VOLTAGE REGULATION OF MICROGENERATION THROUGH VOLTAGE-PHASE ANGLE DROOP

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الملخص

تُوصِّل العديد من أنواع المولدات صغيرة الحجم من تقنيات الطاقه المتجددة مع شبكة التوزيع الكهربائيه ذات الجهد المنخفض من خلال مغيرات الكترونيات القدرة. يوفر المغير تحويل تردد هذه المولدات الصغيره إلى تردد نظام القدرة الكهربائية التقليدي 60/50 هرتز، ويتحكم في تبادل القدرة الكهربائية بين هذه المولدات والشبكة الرئيسية أو الحمل. تم في هذه الورقه تقديم استراتيجية التحكم في الجهد مقابل زاوية الطور كطريقة تحكم في المغير بدلا من التحكم في الجهد مقابل القدرة غير الفعالة وذلك لتحقيق الشروط المطلوبة لربط مولدات التوزيع الصغيرة بشبكة التوزيع. تبين باستخدام هذه الطريقة انه يمكن للمغير أن ينقل بكفاءة طاقة التيار المستمر المتولدة من المولد الصغير والذي يعمل على تحسين استقرارية الجهد وجودة القدرة في منظومة القدرة الكهربائية. تم تقييم مدى إمكانية نظام التحكم المقترح على تحقيق ذلك من خلال دراسات المحاكاة الرقمية التي أجريت باستعمال ألـ PSCAD/ EMTD

ABSTRACT

Many types of microgeneration technologies are interfaced with the low-voltage distribution network through power electronic converters. The converter provides conversion of the microgeneration frequency to the conventional power system frequency of 50/60 Hz, and controls the power exchange between the microgeneration and the load/utility system. In this paper a voltage/phase angle droop control strategy is proposed as alternative to voltage/reactive power droop controller to satisfy the requirements of connection of the microgeneration units to low voltage distribution network. This control technique demonstrates that the converter can transfer efficiently the dc energy from the microgeneration and improves the voltage stability and power quality of the electrical system. The applicability of the proposed control scheme is assessed through digital simulations studies conducted in PSCAD/EMTDC.

KEYWORDS: Microgeneration; Phase Angle; Droop Control.

INTRODUCTION

Microgeneration technologies include small-scale wind turbines, PV arrays, solar thermal collectors and micro combined heat and power (μCHP) connected to the electricity grid at the customer's side (residential) [1]. This effectively eliminates the need to transport electricity from the supplier to the customer. Also micro-generation units have impacts on voltage profile and losses. Unlike conventional synchronous generation plant, many types of these new technologies are interfaced to the low-voltage distribution network through power electronic converters. Some microgeneration technologies such as photovoltaic cells generate DC power whereas other technologies such as gas-fired micro turbines generate AC power at a frequency of a few kHz [2-3].

The output power from these small sources must be first conditioned as required via DC/AC or AC/DC/AC converters before connecting to the system. The converter provides conversion of the source frequency to the conventional network frequency of 50/60 Hz, and controls the power exchange between the generator and the load/utility network playing thus a vital role to facilitate their integration to the network [4].

Before introducing microgeneration units in large quantities there are a number of issues related to their connection to the distribution network that need to be resolve. These issues include stability, voltage and frequency control, maintaining power quality, protection, reliability and safety. As mentioned in papers [1, 5, 6, 7, 8,9,10, 11, 12, 13 and 14] the basic issue for microgeneration is the technical difficulties related to the control of a significant number of microgeneration units. Thus this paper introduces voltage/phase angle droop control scheme. This control scheme has positive impact on voltage stability and power quality. The performance of this controller is demonstrated and tested using case studies implemented in PSCAD/EMTDC.

PROPOSED VOLTAGE /PHASE ANGLE DROOP CONTROL FOR MICROGENERATION

Voltage regulation is necessary for local reliability and stability. Without local voltage control, a system with high penetration of microgeneration could experience voltage and/or reactive power oscillations [11]. In microgeneration systems, there is the problem of circulating reactive currents. With small errors in voltage set points, the circulating current can exceed the rating of the sources. Most research conducted to date uses a voltage/reactive power droop controller to solve this problem [7, 11, 12, 13, 14] However, little attention is given to operating the microgeneration within the appropriate power factor range (0.95 lagging or leading). This range is mentioned in the Engineering Recommendation G83/1 that says that when the DG operates at rated power it should operate at a power factor within the range 0.95 lagging to 0.95 leading [15]. In order to satisfy this requirement the converter droop controller is modified in this work to become a voltage/phase angle droop controller. The controller manipulates the terminal voltage of the converter at the required power factor whilst observing the specified limits. The function of the basic controller is shown in Figure (1). The phase angle limit (φ) shown in the figure is a function of the power factor limit.

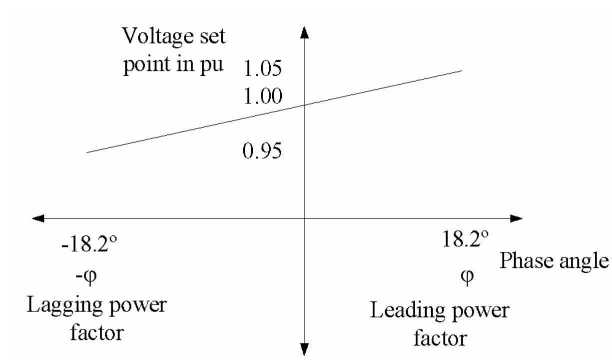

Figure 1: Voltage/phase angle droop.

- **Basic Structure of the Voltage/Phase Angle Droop Controller**

Figure (2) shows a voltage/phase angle droop control block diagram based on specified set points for voltage control of microgeneration. It consists of two PI controllers. RMS phase to ground voltages are measured in the bus where the source is connected. These values are compared with the reference value (for example the nominal value, 1pu). The error voltage is the input of the first PI controller to regulate the terminal voltage within the appropriate power factor range (0.95 lagging or leading) by generating a reference phase angle (limit φ=±18.2). The reference reactive power is produced from the product of the tangent of this phase angle and the reference active power, as described in the following equation.

$$Q_{ref} = P_{ref} \tan\phi \qquad (1)$$

This reference reactive power is the set point of the second PI controller. The second PI controller would suffice to control the flow of reactive power by generating the proper values for V as described in the following equations:

The transfer function of the PI controller is:

$$V_{ref}(s) = \mathrm{K}_{PV}\left[1+\frac{1}{\tau_{iV}S}\right].E_Q(s) \qquad (2)$$

Where $E_Q(s) = \lfloor Q_{ref}(s) - Q_{meas}(s) \rfloor$ (3)

K_{pV} : Proportional gain of the PI controller

τ_{iV} : Integral time constant of the PI controller which equals $\frac{K_{pV}}{K_{iV}}$ where K_{iV} is the integral gain, Q_{meas} : measured reactive power.

The microgeneration injects reactive power if the voltage falls below the nominal value and absorbs reactive power if the voltage rises above its nominal value.

The following equations describe the transfer function of the controller.

$$\phi_{ref}(s) = \mathrm{K}_{pv}\left[1+\frac{1}{\tau_{iv}S}\right].E_{vl}(s) \qquad (4)$$

Where $E_{vl}(s) = \lfloor V_{L-ref}(s) - V_{L-meas}(s) \rfloor$ (5)

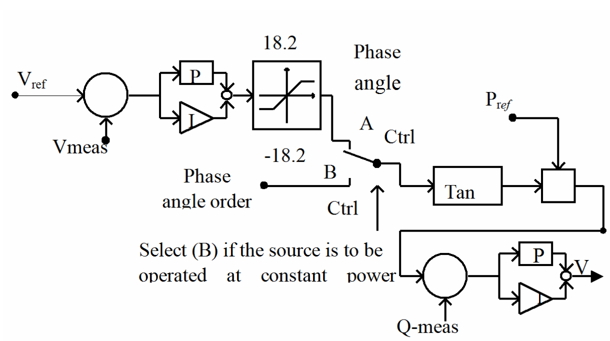

Figure 2: Voltage regulations through voltage-phase angle droop.

In addition, there is an additional switch that allows the controller to operate at constant power factor. For constant power factor operation, the input value to the controller is the phase angle that is related to the chosen power factor.

- **Basic structure of the Active Power (P)-Controller**

The function of the active power (P) controller is to control the active power. As shown in Figure (3), the PI controller would suffice to control the flow of active power by generating the proper values for δ_p, based on the instantaneous values of current and voltage taken from the converter output terminal, as described in the following equations:

From Eq. (4) the transfer function of the PI controller is:

$$\delta_p(s) = K_{p\delta}\left[1 + \frac{1}{\tau_{i\delta} S}\right] . E_P(s) \quad (6)$$

Where $E_P(s) = \left[P_{ref}(s) - P_{meas}(s)\right]$ (7)

$K_{p\delta}$: proportional gain of the PI controller,

$\tau_{i\delta}$: integral time constant of the PI controller equal to $\frac{K_{p\delta}}{K_{i\delta}}$ where $K_{i\delta}$ is the integral gain.

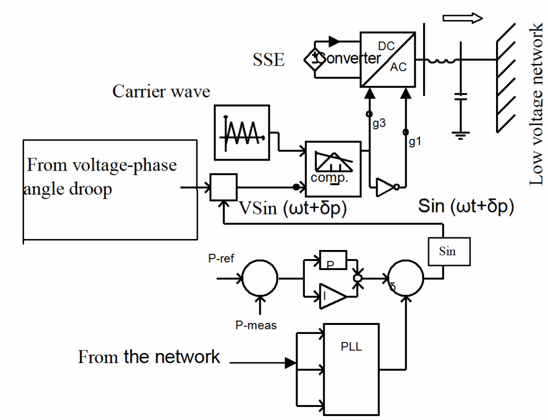

Figure 3: Overall control system

In order to detect the angular positions (ωt) of the voltages waveform, the measured three-phase voltages of the low voltage network are fed to a three-phase PI-controlled Phase Locked Loop (PLL). Then this (ωt) is added to the load angle (δ_p) generated by the active power controller. Then the sin of (ωt +δ_p) is taken and multiplied by the output of the reactive power controller (V) to obtain a single phase sinusoidal voltage waveform as defined bellow:

$$v = V \sin(\omega t + \delta_p) \quad (8)$$

This voltage is the input of the PWM unit to generate the gate signals for the converter.

NETWORK USED IN THE ANALYSIS

Figure (4) shows the configuration of the distribution network used in the analysis. The system comprises a 11 kV three phase source, supplying 11/0.433 kV 500 kVA ground mounted distribution transformer. The load is to two connected 433 V feeders A and B and represented by a fixed PQ load [16]. Table (1) summarises the data used in the distribution network [17].

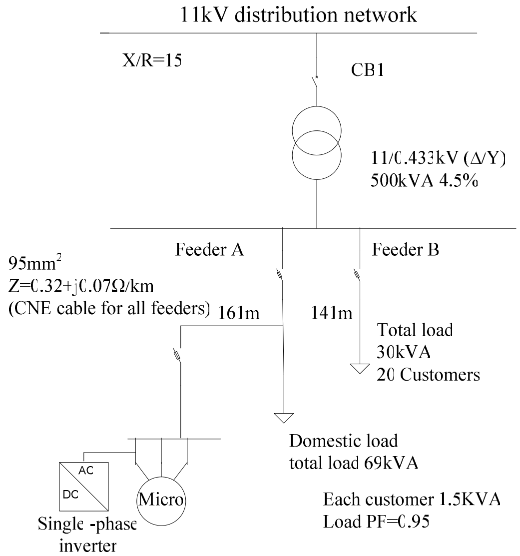

Figure 4: LV network model [17].

Table 1: Data used in the distribution network [17]

Component	Description	Comments
11kV Source	• 11kV source with 25MVA symmetrical break fault level • The system is connected to the main distribution system through a transformer and a circuit breaker CB1	with an X/R ratio of 15.
11/0.433kV Transformer	• 500KVA, 5% impedance,Dy11 windings • X/R ratio of 15,Taps set at –2.5% on HV side • Off load ratio of 11/0.433Kv	The impedance of the transformer is 0.0332+j0.0499p.u.
The electrical system is radial with two feeders A and B	• The voltage level at the loads is 0.433 kV • The feeder A is connected to a microgeneration and load (46customers) through 161m of 95 mm2 CNE cable. • Feeder B consists of a microgeneration providing heat and power to 20 local residential consumers through 141 meters of 95 mm2 CNE cable.	The impedance of the cable is 0.32 + j0.075 ohm/km (per phase).

SIMULATION RESULTS OF THE CONTROLLER

Studies were conducted to explore the performance of the controller in both steady state and transient operation for single-phase and three-phase converters. In the following plots the current and voltage waveforms are shown together. The three-phase voltages and currents are shown only for phase A in the bus where microgeneration is connected to the network. Active and reactive powers measured and reference values, phase angle and load voltage are also shown.

- **Simulation Results for Single-Phase Converter Interfaced Microgeneration**

In this subsection the study was conducted with a single–phase converter (switching model) connected to the network of (Figure 1). The capacity of the source is 3 kVA**,** rated active power is 2850 kW and rated AC voltage is 250 V. The converter is fed by a DC bus voltage source of 370 V. The single-phase converter is connected to the network through a single-phase transformer (250/250 V) for isolation purposes.

- **Output Results for the Controller during Steady State Conditions**

The aim is to investigate the performance of the controller when the load terminal voltage is equal to the set point as shown in Figure (5) (the period between 0-1sec). In this case the controller has to generate unity power factor reference which means there is no reactive power absorbed from or injected to the network.

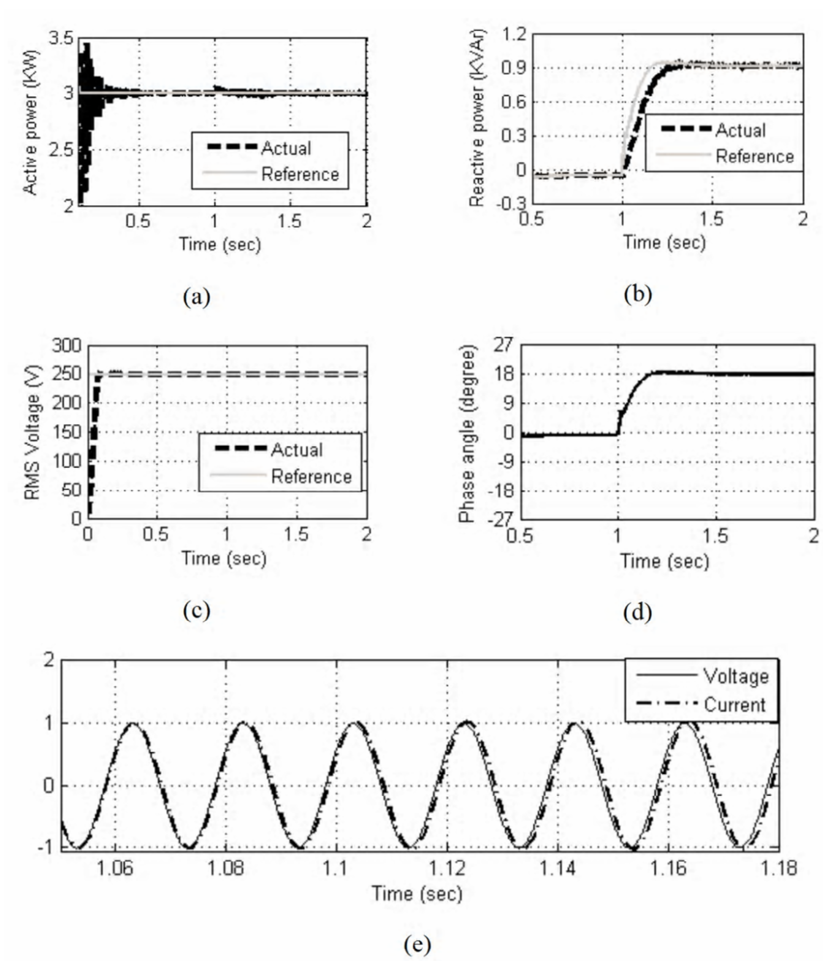

Figure 5: Response of a voltage/phase angle droop controller for single–phase converter to load increase: (a) Active power, (b) Reactive power response, (c) RMS load voltage, (d) phase angle response and (e) Transfer from unity power factor to leading power factor (Fundamental voltage and current waveforms).

- **Response of the Controller to Disturbance**

The aim of this study is to investigate the response of the controller when an additional load (18kW/5.9kVAr) is connected to the low-voltage network at t=1sec. This test was performed when the microgeneration is operating at unity power factor (the voltage set point at V=1pu) as illustrated in Figure (5). When the new load is connected the load voltage decreases but the controller responds rapidly to operate the source at leading power factor in order to inject reactive power to the network.

- **Simulation Results for Three-Phase Converter Interfaced Microgeneration**

In this subsection the phase angle/voltage droop control technique has been used to control a three–phase converter-interfaced microgeneration which is connected to supply a domestic load. The capacity of the microgeneration is 15.1 kVA and it is connected to the low-voltage network (Figure 1) through a three-phase power transformer.

- **Results for the Controller during Steady State**

To investigate the response of the controller the load terminal set point is changed to values over, under and at 1 pu. First the response of the controllers when the load terminal voltage is equal to the set point as shown in Figure (6) (the period between 0-5sec) is investigated. In this case the controller has to generate unity power factor reference which means there is no reactive power absorbed from or injected to the network. The response of the controller when the load terminal voltage is lower than the set point is shown in Figure (7) (the period between 0-5sec). In this case the controller has to generate a leading power factor reference to inject reactive power to the network. Figure (8) (the period between 0-5sec) shows the response of the controller when the load terminal voltage is higher than the set point. In this case the controller has to generate lagging power factor reference to absorb reactive power from the network.

- **Response of the Controller to Load Variations**

The aim of this study is to investigate the response of the controller when an additional load (15 kW/5 kVAr) is connected to the low-voltage network at t=5sec. The first test when the voltage set point at (V=1 pu, unity power factor), the second test when (V>1.00 pu, leading power factor) and the third test when (V<1.00pu, lagging power factor). In the first case the source is operating at unity power factor. However, as shown in Figure (6), when the new load is connected the load voltage decreases but the controller responds rapidly to operate the source at leading power factor in order to inject reactive power to the network to support the voltage. In the second case the source is operated at 0.95 leading power factor when the load is connected at 5 sec. As shown in Figure (7) the voltage decreases but in this case the power factor controller does not modify the source operation because they are already operating at the threshold value of leading power factor. In the third case the source is operated at 0.95 lagging power factor (absorbing reactive power from the network) when the new load is connected at 5 sec. As shown in Figure (8) the voltage decreases, however the power factor controller reacts to modify the operation of the source to leading power factor in order to inject reactive power into the network and compensate for the new load power demand.

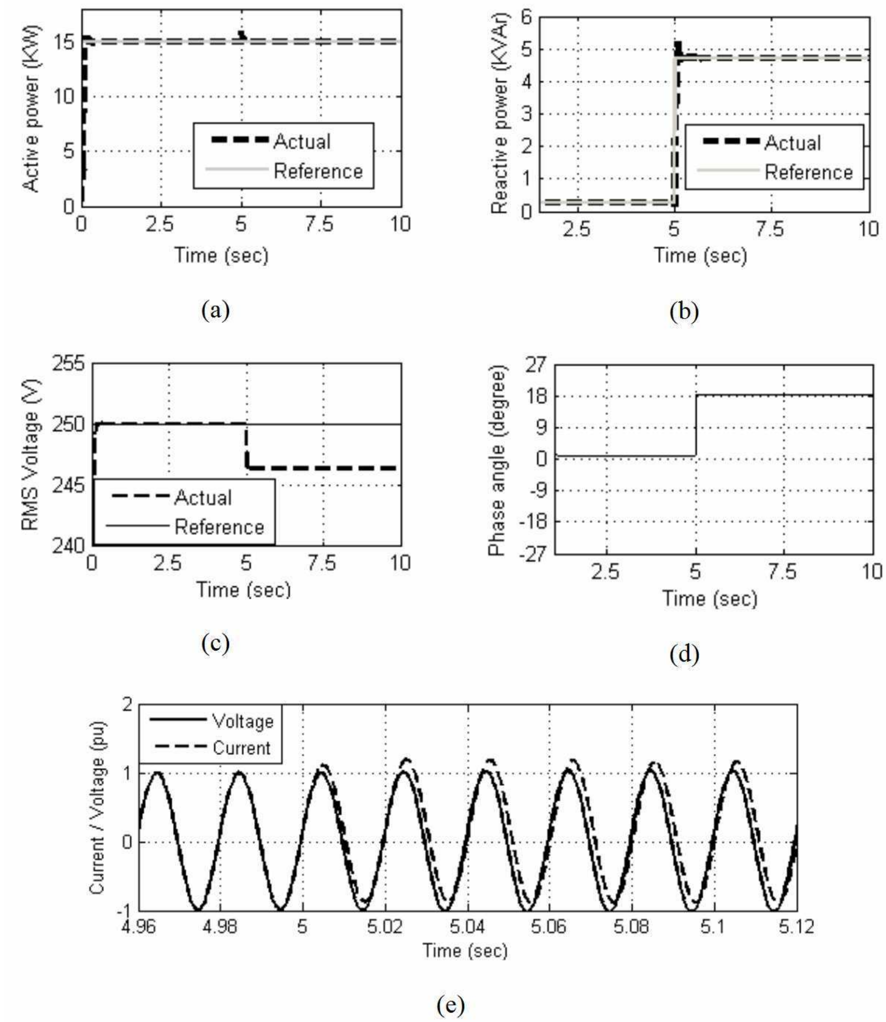

Figure 5: Response of a voltage/phase angle droop controller for three–phase converter to load increase (at unity power factor): (a) Active power, (b) Reactive power response, (c) RMS load voltage (d) phase angle response and (e) Transfer from unity power factor to leading power factor (voltage and current waveforms).

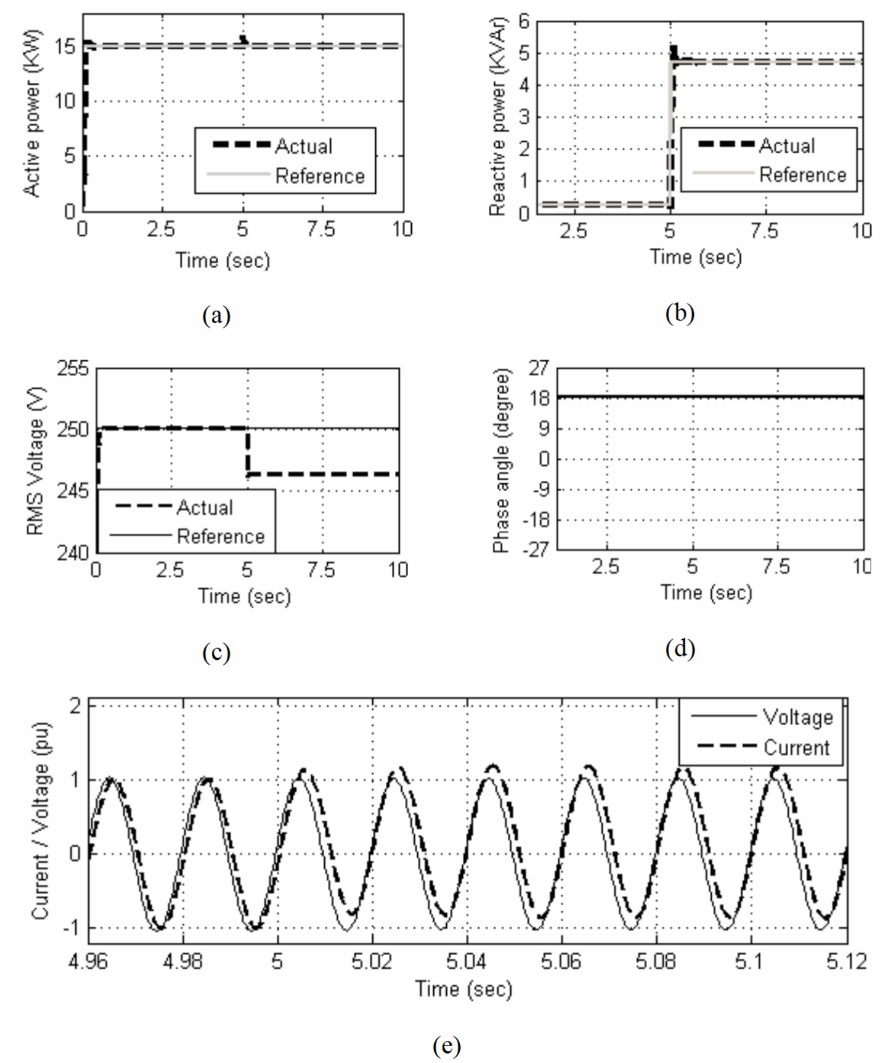

Figure 6: Response of a voltage/phase angle droop controller for three–phase converter to load increase (at 0.95 leading power factor): (a) Active power, (b) Reactive power response, (c) RMS load voltage (d) phase angle response and (e) Voltage and current waveforms.

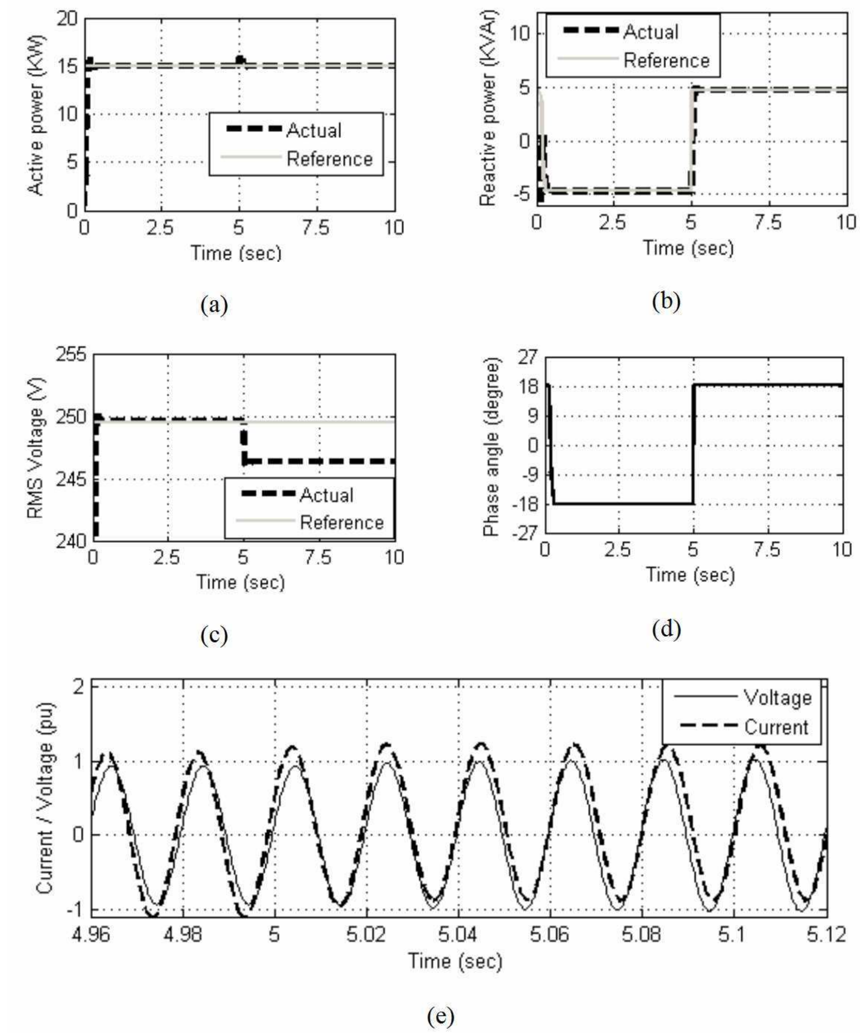

Figure 7: Response of a voltage/phase angle droop controller for three–phase converter to load increase (at 0.95 lagging power factor): (a) Active power, (b) Reactive power response, (c) RMS load voltage (d) phase angle response and (e) Transfer from lagging factor to leading power factor (voltage and current waveforms).

RELATIONSHIP BETWEEN PHASE ANGLE AND CONVERTER TERMINAL VOLTAGE

In this study the relationship between phase angle and converter terminal voltage and the performance of the controller was also investigated for different power factor values (0.95 lagging to 0.95 leading) using the same network (Figure 4). As shown in Figure (9), the simulation results indicate that this relationship is essentially linear.

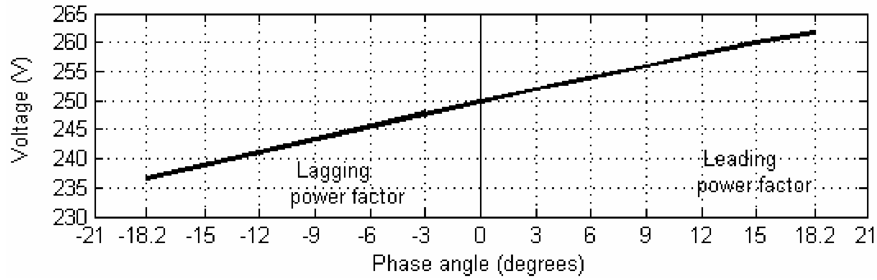

Figure 8: Relationship between phase angle and converter terminal voltage.

CONCLUSION

The main task of this paper was to propose a voltage/phase angle droop control scheme to control output power from a converter interfaced microgeneration. A low-voltage distribution network with embedded generation was modelled and simulated in PSCAD/EMTDC to assess the performance of the proposed control scheme for converter-interfaced microgeneration under different operation conditions. The studies showed that the response of the microgeneration controller was satisfactory during steady state and disturbance conditions. It was also shown that each phase of a three-phase converter can be controlled independently in order to address voltage unbalance problems encountered in microgeneration applications which use single and three-phase converters to interface microgeneration. Therefore the controller has appositive impact on the voltage stability and power quality of the network. Moreover the results show that there is a linear relationship between the phase angle and the microgeneration terminal voltage.

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