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A Novel Control Strategy for a Single-phase Grid-connected Power Injection System

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ABSTRACT

In this paper, a novel and simple control approach to controlling the power injection system (PIS) using state feedback is proposed. The PIS is composed of a DC voltage source, a voltage source inverter (VSI) and an L-C-L filter. The DC source is a battery with boosted voltage. The battery can be charged with photovoltaic cells. Since the grid voltage acts as a disturbance, the state space model is modified to reject the disturbance. The minimum necessary input DC voltage is also calculated according to specified injection power. Moreover, to avoid measurement problems such as noise and cost, an observer is designed. The major problem with single-phase PISs is the injection of some DC current with AC current. We show that the proposed controller not only performs near perfect tracking, but also eliminates the DC current injected into the grid. Further, a Proportional-Resonant (PR) controller is designed and applied to the PIS for comparison. Simulation results show that the proposed method has significant advantages over the PR controller such as simple realization and application, low overshoot, no DC offset at the output current and fast response. The simulations are performed using average and accurate models of PIS. The results confirm the advantages of proposed method over PR controller.

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1. INTRODUCTION

Single-phase voltage source inverters (VSIs) as well as three-phase are used to connect small-scale renewable energy sources such as fuel cells and/or photovoltaic cells to the low voltage distribution networks [1]. Since the voltage of connection terminal is regulated from the network, their operation is to inject sinusoidal current into the network. Therefore, by controlling the current amplitude and phase, one can inject a determined power into grid.

Too many controllers have been introduced to control the injected current into the network. The most popular controller is Proportional-Integral (PI) controller. This type of controller is used in analog and digital modes [2, 3]. The PI controller performance is admissible when it is applied to three-phase inverter because the control variables are transformed to stationary axis (dq) at first. Then, the PI controller acts on the constant commands. For the single-phase inverters, the reference signal is sinusoidal and there will be steady-state error when the PI controller is used [4]. To overcome this shortcoming, the proportional-resonant (PR) controller has been proposed [5-9].

The PR controller has the dynamic of reference signal; therefore, the output can track the reference signal without steady-state error. The gain of PR controller is infinite at resonant frequency. This is the major drawback of PR controller. To overcome this drawback, a feed-forward is applied from the grid voltage [10]. This technique modifies the performance of the inverter but it causes another problem. It injects back the grid harmonics into the current and magnifies the problem [11]. Since the reference signal is periodic, the repetitive controller has also been used [12].

The major advantage of the repetitive controller over PR is that it can be used for tracking a periodic signal with any shape, where the PR controller is used for tracking only a sinusoidal reference. The drawback is that it may be unstable in some circumstances [12]. The pole-placement technique is another controller, which

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has been used to control the inverter [13]. It is shown that its performance is better than conventional PI controller [13] but a PR controller may acts better for his zero steady-state error. The sliding mode controller is a variable structure controller, which is employed in inverters [14]. To implement this controller, a time-varying surface is considered to track a sinusoidal reference. Its major advantage is its robustness on uncertainty and parameter change but it needs complicated computation [15]. The hysteresis controller is also a large usage controller [16, 17]. It is simple and robust. Its major shortcoming is the variability of switching frequency. Deadbeat controller is another simple controller [18, 19] but its performance is drastically depends on passive element variation and control time delay [20]. An Adaptive neuro-Fuzzy controller, [20] has been used to control of a single-phase inverter and its performance compared with the conventional PI controller. The reliability of power injection systems (PISs) is another issue that is investigated and quantified in [21]. Another controller which is practical is polynomials curve fittings [22]. Inthis method, the switching angles using harmonic elimination PWM is calculated. Space vector control is also used to controlling inverters [23]. This controller is complicated in apllication.

One of the most problems in the single-phase inverters, which inject current into the network is that they inject some DC current with AC. The injected DC current must not exceed to a determined value. This value differs in each country. For example, Australian standard AS 4777.2-2005, section 4.9 imposes limits on DC injection into the AC network by grid-connected inverters. Many researches have been done to eliminate this DC offset [24-28]. In this paper, we propose a controller such that in addition to complete reference tracking, it prevents to inject DC current into the grid. The new method is benefited from state feedback technique.

In this paper, our goals is to inject a specified active power into the grid with zero steady-state error and no DC current. In this regard, we use a single-phase voltage source inverter (VSI) to convert the DC voltage to AC and an LCL filter to attenuate undesired harmonics. For this purpose we use the state feedback method. By placing the poles at specific location, desires able to be fulfilled.

The paper is organized as follow: in section 2, the average model of PIS is obtained. The disturbance rejection is discussed in section 3. The minimum necessary DC input voltage is computed in section 4. The section 5 is dedicated to design of proposed modern and conventional classic controller. In section 6, an observer is designed. The simulation results are illustrated in section 7 and finally the conclusion is given in section 8.

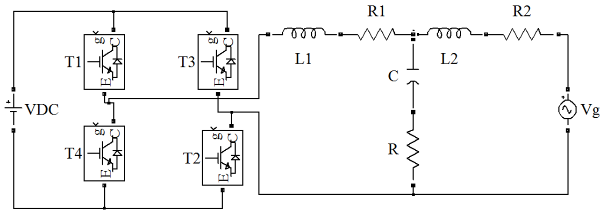


Figure 1. Power injection system to a single phase grid

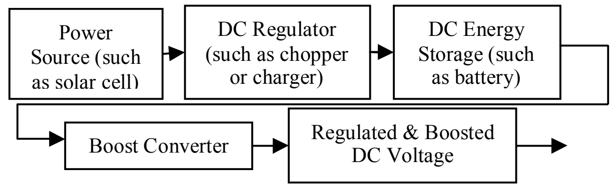


Figure 2. The block diagram of providing DC link voltage

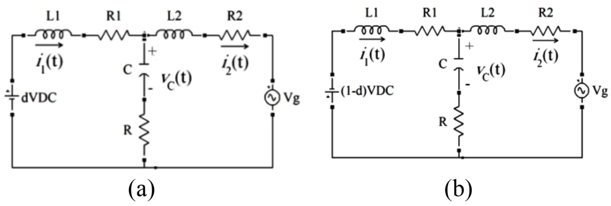


Figure 3. Equivalent circuit of power injection system a) in duty cycle interval and b) in complementary duty cycle interval

2. MODELING OF POWER INJECTION SYSTEM

The system is composed of two parts: power and control. The power part contains of a voltage source inverter and a low-pass filter. The inverter, convert the input DC voltage to unfiltered AC voltage. The filter attenuates undesired harmonics and injects filtered current into the grid. The DC voltage is provided by fuel cells, solar cells, etc. Usually, the output of cells is boosted and stabilized at first by using of a boost DC-DC converter. After that, it is applied to the inverter. In this research, we focus on the inverter control and assume a regulated DC voltage is available. Figure (1) is the circuit diagram of the power part of power injection system.

The switches T1-T4 constitute the VSI, the elements L1, R1, L2, R2,C and R form the filter and Vg is the grid voltage. The DC source can be provided as the following block diagram (Figure 2).

The inverter has two operation modes. Assume that in the first mode (duty cycle interval (d)) the T1 and T2 switches are closed and in the second mode (complementary time (1-d)), the switches T3 and T4. Figures (3a) and (3b) show the equivalent circuit in duty cycle and complementary duty cycle intervals. By assuming the grid voltage with fixed amplitude, it is sufficient to control of the current injected to the grid ($I_2(t)$). This is achievable by controlling the duty cycle (d).

Consider the inductors' currents and capacitor's voltage as the state variables. The state space equations are obtained as follow.

$$\dot{x} = Ax + Bu + D_g v_g(t);\quad y(t) = Ex;\quad x = \begin{bmatrix} i_1(t) \\ i_2(t) \\ v_C(t) \end{bmatrix},$$
$$u = 2d - 1,\ 0 \le d \le 1 \Rightarrow -1 \le u \le 1,$$
$$A = \begin{bmatrix} -\frac{R+R_1}{L_1} & \frac{R}{L_1} & -\frac{1}{L_1} \\ \frac{R}{L_2} & -\frac{R+R_1}{L_2} & \frac{1}{L_2} \\ \frac{1}{C} & -\frac{1}{C} & 0 \end{bmatrix},\ B = \begin{bmatrix} \frac{V_{DC}}{L_1} \\ 0 \\ 0 \end{bmatrix},\ E = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T,\ D_g = \begin{bmatrix} 0 \\ -\frac{1}{L_2} \\ 0 \end{bmatrix} \tag{1}$$

The grid voltage appears as time varying disturbance in the model. We will propose a technique to reject the disturbance.

3. DISTURBANCE REJECTION

For complete disturbance rejection, Firstly, the effect of grid voltage on i_2 is computed. Then, to attain the desired pure active power injection, the desired current i_2 is obtained by considering the effect of grid voltage. The stated approach is accurate but it is difficult to compute. Moreover, it is problematic to control the system to track the calculated current. A simpler and approximate approach is explained as follow:

It was stated that our goal, without loss of generality, is to inject a constant pure active power to the grid for simplicity. Therefore, the current i_2 and the grid voltage v_g must be in-phase synchrony with zero phase difference. In practice, a phase-locked-loop (PLL) can extract the grid voltage phase. Suppose that the desired active power is equal to P. In steady state, we have:

$$v_g(t) = V_m \sin(\omega t),\ i_{2ss}(t) = I_m \sin(\omega t)$$
$$P = \frac{1}{2} V_m I_m \Rightarrow v_g(t) = K_{vi} i_{2ss}(t),\ K_{vi} = \frac{2P}{I_m^2} \tag{2}$$

where, i_{2ss} is the steady state output current. By replacing v_g with $K_{vi} i_2(t)$ in state space model, the model changes as follow:

$$\begin{cases} \dot{x} = A_{\text{modified}} x + Bu \\ y(t) = Ex \end{cases},\ A_{\text{modified}} = \begin{bmatrix} -\frac{R+R_1}{L_1} & \frac{R}{L_1} & -\frac{1}{L_1} \\ \frac{R}{L_2} & -\frac{R+R_2+K_{vi}}{L_2} & \frac{1}{L_2} \\ \frac{1}{C} & -\frac{1}{C} & 0 \end{bmatrix}$$
$$,\ B = \begin{bmatrix} \frac{V_{DC}}{L_1} \\ 0 \\ 0 \end{bmatrix},\ E = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T \tag{3}$$

when it is talked about the power injection using photovoltaic cells, the most power injection is considered. In this study, it is assumed that the photovoltaic cells power can be taken up and stored in batteries. When the energy consumption of the network increases for example at the peak of the load, it is the best time for power injection into the grid. This is very important in smart grids. Furthermore, the injection rate can be expressed by the smart grid-dispatching center and is not very variable.

4. MINIMUM REQUIRED INPUT DC VOLTAGE

To achieve the desired AC current at the output terminal, the input DC voltage should not be less than a minimum value. For the average model (Figure (4)), we have:

$$V_1\angle\theta_v = (j\omega L_2 + R_2) I_{2des}\angle 0 + V_g\angle 0 \quad I_1\angle\theta_i = \frac{V_1\angle\theta_v}{R + \frac{1}{j\omega C}} + I_{2des}\angle 0$$
$$V_{In} = I_1\angle\theta_i (j\omega L_1 + R_1) + V_1\angle\theta_v \quad |V_{In}| = mV_{DC},\ 0 \le m \le 1 \tag{4}$$

where, I_{2des} is the desired output current.

The currents and the voltages have been written in phasor space. The phase of grid voltage is selected as the basis phase. The parameter 'm' is the modulation index and it is usually determined less than one for more precaution.

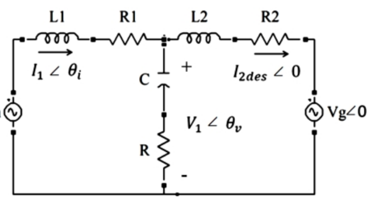


Figure 4. Average model

5. DESIGN OF CONTROLLER

In this section, we design two controllers: PR controller and proposed controller. The PR controller is conventional and is designed only for comparison.

5. 1. PR Controller

Before designing the proposed modern controller, the design of PR controller is explained concisely for tracking sine wave without error. The block diagram in Figure 5 shows the classic configuration of the closed –loop system where

$$g(s) = \frac{RCs + 1}{P(s)} V_{DC},\quad g_g(s) = \frac{Q(s)}{P(s)}$$
$$P(s) = L_1 L_2 C s^3 + \left(L_1 R_2 C + R_1 L_2 C + L_1 RC + L_2 RC\right) s^2$$
$$+ \left(R_1 R_2 C + L_1 + L_2 + (R_1 + R_2) RC\right) s + R_1 + R_1 \tag{5}$$
$$Q(s) = L_1 C s^2 + \left(R_1 + R\right) Cs + 1$$

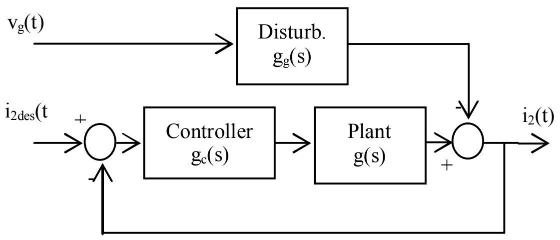


Figure 5. The classic closed –loop system configuration

In order to have a complete tracking, the loop transfer function must contain the desired internal dynamic [29]. Since the reference signal (desired) is sinusoidal, the controller is determined as follow,

$$g_c(s)=\frac{N_c(s)}{s^2+\omega^2} \tag{6}$$

The controller numerator $N_c(s)$ must hold two conditions:

1. Its maximum degree cannot be greater than two for realization problem [30]
2. The closed-loop must be stable.

The PR controller adds two poles and at least one zero to closed-loop system, the poles for complete tracking and the zero for stability.

Assume $N_c(s)$ is a first order polynomial as follow:

$$N_c(s)=as+1 \tag{7}$$

Therefore, the closed-loop transfer function is:

$$T_{c.l.}(s)=\frac{g_c(s)g(s)}{1+g_c(s)g(s)}=\frac{V_{DC}\left(aRCs^2+(a+RC)s+1\right)}{P(s)\left(s^2+\omega^2\right)+V_{DC}\left(aRCs^2+(a+RC)s+1\right)} \tag{8}$$

Parameter 'a' must be chosen such that the roots of the denominator polynomial be in the left-half plane. This procedure can be easily performed by applying Routh-Hurwitz algorithm [29]. The drawback of the aforementioned controller is its high degree, high overshoot, difficulty in realization and application.

5. 2. Proposed Controller

The modern closed –loop system configuration is as follow (Figure 6):

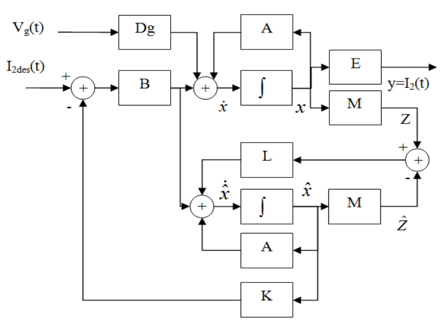


Figure 6. The modern closed –loop system configuration

As mentioned before, the loop transfer function must contain $\frac{1}{s^2+\omega^2}$. Assume the open-loop transfer function is:

$$g(s)=\frac{I_2(s)}{U(s)}=\frac{N(s)}{D(s)} \tag{9}$$

Therefore, the model reference of closed-loop transfer function will be as follow:

$$T_{MR}(s)=\frac{N(s)}{\left(s^2+\omega^2\right)D'(s)+N(s)} \tag{10}$$

Consequently, a pole-placement must be performed in order to meet the goal. Doing this, it is necessary that the system to be controllable. The controllability matrix is:

$$\phi_c=\left[B \quad A_{\text{modified}}\,B \quad A^2_{\text{modified}}\,B\right] \tag{11}$$

The rank of ϕ_c is three according to Equations (1) and (3), hence the system is controllable and the poles can be replaced at the desired points [30] using state feedback.

N(s) is unchangeable under state feedback [30]. Since the degree of the system is unaffected too, the denominator D'(s) has to be first order. Assume D'(s) as follow:

$$D'(s)=s+\alpha \tag{12}$$

N(s) can be determined from open-loop transfer function as below:

$$N(s)=b_1s+b_0,\, b_1=\frac{RV_{DC}}{L_1L_2},\, b_0=\frac{V_{DC}}{L_1L_2C} \tag{13}$$

Therefore, the desired characteristic function is:

$$\Delta_{des}(s)=s^3+\alpha s^2+\left(b_1+\omega^2\right)s+\alpha\omega^2+b_0 \tag{14}$$

Before computing feedback gain, the parameter α should be determined. In this regard, α is chosen such that the closed-loop system has maximum stability. This selection may be done using root locus versus α (Figure 7)

Now, it is time to compute the feedback gain. For this purpose, we require the open-loop characteristic function. The unmodified and modified characteristic functions are as follow, respectively.

$$\Delta_{o-um}(s)=\frac{P(s)}{L_1L_2C};\ \text{for unmodified model} \tag{15}$$

$$\Delta_{o-m}(s)=\frac{1}{L_1L_2C}\left(P(s)+K_{vi}Q(s)\right)\ ;\ \text{for modified model} \tag{16}$$

Having $\Delta_{des}(s)$ and $\Delta_{o-um}(s)/\Delta_{o-m}(s)$, the feedback gain $K=[K_1 \quad K_2 \quad K_3]$ is computed by using Ackermann [31] or Bass-Gura method [30].

The proposed modern controller is designed for a sample PIS in section (7) and its performance illustrated in Figures (8-12)

6. DESIGN OF OBSERVER

The feedback control approach requires all state variables. Therefore, one Voltmeter and two amperemeters are necessary in control part. Application of these instruments has two major drawbacks: cost and noise. To overcome these drawbacks, we propose an observer, which needs only measuring one state variable. Since the voltmeter is cheaper and more accurate in comparison with amperemeter, let the capacitor voltage be considered as the measured signal. This alteration does not effect on the controller and system because the controller needs only the state variables. The proposed observer must estimate the other state variables. The observer dynamical equations are considered as follow:

$$\dot{\hat{x}} = A_{\text{modified}}\hat{x} + Bu + L(Z - M\hat{x})$$
$$y(t) = Ex(t) = i_2(t)$$
$$Z(t) = Mx(t) = v_C(t)$$
$$\hat{x} = \begin{bmatrix} \hat{i}_1(t) \\ \hat{i}_2(t) \\ \hat{v}_C(t) \end{bmatrix}, u = -K\hat{x} + i_{2des},\ B = \begin{bmatrix} \frac{V_{DC}}{L_1} \\ 0 \\ 0 \end{bmatrix},\ M = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}^T,\ E = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}^T \quad (17)$$

where, $\hat{x}$, v_C and i_{2des} are the estimation of the state vector, capacitor voltage and desired output current respectively and L is the observer gain. Z(t) is the measured signal. Note: the output of the system is y(t) but the measurement is performed on the capacitor voltage. Therefore, the estimation must be executed by using the measurement information. The observer error dynamical equation is:

$$\dot{e} = (A - LM)e,\ e = x - \hat{x} \quad (18)$$

The gain L is designed such that the observer error dynamical system is stable.

The performance of the closed-loop system, including proposed controller and observer will be illustrated in Figure (11) in which applied to the average and accurate models.

7. SIMULATION

Assume the goal is to inject 11kW pure active power into the grid. The filter parameters are chosen as [32], L_1=2mH, R_1=0.2Ω, L_2=1mH, R_2=0.1Ω, C=5 μF, R=5Ω. The grid voltage is assumed as $v_g(t) = 220\sqrt{2}\sin(\omega t)$, $\omega = 100\pi$, consequently the reference current is $i_{2des}(t) = 50\sqrt{2}\sin(100\pi t)$, therefore, K_{vi}=4.4. The minimum required DC voltage is calculated based on Equation (4). For a sample modulation index m=0.85, this is equal to 400 volt, V_{DC}=400 v. The parameters and variables/constants are listed in Tables (1) and (2).

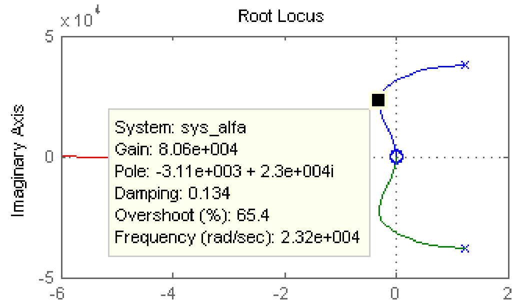


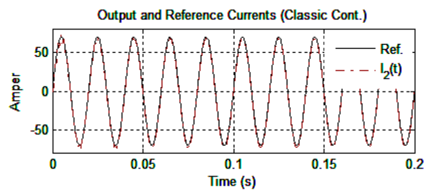
Figure 7. Root locus of closed-loop system versus α

TABLE 1. Filter Parameters

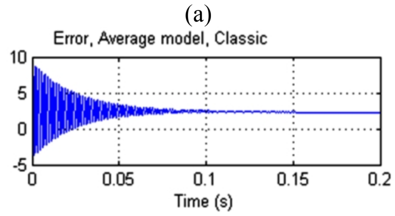
L_1	R_1	L_2	R_2	C	R
2mH	0.2Ω	1mH	0.1Ω	5 μF	5Ω

TABLE 2. Variables and Constants

P_{des}	$v_g(t)$	ω	V_{DC}
11kW	$220\sqrt{2}\sin(\omega t)$	100π	400 v



(a)



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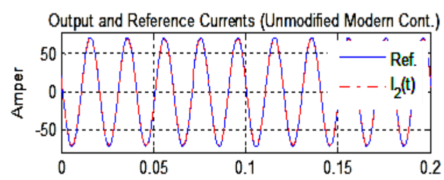

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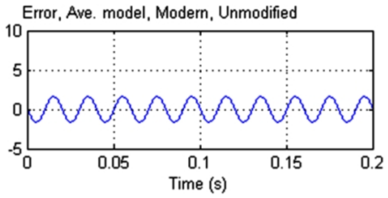


(d)

Figure 8. Output and Reference currents and tracking error for average model a&b) using conventional PR controller c&d) using proposed unmodified modern controller

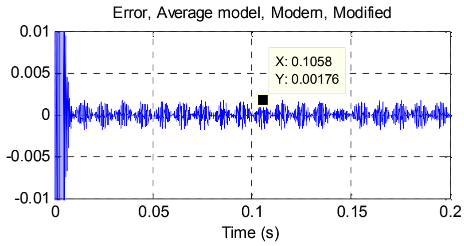


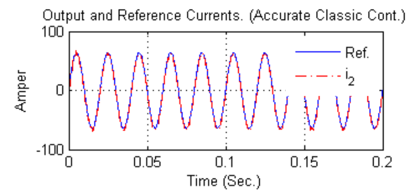
Figure 9. Output current tracking error for average model using proposed modified modern controller

To design the proposed controller, we need to the open-loop and the desired closed-loop characteristic equations. The characteristic functions for unmodified and modified models are:

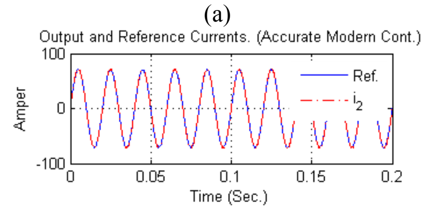
$\Delta_{o-um}(s) = s^3 + 7700\ s^2 + 3.008 \times 10^8 + 3 \times 10^{10}$ and $\Delta_{o-m}(s) = s^3 + 1.21 \times 10^4 s^2 + 3.122 \times 10^8 + 4.7 \times 10^{11}$ respectively. For the closed-loop configuration, the characteristic function depends on the parameter α. $\Delta_{des}(s) = s^3 + \alpha s^2 + \left(1 \times 10^9 + \omega^2\right)s + \alpha\omega^2 + 4 \times 10^{13}$. To find the optimal α from the viewpoint of stability, we rearrange the characteristic equation and plot the root locus versus α (Figure (7))

It can be obtained from the root locus that $\alpha = 80600$ gives the most stability. Using Ackermann method, the feedback gains are calculated for unmodified and modified models as k_{um}=[0.3928 0.6075 -0.0077] and k_m=[0.3708 0.6981 -0.0179], respectively. Moreover, the PR controller is designed such that the closed-loop be stable, therefore we get $g_c(s)=\frac{100s+1}{s^2+\omega^2}$.

Figure (8) illustrate the performance of the classic (PR) and the proposed modern controller on unmodified average model. The simulation results display that the error tends to a constant value (DC current) by using PR controller. In addition, the response has huge oscillations at the beginning. However, by using proposed controller, the error oscillates around zero with small amplitude (less than 3%). The oscillation is imposed by input disturbance. The frequency of oscillation is as much as grid frequency (50Hz). The major drawback of the classic approach is the DC offset current at the output while it is not seen in proposed approach. Figure (9) illustrates the performance of the proposed controller on modified average model. The result shows that the proposed method acts successfully in disturbance rejection and the oscillation amplitude is less than 0.0018 A. Moreover, the proposed and classic PR controllers are applied to accurate model. Tried that in accurate model all physical problems to be considered. The pulse-width-modulation (PWM) method is used to fire the switches. The PWM frequency is selected equal to 10KHz. The simulation has been done under Matlab Simulink software and the results are shown in Figure (10a, b). The simulation results confirm the higher performance of proposed controller over the classic method. The error amplitude, DC offset and the chattering are considerable for classic approach in comparison with proposed approach. Measuring all state variables is not reasonable. According to section (6), an observer system is designed in this regard. The observer gain is obtained as L=[-434.2 778.5 -4600] to locate the observer poles on [-1000 -1500 -5000]. The observer gain seems somewhat high. The reason is that we tried to locate the observer poles far from the imaginary axis. In practice, it cannot be chosen as high as before for noise effects. Reduction of the observer gain only causes slowdown of the rate of reaching the error to zero. Figure (11a) shows the estimation error of the three state variables and Figure (11b) shows the output error (difference between desired and real current) for average model. According to the figures, the observer error tends to zero in two periods (40 millisecond). The output error shows that the error goes to zero rapidly. The observer and controller are applied to accurate model in Simulink Matlab software and the following results are achieved.



(a)



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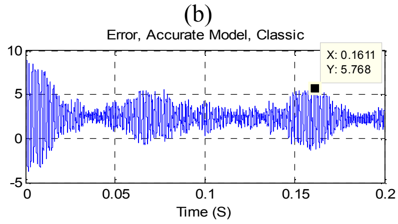

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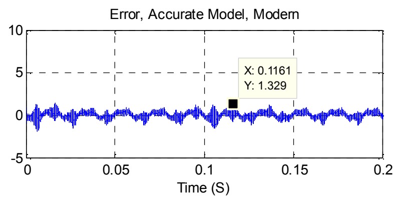
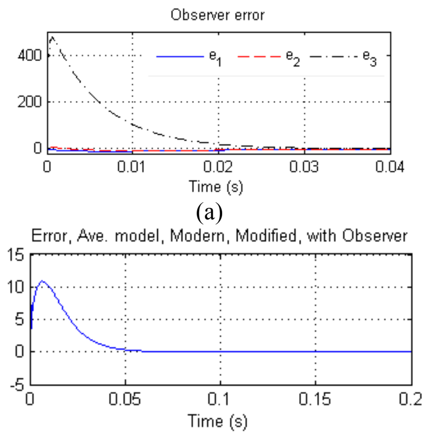


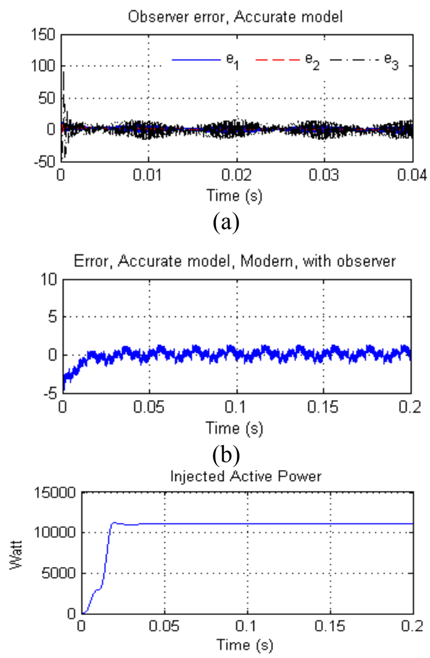
(d)

Figure 10. Output current tracking for accurate model a) Output Current and Reference using conventional PR controller b) Output Current and Reference using proposed modern controller c) tracking error using conventional PR controller b) tracking error using proposed modern controller



(b)

Figure 11. Proposed modern controller with observer applied to the average model, a) observer error, b) output error



(c)

Figure 12. Proposed modern controller with the observer applied to accurate model, a) observer error, b) output error and c) Injected active power

Figure (12a) shows that the observer error goes to zero but there is somewhat vibration on the signal. However, the vibrations on the estimated signals deteriorate slightly the output error but it is tolerable for the small amplitude (Figure (12b)). Figure (12c) shows the desired power injection. Before two periods (40 milliseconds), the injected power reaches to desired value.

8. CONCLUSION

In this paper, it was shown that in order to achieve a good performance, it is not necessary to design complex controllers but by slightly change in conventional controllers, one can achieve good results. In this regard, the conventional feedback controller is applied to power injection system by a little change and the results compared with conventional proportional-resonant method. Moreover, a trick was also used to eliminate the grid negative effects on the performance. Results indicate that the proposed method is far superior to conventional method. The main advantages of the proposed modern controller over conventional PR controller are; simple realization and application; low overshoot; lacking of the DC offset and fastness. However, the drawback of the proposed controller in contrast with classic controller is its prerequisite to all state variables. Furthermore, this shortcoming is also solved with an observer. Another disadvantage of the proposed methods as well as other controllers based on phase space is that they should be implemented in a microprocessor, in which, it imposes several difficulties and complexities such as: analog to digital converter and vice versa, delay in conversion, discretization error and etc.

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A Novel Control Strategy for a Single-phase Grid-connected Power Injection System

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چکیده

در این مقاله، یک رهیافت نو و ساده برای کنترل سیستم تزریق توان (PIS) با استفاده از فیدبک حالت ارائه می شود. PIS از یک منبع ولتاژ DC، اینورتر منبع ولتاژ (VSI) و یک فیلتر L-C-L تشکیل شده است. منبع DC یک باتری ولتاژ افزایش یافته می باشد. باتری می تواند توسط سلولهای فتوولتائیک شارژ شود. از آنجائیکه ولتاژ شبکه مانند اغتشاش در سیستم عمل می کند، مدل فضای حالت برای رفع اغتشاش اصلاح می شود. همچنین، حداقل ولتاژ DC ورودی مورد نیاز بر اساس توان تزریقی مشخص شده محاسبه می شود. علاوه بر این، برای پرهیز از مشکلات اندازه گیری مانند نویز و هزینه، یک مشاهده گر طراحی می شود. یکی از بزرگترین مشکلات سیستمهای تزریق توان تکفاز، تزریق مقداری جریان DC به شبکه است. ما نشان می دهیم که کنترل کننده پیشنهادی نه تنها باعث ردیابی تقریبا کاملی می شود، بلکه تزریق جریان DC به شبکه را نیز حذف می کند. برای مقایسه عملکرد کنترل کننده پیشنهادی، کترل کننده مرسوم تناسبی-رزونانسی (PR) نیز طراحی شده و به سیستم اعمال می شود. نتایج شبیه سازی نشان می دهد که روش پیشنهادی مزیتهای برجسته ای مانند سادگی تحقق و کاربرد، کاهش فراجهش، حذف جریان DC و سرعت پاسخ بالا در مقایسه با روش معمول PR دارد. شبیه سازیها بر روی مدل میانگین و دقیق پیاده سازی می شود. نتایج مزیت روش پیشنهادی را بر روش مرسوم PR تایید می کند.

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