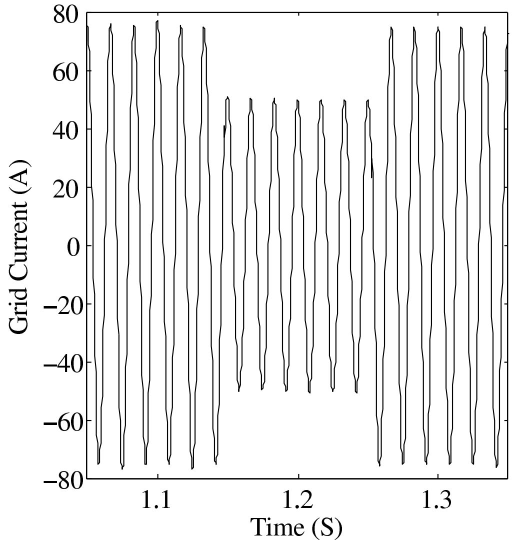

Fig. 7. Grid current with the change in solar irradiation.

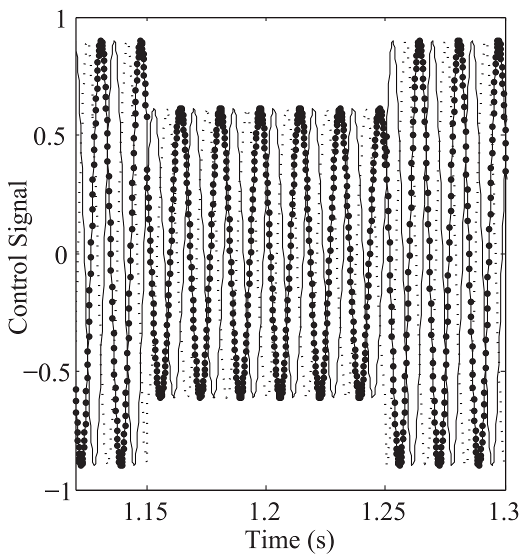

Fig. 8. Control input (Solid line–K_a, dashed line–K_b, and Solid line with dot–K_c).

current is similar to its previous value as the system again operates at standards atmospheric conditions. From the results it is clear that the designed controller performs well at varying atmospheric conditions and provides robust performance. The corresponding control signals are shown in Fig. 8.

VII. Conclusion

In this paper a zero dynamic control scheme is presented to analyze the performance of a three-phase grid-connected PV system and to enhance the dynamic stability limit with the change in atmospheric conditions. The proposed controller design approach cancels all possible nonlinearities by transforming PV system into two decoupled linear subsystems with stable internal dynamics. The DC link voltage and current injected into grid are controlled to ensure the operation of the PV system at unity power factor. From the simulation results, it is clear that the controller performs better under varying atmospheric conditions. Future work will deal with the extension of the proposed method by considering some mismatches within the PV model and implement on a large interconnected system.

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