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Design of a new backstepping controller for control of microgrid sources inverter

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ABSTRACT

Emergency power supply is becoming an important capability for many home or industrial electronic and computer devices. Therefore, the performance of the designed uninterruptible power supplies (UPS) inverters has low distortion at the output voltage. Initially, such inverters were controlled by proportional integral (PI) control classic rules. This method is difficult to understand the limitations of stability and to apply transient response to strong external disturbances. In this paper, an inverter is simulated and offered for single-phase and three-phase voltage controlled by a non-linear controller. For this purpose, a comparison has been made between the controller performance and the PI controller. In the first step, there is a backstepping regulator that uses the stability tool next to the Lyapunov function. And the other regulator operates according to the PI method. The performance of these two regulators is simulated during a change in reference or a load change in MATLAB. Also, a method of feedback voltage control based on the Lyapunov theory for controlling of the distributed generation (DG) unit independent inverter is presented. The proposed controller is not only simple, but also against the sudden changes in load and the unspecified system is resistant.

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1. INTRODUCTION

Distributed generation sources have enormous advantages so that it is expected to play an important role in the operation and planning of power systems in the near future. The status is changing, economic stimuli, technology growth, and environmental issues are shifting the configuration and current view of the power grid from generation to distribution [1]. Every microgrid is consisted number of new energy sources that require a voltage source or inverter to manage the voltage and power of each source to use the power output of these resources and to connect to the network. Converters such as a voltage source inverter (VSI) are commonly used as power interfaces in many applications including uninterruptible power supplies (UPS) and renewable energy systems (such as solar cells and wind turbines) [2]. Also, the good performance of the inverter independently and connected in the network, requires accurate voltage and frequency control to maintain the function and control the output power. The proper control of the voltage and frequency for the operation of the inverter in systems such as emergency power systems (EPS) and microgrid systems are required [3].

Different control schemes for the control of inverters in the grid are provided in the relevant literature. In the study [4], a proportional derivative (PD) controller with a proportional integral (PI) controller structure for the photovoltaic (PV) system is presented. The controller detects a voltage reference that shows with the specified error and the algorithm for maximum detection of the P, Q point of power. The main problem with the maximum power tracking algorithm is that in the steady state, the operating point varies around the maximum power point. Chapuis *et al.* [5] emphasizes the control of a single-phase direct current-alternating current (DC-AC) compensator used to provide uninterrupted power supply. The control goal in this field is to produce a sine voltage at the output of the system with amplitude and frequency fixed by the reference signal. Abdel-Rahim and Elshafei [5] have proposed the application of hierarchical fuzzy logic controllers for UPS applications. The proposed control scheme consists of two fuzzy controllers implemented in a nesting mode to create two control loops. Sustainability has a fundamental role in the theory and engineering of systems.

There are various sustainability issues that are being studied in the study of dynamical systems. Usually, the stability of points of equilibrium is checked by Lyapunov [6]. In this paper, we intend to control the output voltage of an inverter of distributed generation source in island condition by using a backstepping controller under ohmic, inductive and nonlinear load conditions, and the stability of the system is studied according to Lyapanov theory. Finally, it is compared with classic controllers. Inverter output voltage control is a distributed generation (DG) unit under different load conditions such as ohmic load, ohmic-inductive load, nonlinear load and no-load. The backstepping controller has a steady state error close to zero in following the reference signal. Backstepping controller is resistant to unmodulated dynamics and disturbances and noise.

2. METHOD

2.1. The structure of a single-phase inverter and mathematical modeling

The pulse width modulation (PWM) single-phase inverter shown in Figure 1. It consists of two arms with bi-directional couplings insulated gate bipolar transistors (IGBTs) or metal-oxide semiconductor filed effect transistor (MOSFET) with reverse parallel diodes that operate complementarily. The control signal μ is generated by the PWM generator and has a value between {1, -1} and in summary the binary commands μ1 and μ2 are of the two switching parts [7], [8].

$$\mu = \mu 1 - \mu 2$$
$$\mu = \begin{cases} : \mu_1 = 1 \; and \; \mu_2 = 0 \; \rightarrow (k_1, k_2')ON \; and \; (l_2, k_1')OFF \\ -1: \mu_1 = 0 and \; \mu_2 = 1 \rightarrow (l_2 . l_1')ON \; and \; (k_1, k_2')OFF \end{cases} \quad (1)$$

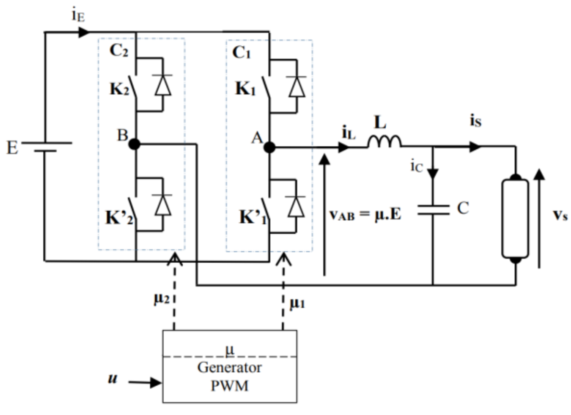


Figure 1. Design of a single-phase inverter with an LC filter [7]

For mathematical modeling of the inverter with a LC filter, uses mesh law and the mathematical equations node:

$$L\frac{di_L}{dt} = v_{AB} - V_s \quad (2)$$

$$c\frac{avs}{dt} = i_L - i_s \quad (3)$$

The output voltage of the inverter vAB, depending on the switch state (μ control signal), can have two values:

$$v_{AB} = \begin{cases} E \ when \ only \ (k_1, k_2') are \ ON \ ie \ \ \mu = 1 \\ -E \ when \ only \ (k_2, k_1') are \ ON \ ie \ \ \mu = -1 \end{cases} \quad (4)$$

Therefore, one can conclude:

$$v_{AB} = \mu E \quad (5)$$

This model is a system with variable structure: vAB is not a continuous variable and can be two discrete values of E and -E, so it is inappropriate to design a continuous control rule. To overcome this problem, we often have to use the average model (widely used for modeling static converters) [8], [9] the switching period in this case is assumed to be much smaller than the dynamic system. In our study, this is very acceptable. We have:

$$C\dot{x}_1 = x_2 - i_s \quad (6)$$

$$L\dot{x}_2 = uE - x_1 \quad (7)$$

Here, $\boldsymbol{x_1}$ and $\boldsymbol{x}_2$ represent the average value of sampling period of the Vs output voltage across the capacitor C and current i_L in the inductor L. The control variable $u \ \epsilon \ [-1,1]$ has between values -1 and 1 and represents the Average value of the control signal μ which is formed by rectangular pulse width modulation [10], [11]. It can be shown that a three-phase four-leg inverter (TPFLI) is equivalent to three independent single-phase inverters. It makes sense to design a voltage and current controller for single-phase parallel inverters instead of a direct controller design four-leg inverters. Then apply the same controllers to the four-leg parallel system using the T_(4_qdo) conversion matrices and vice versa. The noteworthy point here is that all the controllers are designed and implemented in the stationary device and the conversion is used only for modeling a four-leg inverter to three single-phase inverters. Figure 2 shows the proposed control structure for a four-leg inverter. In this figure, the two blocks of conversion from the abc to qdo and vice versa are the same transformations $T_{4\_qdo} \ and \ T_{4\_qdo}{}^{-1}$ [12].

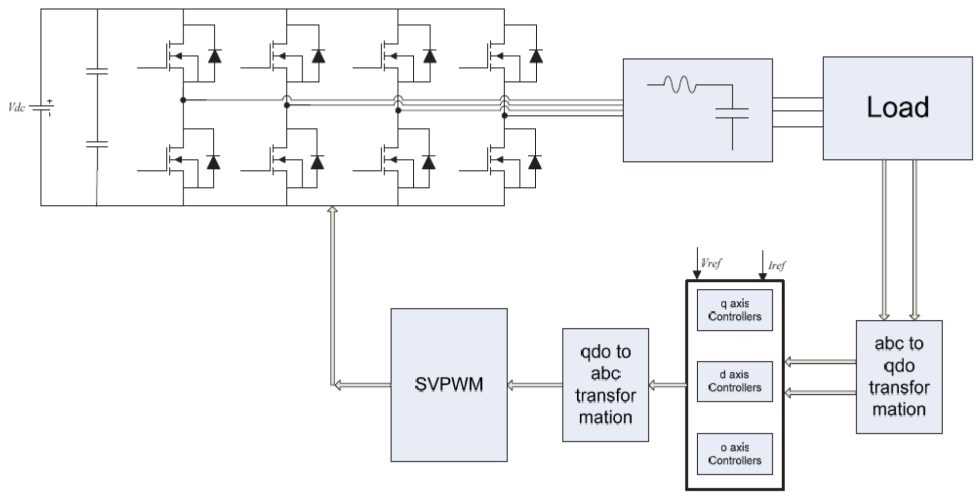


Figure 2. Block diagram of control strategy of a four-leg inverter [12]

Here, the voltage loop reference of a harmonic-free sinusoidal signal is considered. In the control block, there are three independent controllers of parallel single-phase inverters whose design method we have described, which are used to apply to the content of d, q and o voltage and current signals. Each of these sections has two voltage controllers and a current divider. The three outputs of the axes d, q and o are returned to the abc device by the reverse conversion $T_{4\_qdo}{}^{-1}$. The output of the controllers in the abc device, as a reference, enters the space vector pulse width modulation (SVPWM) modulation block, which cannot be addressed in this section [13].

2.2. Design of backstepping controller

The proposed controller allows the converter to provide a fully sine voltage with constant amplitude and frequency independent of load. The output voltage should follow the reference signal [14], [15].

$$x_1^*(t) = V\sqrt{2}\,sin(\omega t) \tag{8}$$

In which, $v = 230, f = 50\,Hz(\omega = 2\pi f)$, the value of the root mean square (RMS) voltage and the reference sine wave frequency, respectively. In control theory, backstepping is a technique developed in 1990 to design the stability control of dynamic systems. These systems are made of irreducible subsystems that can be stabilized using other methods [16]. Due to this recursive structure, the designer can start the design process at the known-stable system and "back out" new controllers that progressively stabilize each outer subsystem. The process terminates when the final external control is reached [17]. Hence this process is known as backstepping. We consider Z_1as tracking error and we define it:

$$Z_1 = C(x_1 - x_i) \tag{9}$$

The dynamics:

$$\dot{z}_1 = C(\dot{x}_1 - \dot{x}_1^*) \tag{10}$$

$$\dot{Z}_2 = x_2 - i_s - C\dot{x}_1^* \tag{11}$$

The proposed Lyapunov function is defined as (12) [18].

$$v_1 = \frac{1}{2}z_1^2 \tag{12}$$

Derived from time:

$$\dot{V}_1 = \dot{Z}_1\dot{Z}_1 \tag{13}$$

By choosing:

$$\dot{Z}_1 = -k_1 z_1 \rightarrow z_1(\tau) = z_1(0)e^{-k_1\tau} \tag{14}$$

Here, $k_1$is a positive constant. This leads to a candidate function of Lyapunov, which has a completely negative dynamic. So, we get:

$$\dot{V}_1 = -k_1 z_1^2 \tag{15}$$

As a result, the asymptotic stability is achieved and Z_1ultimately aspires to zero [19], [20]. In the system $X_2(7)$, it is like a virtual control input. So Z_1can be set to zero if: $x_2 = x_2^*$

$$x_2^* = -k_1 z_1 + i_s + C\dot{x}_1^* \tag{16}$$

Here, X_2 is called constant stability. A new variable error is defined between the virtual value and the desired value [21], [22].

$$z_2 = x_2 + x_2^* \tag{17}$$

This can be deduced from (10), (16), and (17).

$$\dot{Z}_1 = -k_1 z_1 + z_2 \tag{18}$$

The Z_2 time derivative is calculated [23]:

$$\dot{x}_2^* = \dot{x}_2 - \dot{x}_2^* \tag{19}$$

$$\dot{Z}_2 = \frac{1}{L}(uE - x_1) - \dot{x}_2^* \quad (20)$$

The actual control system should be considered. The system stability problem presented in (18) and (21) can be understood by the following Lyapunov function [24]–[26]:

$$v_2 = \frac{1}{2}z_1^2 + \frac{1}{2}z_2^2 \quad (21)$$

$$\dot{V}_2 = \dot{Z}_1 Z_1 + \dot{Z}_2 Z_2 \quad (22)$$

$$\dot{v}_2 = -k_1 z_1^2 + z_2\left(z_1 + \dot{Z}_2\right) \quad (23)$$

Applying the (24):

$$\left(z_1 + \dot{Z}_2\right) = -k_2 z_2 \quad (24)$$

we get:

$$\dot{V}_2 = -k_1 z_1^2 - k_2 z_2^2 \quad (25)$$

Therefore, (20) and (24) lead to the development of a Backstepping controller [27].

$$u = -\frac{L}{E}\left(z_1 + k_2 z_2 - \frac{x_1}{L} - \dot{x}_2^*\right) \quad (26)$$

The control rule is chosen so that V2<0 and allows the $(Z_1\ , Z_2)$system to be asymptotically stable [28], [29].

3. RESULTS AND DISCUSSION

In this section, the system and the simulation results are expressed under different conditions such as ohmic load, inductive load and non-linear. Simulation is based on MATLAB software. Simulation to determine the response of supposed controllers relative to the transient state and the steady state under four the following is conducted: i) symmetrical resistive load (transient behavior from 0% to 100%), ii) symmetrical resistive load (transient behavior from 100% to 0%), iii) inductive ohmic load, and iv) nonlinear load. The simulated inverter parameters are shown in Table 1, where f_s is the switching frequency of the system.

Table 1. Parameters of simulated single-phase inverter

Parameter	Value
V_{DC}	100 V
V_{out}	50 peaks
f_S	15000
F	50
R (full load)	200

Single-phase nonlinear load is designed according to IEC62040-3 standard, shown in Figure 3. Also, the reference signal with amplitude 50 and frequency 50 Hz is shown in Figure 4. The parameters of single-phase non-linear load are shown in Table 2. Figure 5 shows the schematic diagram of the controller. As shown in Figure 5, the capacitor current (i_c), the load output voltage (v_o) and the output current (i_o) are considered as inputs of the control system. The crest factor (CF) and power factor (PF) of nonlinear load are 2.75 and +0.7, respectively [30].

Table 2. Parameters of single-phase non-linear load [31]

Parameter	Value
R_s	2 Ω
R_{NL}	18 Ω
C_L	8200 μF

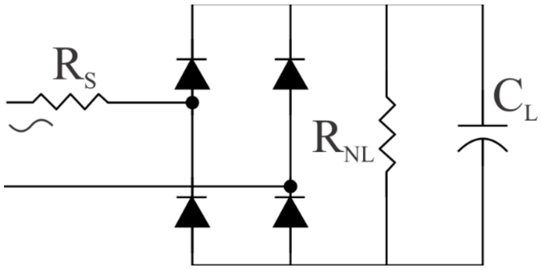


Figure 3. Single-phase nonlinear load according to IEC62040-3 [32]

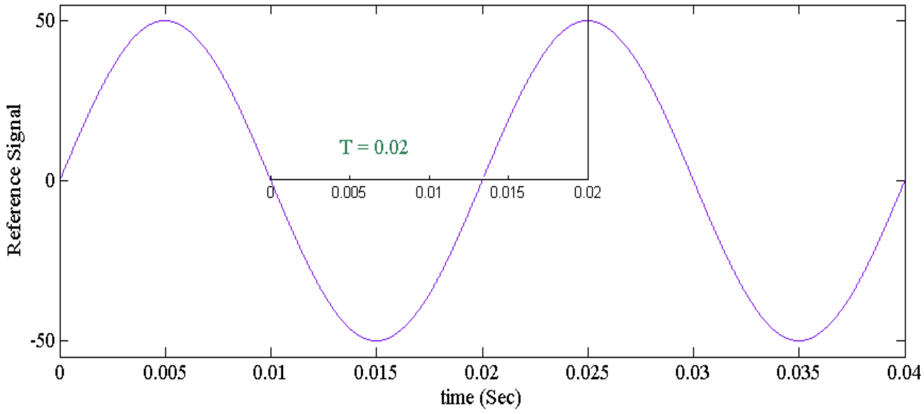


Figure 4. Waveform of the reference signal

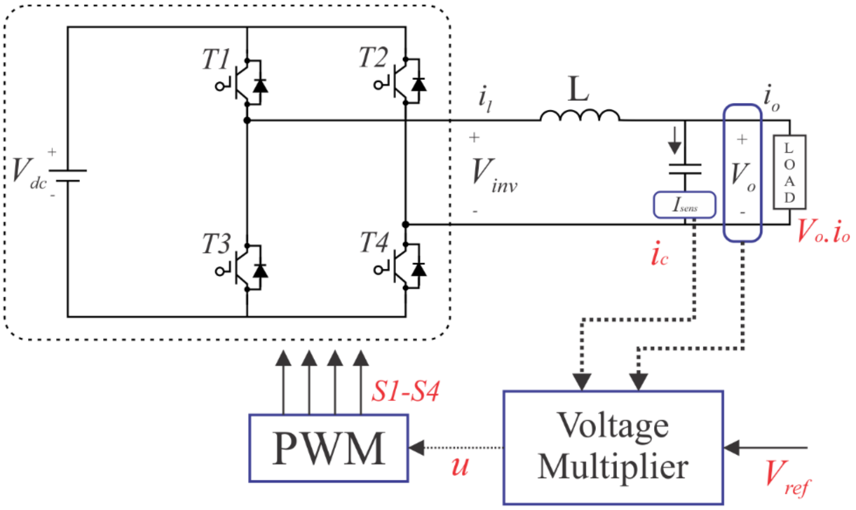


Figure 5. General block diagram of the assumed control system

Simulation results of assumed controller, includes load output voltage (V), output current (A), which is considered as the input of the control system, the error between the output voltage and the reference signal and harmonic analysis of steady stat are shown in Figure 6(a) to (d). The simulation results to determine the response of the assumed controllers to the transient state under symmetric resistive load, inductive ohmic load and nonlinear load are shown in Figure 7(a) to (d). As can be seen from the figure, the transient response of the system can be observed and investigated in two situations. The state where all these loads are disconnected from the system (a), and the state where the resistance load, the inductive ohm load and the nonlinear load are connected to a system (b, c, d).

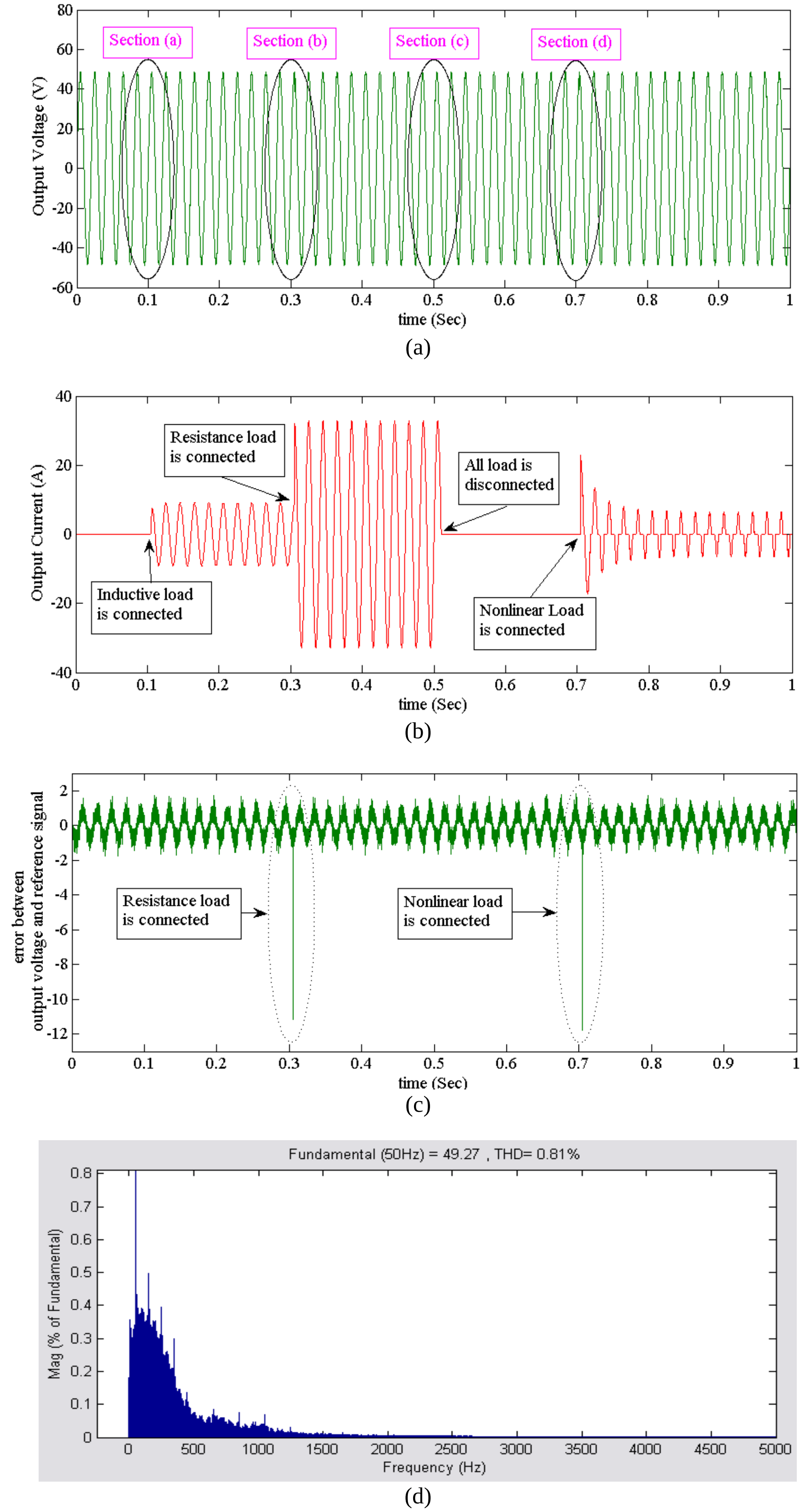
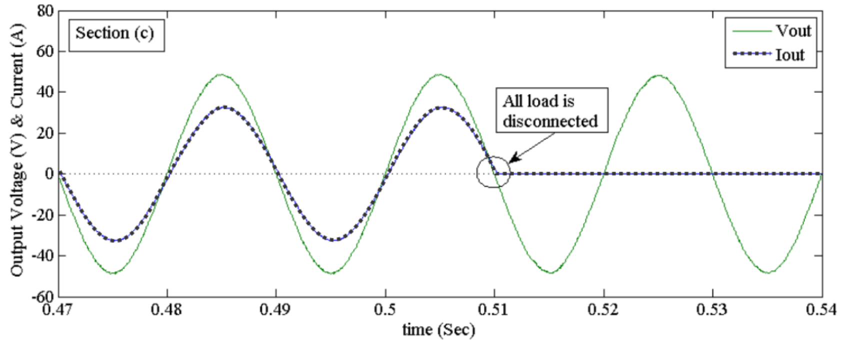
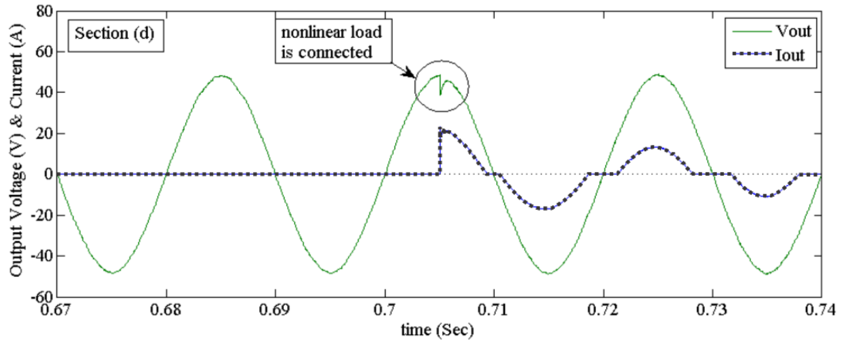


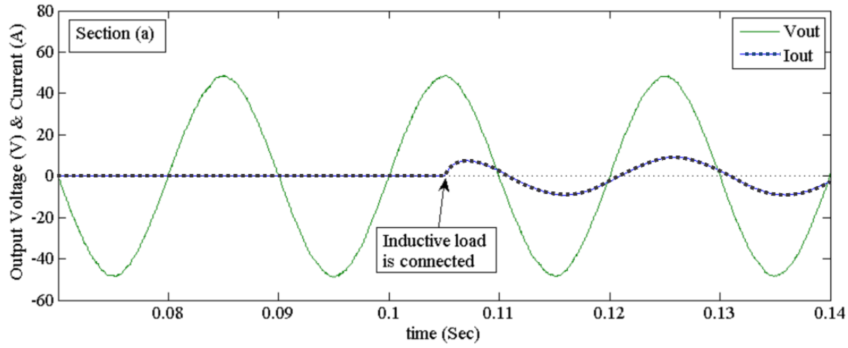
Figure 6. Simulation results of controller: (a) output voltage (v), (b) output current (A), (c) error between output voltage and reference signal, and (d) harmonic analysis of steady stat



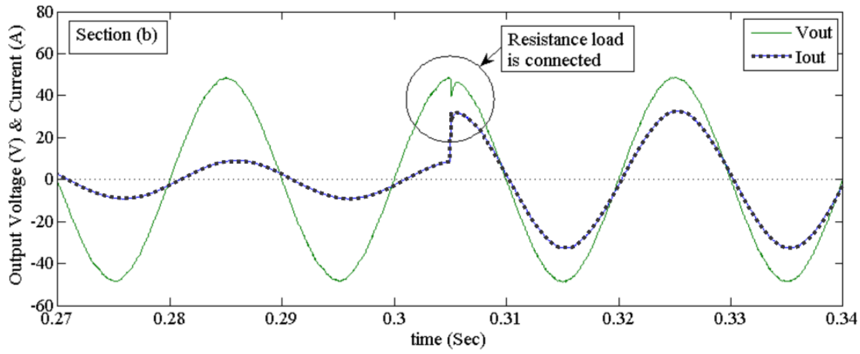
(a)



(b)



(c)



(d)

Figure 7. Simulation results of the assumed controller: (a) transient response (all load is disconnected), (b) transient response of a nonlinear load, (c) transient response to the inductive ohmic load, and (d) transient response to resistance load

Figure 8 illustrates the schematic of a three-phase DC/AC inverter with an LC filter. This schematic includes a three-phase inverter, an LC output filter connected to local loads. The LC filter function eliminates the harmonic components of the inverter output voltage due to the high frequency switching operation. So, this filter is an essential part of circuit and non-removable. The system model as shown in Figure 8, can be reduced to the unit's single-phase equivalent circuit according to Figure 5. So, based on the previous section, for each phase, the dynamically model is extracted, and a controller is designed. The proposed controller is investigated in a three-phase system under conditions of symmetric ohmic load, asymmetric ohmic load, inductive ohmic load, and nonlinear load to control the voltage of a DG unit in island mode.

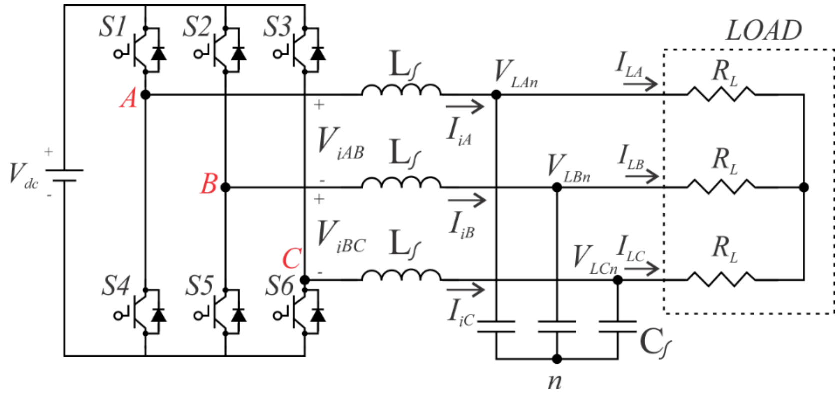


Figure 8. Schematic of a three-phase DC/AC inverter with LC filter

Simulation to specify the controller response assumed to be transient and steady state under the following four conditions: i) symmetrical resistance load, ii) asymmetrical resistive load, iii) inductive ohmic load, and iv) nonlinear load. The parameters of each phase of the inverter simulated are given in Table 1. Three phase nonlinear load is designed according to IEC62040-3, as shown in Figure 9.

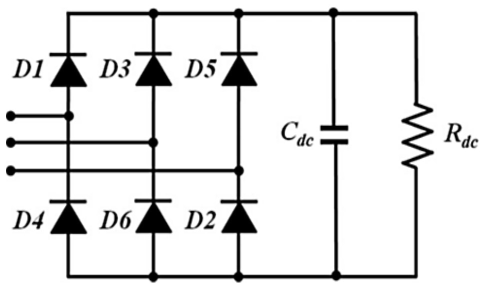


Figure 9. Three phase nonlinear load according to IEC62040-3 [34]

Also, a three-phase reference signal with amplitude 50 and a frequency of 50 Hz is shown in Figure 10(a), hat each phase has a phase difference of 120 degrees with two other phases. The parameters of three-phase non-linear load are shown in Table 3 [33], [34]. Simulation results of controller, includes load output voltage (three-phase), load output current (three-phase), voltage during resistive load, voltage under no-load, voltage resistive load during asymmetric resistive load, and voltage during nonlinear load are shown in Figure 10(b) to (g). In this section, the circuit of Figure 11 is simulated in MATLAB software. Table 4 shows the numerical results of the steady state analysis in the three-phase state for one of the phases (phase a) in the no load, symmetric resistance load, asymmetric resistance load, and nonlinear load.

Table 3. Parameters of three-phase non-linear load [34]

Parameter	Value
R_{dc}	500 Ω
C_{dc}	3300 μF

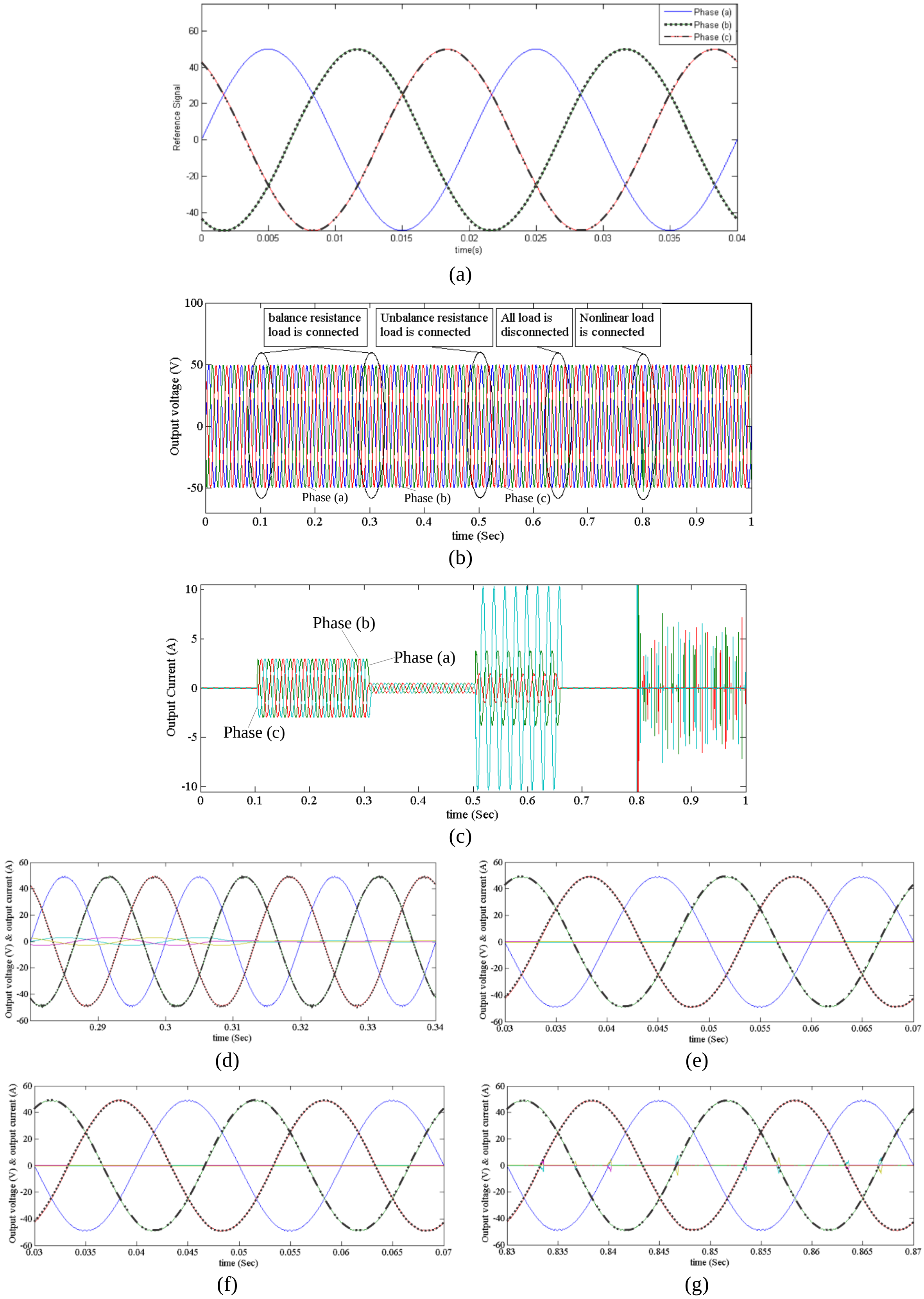


Figure 10. Simulation results of controller: (a) three-phase reference signal, (b) load voltage, (c) load current (d) voltage during resistive load, (e) voltage under no-load, (f) voltage resistive load during asymmetric resistive load, and (g) voltage during nonlinear load

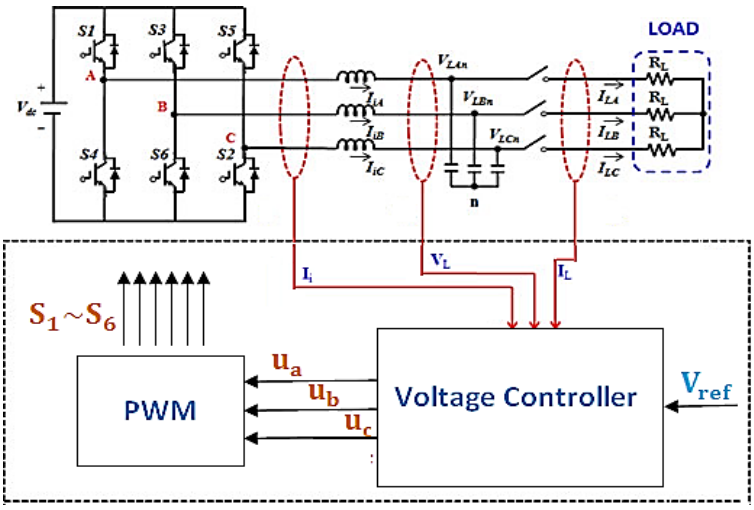


Figure 11. Block diagram of the three-phase voltage control system

Table 4. Results of steady state analysis of phase (a)

Load type	Output voltage peak	Effective output voltage	THD (%)	2^{th} harmonic	3^{th} harmonic	4^{th} harmonic	5^{th} harmonic	Robustness
No load	47.82	33.82	0.49	0.22	0.09	0.25	0.17	Robust to parameters
Symmetric resistance load	47.74	33.76	0.55	0.15	0.21	0.28	0.10	
Asymmetric resistance load	47.69	33.72	0.76	0.25	0.35	0.41	0.16	
Nonlinear load	47.28	33.43	3.02	1.37	1.58	1.34	0.96	

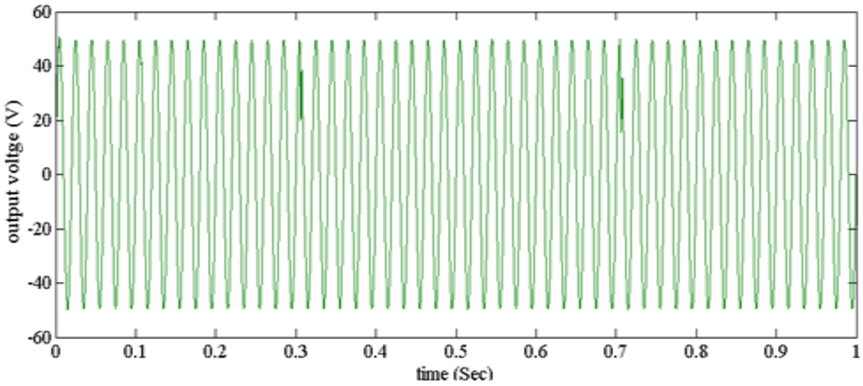
In this section, we use a classical controller to compare the results of the proposed controller in this paper. PI controllers are created by combining two proportional and integral control operations. This controller is a closed loop control algorithm and method using the concept of feedback that is used in many industrial processes to control. The simulation results are expressed with a PI controller for a single-phase system. The simulation results show that the PI controller is sensitive to load variations and its steady state error varies under different conditions [35]. Therefore, the proposed controller is a robust controller that is not only simple but also resistant to sudden load changes. And system uncertainties are also resistant. Figure 12 (in appendix) shows the voltage control based on the PI controller. According to the figure of the output voltage of the controller, error between output voltage and reference signal (under all load conditions), and harmonic analysis of the steady stat are shown.

4. CONCLUSION

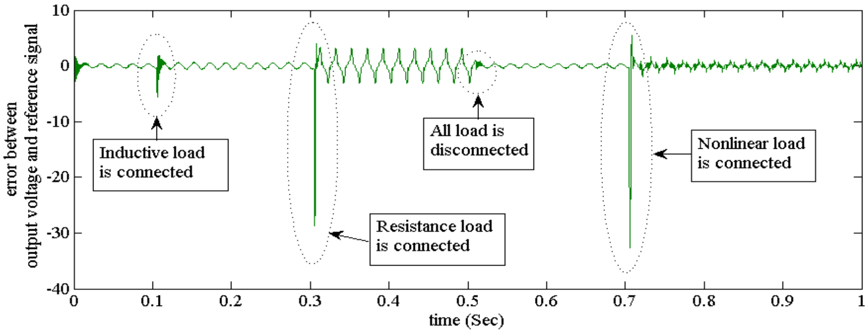
In this paper, a method of feedback voltage control based on the Lyapunov theory for controlling of the DG unit independent Inverter is presented. The proposed controller is not only simple, but also against the sudden changes in load and the unspecified system is resistant. In addition, the stability of the control system of the closed loop is also proven by the method of the Lyapunov. To provide validation of the proposed control method, simulations are provided through the MATLAB software. Finally, the simulation results have shown that the proposed control method provides convincing voltage regulation, such as fast dynamics, lower steady state error, and low total harmonic distortion (THD) for various loads, including linear and nonlinear loads. It is also shown by changing the amplitude of the reference signal that follows the reference signal controller and causes the steady state error between the output voltage signal and the reference signal of the voltage to zero.

Some suggestions for continuing research in this area can be expressed as follows: Investigation and presentation of a robust controller to improve of voltage and frequency stability in a microgrid in island mode. Investigation and presentation of a feedback controller based on Lyapunov theory to improve the damping of low frequency fluctuations in a power system. Investigation and presentation of a feedback controller based on Lyapunov theory to control power directly in the microgrid. Provide a feedback controller based on Lyapunov theory to control the current of a grid-connected inverter.

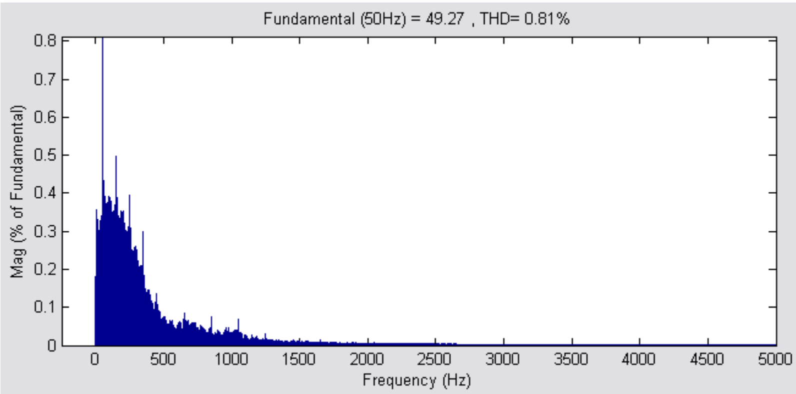
APPENDIX



(a)



(b)



(c)

Figure 12. Voltage control based on the PI controller (a) output voltage, (b) error between output voltage and reference signal, and (c) harmonic analysis of the steady stat

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