

Robust Control Design for Three-Phase Power Inverters using Genetic Algorithm

Natthaphob Nimpitiwan¹ and Somyot Kaitwanidvilai², Members

ABSTRACT

This paper proposes a new technique to design a fixed-structure robust controller for grid connected three-phase inverter systems. The proposed technique applies the Genetic Algorithm to evaluate the optimal controller parameters. The integral squared error (ISE) of the controlled system is minimized and the robust performance (RP) of the system is satisfied. In the proposed design, the structure of controller is specified as a decentralized Proportional-Integral (PI) controller which is preferred for practical implementations. Simulation results show that the proposed technique is promising. Applying the proposed technique ensures wide operating conditions for three-phase power inverters.

Keywords: Pulse Width Modulation (PWM) Inverters, Robust Control, Genetic Algorithms, Fixed Structure Robust Controller Design, Grid Connected Inverters, Current-Controlled Inverter

1. INTRODUCTION

Inverter systems are one of important parts of electric energy conversion from renewable resources to grid systems. Higher penetration level of grid connected inverter based distributed generations tends to increase the operational impacts on power systems (e.g., power quality, stability, reliability). Several developed countries aim to increase the generation of electricity from renewable energies. Grid connected inverters with robust performance (RP) are necessary for ensuring reliability/stability of interconnected systems. H_∞ optimal control theories have been widely applied to several control problems.

As shown in previous works, H_∞ optimal control is a powerful technique to design a robust controller. However, due to complications of controllers from conventional H_2 optimal theories, implementations of the high order controllers may be difficult for practical multiple input-multiple output (MIMO) control applications. An alternative solution to reduce the order of controllers is to formulate problems as a fixed

structure controller design [1, 2]. The design of a fixed-structure robust controller becomes an interesting area of research because of its simple structure and acceptable controller order. Several approaches to design a fixed-structure robust controller are proposed in [2-4]. In [2], a robust H_∞ optimal control problem with a structure specified controller is solved by using genetic algorithm (GA). As concluded in [2], genetic algorithm is a simple and efficient tool to design a fixed-structure H_∞ optimal controller. C. Bor-Sen and C. Yu-Min in [3] propose a PID design algorithm for mixed H_2/H_∞ control. In their paper, PID control parameters are tuned in the stability domain to achieve mixed H_2/H_∞ optimal control. A similar idea is proposed in [4] by using the intelligent genetic algorithm to solve the mixed H_2/H_∞ optimal control problem.

A simplified dynamic model of self-commuted photovoltaic inverter system is proposed in [5]. The voltage control mode is designed to regulate the terminal voltage by supplying reactive power to load. Reference [6] proposes a grid connected PWM voltage source inverter (VSI) to mitigate the voltage fluctuations by designing a proper PI controller.

For current-controlled mode, state-space models of grid connected current control PWM inverters with PI controllers have been well studied in [7-9]. These papers analyze and design robustness of the systems by using modal/sensitivity analysis; also, time domain simulations are illustrated to verify the effectiveness of the proposed control strategy. Reference [8] applies feed forward compensation to the dc-link voltage-control loop to mitigate the impact of the nonlinear characteristic of the PV array. Z. Shicheng, W. Pei-zhen and G. Lu-sheng in [10] employ current-controlled mode to regulate the power output. In [10], to improve the inverter stability, the feed forward compensation is adopted to compensate the instantaneous variation of utility grid voltage and to restrain the disturbances at the inverter terminal.

Designs of the controllers in [5-10] are accomplished under a single operating point. Hence, by considering uncertainties/variations of several system parameters, performance and stability of these controllers may be deteriorated. Designing the controllers by applying robust control design may assure the dynamic performance and stability of systems under several circumstances.

In this paper, a design of grid connected three-phase current control inverters is proposed by apply-

Manuscript received on August 1, 2011 ; revised on October 25, 2011.

¹ The author is with the Department of electrical engineering, school of Engineering at Bangkok University, Thailand, E-mail: natthaphob.n@bu.ac.th

² The author is with the Department of electrical engineering, Faculty of engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand., E-mail: drsomyot@gmail.com

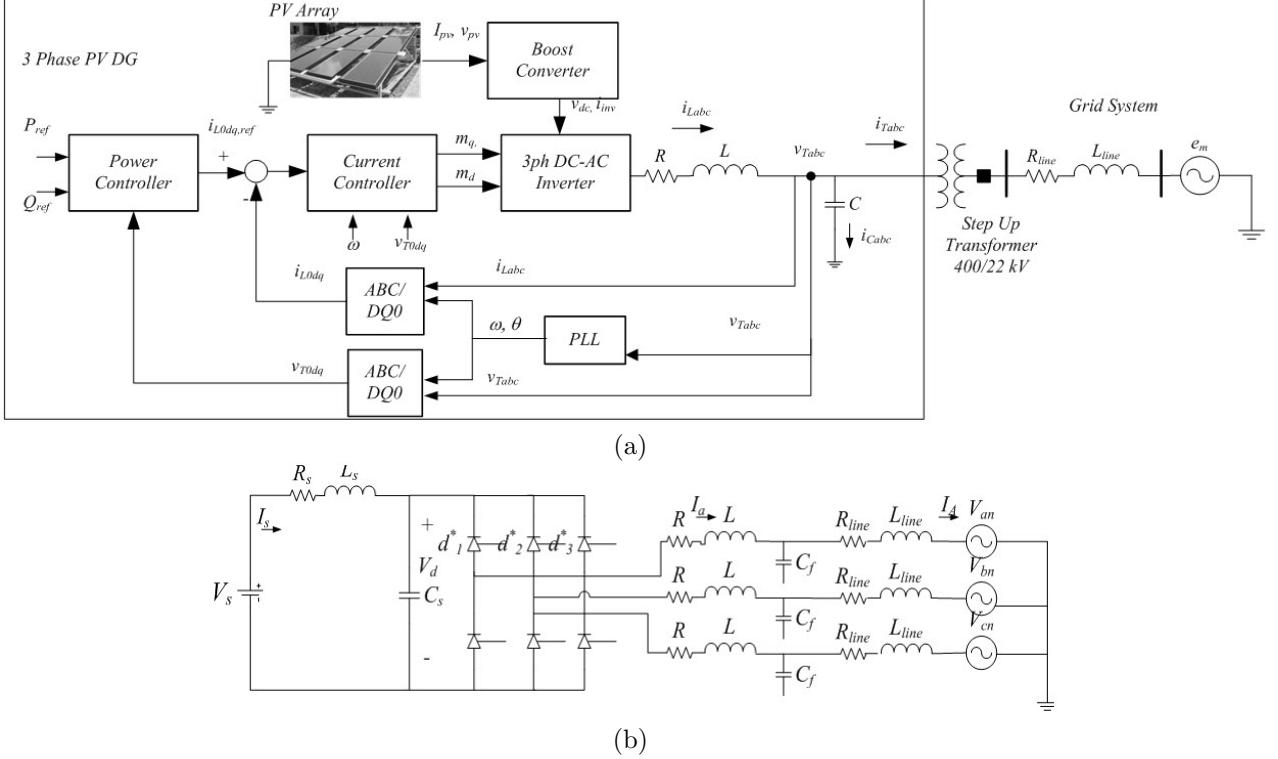


Fig.1: Model of a three-phase grid connected inverter: a) System diagram b) Circuit diagram of the three-phase inverter.

ing the fixed structured H_∞ optimal control design. Controllers with robust stability (RS) and nominal performance (NP) are main concerns of the proposed design. Genetic algorithm is employed to solve for the optimal parameters of controllers. During the controller design process, the DC voltage source is considered as an ideal voltage source for the grid connected three-phase inverter. Performances of the proposed controller can be further investigated by applying the detail model of DC voltage source (e.g., photovoltaic arrays, fuel cells or micro turbines).

In this paper, applications of the proposed controller are mainly focused on designing a fixed-structure controller for constant power factor photovoltaic distributed generations (PVDGs). Structure of the controller is a proportional integral (PI) controller with multiple inputs multiple outputs (MIMO). Dynamic responses of an illustrative test system are investigated under several uncertainties, such as fluctuations of DC voltage sources and variations of power output of DGs.

Two illustrative cases are employed to investigate dynamic performances of the proposed controller. Analysis is accomplished to ensure wide operating conditions of the PVDGs under variations of irradiance.

This paper is organized as follows: Sections II discusses the models of a photovoltaic array, state space model of a three-phase inverter and the current control model of the inverter. Section III discusses

the proposed technique for designing a fixed-structure controller with Robust Stability and Robust Performance. Section IV briefly explains the concept of GA and finally the simulations of illustrative cases are depicted in Section V.

2. MODEL OF GRID CONNECTED THREE PHASE INVERTER

A. Three phase inverter model

A three phase inverter as shown in Fig. 1 can be represented by a nonlinear state-space model in rotational frame of reference. By applying the 0dq-abc transformation matrix defined by

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1/\sqrt{2} & \cos \omega t & \sin \omega t \\ 1/\sqrt{2} & \cos(\omega t - \frac{2\pi}{3}) & \sin(\omega t - \frac{2\pi}{3}) \\ 1/\sqrt{2} & \cos(\omega t + \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad (1)$$

, a grid connected three phase inverter can be represented with variables in rotational reference frame by [7]

$$\begin{aligned} \dot{x}_r &= A_r x_r + M_r(x_r, u_r) \\ y_r &= N_r(x_r, u_r) \end{aligned} \quad (2)$$

where

$$A_r = \begin{bmatrix} -R/L & -\omega & 0 & 0 & -\frac{1}{L} & 0 & 0 & 0 \\ \omega & -R/L & 0 & 0 & 0 & -\frac{1}{L} & 0 & 0 \\ 0 & 0 & -\frac{R_s}{L_s} & -\frac{1}{L_s} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{C_s} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 & -\omega & -\frac{1}{C} & 0 \\ 0 & \frac{1}{C} & 0 & 0 & \omega & 0 & 0 & -\frac{1}{C} \\ 0 & 0 & 0 & 0 & \frac{1}{L_{line}} & 0 & -\frac{R_{Line}}{L_{line}} & -\omega \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{line}} & \omega & -\frac{R_{Line}}{L_{line}} \end{bmatrix}$$

$$M_r = \begin{bmatrix} \frac{\sqrt{6}}{4L} V_d m_d \\ \frac{\sqrt{6}}{4L} V_d m_q \\ \frac{1}{L_s} V_s \\ -\frac{\sqrt{6}}{4C_s} I_d m_d + \frac{\sqrt{6}}{4C_s} I_q m_q \\ 0 \\ 0 \\ -\frac{1}{L_{line}} \frac{\sqrt{6}}{2} e_m \cos(\varphi) \\ + \frac{1}{L_{line}} \frac{\sqrt{6}}{2} e_m \cos(\varphi) \end{bmatrix}, x_r = \begin{bmatrix} I_d \\ I_q \\ I_s \\ V_d \\ V_{cf_d} \\ V_{cf_q} \\ I_{LD} \\ I_{LQ} \end{bmatrix}, u_r = \begin{bmatrix} m_d \\ m_q \end{bmatrix}$$

Note that by assuming a three phase balance system, all components in zero axis (i.e., I_0, V_{cf0} and I_{L0}) are omitted. After transforming to rotational reference frame, the state space representation of inverter based DGs is a non-linear time invariant system. By employing Taylor's series expansion to (1), the linearized state space model around "a normal operating point" can be written as

$$\Delta \dot{x}_{Lr} = A_{Lr} \Delta x_{Lr} + B_{Lr} \Delta u_{Lr} \quad (3)$$

where $\Delta x_{Lr} = [\Delta I_d \ \Delta I_q \ \Delta I_s \ \Delta V_d \ \Delta V_{cf_d} \ \Delta V_{cf_q} \ \Delta I_{LD} \ \Delta I_{LQ}]^T$ and $\Delta u_{Lr} = [\Delta m_d \ \Delta m_q]$

$$A_{Lr} = \begin{bmatrix} -R/L & -\omega & 0 & \frac{\sqrt{6}}{4L} m_d & -\frac{1}{L} & 0 & 0 & 0 \\ \omega & -R/L & 0 & \frac{\sqrt{6}}{4L} m_q & 0 & -\frac{1}{L} & 0 & 0 \\ 0 & 0 & -\frac{R_s}{L_s} & 0 & 0 & 0 & 0 & 0 \\ -\frac{\sqrt{6}}{4L} m_d & \frac{\sqrt{6}}{4L} m_q & \frac{1}{C_s} & 0 & 0 & 0 & 0 & 0 \\ \frac{1}{C} & 0 & 0 & 0 & 0 & -\omega & -\frac{1}{C} & 0 \\ 0 & \frac{1}{C} & 0 & 0 & \omega & 0 & 0 & -\frac{1}{C} \\ 0 & 0 & 0 & 0 & \frac{1}{L_{line}} & 0 & -\frac{R_{Line}}{L_{line}} & -\omega \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{L_{line}} & \omega & -\frac{R_{Line}}{L_{line}} \end{bmatrix}$$

$$B_{Lr} = \begin{bmatrix} \frac{\sqrt{6}}{4L} V_d & 0 \\ 0 & \frac{\sqrt{6}}{4L} V_d \\ \frac{\sqrt{6}}{4C_s} I_d & \frac{\sqrt{6}}{4C_s} I_q \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}, \Delta x_r = \begin{bmatrix} \Delta I_d \\ \Delta I_q \\ \Delta I_s \\ \Delta V_d \\ \Delta V_{cf_d} \\ \Delta V_{cf_q} \\ \Delta I_{LD} \\ \Delta I_{LQ} \end{bmatrix}, \Delta u_r = \begin{bmatrix} \Delta m_d \\ \Delta m_q \end{bmatrix}$$

Note that in practical, the normal operating point of PVDGs may be designed based on the standard test conditions or STC (i.e., irradiance at 1,000 w/m² and cell temperature at 25° C). Hence, the performance of a controller designed under STC may vary under different circumstances.

B. Power Control Unit

From the definition of rotational reference frame in (1), real power and reactive power outputs (P^{ref} and Q^{ref}) of inverter based DGs with balanced three-phase loads can be calculated as

$$S^{ref} = 3(V_{TD} - jV_{TQ})(I_{LD} - jI_{LQ})^* \\ = \underbrace{(V_{TD}I_{LD} + V_{TQ}I_{LQ})}_{P^{ref}} + j\underbrace{(V_{TD}I_{LQ} + V_{TQ}I_{LD})}_{Q^{ref}} \quad (4)$$

To control output powers from inverters, output currents in the rotational reference frame (I_{LD} and I_{LQ}) can be determined from (4) as

$$I_{LD} = \frac{V_{Td}P^{ref} - V_{Tq}Q^{ref}}{v_d^2 + v_q^2} \quad I_{LQ} = \frac{v_qP^{ref} - v_dQ^{ref}}{v_d^2 + v_q^2} \quad (5)$$

3. FIXED STRUCTURE CONTROLLER DESIGN WITH ROBUST STABILITY AND ROBUST PERFORMANCE

By applying the H_∞ theory with a fixed structure controller design, structures of controllers can be significantly reduced to avoid difficulties during controller implementations. Two main criterions for a system with RS are RP and nominal performance (NP). The NP problem is how to determine a controller which will stabilize a plant with uncertainty (i.e., parametric uncertainty and dynamic uncertainty). Consider a control system in Fig. 1, a plant with uncertainty can be represented with multiplicative uncertainty (W_m) as

$$P(s) = P_0(s)(I + W_m(s)\Delta_m(s)); |\Delta_m(s)|_\infty \leq 1 \forall \omega \quad (6)$$

where $P_0(s)$ is a nominal plant model (without uncertainty), $P(s)$ is a perturbed plant model, $W_m(s)$ is a boundary function of a plant with perturbations, $\Delta_m(s)$ is a normalized perturbation with H_∞ norm less than 1. The condition for robust performance is

$$\|W_m T\|_\infty < 1 \quad (7)$$

; and the condition for disturbance attenuation performance is

$$\|W_m S\|_\infty < 1 \quad (8)$$

where $S(s)$ is a sensitivity function, $T(s)$ is a transfer function of feedback loop and $W_s(s)$ is a stable weighting function chosen by designer. Having both conditions in (7) and (8) provide RP condition which can be represented as

$$\left\| \frac{W_m T}{W_s S} \right\|_\infty = \max_\omega \sqrt{|W_m T|^2 + |W_s S|^2} < 1$$

To apply a fixed structure controller design, the problem starts with choosing a configuration of the

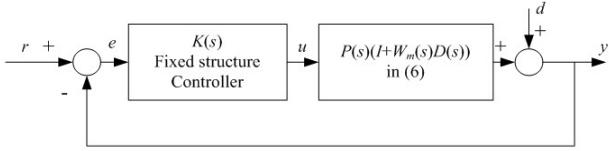


Fig.2: A control system with plant uncertainty and external disturbance.

controller. In general, a pre-specified controller can be written as [1, 2]

$$K(s) = \frac{N(s)}{D(s)} = \frac{B_m s^m + B_{m-1} s^{m-1} + \dots + B_0}{s^n + a_{n-1} s^{n-1} + \dots + a_0} \quad (9)$$

where m and n are order numbers of the controller.

$$B_k = \begin{bmatrix} b_{k11} & \dots & b_{k1n_i} \\ \vdots & \ddots & \vdots \\ b_{kn_o1} & \dots & b_{kn_on_i} \end{bmatrix}, \text{ for } k = 0, 1, \dots, m.$$

n_i and n_o are numbers of input and output of the controller, respectively. The order number of controller may be increased corresponding to complication of plants and the rigorousness of performance specifications.

4. CURRENT CONTROL INVERTER DESIGN USING GENETIC ALGORITHMS

A. Genetic Algorithm optimization

Introduced by Holland in 1962, Genetic algorithm (GA) – an evolutionary optimization technique – is inspired by the natural evolution. Possible solutions of an optimization problem are represented by each “chromosome”, an individual of population. A fitness function, defined by optimization problem, is applied to evaluate the merit of each chromosome. Therefore, searches for the optimal solution are implemented in parallel processes. For this reason, GA can provide both global and local optimum solutions in large search spaces. In this section, GA processes are briefly discussed; details of the GA optimization are well written and can be followed in [11].

GA starts from randomly initializing population. The evolutions of each generation are accomplished through several processes, (i.e., selection, crossover and mutation). The steps of the proposed strategy for designing fixed-structure controllers are outlined as follows:

Step 0: Initialize the parameters (Θ), crossover rate (p_c), mutation rate (p_m), population size (N_{ind}), elite count (N_{el})

Step 1: Initialize population for the first generation ; $k = 0$

Step 2: Calculate the fitness value and perform a selection process to the current generation;

Step 4: Perform a crossover operation on selected chromosomes;

Step 5: Apply a mutation operator and a shift operator;

Step 6: Perform an elitism mechanism;

Step 7: Find the best chromosome of generation;

Step 8: If the stopping criterion is not satisfied, increase the counter k by 1 and go to step 2;

Real and reactive power outputs of a three-phase inverter are controlled by regulating the injected currents (I_{LD} and I_{LQ}) to grid systems. In this paper, the injected currents corresponding to reference output powers (P^{ref} and Q^{ref}) and terminal voltages (V_{TD} and V_{TQ}) are directly determined without feedback control by (5). Then, the configuration of a robust fixed-structure current controller is designated as (9). By applying binary coding, all controller parameters (b_{kij}) is encoded to a bit string or so called chromosome. All parameters is arranged in a vector form as

$$\Theta = [a_0, a_n, b_{k11}, b_{kn_o1}, \dots, b_{k1n_i}, \dots, b_{kn_on_i}] \quad (10)$$

Bit length of each parameter (ℓ_i) with a pre-specified interval $[\theta^{U_i}, \theta^{L_i}]$ can be chosen as

$$\ell_i = \log_2 \left(\frac{\theta^{U_i} - \theta^{L_i}}{R_i} \right) \quad (11)$$

where R_i is the resolution of parameter.

B. Problem formulation In this paper, time domain performance (e.g., speed, overshoot) of the controller is evaluated by applying integral squared error (ISE) or the “cheap” linear quadratic regulator (LQR) cost function as

$$J = \sqrt{\int_0^\infty \|e(\tau)\|^2 d\tau} \quad (12)$$

where $e(t)$ is a vector of error signals The cost function J can be written in frequency domain as

$$J(s, \Theta) = \|E(s)\|_2 = \frac{1}{2\pi j} \int_0^\partial E(s)E(-s)ds$$

where

$$E(s) = \frac{1}{1 + K(s, \Theta)P(s)} R(s) \quad (13)$$

$K(s)$ is function of controller, $R(s)$ is reference signal and $P(s)$ is a plant function with model uncertainty.

The objective function of the robust control optimization problem is

$$\underset{\Theta}{\text{minimize}} J(\Theta)$$

subject to

$$\left\| \begin{bmatrix} W_m T \\ W_s S \end{bmatrix} \right\|_{\infty} = \max_{\omega} \sqrt{|W_m T|^2 + |W_s S|^2} < \gamma. \quad (14)$$

where γ is a pre-specified upper bound which defines the rigorousness of control specifications, W_m is a multiplicative weight function of a plant, W_s is weighted sensitivity function.

5. RESULTS AND SIMULATIONS

In this section, a fixed-structure current controller is designed for a grid connected 500 kW three-phase inverter as shown in Fig. 1. Performances of the proposed controller are depicted in two illustrative cases; Case I: three-phase grid connected inverter with an ideal DC voltage source and Case II: three-phase grid connected inverter with photovoltaic array as DC voltage source. In Case II, the proposed controller is applied for three-phase inverters and employed as a part of photovoltaic distributed generations (PVDGs). Photovoltaic array are modeled and applied as DC voltage source of the system. The reference power output of the PVDG is provided by a maximum power point tracking (MPPT) module. Specifications of the inverter are shown in Table I.

Table 1: Parameters of a grid connected three phase inverter

Controller parameters	Value
Switching frequency, f	7 kHz
DC voltage source (V_d)	1900V (with 12 percent uncertainty)
Rated output voltage(V_T)	380 Vrms, $f = 50$ Hz
Nominal output power (P_L)	500 kW
Grid connection	$R_{Line}=300\text{m}\Omega$, $L_{Line}=300\mu\text{H}$, $C_f=3.000\mu\text{F}$
AC-DC inverter	$R_s=3\text{m}\Omega$, $L_s=3\mu\text{H}$, $C_s=5,000\mu\text{F}$ (with 1.0 percent uncertainty)

In case I, the three phase inverter is designed with parametric uncertainties of 4 variables (see Fig. 1): an ideal DC voltage source (V_d), coupling impedance (R_{Line} , L_{Line} and C_f). Dynamics of the three phase inverter are represented by the linearized state space form in (3). With uncertainty specified in Table I, singular values of the illustrated plant, $P(s)$, is shown in Fig. 3. Multiplicative weight of a plant (W_m) is obtained from considering possible plants from parametric uncertainty. For the illustrative plant, the multiplicative weight function (W_m) requires a steep bound in the form [12]

$$W_m = \left(\frac{1}{k_m \sqrt{\epsilon}} \left[\frac{s + \frac{\omega_{bc}}{k_m \sqrt{M_u}}}{s + \frac{\omega_{bc}}{k_m \sqrt{\epsilon}}} \right] \right)^{k_m} I_{2 \times 2} \quad (15)$$

; parameters in (15) are chosen as follow: $\epsilon = 0.01$, $k_m = 3$, $M_u = 7$, $\omega_{bc} = 2.5$ kHz. The weighted sensitivity function (W_S) is chosen as

$$W_s = \left(\frac{1}{k_s \sqrt{M_s}} \left[\frac{s + k_s \sqrt{M_s} \omega_b}{s + k_s \sqrt{\epsilon} \omega_b} \right] \right)^{k_s} I_{2 \times 2} \quad (16)$$

; parameters in (16) are chosen as follow: $\epsilon = 0.01$, $k_s = 1$, $M_s = 10$, $\omega_b = 10$ Hz.

To avoid difficulty in implementation (i.e., controller with higher order), a PI controller is pre-specified as the configuration of $K(s)$. Hence, the controller configuration is

$$K(s) = \begin{bmatrix} K_{PD} + \frac{K_{ID}}{s} & 0 \\ 0 & K_{PQ} + \frac{K_{IQ}}{s} \end{bmatrix}$$

The parameters of PI controllers are defined as

$$\Theta = [K_{PD}, K_{ID}, K_{PQ}, K_{IQ}].$$

GA optimization is accomplished with $p_c = 0.8$, $p_m = 0.2$, $N_{ind} = 40$ and $N_{el} = 5$. The best fitness value and the optimal solution are 0.0731 with $K_{PD}=K_{PQ}=0.00033$ and $K_{ID}=K_{IQ}=0.11246$. The objective functions from each generation are shown in Fig. 5.

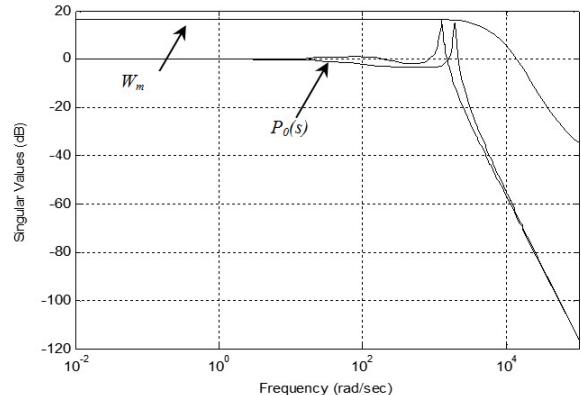


Fig.3: Singular values of W_m and the plant.

In both cases, the proposed fixed structure PI controllers designed by GA optimization are tested with a three phase inverter switching model in Matlab/Simulink. In Case I, results of a simulation with a reference signal average power output (P^{ref}) at 500 kW are shown in Fig. 6. By applying the model of a grid connected three-phase inverter as shown in Fig. 1, the ideal DC voltage source (V_{DC}) is perturbed from 1,900 V to 1,700 V at $t = 0.15$ ms and 1,500 V at $t = 0.30$ ms in order to demonstrate the stability of the plant. Note from Fig. 6 that the average output power has a capability to recover from DC voltage drop up to 21 percent within 2-3 cycles.

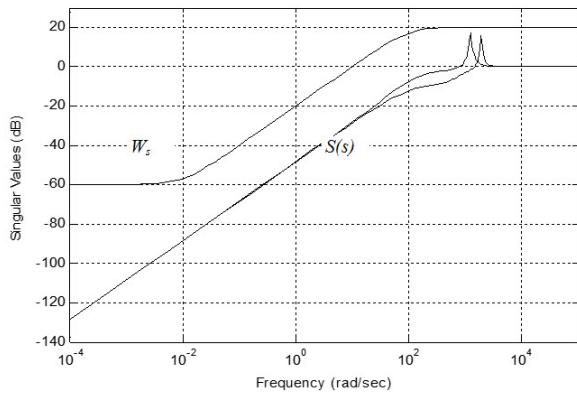


Fig.4: Singular values of W_S and the sensitivity function (S).

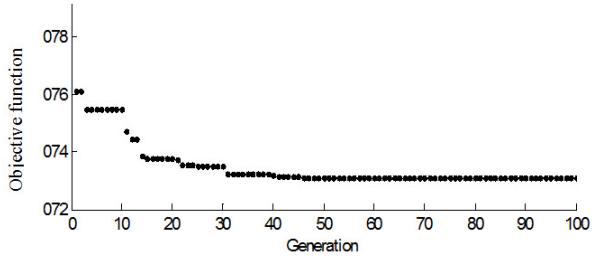


Fig.5: Objective function of the illustrative case.

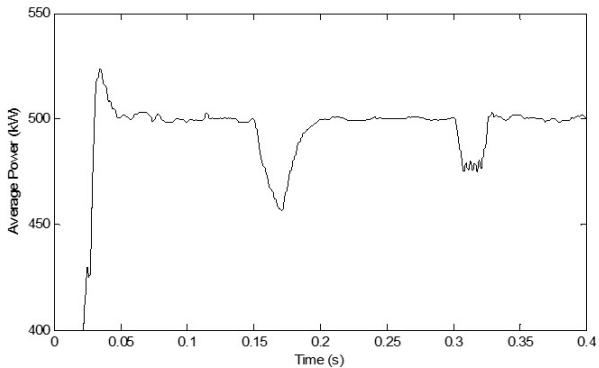


Fig.6: A simulation result of a three phase inverter with $P^{ref} = 500$ kW and V_{DC} perturbations.

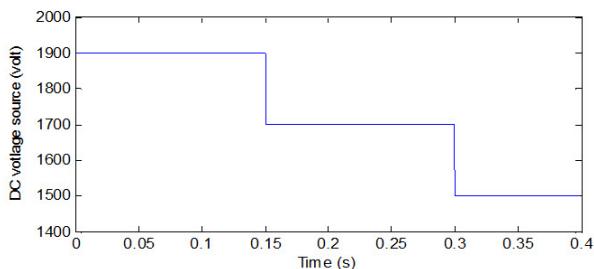


Fig.7: Step changes of DC source voltage.

In Case II, the fixed-structure controller for three-phase inverters designed in Case I is employed as a part of Photovoltaic distributed generations (PVDGs). A set of Equations which describes characteristics of a PV array can be written as [13]:

$$V^M = N_{SM} V_t^C \ln \left(1 - \frac{I_M}{N_{PM} I_{SC}^C} \right) + N_{SM} V_{OC}^C + I_M R_S^C \frac{N_{SM}}{N_{PM}} \quad (17)$$

$$I_{SC}^C = C_1 G_a \quad (18)$$

$$V_{OC}^2 = V_{OC,0}^C + C_2 (T^C - T_0^C) \quad (19)$$

$$V_t^C = \frac{mk}{e} (273 + T^C) \quad (20)$$

where V^M voltage at PV array terminal, I^M output current of PV module, N_{SM} is number of PV cell with series connected, N_{PM} is number of PV cell with parallel connected, V_{OC}^C is open circuit voltage of PV cell, T^C is temperature of cell, G_a is irradiance level, I_{SC}^C is short circuit current of PV cell, C_1 and C_2 are PV cell's constants, m and k are diode quality factor and Boltzmann's constants, respectively. The total power output of the photovoltaic array is 720 kW with 40 series connected modules and 150 parallel connected PV modules. The parameters of each PV module under standard test conditions (1,000 w/m² and 25°C) are shown in Table II.

Table 2: Parameters of each PV module under standard test conditions

Controller parameters	Value
Maximum power output	120 W
Short circuit current	7.54 A
Open circuit voltage	22.1 V
Current at maximum power	7.05 A
Voltage at maximum power	17.7 V
PV cell with series connected	40
PV cell with parallel connected	150

The MPPT module is modeled by perturb-and observe (P&O) method. By applying P&O, the operating current is perturbed to observe the rate of change of the output power to the output current (dP/dI) of PV array. The MPPT module adjusts the output current to the direction of maximum power point corresponding to the result from dP/dI. Details of the MPPT by P&O method can be found in [14, 15]. The sampling interval in this simulation is 20 ms with 0.2 A in each step change.

In practical, the output voltage from PV array may be stepped up to a higher level by using a boost converter. In this paper, to reduce the complexity of the system state space model, dynamic responses of the boost converter are not taken into consideration. The boost converter is modeled as an ideal step up converter.

In Case II, dynamic performance of the proposed controller are inspected by fluctuating solar irradiance from $1,000 \text{ w/m}^2$ to 600 w/m^2 at $t = 0.10 \text{ s}$ and back to $1,000 \text{ w/m}^2$ at $t = 0.30 \text{ s}$ (see Fig.8). The high frequency oscillation of the MPPT is filtered out by applying a low pass filter. Determined by the MPPT, the reference real power output (P^{ref}) with a unity power factor ($Q^{ref} = 0$) of the three-phase inverter is shown in Fig.8.

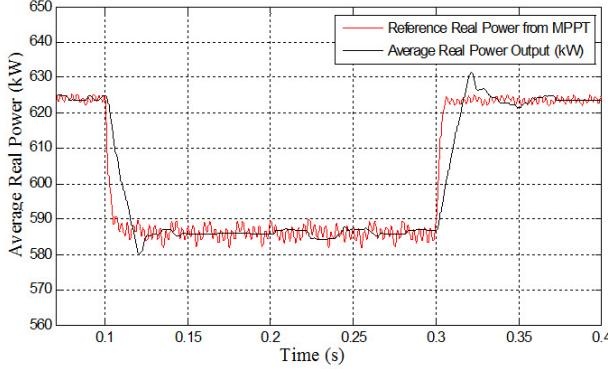


Fig.8: Average real power output of the PVDGs in Case II with reference command from MPPT

Also note that the average real power output is calculated over 1 cycle (20 ms). From a step change of irradiance at $t = 0.1 \text{ s}$, the DC link voltage (v_{dc} in Fig. 1a) as the input of the three-phase inverter is fluctuated as shown Fig. 9. Fig. 10 shows the output current at the terminal of the PVDG. The output current in Fig. 10 also has the 3rd and the 5th harmonics due to overmodulation (i.e., $m_a = (\sqrt{m_d^2 + m_q^2})$ is higher than 1) as shown in Fig. 11.

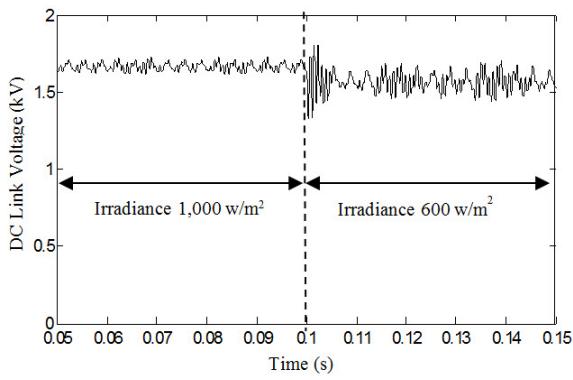


Fig.9: DC Link voltage in Case II

In Case II, Operations of the three-phase inverter PVDG at irradiance less than 600 w/m^2 causes the DC link voltage (V_d) significantly decreased from the standard test conditions. Hence, this requires the current controller to compensate the DC input voltage drop by raising the m_d and m_q . Operations under these circumstances are undesirable; to avoid instability of the PVDGs and power quality issues in grid

systems, the PVDGs operation is required to be terminated.

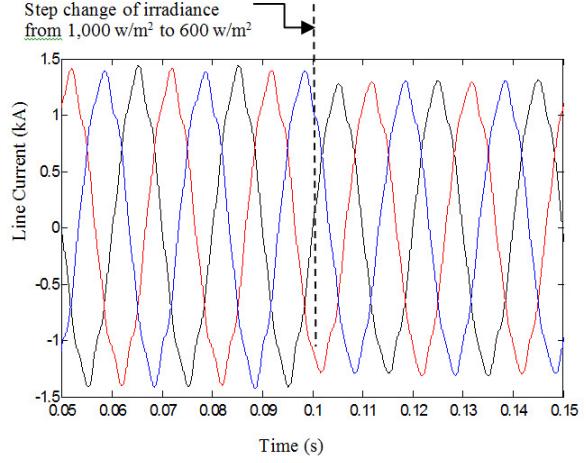


Fig.10: Line current of the PVDGs in Case II

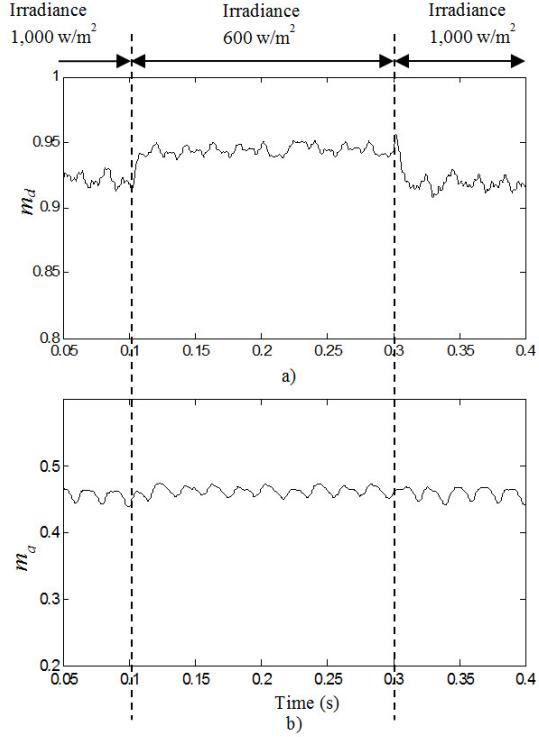


Fig.11: Modulation index in dq0 reference frame a) d axis b) q axis

6. CONCLUSIONS

The proposed technique employs GA to determine the optimal controller parameters; also, it achieves both performance and robustness of the controlled system. The effectiveness of the proposed controller is verified by the time domain responses under step changes of the ideal DC source voltage in Case I. This

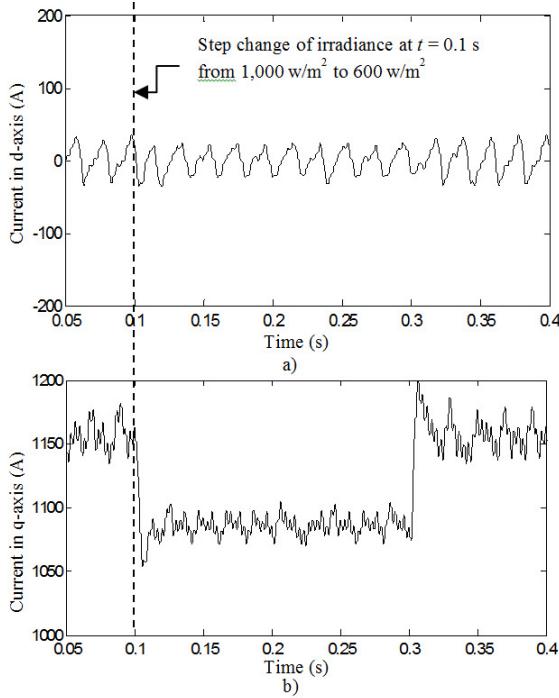


Fig. 12: Output current in dq0 reference frame a) d axis b) q axis

operating condition simulates the fluctuation of DC voltage level from renewable resources (e.g., fuel cells, solar cells, wind turbines), which may results from variations of environmental conditions. To verify the robustness of the proposed controller, the controller also applied to control a 720 kW PVDG in Case II. As seen in the results, the proposed controller is robust to the variations of DC source voltage. Moreover, the structure of controller is specified as a decentralized PI controller which can be practically implemented.

References

- [1] I. Kitsios, T. Pimenides, "Structured-specified robust-multivariable-controller design for practical applications using genetic algorithms," in *Proc. IEE Control Theory Appl.*, vol. 150, no. 3, pp. 317-323, 2003.
- [2] C. Bor-Sen, C. Yu-Min, "A structure-specified H_∞ optimal control design for practical applications: a genetic approach," *IEEE Trans. Control Systems Technology*, vol. 6, no. 6, pp. 707-718, 1998.
- [3] C. Bor-Sen, C. Yu-Min, L. Ching-Hsiang, "A genetic approach to mixed H_2/H_∞ optimal PID control," *IEEE Control Systems*, vol. 15, no. 5, pp. 51-60, 1995.
- [4] H. Shinn-Jang, H. Shinn-Ying, H. Ming-Hao, S. Li-Sun, H. Hui-Ling, "Designing structure-specified mixed H_2/H_∞ optimal controllers using an intelligent genetic algorithm IGA," *IEEE Trans. Control Systems Technology*, vol. 13, no. 6, pp. 1119-1124, 2005.
- [5] O. Wasynczuk, N. A. Anwah, "Modeling and dynamic performance of a self-commutated photovoltaic inverter system," *IEEE Trans. Energy Conversion*, vol. 4, no. 3, pp. 322-328, 1989.
- [6] Y. A. R. I. Mohamed, E. F. El-Saadany, "A Control Method of Grid-Connected PWM Voltage Source Inverters to Mitigate Fast Voltage Disturbances," *IEEE Trans. Power Systems*, vol. 24, no. 1, pp. 489-491, 2009.
- [7] N. Kroutikova, C. A. Hernandez-Aramburo, T. C. Green, "State-space model of grid-connected inverters under current control mode," *IET Electr. Power Appl.*, vol. 1, no. 3, pp. 329-338, 2007.
- [8] A. Yazdani, P. P. Dash, "A control methodology and characterization of dynamics for a photovoltaic (PV) system interfaced with a distribution network," *IEEE Trans. on Power Delivery*, vol. 24, no. 3, pp. 1538-1551, Jul. 2009.
- [9] W. Li, L. Ying-Hao, "Small-signal stability and transient analysis of an autonomous PV system," in *Proc. Transmission and Distribution Conf. and Expo. (IEEE/PES)*, pp. 1-6, 2008.
- [10] Z. Shi-cheng, W. Pei-zhen, G. Lu-sheng, "Study on Pwm Control Strategy of Photovoltaic Grid-connected Generation System," in *Proc. Int. Conf. IPEMC Power Electronics and Motion Control*, vol. 3, pp. 1-5, 2006.
- [11] D. E. Goldberg, *Genetic algorithms in search, optimization, and machine learning*. Reading, Mass.: Addison-Wesley Pub. Co., 1989.
- [12] A. A. Rodriguez, *Analysis and design of multivariable feedback control systems*. Tempe, AZ: Control3D, 2005.
- [13] A. D. Hansen, P. Sørensen, L. H. Hansen, H. Bindner, "Models for a Stand-Alone PV System," Risø National Laboratory, Roskilde 2000.
- [14] Y. Ting-Chung, C. Tang-Shiuan, "Analysis and simulation of characteristics and maximum power point tracking for photovoltaic systems," in *Proc. Int. Conf. Power Electronics and Drive Systems*, pp. 1339-1344, 2009.
- [15] L. Fangrui, K. Yong, Z. Yu, D. Shanxu, "Comparison of P&O and hill climbing MPPT methods for grid-connected PV converter," in *Proc. Industrial Electronics and Applications Conf.*, pp. 804-807, 2008.



Natthaphob Nimpitiwan (StM'01, M'07) received the B.Eng. degree from Kasetsart University, the M.S. and Ph.D. degrees in electrical engineering from Arizona State University, Tempe, AZ. Presently, he is a faculty member in the Department of Electrical Engineering at Bangkok University, Pratumthani, Thailand. His research interests include distributed/dispersed generation, optimization for power systems, modeling /simulation of power systems, artificial neural network, and engineering education.



Somyot Kaitwanidvilai received the B.Eng and M. Eng. degrees in Electrical Engineering from King Mongkut's Institute of Technology Ladkrabang, (KMITL), Thailand, in 1996 and 2000, respectively. He received his Ph.D. Degree in Mechatronics Engineering from Asian Institute of Technology, in 2005. Currently, he is a lecturer at the department of electrical engineering, Faculty of engineering, KMITL. His research interests include artificial intelligence in control system, mechatronics, power electronics, robust and adaptive control in power systems.