Primary Voltage Control of a Single-phase Inverter using Linear Quadratic Regulator with Integrator

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***Abstract*—This paper proposes a linear quadratic regulator with integration action, ensuring fast dynamic response and resisting capability of voltage deviation from instantaneous reference grid voltage, to control the inverter voltage that can also be used in a microgrid. The proposed control strategy is based on linear quadratic regulator, minimizing the cost function of the system, with integral action used to impede voltage degradation from a reference voltage for outside disturbances of the system, such as abrupt load change. The combined integral term assists to recover the voltage difference between grid and reference grid voltage. The validity of proposed controller has been tested with linear and non-linear loads with various conditions. In both cases, the effectiveness of the controller has been proved. Moreover, the robustness of the proposed controller for considering the practical situation has been examined applying a noise signal to the measured quantities. The result of the proposed controller is superior to track the instantaneous reference grid voltage.**

***Index Terms*— Voltage control, microgrid, linear quadratic integrator, inverter.**

I. INTRODUCTION

In the last decades, the increase of distributed generation (DG) compared to centralized power generation has drawn attention to the researcher because of its flexibility, stability, reliability, power quality, low cost and pollution [1]. Most of the DG units consisting of renewable energy sources that require power electronic converter, which initiate system resonance and protection interference. To surpass the issue, microgrid concept is evolved [2], shown in Fig. 1. Microgrid can ameliorate the reliability, local voltage, and efficiency through CHP and provide UPS function [3], [4]. Microgrid consisting of a micro-gas turbine, wind generator, photovoltaic generator and fuel cell can either operate with grid utility or alone considering self autonomous to protect, control and management. In microgrid, the inverters are used as interface devices with distributed energy sources for the energy conversion process. These interface devices have various characteristics as compared to conventional power plant [5]. So, improved performance of an inverter is an importance issue for stable and efficient operation in a power system network [6].

Most of the control strategies integrated in DG inverters to have better performance in voltage tracking and/or power sharing have been derived from an uninterrupted power supply (UPS) controller [7], [8], [9]. And the UPS utilized the complicated multi-loop feedback control strategy for power sharing that has voltage and frequency deviation [10], [11], [12], [13]. The most popular control strategy used for power sharing is droop derived from conventional power generation control strategy, and the majority of the researcher is concerned regarding power sharing among DG/UPS because droop control strategy can restore the voltage and frequency deviation [14]; however, the contribution of primary controller is not negligible to restore the voltage amplitude error after disturbance. The principle reason of the enormous research on droop control employment in an inverter/UPS is accurate power sharing with minimal voltage and frequency deviation, but little research has been conducted in the primary control strategy of a microgrid that can also assist to improve the power quality.

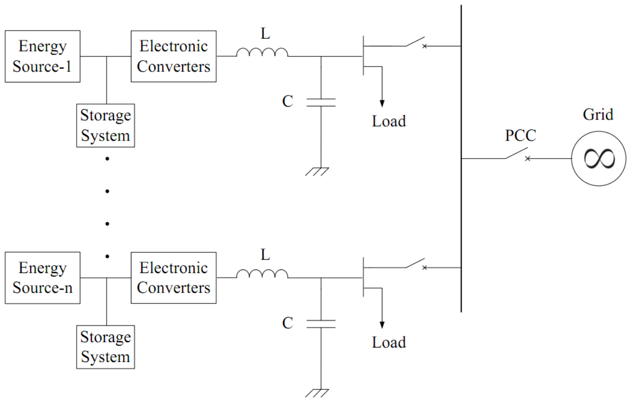


Fig. 1: Microgrid architecture

Inverter control in a microgrid is an essential task to provide a clean power into the grid. The control algorithm of an inverter should be capable of sending and/or receiving active and reactive power with stability. The error of tracking should be minimized as small as possible, and the transient response should be fast enough to remain stable. To achieve the effective operation of an inverter prescribed in [15], control algorithms require to improve.

The control approach of an inverter is usually performed by the mean of Clarke and Park transformation in dq-reference frame [16], [17], [18], [19], but it has numerical complexity as it requires harmonic reference too. Hence, it does not work accurately in the present of voltage harmonics. Moreover, this method can be used only in the three phase system, that is, its transformation cannot be converted into the single phase system. Therefore, a simple control strategy based on time domain without transforming to reference frame has been proposed to implement in the inverter controller [20]. In this paper, grid voltage is controlled applying inner current control loop and outer voltage control loop. In the inner current loop and outer voltage loop, proportional integral (PI) controllers are applied, but it requires much tuning effort to ascertain the system stability, which is arduous to implement in practice [21].

To abstain multi-loop control strategy in microgrid, [21] proposed a virtual flux droop method, calculating first mathematical relation between virtual flux and power, to share the power between two inverters with improved voltage and frequency deviation. This paper used droop of flux amplitude and angle as a performance index of power sharing, and applied in the inverter to improve the voltage and frequency deviation. In [22], a kind of robust iterative learning control is presented for single phase grid connected inverter that utilize the characteristics of power droop of an inverter to produce reference current, and hence track the reference current. This paper shows the enhanced tracking ability and distortion reduction of current waveform compared to the repetitive controller.

Among control algorithm, state feedback of pole placement has merit of high degree freedom and simplicity in implementation. The result of this method is effective performance in both steady state and transient condition [23], [24], [25]. The optimal linear quadratic regulator (LQR) has some characteristic that provide better system response minimizing transient error, and has an effective dynamic response for state variables. It is inherently stable and can be implemented independently of system order [26]. In [27], a linear quadratic regulator is proposed to control the reference grid voltage. Although, it is shown that LQR shows good tracking performance; it has an amplitude error after disturbance, for example, load change in the system that has been addressed in the current paper.

The majority of the above paper emphasize on the power/load sharing applying droop control characteristics of an inverter that employs multi-loop control strategy, but the primary control of an inverter is limited to root locus and bode plot analysis. Therefore, in this paper, primary control of an inverter has been demonstrated using linear quadratic integrator, minimizing the cost function of the system, to satisfy the fast dynamic response and nullify the steady-state voltage error between grid voltage and reference grid voltage during load changes. The integral term of proposed controller is used as an error reducing component. This approach is simple to find the optimal gain that provides an acceptable tracking with zero steady state error.

The organization of the remainder paper as follows: In Section 2, the state space dynamic model of a single phase inverter with LC filter is derived. Control design of voltage tracking is described using a linear quadratic regulator, and its limitation is addressed; then a proposed controller of the linear quadratic integrator is presented to overcome the shortcoming of LQR in Section 3. In Section 4, the simulation result of a shortcoming of LQR is presented first, after then the performance of proposed controller is executed.

II. SYSTEM MODELLING

The modelling of single phase grid connected voltage source inverter is shown in Fig. 2.

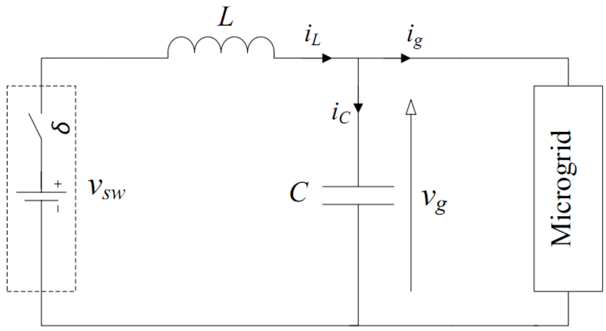


Fig. 2: Single phase single energy source microgrid

Microgrid, consisting of single or multiple power sources, extract power from the energy sources, such as wind and solar, which is represented as a constant dc voltage source for analytical simplicity. An LC filter is used immediately after the PWM inverter to eliminate the higher order harmonics. The duty ratio of the PWM is calculated by LQI to track the reference grid voltage, V_g^*.

Applying KVL and KCL in the Fig. 2, it can be written as

$$v_{sw} = L\frac{di_L}{dt} + v_g \tag{1}$$

and

$$i_L = i_g + i_C \tag{2}$$

where, $v_{sw} = \delta V_{dc}$ is the average switching voltage; and $\delta =$ duty ratio; $\quad -1 < \delta < 1$

The current through the capacitor can be written

$$i_C = C\frac{dv_g}{dt} \tag{3}$$

The modified equation can be written using (1), (2) and (3)

$$\frac{dv_g}{dt} = \frac{i_L - i_g}{C} \tag{4}$$

$$\frac{di_L}{dt} = \frac{v_{sw} - v_g}{L} \tag{5}$$

The state space equation of the system is represented by

$$\begin{bmatrix} \dot{v}_g \\ \dot{i}_L \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{C} \\ -\frac{1}{L} & 0 \end{bmatrix} \begin{bmatrix} v_g \\ i_L \end{bmatrix} + \begin{bmatrix} 0 \\ V_{dc}/L \end{bmatrix} \begin{bmatrix} \delta \end{bmatrix} + \begin{bmatrix} -1/C \\ 0 \end{bmatrix} \begin{bmatrix} i_g \end{bmatrix} \tag{6}$$

The variation in i_g can be treated as a disturbance to the system during load variation, and the microgrid load is changed randomly by connecting and disconnecting of a generator and load.

As the voltage is considered as a tracking parameter of the system, so v_g is taken as an output

$$\begin{bmatrix} v_g \end{bmatrix} = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} v_g \\ i_L \end{bmatrix} \tag{7}$$

In the general form of the state space equation of (6) and (7) is given below

$$\dot{x} = Ax + Bu \tag{8}$$

$$y = Cx + Du \tag{9}$$

here, $D = 0$ and $u = \delta$

III. CONTROLLER DESIGN

A. Linear quadratic regulator

In the linear-quadratic regulator, ensuring stability of the system, the optimal control is synthesis with respect to the cost function of the system. To implement the linear-quadratic regulator, an appropriate model of microgrid has been developed in the previous section.

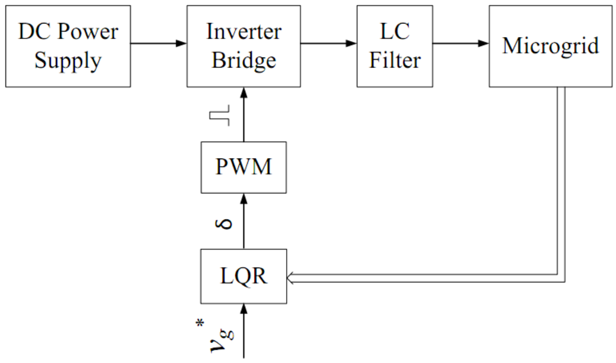


Fig. 3: Application of linear quadratic regulator

The state of the system is feedback into the input while minimizing quadratic cost function. The cost function can be determined by the following equation

$$J(u) = \int_0^\infty (x^T Qx + u^T Ru + 2x^T Nu)dt \tag{10}$$

where, Q and R are the state and input control weighting cost square symmetric matrices. Here, $Q - NR^{-1}N^T \geq 0$, and $R > 0$.

The input, u, is defined by $u = -Kx$, the K is Kalman gain and defined by

$$K = R^{-1}(B^T S + N^T) \tag{11}$$

The matrix Riccati-equation provides the value of S

$$-\dot{S} = A^T S + SA - (SB + N)R^{-1}(B^T S + N^T) + Q \tag{12}$$

Equation (12), a time varying, provides a set of differential equation. The steady state solution of (12) is convenient to use than time varying. As (12) is time varying, instantly, (11) is also time varying. To solve the problem into a simple form, the steady state solution is considered known as suboptimal solution. The state solution of (12) is given by

$$A^T S + SA - (SB + N)R^{-1}(B^T S + N^T) + Q = 0 \tag{13}$$

In the above equation, the matrix S must satisfy (13). Using the LQR equations, controller design can be simple, but the main difficulty of this existing controller is vulnerable due to disturbance, because it has no error reducing term. Consequently, implementing the controller in the practical situation can lead into high steady-state tracking error.

B. Proposed controller

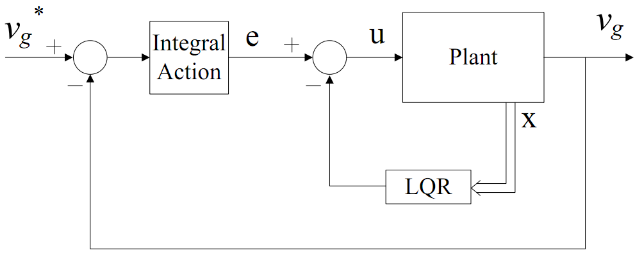


Fig. 4: Linear quadratic regulator with integral term

In order to solve the problem raised from the LQR, it is proposed to impart an integral term, that will track the controlled parameter, with the LQR controller. As, a new integral term will be added; the control law requires modification, and its input can be computed using following formula

$$u' = -Kx + K_i \int_0^\infty (v_g^* - v_g)dt \tag{14}$$

K_i = the integral gain used to minimize the the error between v_g^* and v_g; K = LQR gain; v_g^* = reference grid voltage; v_g = grid voltage

Error term requires to define to solve the integral gain, K_i, value

$$e = \int_0^\infty (v_g^* - v_g)dt \tag{15}$$

Differentiating (15) and substituting the value of v_g=Cx; the above equation can be written

$$\dot{e} = v_g^* - Cx \tag{16}$$

The modified state space equation can be written as

$$\dot{x} = A'x + B'u' \tag{17}$$

$$y = Cx \tag{18}$$

where, $A' = [A \quad 0; -C \quad 0]$; and $B' = [B \quad 0]$

Rewriting the control law

$$u = -Kx + K_i e \tag{19}$$

Further reducing to

$$u = -K'x' \tag{20}$$

where, $K' = [K \quad -K_i]$; and $x' = [x \quad e]$

The solution of K' should converse the error, produced by disturbance, to zero provided system stable and minimization of the cost function

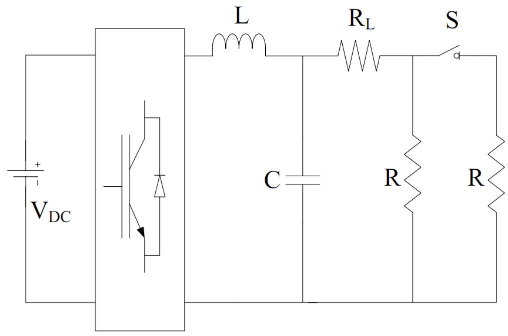
$$J' = \int_0^\infty (v_g'^T Qx + u'^T Ru + 2v_g'^T Nu)dt \tag{21}$$

To have better performance, Q and R are synthesis in a state that satisfy the controller requirement. After determining these two values, the matrix S can be determined by solving modified algebraic Riccati-equation

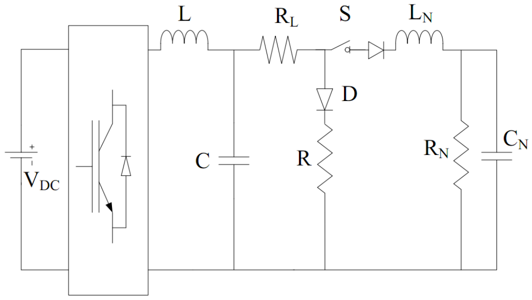
$$A'^T S + SA' - (SB' + N)R^{-1}(B'^T S + N^T) + Q = 0 \tag{22}$$

The optimal state feedback gain matrix K' can be determined by

$$K' = R^{-1}(B'^T S + N^T) \tag{23}$$



(a) Linear load topology



(b) Non-linear load topology

Fig. 5: Simulation diagram of microgrid

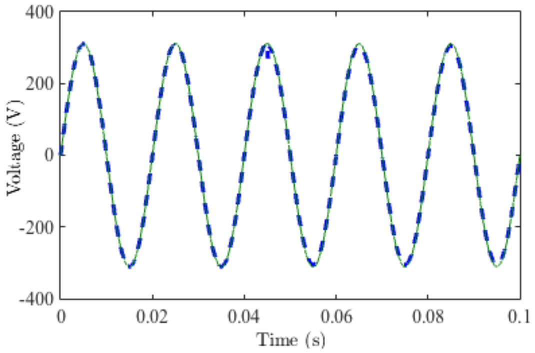
The output of the controller is the value of duty ratio that is proportional to the inverter voltage obtained from the dc bus voltage.

IV. SIMULATION

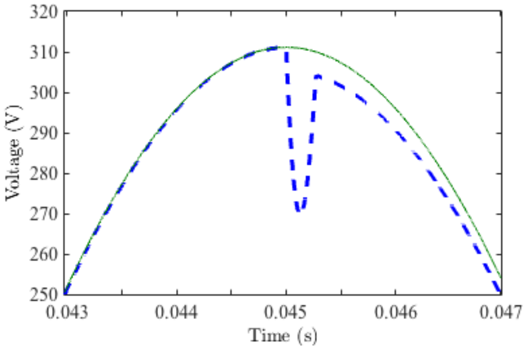
The simulations are carried out using MATLAB/SimPowerSystems for both LQR and LQI controller. For the simplicity purpose of controller implementation, the microgrid is considered as a resistive line and load with a dc bus voltage connected VSI shown in Fig. 5a . The dc bus voltage equal 400V, filter inductor and capacitor equal 2mH and 12μF, respectively. The carrier frequency of the PWM is taken 10kHz. The reference sinusoidal RMS grid voltage is 220V with frequency 50Hz. The simulation is carried out mainly two cases: linear load and non-linear load. In simulation process, first, a principle difficulty of LQR controller in a system is addressed, then, a proposed controller is performed throughout the paper.

A. Linear load

To address the issue of LQR controller during load change, the simulation is carried out in two parallel connected resistive loads of 30Ω with a switch, S, that is turn on after 0.045s, and a transmission line resistance equal 0.40Ω considering the 1km line, simulation topology is shown in Fig. 5a. From the Fig. 6, it is observed that a better tracking performance was achieved before the disturbance, but after the disturbance, remarkable voltage deviation is occurred from the reference grid voltage. A chief reason of this voltage difference is because of not having any error minimizing strategy in LQR. The gain of LQR only multiplies with the measured quantities, but when any outside disturbance happens; it also multiplies gain with measured quantities, that is why voltage deviation after any disturbance, and this disturbance is the general case of practical situation as load is unpredictable. The problem

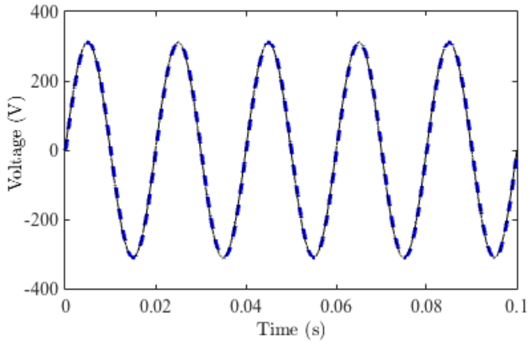


(a) LQR:grid voltage tracking

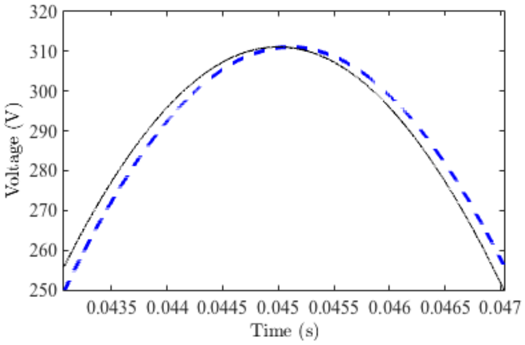


(b) Zoom In: amplitude error

Fig. 6: The performance of LQR (—— = desired, - - - = obtain)

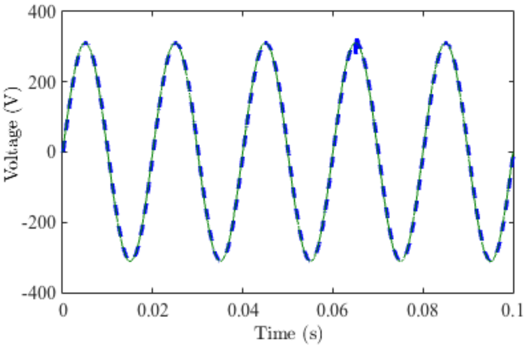


(a) Overview

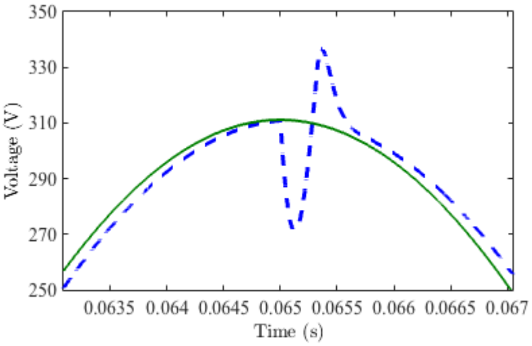


(b) Zoom In: amplitude error

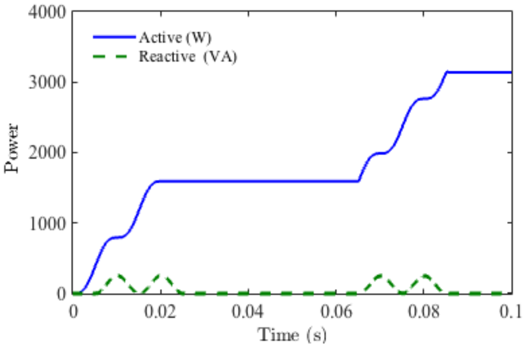
Fig. 7: Linear load: steady state grid voltage tracking (—— = desired, - - - = obtain)



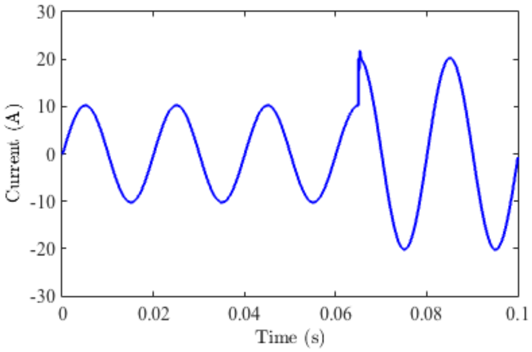
(a) Overview



(b) Zoom In: amplitude error



(c) Supplied power



(d) Grid current, i_g

Fig. 8: Linear load: grid voltage tracking during load change (—— = desired, - - - = obtain)

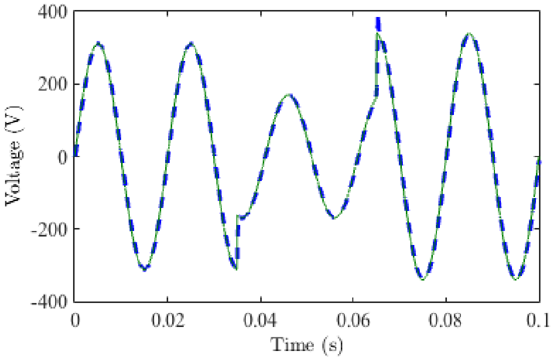


Fig. 9: Changing reference voltage, v_g^*, tracking (—— = desired, - - - = obtain)

exploded in LQR problem after connecting the resistor, the current supplied to the load before is double; hence, LQR controller can not compensate this extra current that leads toward voltage deviation.

To compare the two controller strategies, tuning of a controller and its appropriate value selection are essential task. Hence, both simulations for LQR and LQI are first executed in Matlab/Simulink model, after then, its value has been chosen to use in SimPowerSystems.

In the next simulation, the performance of proposed controller has been evaluated in the following consideration:

1. Steady state voltage tracking
2. Voltage tracking during load change, and
3. Changing reference voltage tracking

In each of the three cases of voltage tracking has been considered for both linear and non-linear loads. The first simulation of the proposed controller has been demonstrated with a resistive load of 30Ω, the simulation topology is demonstrated in Fig. 5a.

The performance of grid voltage tracking for steady state waveform is observed effectively in Fig. 7. A detail of amplitude of grid voltage tracking, Fig. 7a, is provided in Fig. 7b. From the Fig. 7b, the difference between grid voltage and reference grid voltage is negligible in phase error and almost zero steady state amplitude error.

The assumed load cannot be a constant parameter in practice. It is changed randomly because of the consumer requirement of turning on or off the load at any time in 24 hours. Consequently, it is important to perpetrate the grid voltage tracking during maximum load variation. The greatest load variation can only be obtained in parallel connection of same consumer load. So, in this simulation, another load of 30Ω is connected parallel to the existing load, that is, the two loads are 30Ω, and a switch is engaged between them to turn on the load after 0.065s to observe the maximum load change voltage tracking, the connection topology is shown in Fig 5a. From the Fig. 8a, it is notice that controller is working effectively with minimal tracking error as did in Fig. 7a. A detail of fluctuating voltage is given in Fig. 8b at time 0.065s. The corresponding power and current waveform due to load change in the circuit is also captured to understand the theoretical concept with simulation values. The active power supplied by the DG can be calculated using the following equation

$$P = \frac{V_g^2}{R} \tag{24}$$

where v_g = rms grid voltage, and R = total resistance of microgrid

For the reference grid voltage of 220V(rms), the steady state active power equal 1.61kW for load resistance of 30Ω that can be found in the final steady state value of the simulation in Fig. 8c before 0.065s. After the turning on the switch at 0.065s, the total resistance equal 15Ω, so, steady state power equal 3.23kW that is also reflected with Fig. 8c after 0.065s. The increasing power is caused by increasing grid current, double, that is shown in Fig. 8d.

A rapid voltage change in a system is general phenomena that can be occurred at any time due to switching operation such as switching load, starting motor and switching on/off reactive power compensator. This voltage change also causes of output power change of distributed generator such as wind and solar power. To accomplish the grid voltage change in a system and observe the controller performance, the reference rms voltage, v_g^*, is changed, and the corresponding response of voltage tracking has been executed in the simulation. To carry out this phenomena, a resistive load of 30Ω is taken into account, and the grid voltage, v_g^*, is changed accordingly:

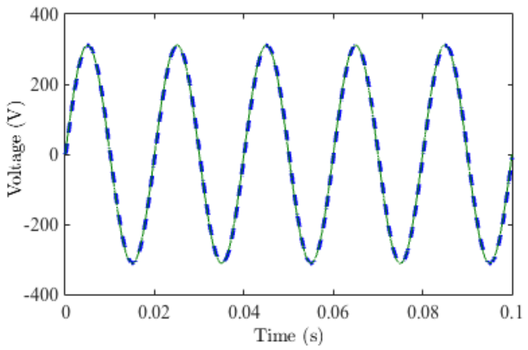
v_g^*=220(rms) $0.0 < t(ms) \leq 3.5$
v_g^*=120(rms) $3.5 < t(ms) \leq 6.5$
v_g^*=240(rms) $6.5 < t(ms) \leq 0.1$

From the Fig. 9, it is notice that the difference between grid voltage and reference grid voltage is negligible, and the transient response is acceptable. Therefore, it is concluded that the controller is robust in the term of linear load subjected to above three situations.

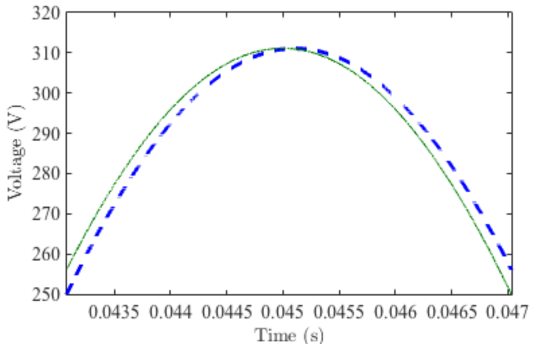
B. Non-linear load

The application of electronic equipments such as computer, converter and electronic-ballast are increasing dramatically recently, and all electronic equipments contain non-linear elements such as diode, MOSFET and SCR that generate harmonic current caused voltage distortion. To investigate the non-linear load effect on voltage tracking strategy, a series connected diode with a resistive load of 30Ω, shown in Fig. 5b, is simulated first to see the steady state voltage tracking waveform. The forward voltage and internal resistance of the diode are taken 0.7V and 0.0001Ω, respectively. The performance of the controller is analogous, found in Fig. 10a, to that of the linear steady state controller.

In the second simulation of the controller, another non-linear load that is parallel connected through a diode and switch, S, demonstrated in Fig. 5b. Load consisting of a series connected inductor with parallel resistor and capacitor. The value of inductor, resistor and capacitor are 0.084H, 30Ω and 235μF, respectively. In the Fig. 11a, it is marked that the grid voltage track perfectly the reference grid voltage even after the turning on the switch, S, at time 0.045s. The detail of switching is exhibited in Fig. 11b. As the load consisting of reactances; both active and reactive power will be supplied by the source that is displayed in Fig. 12b as well as the corresponding grid current shown in Fig. 12a.

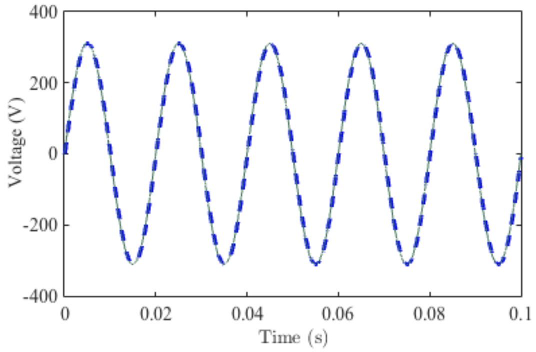


(a) Overview

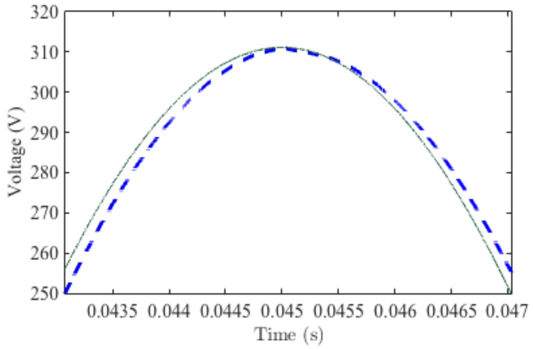


(b) Zoom In: amplitude error

Fig. 10: Non-linear load: steady state grid voltage tracking (—— = desired, - - - = obtain)

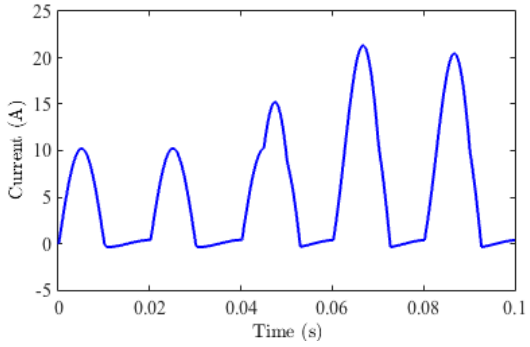


(a) Overview

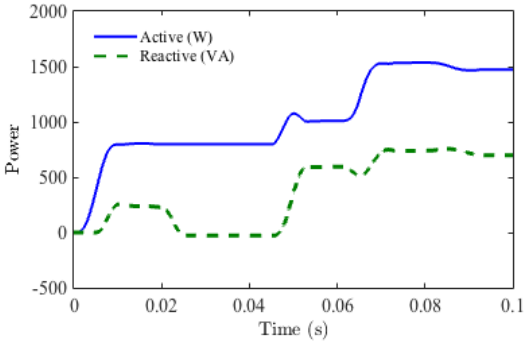


(b) Zoom In: amplitude error

Fig. 11: Non-linear load: grid voltage tracking during load change (—— = desired, - - - = obtain)

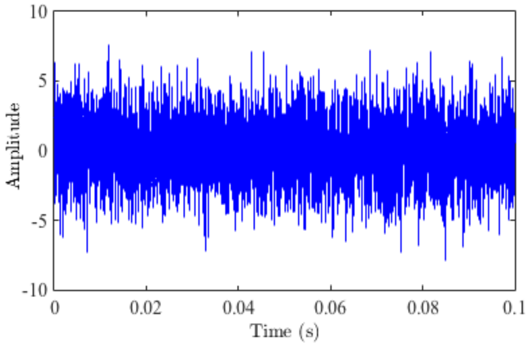


(a) i_g

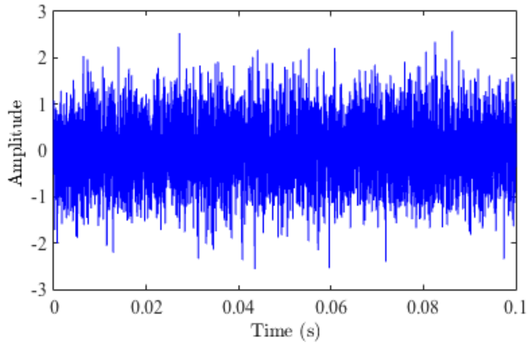


(b) Power

Fig. 12: Non-linear load: power and grid current waveform

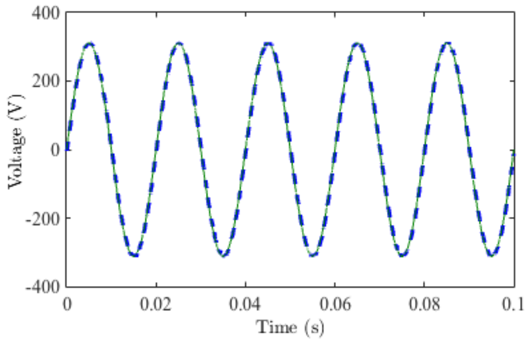


(a) Added noise to the voltage measurement

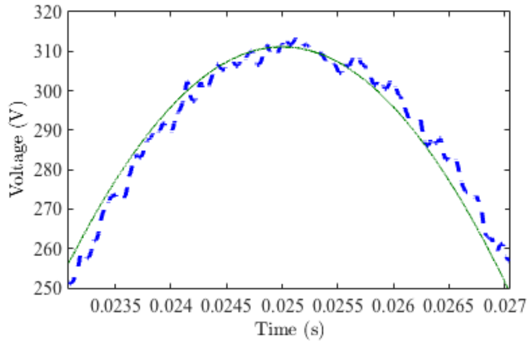


(b) Added noise to the current measurement

Fig. 13: Noise in signal



(a) Overview



(b) Zoom In: amplitude error

Fig. 14: Linear load: grid voltage tracking after noise affected signal(—— = desired, - - - = obtain)

At present, most of the loads connected in distributed side are non-linear nature. Therefore, sudden changing of reference voltage is also executed in this load condition, and its result analogous to the linear load; consequently, redundant figure is omitted.

C. Robustness

In practice, a plant is generally installed far away from the controlling unit, and the effort of controlling unit depends on the feedback signal of the system. The feedback signal has the possibility of getting noise affected, generated by different sources such as electric and/or magnetic field that superimpose noise on the measured signals. In the next simulation, noise is incorporated with the measured signal of both current and voltage. The associated noise for current and voltage is demonstrated in Fig. 13. After adding noise in the measurement signal, the voltage tracking strategy is applied and found working perfectly that has been shown in Fig. 14a. A detail of amplitude error is exhibited in Fig. 14b

V. CONCLUSION

In this paper, a new tracking control strategy of an inverter connected grid, a linear quadratic integral controller, eliminating amplitude error of instantaneous grid voltage during load changes of power system, is proposed. By assigning the proposed integral term with LQR, the voltage deviation error, that is produced in LQR controller addressed with the aid of SimPowerSystem, can be nullified under power system load change. The fundamental convenience of proposed controller is that the integral term diminishes the grid voltage amplitude error produced from sudden load change. Moreover, the transient response of the controller is praiseworthy to track the reference grid voltage, v_g^*. This proposed controller strategy is superior to have a better tracking.

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