

Design of a new backstepping controller for control

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ABSTRACT

An emergency power source is becoming a crucial feature for a lot of electrical and computer gadgets in homes and businesses. As a result, the uninterruptible power supply (UPS) inverters' performance exhibits little distortion at the output voltage. At first, proportional integral (PI) control classic rules were used to regulate such inverters. It is challenging to comprehend the stability constraints of this approach and to implement a transitory reaction to powerful external shocks. This study presents a simulation and offer for a non-linear controller-controlled inverter for single-phase and three-phase voltage. The controller performance and the PI controller have been compared for this reason. Next to the Lyapunov function in the first step is a backstepping regulator that makes use of the stability tool. Additionally, the PI approach is used by the other regulator. In MATLAB, the operation of these two regulators is simulated when the reference or load changes. Additionally, a Lyapunov-based feedback voltage control approach for the distributed generation (DG) unit independent inverter is provided. In addition to being straightforward, the suggested controller is resistant to abrupt changes in load and the unidentified system.

INTRODUCTION

1. Given their many benefits, distributed generating sources are anticipated to become more significant in power system design and operation in the near future. Economic pressures, technological advancements, and environmental concerns are causing the power grid's existing design and perspective to move from generating to distribution [1]. Each microgrid is made up of many new energy sources that need an inverter or voltage source to control their power and voltage so they may connect to the network and utilize their power output. In various applications, such as renewable energy systems (like solar cells and wind turbines) and uninterruptible power supply (UPS), converters like a voltage source inverter (VSI) are often employed as power interfaces [2]. Additionally, for the inverter to operate well both alone and in a network, precise voltage and frequency control are necessary to preserve operation and regulate output power. For the inverter to function in systems like emergency power systems (EPS) and microgrid systems, the voltage and frequency must be properly controlled [3]. The relevant literature offers a variety of control systems for managing inverters in the grid. For the photovoltaic (PV) system, a proportional derivative (PD) controller with a proportional integral (PI) controller structure is introduced in the research [4]. When a voltage reference appears with the appropriate error and the method for maximum detection of the P, Q point of power, the controller detects it. The operating point fluctuates around the maximum power point in the steady state, which is the primary issue with the maximum power tracking algorithm. In order to provide a continuous power supply, Chapuis et al. [5] focus on controlling a single-phase direct current-alternating current (DC-AC) compensator. Producing a sine voltage at the system's output with amplitude and frequency set by the reference signal is the control objective in this area. The use of hierarchical fuzzy logic controllers for UPS applications has

been suggested by Abdel-Rahim and Elshafei [5]. Two fuzzy controllers are used in a nesting mode to generate two control loops in the suggested control system. Systems engineering and theory both heavily rely on sustainability. The study of dynamical systems involves a number of sustainability-related topics. Lyapunov is often used to verify the stability of points of equilibrium [6]. Using a backstepping controller under ohmic, inductive, and nonlinear load circumstances, we aim to manage the output voltage of an inverter of a distributed generation source under island condition in this study. The stability of the system is examined using Lyapunov theory. Lastly, a comparison with traditional controllers is made. Under various load situations, including ohmic, ohmic-inductive, nonlinear, and no-load, inverter output voltage control functions as a distributed generation (DG) unit. The backstepping controller follows the reference signal with a steady state error that is almost zero. The backstepping controller can withstand noise, disturbances, and unmodulated dynamics.

2. METHOD

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

Figure 1 depicts a single-phase inverter using pulse width modulation (PWM). It is made composed of two arms that are bi-directionally coupled to either metal-oxide semiconductor field effect transistors (MOSFETs) or insulated gate bipolar transistors (IGBTs) with reverse parallel diodes that work in tandem. The binary instructions μ_1 and μ_2 are of the two switching portions, and the PWM generator generates the control signal μ , which has a value between $\{1, -1\}$ [7], [8].

$$\begin{aligned} \mu &= \mu_1 - \mu_2 \\ &= \begin{cases} 1: \mu_1 = 1 \text{ and } \mu_2 = 0 \rightarrow (k_1, k'_2) \text{ ON and } (l_2, k'_1) \text{ OFF} \\ -1: \mu_1 = 0 \text{ and } \mu_2 = 1 \rightarrow (l_2, l'_1) \text{ ON and } (k_1, k'_2) \text{ OFF} \end{cases} \end{aligned} \quad (1)$$

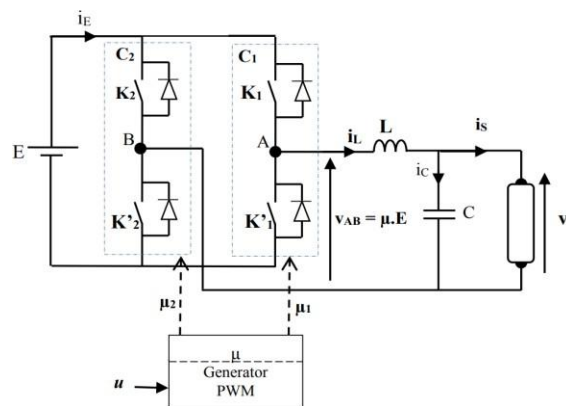


Figure 1. Design of a single-phase inverter with an LC filter [7]

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

$$- = - V \quad (2)$$

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

$$E \text{ when only } (k_1, k') \text{ are ON ie } \mu = 1$$

Therefore, one can conclude:

$$\dots \tag{5}$$

Since v_{AB} is not a continuous variable and might have two discrete values of E and $-E$, it is improper to develop a continuous control rule for this model, which is a system with variable structure. The average model, which is often used to represent static converters, is frequently utilized to get around this issue [8], [9]. In this situation, the switching time is thought to be much shorter than in the dynamic system. This is perfectly appropriate in our research. We possess:

$$C\dot{x}_1 = x_2 - i_s \tag{6}$$

$$L\dot{x}_2 = uE - x_1 \tag{7}$$

The average values of the sampling period of the V_s output voltage across the capacitor C and current i_L in the inductor L are denoted by x_1 and x_2 . The average value of the control signal μ , which is created via rectangular pulse width modulation, is represented by the control variable $u \in [-1,1]$, which has values ranging from -1 to 1 [10], [11]. It can be shown that three separate single-phase inverters are equal to a three-phase four-leg inverter (TPFL). For single-phase parallel inverters, it makes more sense to construct a voltage and current controller rather than a direct controller for four-leg inverters. Next, use the $T_{(4_qdo)}$ conversion matrices to apply the identical controllers to the four-leg parallel system, and vice versa. Notably, the conversion is simply utilized to transform a four-leg inverter to three single-phase inverters, and all of the controllers are created and implemented in the stationary device. The suggested control mechanism for a four-leg inverter is shown in Figure 2. The conversion blocks from ABC to QDO and vice versa in this image are identical transformations T_{4_qdo} and $T_{4_qdo}^{-1}$ [12].

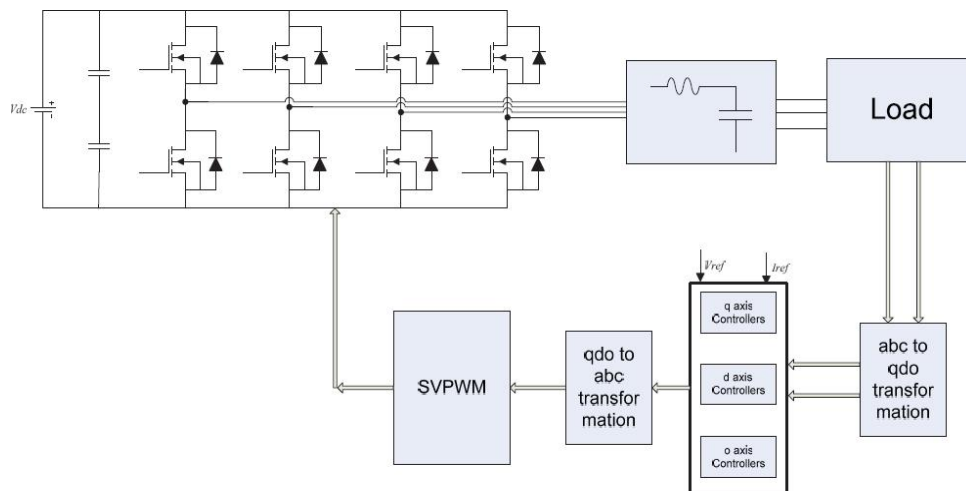


Figure 2. Block diagram of control strategy of a four-leg inverter [12]

In this case, a harmonic-free sinusoidal signal's voltage loop reference is taken into account. Three separate controllers of parallel single-phase inverters, whose design process we have explained, are located in the control block and are used to apply to the voltage and current signals of d, q, and o. There are two voltage controllers and a current divider in each of these parts. The reverse conversion $T_{4_qdo}^{-1}$ returns the three outputs of the axes d,

International Journal of Electronics and Telecommunication Systems Volume1, Issue01 2025

q, and o to the ABC device. This section cannot handle the space vector pulse width modulation (SVPWM) modulation block, which receives the controllers' output in the ABC device as a reference [13]. 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].

$$x^*(t) = V\sqrt{2} \sin(\omega t) \quad (8)$$

where $v = 230$ and $f = 50 \text{ Hz} (\omega = 2\pi f)$ represent the reference sine wave frequency and the root mean square (RMS) voltage, respectively. Backstepping is a control theory approach that was created in 1990 to construct dynamic systems' stability control. Irreducible subsystems that can be stabilized in other ways comprise these systems [16]. The designer may begin the design process at the known-stable system and "back out" new controllers that gradually stabilize each outer subsystem because of its recursive nature. When the last external control is achieved, the procedure comes to an end [17]. This procedure is hence referred to as backstepping. We define Z_1 , which we regard to be tracking error:

$$Z_1 = C(x_1 - x_i) \quad (9)$$

The dynamics:

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

$$Z_2 = x_2 - i_s - C\dot{x}_1^* \quad (11)$$

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

$$V_1 = \frac{1}{2} Z_1^2$$

Derived from time:

$$\dot{V}_1 = Z_1 \dot{Z}_1 \quad (13)$$

By choosing:

$$\dot{Z}_1 = -k_1 Z_1 \rightarrow z_1(\tau) = z_1(0)e^{-k_1\tau} \quad (14)$$

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

$$\dot{V}_1 = -k_1 Z_1^2 \quad (15)$$

As a result, the asymptotic stability is achieved and Z_1 ultimately aspires to zero [19], [20]. In the system $X_2(7)$, it is like a virtual control input. So Z_1 can be set to zero if: $x_2 = x_2^*$

$$x_2^* = -k_1 Z_1 + i_s + C\dot{x}_1^* \quad (16)$$

Here, Z_2 is called constant stability. A new variable error is defined between the virtual value and the desired value [21], [22].

$$z_2 = x_2 - x_2^* \quad (17)$$

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

$$\dot{Z}_1 = -k_1 Z_1 + z_2 \quad (18)$$

The Z_2 time derivative is calculated [23]:

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

2

The control rule is chosen so that $V_2 < 0$ and allows the (x_1, x_2) system to be asymptotically stable [28], [29].

3. RESULTS AND DISCUSSION

This section presents the system and simulation results under various scenarios, including non-linear, inductive, and ohmic loads. MATLAB software is the foundation of simulation. Symmetrical resistive load (transient behavior from 0% to 100%), symmetrical resistive load (transient behavior from 100% to 0%), inductive ohmic load, and nonlinear load are the four scenarios in which simulation is used to ascertain the response of purported controllers with respect to the transient state and the steady state. Table 1 displays the simulated inverter parameters, where f_s is the system's switching frequency.

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

Figure 3 illustrates how a single-phase nonlinear load is constructed in accordance with the IEC62040-3 standard. Additionally, Figure 4 displays the reference signal with an amplitude of 50 and a frequency of 50 Hz. Table 2 displays the single-phase non-linear load parameters. The controller's schematic diagram is seen in Figure 5. The output current (i_o), load output voltage (v_o), and capacitor current (i_c) are regarded as inputs of the control system, as shown in Figure 5. Nonlinear load has a crest factor (CF) of 2.75 and a power factor (PF) of +0.7 [30].

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

Parameter	Value
R_s	2Ω
R_{NL}	18Ω
C_L	$8200 \mu F$

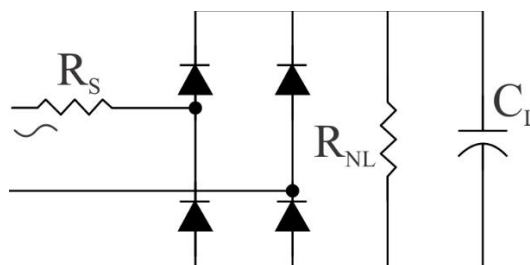


Figure 3. Single-phase nonlinear load according to IEC62040-3 [32]

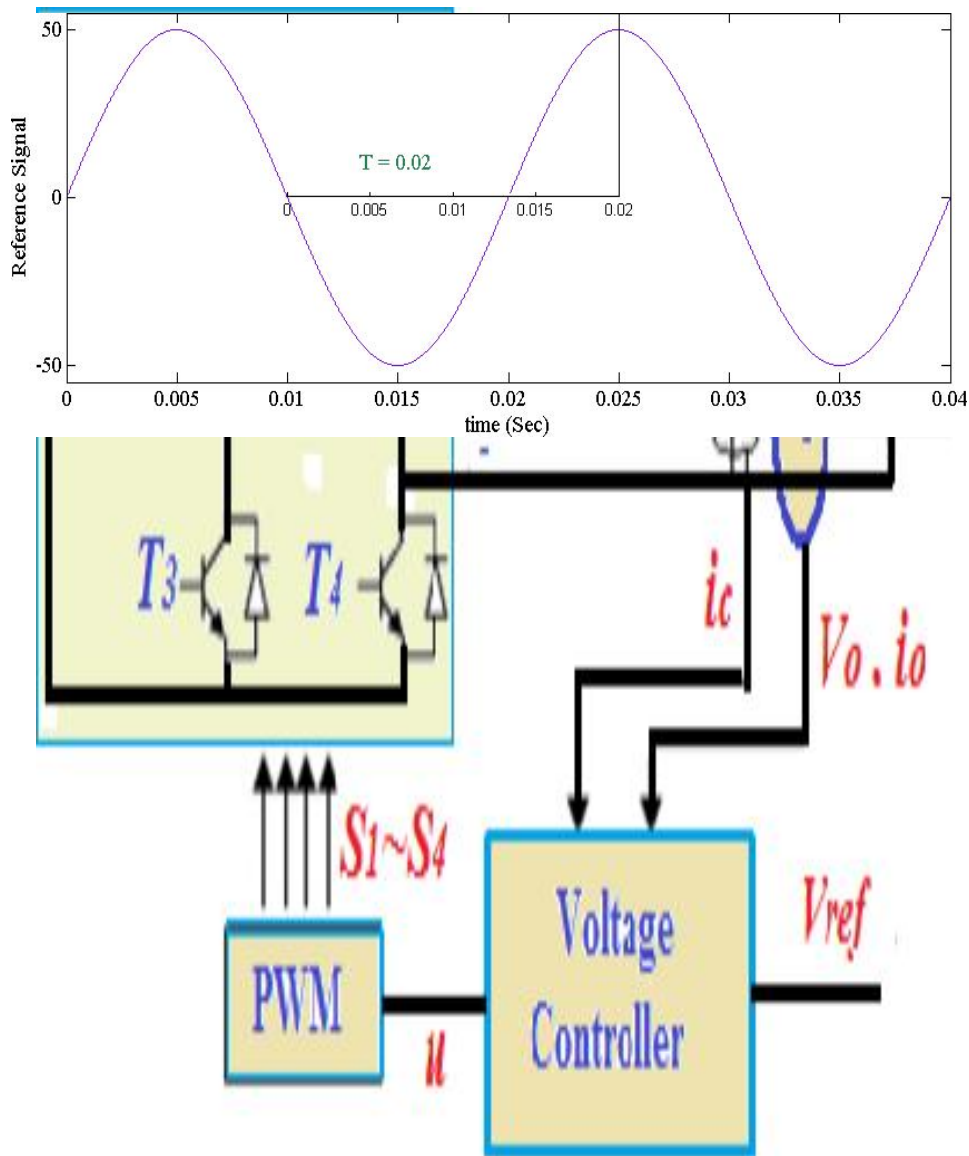
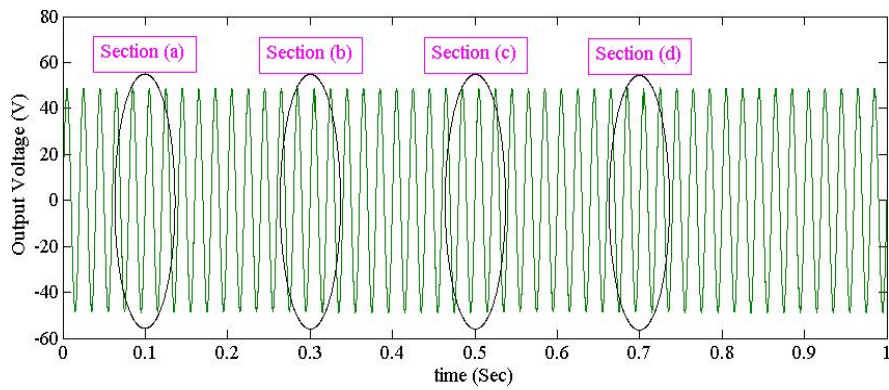


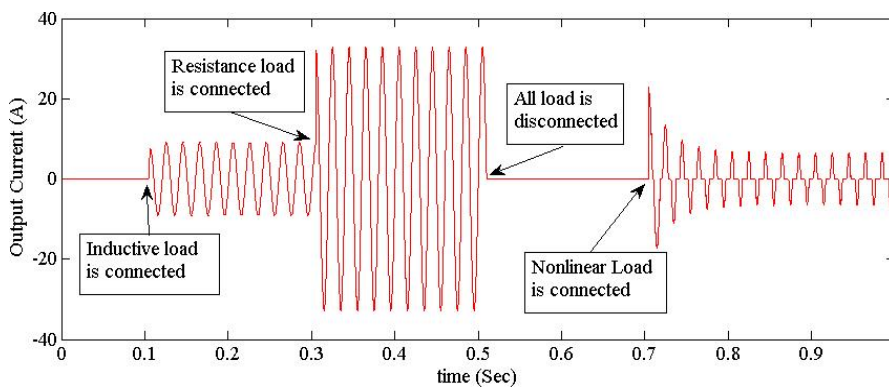
Figure 4. Waveform of the reference signal

Figure 5. General block diagram of the assumed control system

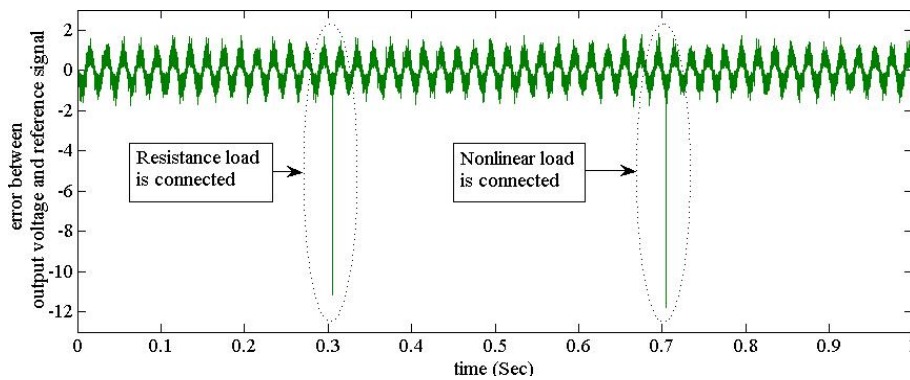
Assumed controller simulation results are shown in Figure 6(a) to (d). These results include the load output voltage (V), output current (A), which are regarded as the control system's inputs, the error between the output voltage and the reference signal, and harmonic analysis of steady state. Figure 7(a) to (d) displays the simulation results used to ascertain how the anticipated controllers would react to the transient state under symmetric resistive load, inductive ohmic load, and nonlinear load. The graphic illustrates how the system's transitory reaction may be viewed and examined in two different scenarios. The states in which the resistance load, the inductive ohm load, and the nonlinear load are connected to a system (b, c, d) and in which all of these loads are detached from the system (a).



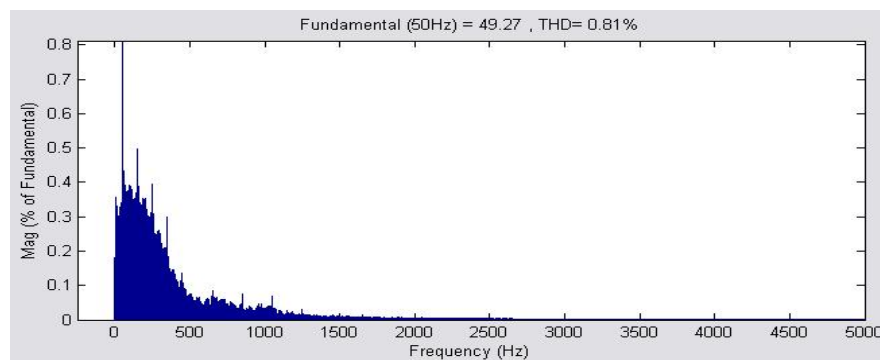
(a)



(b)



(c)

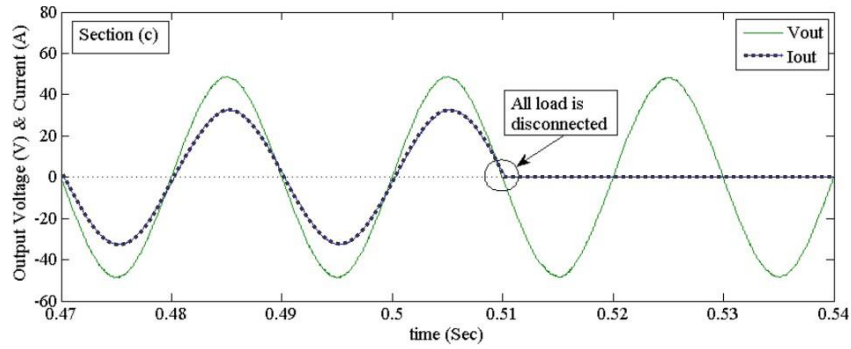


(d)

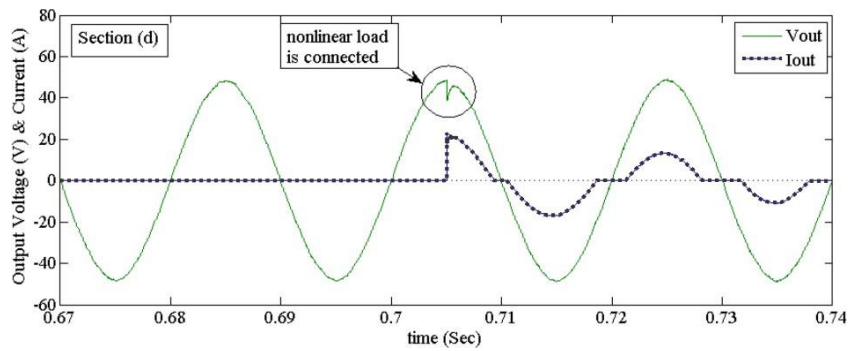
International Journal of Electronics and Telecommunication Systems

Volume1, Issue01 2025

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



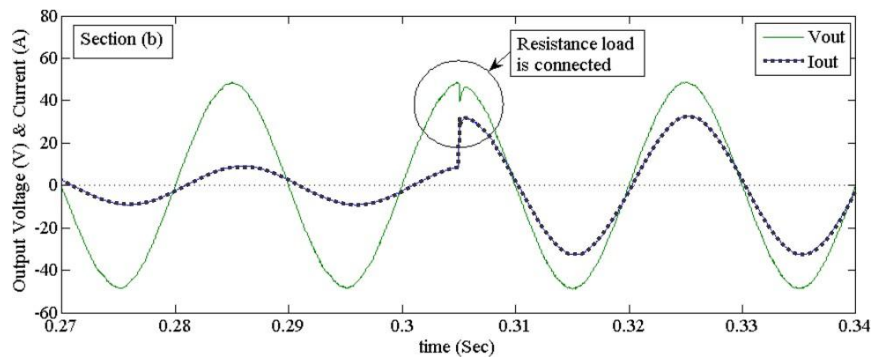
(a)



(b)



(c)



(d)

International Journal of Electronics and Telecommunication Systems Volume1, Issue01 2025

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

The concept of a three-phase DC/AC converter with an LC filter is shown in Figure 8. A three-phase inverter and an LC output filter coupled to local loads are shown in this design. Because of the high frequency switching action, the LC filter function removes the harmonic components of the inverter output voltage. Therefore, this filter is a non-removable and necessary component of the circuit. According to Figure 5, the system model shown in Figure 8 may be simplified to the unit's corresponding single-phase circuit. In light of the preceding section, a controller is created for each phase once the dynamic model is retrieved. To regulate the voltage of a DG unit in island mode, the suggested controller is tested in a three-phase system with symmetric ohmic, asymmetric, inductive, and nonlinear loads.

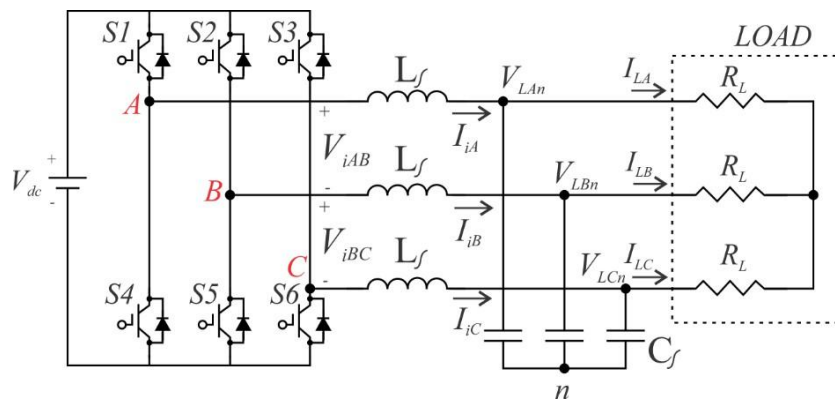


Figure 8. Schematic of a three-phase DC/AC inverter with LC filter

Four circumstances were used in the simulation: i) symmetrical resistance load, ii) asymmetrical resistive load, iii) inductive ohmic load, and iv) nonlinear load. The controller response was supposed to be both transient and steady state. Table 1 lists the parameters for each simulated inverter phase. Figure 9 illustrates how a three-phase nonlinear load is developed in accordance with IEC62040-3.

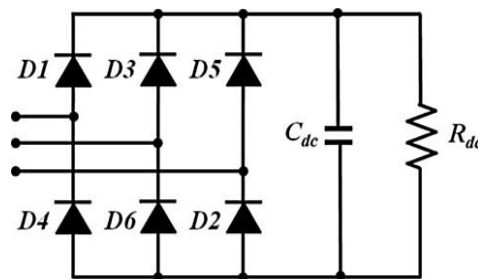


Figure 9. Three phase nonlinear load according to IEC62040-3 [34]

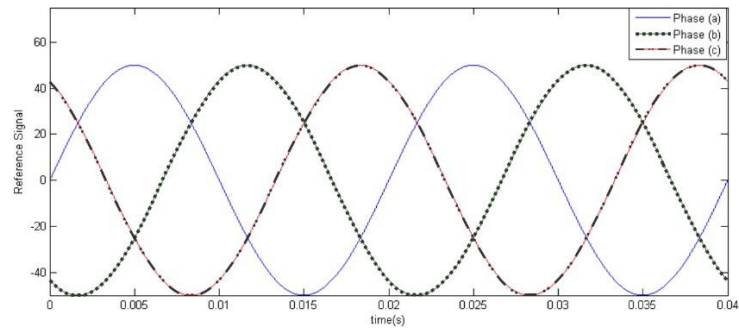
Additionally, Figure 10(a) displays a three-phase reference signal with an amplitude of 50 and a frequency of 50 Hz. Each phase has a 120-degree phase difference with the other two phases. Table 3 displays the three-phase nonlinear load characteristics [33], [34]. Figure 10(b) to (g) displays the controller's simulation results, which include the three-phase load output voltage, three-phase load output current, resistive load voltage, no-load voltage, resistive load voltage under asymmetric resistive load, and nonlinear load voltage. This part uses MATLAB software to model the circuit shown in Figure 11. The steady state analysis numerical results for one of the phases (phase a) in the three-phase state with no load, symmetric resistance load, asymmetric resistance load, and nonlinear load are shown in Table 4.

International Journal of Electronics and Telecommunication Systems

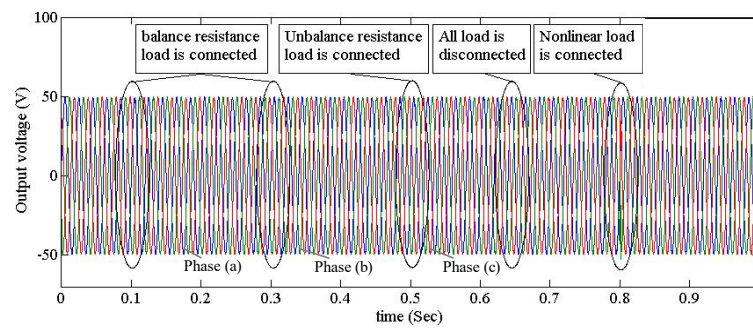
Volume1, Issue01 2025

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

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

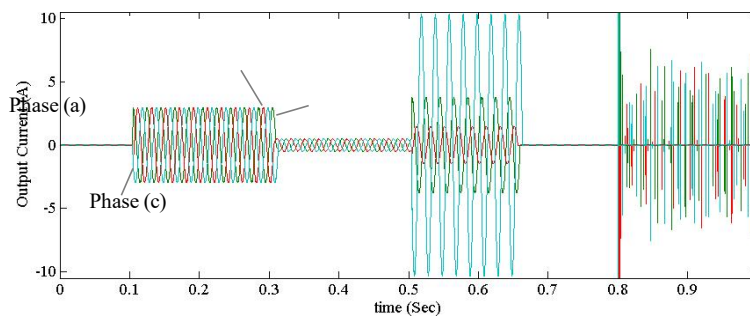


(a)

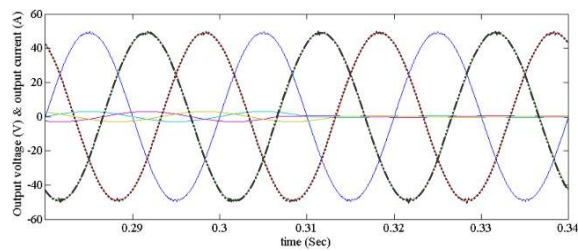


(b)

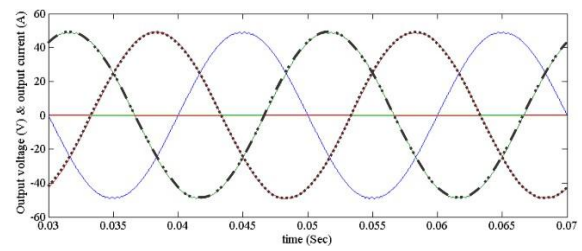
Phase (b)



(c)



(d)



(e)

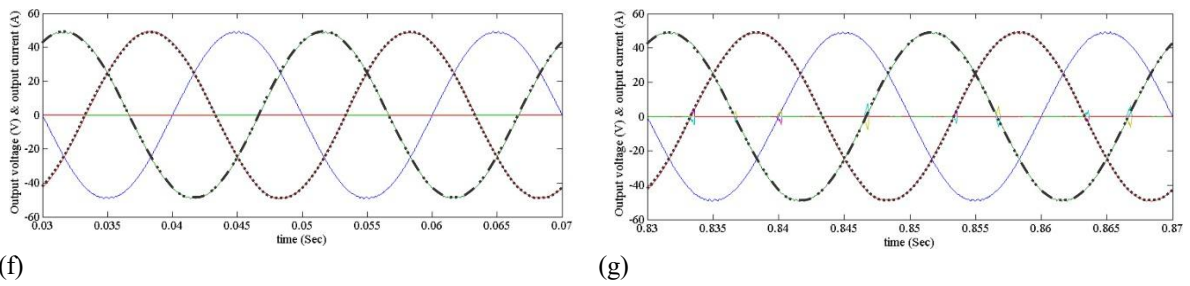


Figure 10. Simulation results of controller: (a) three-phase reference signal, (b) load voltage, (c) load current (d) voltage during resistive load, (e) voltage under no-load, (f) voltage resistive load during asymmetric resistive load, and (g) voltage during nonlinear load

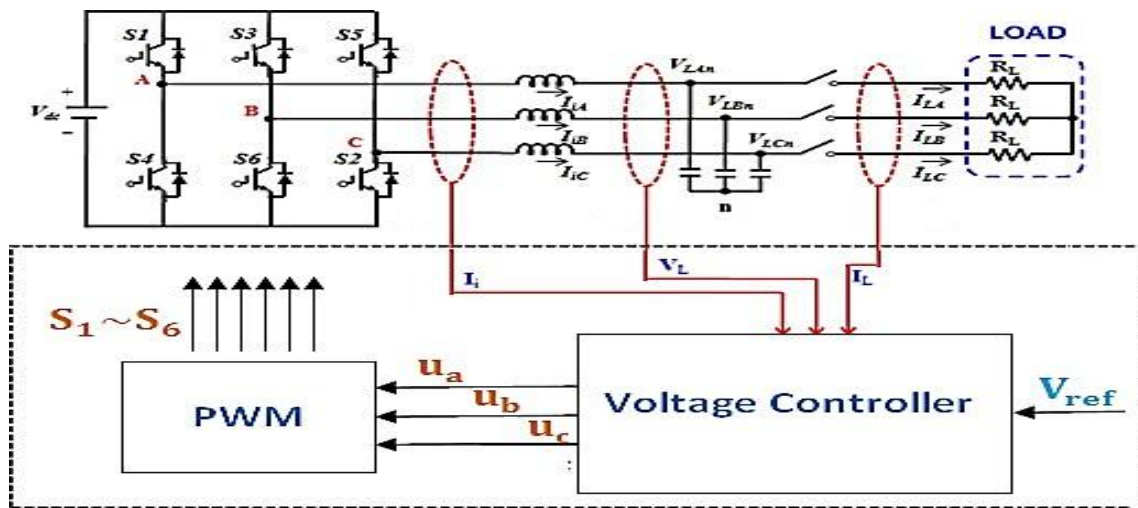


Figure 11. Block diagram of the three-phase voltage control system

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 part, we compare the outcomes of the suggested controller in this study using a classical controller. Two proportional and integral control processes are combined to make PI controllers. This controller uses the feedback idea, which is a closed loop control technique and approach utilized in many industrial processes. A PI controller for a single-phase system is used to represent the simulation findings. According to the simulation findings, the PI controller's steady state error fluctuates depending on the situation and is sensitive to changes in load [35]. As a result, the suggested controller is a reliable one that is easy to use and resilient to abrupt changes in load. Additionally, system uncertainties are resilient. The voltage control based on the PI controller is shown in Figure 12 (appendix). Harmonic analysis of the steady state and the error between the output voltage and reference signal (under all load situations) are shown based on the controller's output voltage figure.

4. CONCLUSION

This work presents a feedback voltage control approach for the DG unit independent inverter that is based on the Lyapunov theory. In addition to being straightforward, the suggested controller is resistant to abrupt changes in load and the unidentified system. Furthermore, the Lyapunov approach is used to demonstrate the stability of the closed-loop control system. The MATLAB program is used to perform simulations that validate the suggested control approach. Lastly, the simulation results demonstrate that the suggested control approach offers convincing voltage regulation for a range of loads, including linear and nonlinear loads, with features like quick dynamics, reduced steady state error, and low total harmonic distortion (THD). The steady state inaccuracy between the output voltage signal and the reference signal of the voltage is also reduced to zero by altering the amplitude of the reference signal that follows the reference signal controller. The following are some recommendations for further study in this field: Research and demonstration of a reliable controller to enhance frequency and voltage stability in an island mode microgrid. A feedback controller based on Lyapunov theory is investigated and presented in order to enhance the damping of low frequency fluctuations in a power system. A feedback controller based on Lyapunov theory is investigated and presented for direct microgrid power regulation. To regulate the current of a grid-connected inverter, implement a feedback controller based on Lyapunov theory.

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Volume1, Issue01 2025

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