

Simulating Annealing PLL for Autonomous Microgrid Systems

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Abstract

The Phase Locked Loop controller parameters are the key-point that affects the dynamic performance of the autonomous microgrid. They have to be optimally tuned to guarantee enhanced overall system stability. In this paper, two-microgrid plant with their associate PWM inverter connected to the ac main grid and the load is used as an example to demonstrate the capabilities of the proposed system. The Phase Locked Loop controller is designed and tuned using the Simulating Annealing algorithm. This algorithm is used to select the Phase Locked Loop PI controller gains with optimal percentage overshoot, rise time and settling time. The controller is tested during the transition between grid-connected and autonomous operation and in reverse order. The controller is compared with Ziegler and Nichols P and PI controllers. It shows the effectiveness and the extraordinary control response of the proposed control technique with respect to percentage overshoot, rise time and settling time control parameters compared to the conventional one.

Keywords

Simulating Annealing, PI Controllers, Microgrid Operations

1. Introduction

Distributed generation (DG) resources are gaining a rapid growth connection to the utility grid, due to many factors including economics profits, environmental problems, global warming, gas emission, and tax encouragements [1]. Microgrids are reliable, due to their capability to island. It provides their customers with the power source to be supplied when the main ac grid is disconnected. Moreover, the microgrid should be adopted to be added to another microgrid sources and functions appropriately without any exceptional proposal [2]. Stability analysis for PWM-inverter microgrid is one of the apprehensions to function at the distribution level of the utility grid [3] [4] [5] [6] [7]. Although, ac-

tive-power/frequency and reactive-power/voltage drop controls have been introduced to permit the microgrid sources to share power and preserve stability without the necessity for fast communications [1].

Phase locked loop (PLL) is used for synchronization [8]. There are some challenges in designing these PLLs. Some of them are: tuning the PLL gain parameters, its negative effects on the controller response, and coupling effects and interaction between itself and the system impedance [9] [10]. PLLs regularly engage a P or PI controller as the loop filter [11]. The classical controller has a limited potential to alleviate disturbance in PLL control loop which may exist due to a weak design or polluted grid. To develop the disturbance rejection ability of PLLs, cascading extra filters such as the moving average filter (MAF) [12] and the notch filters [13] may improve their functioning. But those filters diminish the dynamic performance of PLL as their target is to minimize their bandwidth. Another method is anticipated in [14], which uses a lead compensator, an effective approach to obtain both high dynamic performance and excellent disturbance rejection. Adaptive Fuzzy is proposed in [15] to obtain fast and robust PLL system.

Evolutionary computations with stochastic search techniques assured to be a more brilliant method which affords a robust technique to resolve the controller parameters problem. The evolutionary computation for controller parameters identification is applied in many applications. Genetic algorithm (GA) is used to find out the controller parameters of the BLDC motor [16]. An evolutionary algorithm based on Particle Swarm Optimization (PSO) with weighting factors has been introduced for induction motor controllers' parameters [17]. It should be noted that even the most successful nature-inspired optimization techniques, such as GA and PSO, are also sensitive to the increase of the problem difficulty and dimensionality, due to their stochastic type [18]. In previous years, more awareness is provided to bacterial foraging optimization (BFO) which has a powerful foundation for engineering applications. A few models have been achieved to signify bacterial foraging performances and use it for solving different challenges [19]. It solved these engineering challenges effectively.

In this paper, the simulating annealing (SA) technique is used to select the PLL PI-controller gains with a minimal percentage overshoot, rising time and settling time. These control parameters are having sensitive values that affect the dynamic performance of the autonomous microgrid. They have to be optimally adjusted to assure great improvement in the overall system stability. It organized as follows: Section 2 introduces the microgrid proposed system description. The problem formulation is given in Section 3. It includes inverter-main grid model, PLL model and system control methodology. In Section 4, the SA proposed technique is introduced. Results are given in Section 5. Finally, conclusions are presented in Section 6.

2. System Description

The overall block diagram for proposed autonomous microgrid system is given

in **Figure 1**. It is consisting of two dc microgrids each is feeding a PWM inverter. Both are connected to the load and the main ac grid through transmission lines, transformers and circuit breaker. The two microgrids is connected to the main grid through circuit breaker, therefore it is certainly islanded by opening this circuit breaker (CB). In the islanding mode, the microgrids will continue serving the loads without any interruption. The two microgrids are able to re-synchronize with the main grid when the islanding condition is cancelled.

3. Problem Formulation

The proposed control block diagram is shown in **Figure 2**. The idea is based on frequency and phase detection using the phase-locked loop (PLL) combined with the traditional control for active power to frequency drop and reactive power to voltage drop of the microgrid systems.

a) Inverter-main grid model

The inverter-main grid model is illustrated in **Figure 3**. The phase ac voltages at the terminal of the PWM inverter is $V_i \angle \delta_i$ and the terminal bus that is connected to the main ac grid is $V_i \angle \delta_i$. Their phase angles (δ_i, δ_i) are calculated with respect to the main grid sinusoidal waveform at the nominal frequency. The two busses are connected via a transformer and a transmission line, the overall impedance for them will $jX = jX_{Trans} + jX_{TL2}$.

b) Phase-locked loop model

The Block diagram for the PLL is illustrated in **Figure 4**. The concept is: the three-phase voltage (abc) are transformed into two phase-voltage ($\alpha\beta$) and then into two dc voltages (dq). The d-voltage component is the input to the PLL loop. The angle δ_p is the estimate output of the phase angle given by the PLL loop. The V_d can be expressed by:

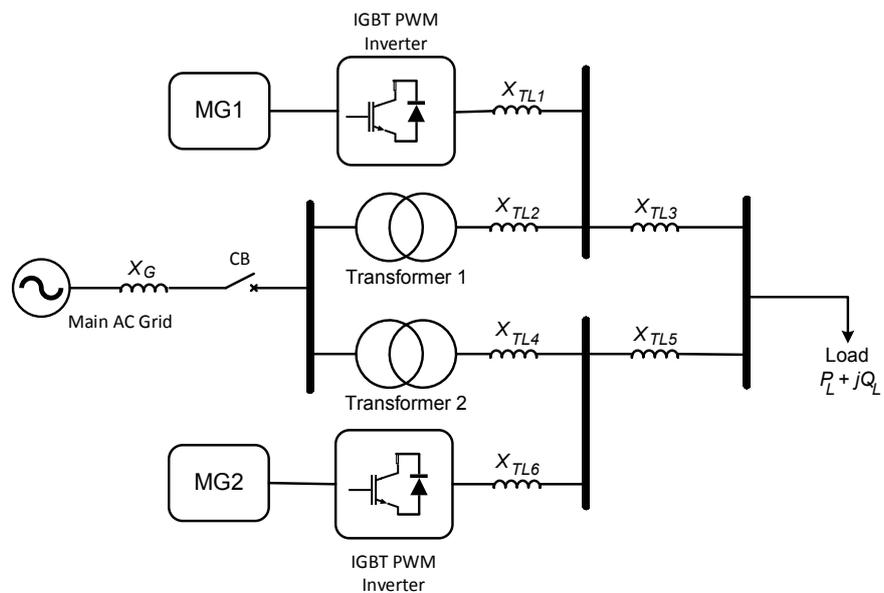


Figure 1. The microgrid proposed system.

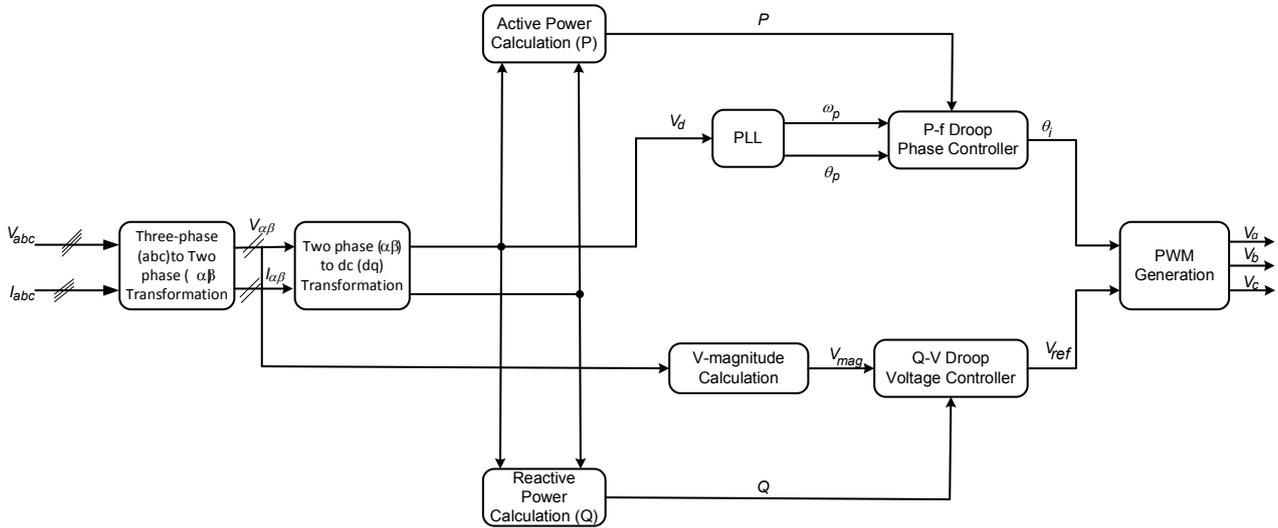


Figure 2. Block diagram for controlling the proposed system.

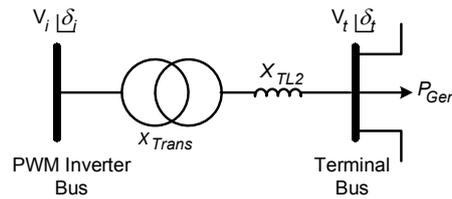


Figure 3. PWM Inverter-main grid model.

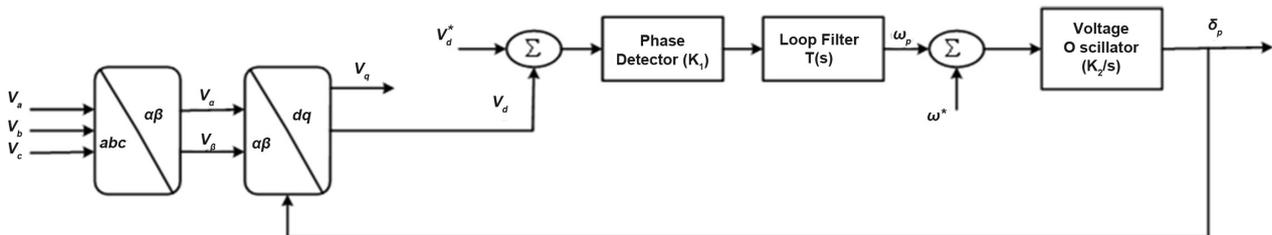


Figure 4. The PLL block diagram.

$$V_d = -V_t \sin(\delta_t - \delta_p) \tag{1}$$

As $(\delta_t - \delta_p)$ is too small, Equation (1) can be rewritten:

$$V_d = -V_t (\delta_t - \delta_p) \tag{2}$$

The PLL frequency can be also expressed as:

$$\dot{\delta}_p = \omega_p \tag{3}$$

The loop filter for the PLL can be represented either by a P [1] controller or PI controller [20].

c) System control methodology

The main control goals are to adjust the terminal bus voltage magnitude and the active power provided to the ac main grid P_{Gen} . The mathematical model de-

scribes the control idea of the autonomous microgrid system is given in [1]. Which can be summarized by the following equations and described in **Figure 5**:

$$\begin{aligned}
 \dot{m} &= K_m (V_{set} - V_t) \\
 \dot{\theta} &= K_\theta (P_{set} - P_{Gen}) \\
 \dot{x} &= K_3 (\delta_t - \delta_p) \\
 \dot{\delta}_p &= \omega_p \\
 0 &= V_i - \frac{mV_{dc}}{V_{base}} \\
 0 &= P_{set} - (P_o - R\omega_p) \\
 0 &= \theta - (\delta_i - \delta_p) \\
 0 &= x - (\omega_p - K_4\theta) \\
 0 &= P_{Gen} - \frac{V_{dc}I_{inv}}{P_{base}}
 \end{aligned} \tag{4}$$

where,

m : the modulation index of the PWM inverter

K_m : PWM inverter constant for integral control

V_{set} : voltage constant follow a droop characteristic that is function on the grid power

θ : the phase angle difference between the inverter angle and the PLL angle

K_θ : active power constant for integral control

P_{set} : active power depend on droop characteristic

P_o : nominal active power output of the microgrid

R : droop constant

V_{dc} : dc voltage output from the PWM inverter

I_{inv} : PWM inverter output current

V_{base} : per-unit base voltage for the dc bus and PWM inverter

P_{base} : per-unit base active power for the dc bus and PWM inverter

In [1] the mathematical model in Equation (4) is used and implemented as seen in **Figure 5**. The loop filter employed in method (1) was P-controller as illustrated in **Figure 5**. In the second method the loop filter used was PI-controller and the block diagram is simplified as shown in **Figure 6** [20].

4. Proposed Control Technique

In **Figure 6**, there are two controllers one for the PLL and the other for the active power. A PI controller is used for the PLL loop, while a P controller is used for the active power loop. The gains for both controllers are tuned via evolutionary methods based on simulating annealing techniques. The tuned gains are guaranteed high-quality control responses for these controllers in regard of optimizing the control response parameters; minimum over-shot, rise-time and settling time control.

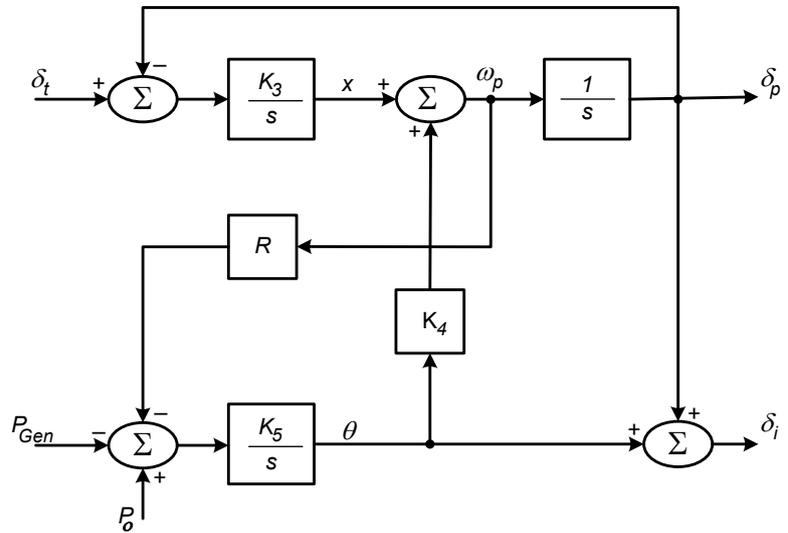


Figure 5. PLL and active power controllers block diagram, method (1) [1].

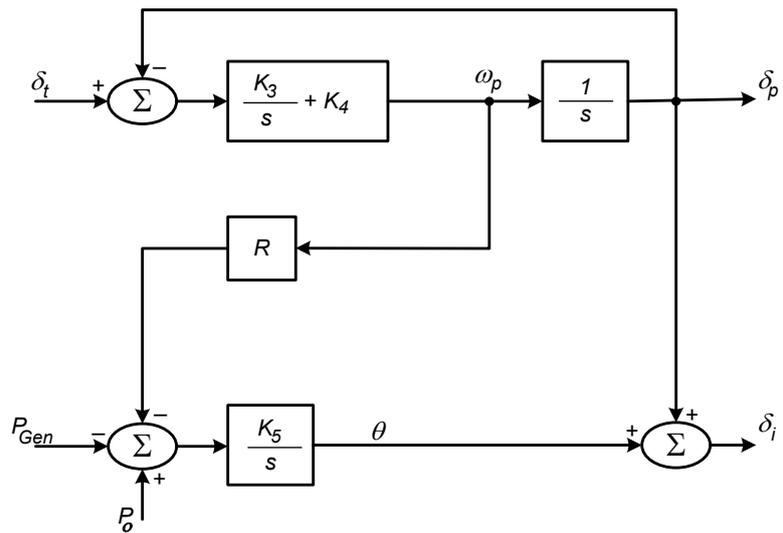


Figure 6. PLL and active power controllers block diagram, method (2) [20].

a) *Simulating Annealing*

Simulated Annealing (SA) is a straightforward efficient optimization technique presented in [21]. The function to be optimized in SA is called the energy, $E(x)$, of the state x , and at the same point, the computational temperature (T), is dropped throughout the process. SA is an iterative trail algorithm that preserves a single candidate solution at any time [22]. Moreover, the main benefit of using SA is its capability to prevent being stuck in local optima. SA has been examined and showed a well performance in a variety of single-objective and multi-objective optimization application [23] [24].

The SA is used to optimize P and PI controller parameters of the active power and the PLL respectively. It is a multi-objective optimization problem as three step response parameters are simultaneously adjusted. In the proposed system, SA will accept a transition that leads to a decrease in all objectives (overshoot,

rise time and settling time) or a decrease in one of the objectives if other objectives are not changed. SA will also accept a transition from state S_1 to S_2 if S_2 does not dominate S_1 with a probability of $e^{-\Delta f/T}$, where $\Delta f = f(S_2) - f(S_1)$, and T is the temperature parameter which is being reduced over time during the process in order to decrease the possibility of accepting such transitions. The SA proposed approach for the PI-controller gains selection is summarized in flow-chart shown in **Figure 7**.

5. Results

The microgrid proposed system in **Figure 1** is used to demonstrate and test the dynamic behavior of the components of this system. All the ac quantities used in this system is articulated in per-unit values. The base values are given in **Table 1**.

In the proposed system, the set values for different elements are shown in **Table 2**.

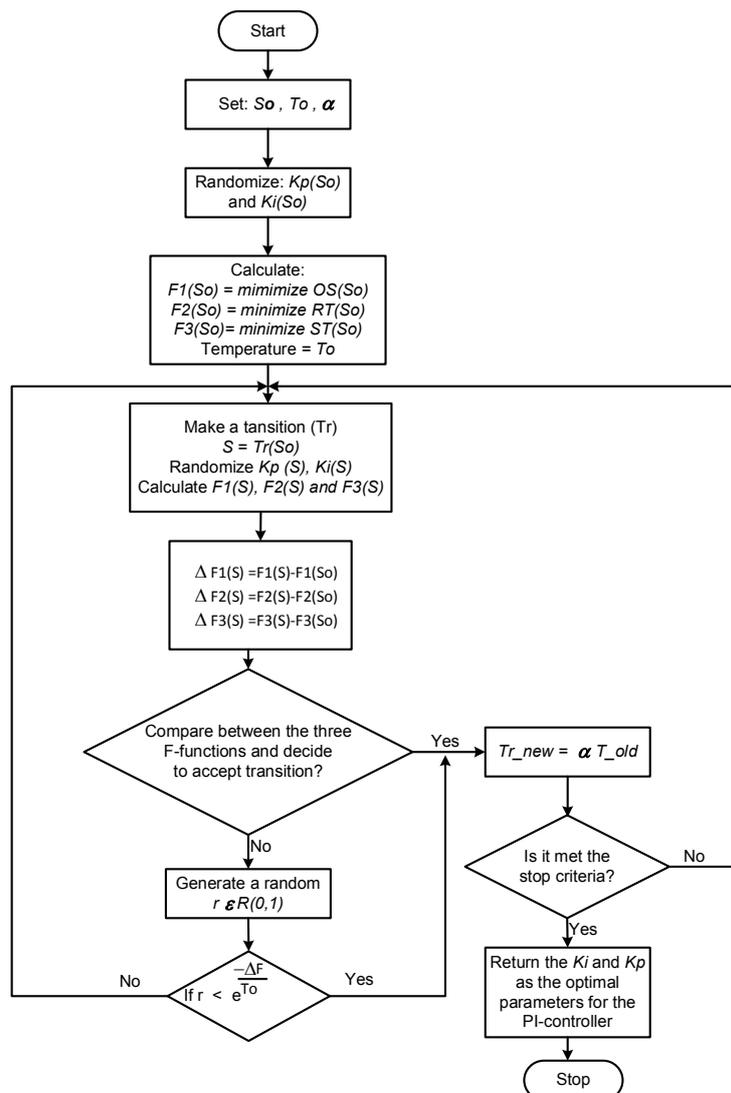


Figure 7. The SA proposed approach for the PI-controller gains selection.

Table 1. Base value used in the proposed system.

Quantity	Base value	Description
Power	100 kVA	Is used for the inverter and the grid
Voltage	240 V	DC bus and the inverter

Table 2. Set values of the proposed system.

Element	Value
Plant 1 power set point	0.7 pu (70 kW)
Plant 2 power set point	0.6 pu (60 kW)
Load power	1.7+ j 0.6 pu
Grid voltage	1 pu

The parameters of the two-PWM inverters and the PLL used in [1] are given **Table 3**. The controller parameters selected by SA is illustrated in **Table 4**.

The main test is implemented as given in [1] on the proposed system, the test scenario is as follows:

- 1) The CB connected to the grid is initially closed.
- 2) The two microgrids plants supply 1.3 pu of the active power demand by the load.
- 3) The remaining 0.4 pu active power is drawn from the main grid.
- 4) At $t = 1$ sec, the CB is opens and the total load has to be supplied by the two-microgrids plants.
- 5) At $t = 7$ sec, the CB is signaled to close, but closing is prevented until the voltage magnitude across the CB contacts reduces to the threshold $\sqrt{0.05}$ pu³.
- 6) At $t = 13.01$ sec, the CB contacts are closed.

This test scenario is done for three PLL cases, case (1) is for PLL P-controller as in [1] and case two for PLL PI-controller designed by Ziegler and Nichols, and the proposed technique in case (3) is for PLL SAPI-controller in which the maximum overshoot, rising time, and settling time parameters of the controlled parameter response is minimized.

Tuning the PLL controller parameters is a vital process in autonomous microgrid plants as it will reflect on many parameters response in these systems, as power, current and voltage. In this paper, the up given test scenario is done, and the results are given in **Figures 8-11**. **Figure 8** shows the power delivered by each PWM inverters in the three-cases. In **Figure 8(a)** it shows the power delivered by the two plants, up is plant 1 and down is plant 2. Note that, Plant 1 has a higher set point than Plant 2. Therefore, the overshoot in Plant 1 for case (1) and case (2) is higher than in Plant 2 as shown in **Figure 8(b)** and **Figure 8(c)**. Although, in the proposed technique (case (3)), the both plants have dead beat responses. Based on **Figure 8** result, a comparison between overshoot, rise-time and settling-time parameters for the three-cases are given in **Table 5**. Based on this comparison the proposed technique case is the best compared to the other two cases.

Table 3. PWM inverters and PLL parameters.

Parameters	Value
K_3	20
K_4	10
K_5	20
R	0.4
X	0.2 pu
V_{set}	1 pu
V_{dc}	480 V

Table 4. SA controllers' parameters for PLL and active power.

Parameters	Value
K_3	9.67
K_4	18.89
K_5	9.52

Table 5. Control index-parameters comparison based on **Figure 8**.

Plant number	Controller Type	Control index-parameters		
		Maximum overshoot (%)	Rise time (sec)	Settling time (sec)
Plant 1 CB open	PLL P-controller	27.3	0.252	1.457
	PLL PI-controller	11.05	0.215	0.982
	PLL SAPI-controller	2.05	0.162	0.213
Plant 1 CB close	PLL P-controller	25	0.231	1.41
	PLL PI-controller	10	0.212	0.972
	PLL SAPI-controller	1.98	0.159	0.208
Plant 2CB open	PLL P-controller	22.1	0.243	1.402
	PLL PI-controller	9.56	0.187	0.971
	PLL SAPI-controller	1.92	0.129	0.195
Plant 2CB close	PLL P-controller	21.11	0.241	1.398
	PLL PI-controller	9.23	0.181	0.962
	PLL SAPI-controller	1.89	0.127	0.194

The PLL frequency deviation for the two microgrid PWM inverters in the three cases is illustrated in **Figure 9**. The PLL SAPI-controller gives the best response from the three selected control parameters (percentage of maximum overshoot, rise time and settling time).

Moreover, the proposed technique in **Figure 8**, and **Figure 9** are characterized by a deadbeat response which reflects the effectiveness realization of the proposed SAPI-controller designed in this paper.

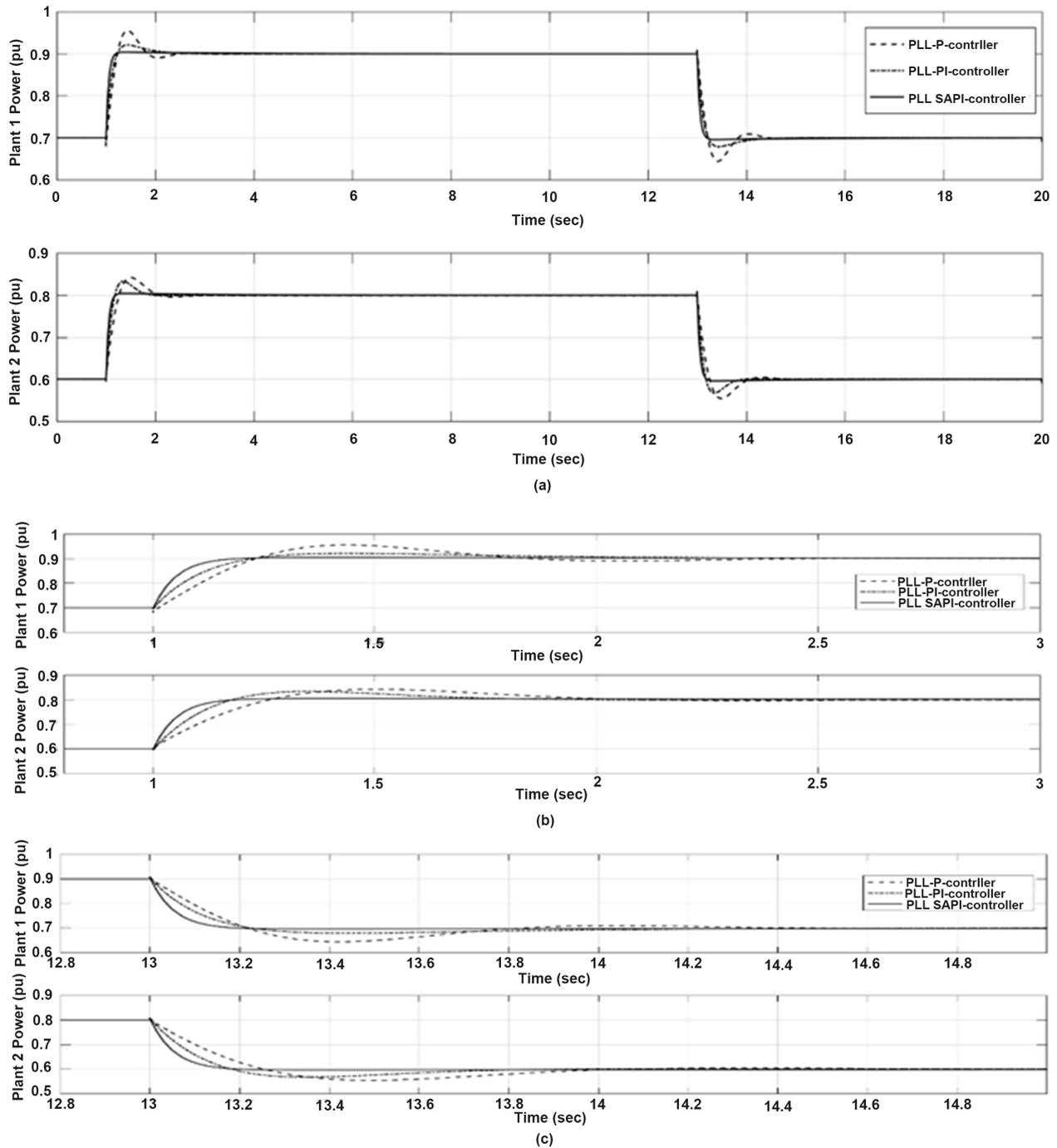


Figure 8. Active Power output from the two microgrid PWM inverter plants during open and reclose of CB, (a) overall, (b) CB open, and (c) CB reclose.

Figure 10 presents the microgrid Plant 1 PWM inverter angle with respect to synchronous reference in the three cases. It also shows that the PLL angle strictly tracks the terminal bus angle. The differences between these quantities is provided obviously in **Figure 11**. It has been shown that the PLL SAPI-controller is the best and the fastest to derive this difference to zero. Although, when the CB is closed, the subsequent phase shift in the PWM inverter terminal bus voltage

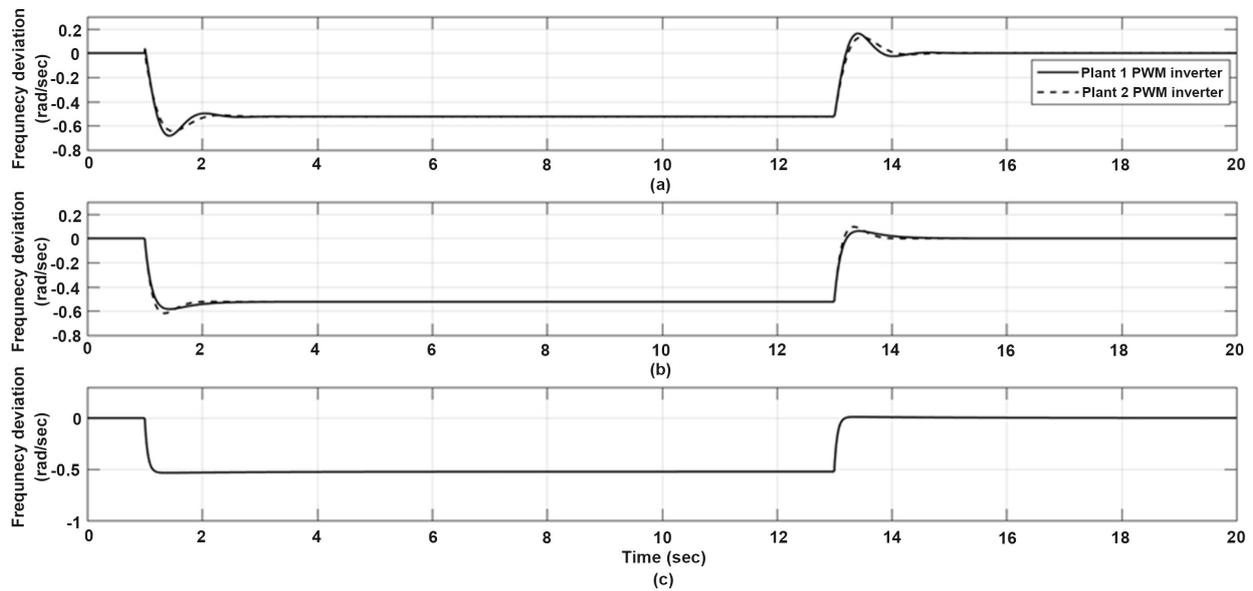


Figure 9. The PLL frequency deviation for the two microgrid PWM inverters in the three cases. (a) PLL P-controller, (b) PLL PI-controller, and (c) PLL SAPI-controller.

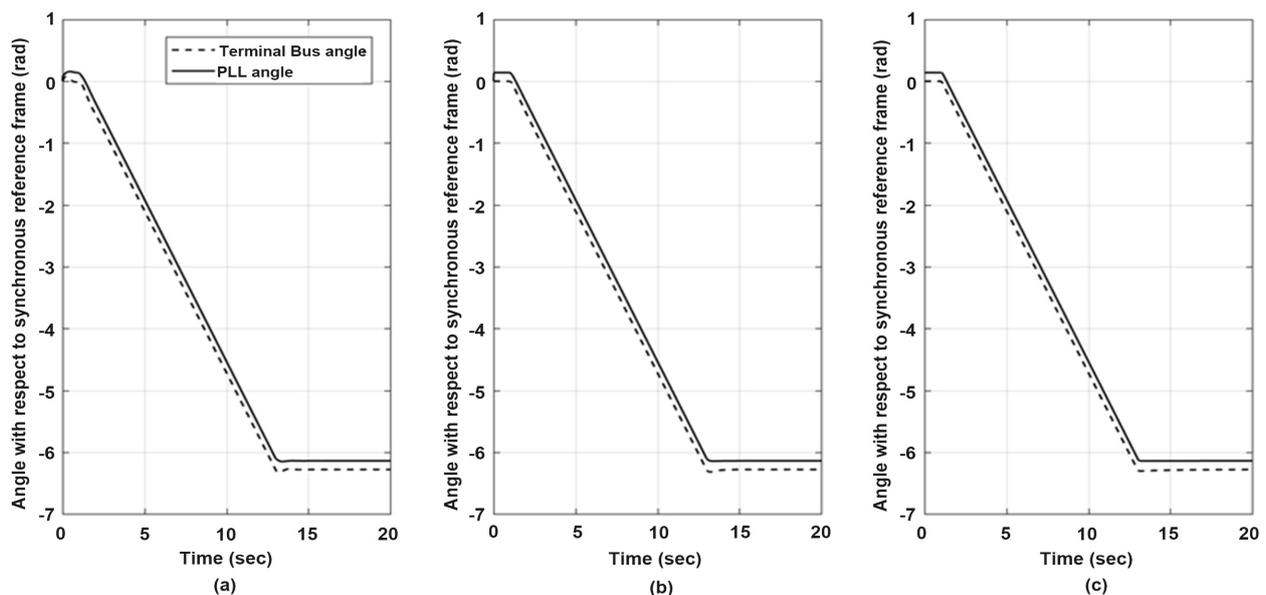


Figure 10. Microgrid Plant 1 PWM inverter angle with respect to synchronous reference in the three cases. (a) PLL P-controller, (b) PLL PI-controller, and (c) PLL SAPI-controller.

produces a spike in the angle difference across the PWM inverter and the transformer. That spike in angle difference is similar to spike in active power P_{gen} detected in **Figure 8**. In practice, the transformer inductance would limit most of these spikes.

6. Conclusions

Autonomous microgrid is being rapidly connected to the utility grid at the distribution level. For enhancing and improving the microgrid dynamic performance,

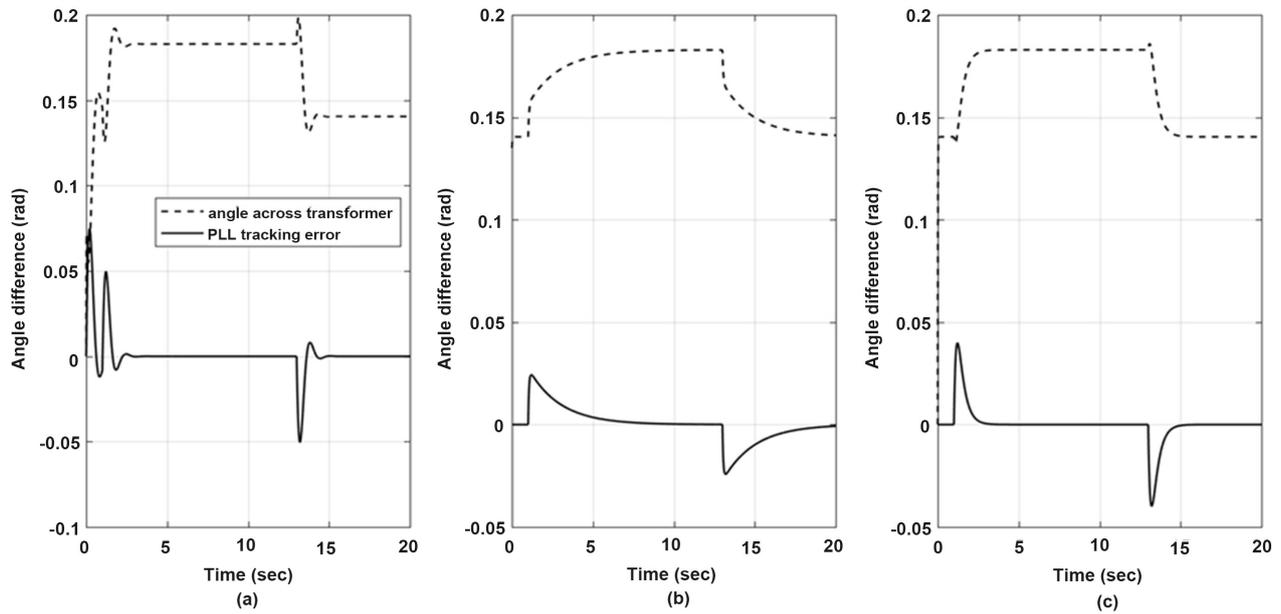


Figure 11. Microgrid Plant 1 PWM inverter angle differences in the three-cases. (a) for PLL P-controller, (b) for PLL PI-controller, and (c) for PLL SAPI-controller.

the active load needs to be synchronized with it. The phase locked loop (PLL) is used for this purpose. The main challenge in designing the PLL is tuning the gains for PLL active loop filter. In this paper, an example of two microgrids connected to the utility grid and the load is proposed. The dynamic model of the proposed system is given. The interaction between the dynamics of PWM inverter of any of the microgrid and the PLL can introduce oscillations. The gain selection of the PLL PI control is done by simulating annealing (SA) technique that granted minimal overshoot, rise time and settling time. The proposed PLL SAPI-controller provides an extraordinary response with these features. Results confirm the effectiveness of the proposed PLL controller to enrich the system dynamics and acts as a platform for autonomous microgrid systems.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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