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A LINEARIZATION CONTROL STRATEGY FOR MICROGRID VIA VIRTUAL SYNCHRONOUS GENERATOR

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Abstract. *In this paper, a novel linearization control strategy on microgrid (MG) for traditional voltage source three-phase converters (VSC) is proposed to improve the low inertia characteristics of the overall power system with the renewable energy sources (RES). The virtual synchronous generator (VSG) emulates the behavior of traditional synchronous generator by power electronic converters and adds virtual inertia to the MG. In order to improve the robustness of the power system, feedback linearization controller is used in the VSG model. Considering the adjustment of control parameters is the key to the controller design, linear quadratic regulator (LQR) approach is used to determine the gains of mentioned controller, which enables state linear feedback obtaining the optimal control law. The anti-interference performance of the proposed control scheme for MG is demonstrated through the simulation results.*

Keywords: Virtual synchronous generator, Feedback linearization, Microgrid, Linear quadratic regulator

1. **Introduction.** Over the last decades, the price of variable renewable energy is falling drastically, distributed energy resources are causing bidirectional power flows and voltage fluctuations and being added to electric grids that can impact system operation and optimal control [1], and electric power system is undergoing a gradual but steady transition from conventional power system to the use of electricity generation from renewable energy sources (RES) [2, 3, 4]. The synchronous generator which is stored kinetic energy, plays an important role in the inertial response. As a consequence, more renewable energy sourced generators, through the converters, are connected to the power grid, and the system inertia of the overall power system decreases. System inertia plays a vital role in power system. The phenomenon of low inertia in a weak grid results in a high rate of change of frequency and large frequency deviations, which may cause protective relay tripping, load shedding, and cascading failure [5]. Therefore, operating grid-connected inverter as synchronous generator virtual synchronous generator (VSG) is presented as a novel mean [6, 7, 8]. VSG is used for providing artificial or virtual inertia into a power system by using an inverter, and energy storage system with a suitable control strategy. Thus, the stability of synchronization in the power system can be enhanced. In an MG system, large-signal disturbances include transition between grid connected and islanding modes, and sudden large load demands. A novel control topology for microgrids is proposed, which can run in both grid-connected and islanding modes [9]. VSG technology helps to regulate the frequency of the power system, and in the event of grid outages, VSG-based electric vehicles can support local loads through the batteries of electric vehicles. At the

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same time, through VSG technology it can have good results in both island and grid-connected modes [10]. The VSG is equivalent to small-signals under certain conditions [11]. DC microgrids provide an ideal environment for the integration of large numbers of random renewable energy sources. To prevent sudden and large power changes, power generation, and demand, it is usually achieved through linear controllers designed based on linearized object models [12].

The power system consists of a large number of power devices with significant nonlinear performances, which can convert the nonlinear power system into a linear system, by feedback linearization. To provide robustness against external disturbances in MG feedback linearization is applied to designing controller [13]. An adaptive control scheme for higher-orders model of synchronous generators can offer better transient performance and avoid the problem of explosion of terms inherent in backstepping approach as compared with the conventional adaptive backstepping control [14]. Feedback linearization control, which is appropriate and effective when wishing to use the linear model, is a robust control technique for nonlinear power system. After getting a new linear state space model of MG, we can utilize linear quadratic regulator (LQR), which enables feedback linearization controller obtaining the optimal control law. Feedback linearization controller based LQR shows kind of stabilizing and anti-interference under different bounded load variations due to variation of parameters [15, 16, 17]. We use LQR generating optimal parameters of feedback linearization controller for the state space model of VSG in voltage source three-phase converters (VSC) for MG, to realize and improve the stability and anti-interference performance of the power system. To demonstrate the validity of the proposed control strategy design approach, a simulation model of the grid-connected and island MG is constructed.

This paper focuses on the design of controller for power systems based on the exact linearization of power systems. The novel contribution of this paper is that a linear controller based on VSG system is designed to guarantee the stability of the system in the islanded, grid-connected and transition modes. The major contribution of this paper is to take the state variables of the complex nonlinear power system based on VSG as feedback, and to transform the state variables of the system by linearizing feedback, so as to obtain the fully linearized system. The significance is to make the resulting linear system as an intelligent body object, so that in the later work, the system can be used as an intelligent body, in order to design distributed controllers, simplify the coordination and control of multi-area microgrid. Through linear control technology, the distributed control rate of each subsystem can be obtained easily.

The rest of this paper is organized as follows. In Section 2, a state space model of the VSG system is introduced. In Section 3, after getting the exact linearization of power system model, the feedback linearization control is obtained according to the structure of the controller. And to generate optimal parameters of feedback linearization controller LQR is applied in the calculation. In Section 4, simulation results for the grid-connected and island MG and comparisons with traditional VSG control methods are presented to demonstrate the effectiveness of the proposed controller. Concluding remarks and suggestions for future works are written in Section 5.

2. State Space Model of VSG.

Figure 1 illustrates the control block diagram of the MG based on VSG control technique. The model of VSG can be found in many sources such as [18]. In order to make the inverter have more precise operation mechanism of synchronous generator, the rotor motion equation of synchronous generator is added in the control part [5]. To design a feedback linearization controller, first of all, the state space model of the system must be obtained. The distributed generation is connected to the MG bus by a voltage source inverter, and the energy storage is to maintain the VSG direct voltage side voltage constant that is V_{dc}. In order to filter out the effect of high

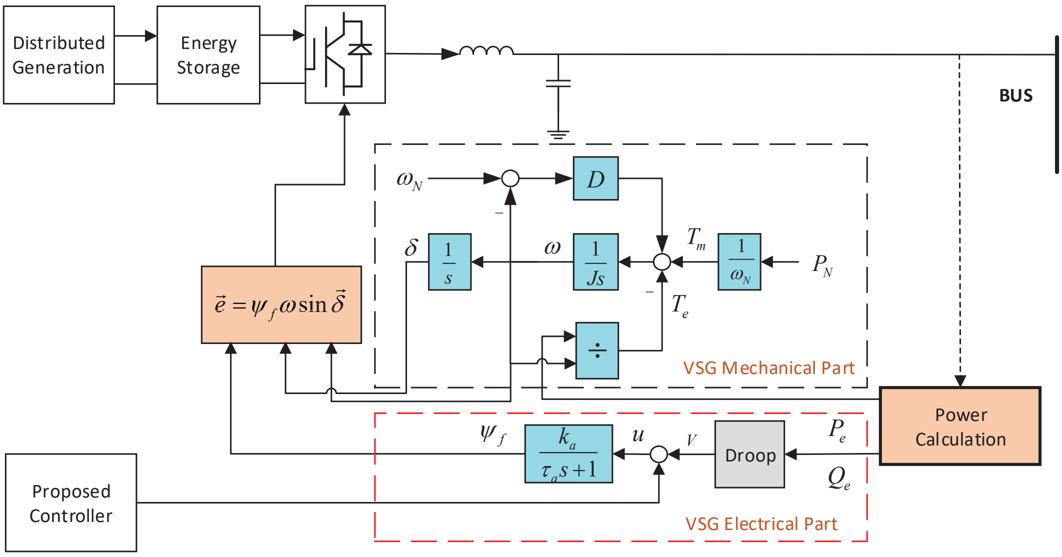

FIGURE 1. Block diagram of a VSG-based MG

frequency switch on power quality, a filter circuit is connected at the inverter output. The mathematical model of the VSG can be formulated as shown in the mechanical part and electrical part. The selected system state space variable determines the system linearization model by feedback linearization, controls the magnetic chain of the VSG, and then converts the resulting voltage into PWM signal to control the inverter.

It is a third-order VSG model, which consists of mechanical part and electrical part [7]. In the proposed VSG control strategy power angle (δ), virtual rotor speed (ω), virtual electromagnetic torque (T_e) are the state space variables.

VSG mechanical dynamics:

$$\dot{\delta} = \omega - \omega_N \tag{1}$$

$$\dot{\omega} = -\frac{D}{J}(\omega - \omega_N) - \frac{1}{J}(T_e - T_m) \tag{2}$$

where δ is the power angle of the VSG, which is the difference between the virtual rotor angle and the virtual angular velocity of the machine, ω is the rotor speed of the VSG with respect to synchronous reference, ω_N is the rated angular frequency of the rotor, J is the virtual rotor momentum of inertia constant, T_m is the virtual mechanical torque which is assumed to be constant which can be calculated by the initial set-point of power: P_N, D is the virtual damping constant, and T_e is the virtual electromagnetic torque delivered by active electrical power of the generator.

VSG electrical dynamics:

$$\dot{T}_e = \frac{3}{2}\frac{k_a}{\tau_a}uI\cos\delta - \frac{c}{\tau_a}T_e + \frac{3}{2}\psi_f \dot{I}\cos\delta - \frac{3}{2}\psi_f I(\omega - \omega_N)\sin\delta \tag{3}$$

where ψ_f is the virtual rotor flux of the VSG, k_a, τ_a and c are parameters of a low-pass filter to generate the virtual rotor flux, I is the three-phase current, and u is control input. It is observed that the mathematical model of a VSG power system is a nonlinear power system model.

3. **Feedback Linearization Control.** In order to design the proposed feedback linearizing controller, it is necessary to achieve the feedback linearized models. To do this, for the dynamics of VSG in the microgrid, as represented by (1)-(3), it is a nonlinear system. The general form of the nonlinear system can be written as

$$\dot{x} = f(x) + g(x)u \tag{4}$$

where

$$x = \begin{bmatrix} \delta & \omega & T_e \end{bmatrix} \tag{5}$$

$$f(x) = \begin{bmatrix} \omega - \omega_N \\ -\dfrac{D}{J}(\omega - \omega_N) - \dfrac{1}{J}(T_e - T_m) \\ -\dfrac{c}{\tau_a}T_e + \dfrac{3}{2}\psi_f \dot{I}\cos\delta - \dfrac{3}{2}\psi_f I(\omega - \omega_N)\sin\delta \end{bmatrix} \tag{6}$$

$$g(x) = \begin{bmatrix} 0 & 0 & \dfrac{3}{2}\dfrac{k_a}{\tau_a}I\cos\delta \end{bmatrix}^T \tag{7}$$

where x is a state vector, $f(x)$, $g(x)$ are smooth vector fields that are associated to states and u is the input vector. The feedback linearization of the model determines the efficiency of the controller of the microgrid power conversion system, and the feedback linearization characteristic is determined by the relative number of the system, which is determined by the output function [19]. The output function $y = h(x)$ should be selected in such a way that $r = n$. For the mentioned system, the output function is chosen as

$$y = h(x) = \delta - \delta_N \tag{8}$$

The mathematical model of the nonlinear system as presented in (4) can be linearized using feedback linearization when some conditions as described latter are satisfied. Consider the following nonlinear coordinate transformation

$$z = \phi(x) = \begin{bmatrix} h(x) & L_f h(x) & \cdots & L_f^{r-1}h(x) \end{bmatrix} \tag{9}$$

where $r < N$ is the relative degree corresponding to output function $h(x)$, and $L_f h(x)$ are the Lie derivative [20] of $h(x)$. z and x are the vectors of the same dimension and ϕ is the nonlinear function of x. Now, by nonlinear coordinate transformation, the original x states are transformed into z states. The control input has a state feedback component, the Lie derivates are given by the following equations:

$$L_g h(x) = \frac{\partial h(x)}{\partial x} g(x) = 0 \tag{10}$$

Again

$$L_f h(x) = \frac{\partial h(x)}{\partial x} f(x) = \omega - \omega_N \tag{11}$$

and

$$L_g L_f h(x) = \frac{\partial (L_f h(x))}{\partial x} g(x) = 0 \tag{12}$$

Finally

$$L_f^2 h(x) = -\frac{D}{J}(\omega - \omega_N) - \frac{1}{J}(T_e - T_m) \tag{13}$$

and

$$L_g L_f^2 h(x) = L_g L_f h(x) = \frac{\partial \left(L_f^2 h(x)\right)}{\partial x} g(x) = -\frac{3}{2J}\frac{k_a}{\tau_a} uI\cos\delta \neq 0 \tag{14}$$

where $L_g L_f h(x)$ is the Lie derivative of $L_f h(x)$ along $g(x)$. In Formula (14), the value of I is always greater than zero, because it is the dq-transformation from the virtual stator currents of phases A, B and C. At the same time, δ, the power angle of VSG is the integral of ω. The value of power angle is positive as long as the frequency of the MG changes. And the parameters of the low-pass filter to generate the virtual rotor flux also is a non-zero value. From the above calculation, it is clear that the relative degree of the system is equal to the order of the system which is 3. Thus, the system is exactly linearizable. The direct coordinates transform is expressed as follows:

$$\begin{cases} \dot{z}_1 = z_2 = L_f h(x) \\ \dot{z}_2 = z_3 = L_f^2 h(x) \\ \dot{z}_3 = v = L_f^3 h(x) + L_g L_f^2 h(x) u \end{cases} \tag{15}$$

The linearized system can be expressed as follows:

$$\dot{z} = Ax + Bv \tag{16}$$

where

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} \tag{17}$$

$$B = \begin{bmatrix} 0 & 0 & 1 \end{bmatrix}^T \tag{18}$$

To determine the input variable v, from (15) and (16), v is the "control" input of the linear system of the Brunovsky normal form, so the most reasonable way is using the linear optimal control design method with the quadratic performance index (LQR method) to produce the v. In the linear control system (16), matrices A and B satisfy the following condition, namely the matrix

$$D = \begin{bmatrix} B & AB & A^2B \end{bmatrix} \tag{19}$$

has rank 3. This condition means that the system is controllable. The performance index of the system is quadratic.

$$J = \frac{1}{2} \int_0^\infty \left(Z^T Q Z + V^T R V \right) dt \tag{20}$$

where Q is a semi-positive definite weighting matrix, and R is a positive definite weighting matrix. The problem can be granted as obtaining the state feedback vector

$$v = v(Z(t)) = v(z_1, z_2, z_3) \tag{21}$$

which is able to make the performance index J reach its extremum. This is called the LQR problem. When the system is disturbed by the outside world and deviates from the zero state, there is a control v, so that the system target function v to the minimum, then the v is called optimal control. The LQR problem is a constrained variational problem, that is, to find the extremum conditions of the functional J shown in (20). The optimal control is

$$v = -R^{-1} B^T P x = -Kz \tag{22}$$

where P is the solution of Riccati equation and $K = \begin{bmatrix} k_1 & k_2 & k_3 \end{bmatrix}$ is the linear optimal feedback gain matrix. In order to get the values of P and K, the Riccati algebraic equation needs to be solved:

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{23}$$

After we calculate K with Q and $R = 1$. Therefore, by using the value of $L_f^3 h(x)$, $L_g L_f^2 h(x)$ and v, the control law can be simplified as

$$\begin{aligned} u &= \frac{-L_f^3 h(x) + v}{L_g L_f^2 h(x)} \\ &= \frac{-k_1(\delta - \delta_N) + \left(\frac{k_3 D}{J} - \frac{D^2}{J^2} - k_2 \right)(\omega - \omega_N) + \left(\frac{k_3}{J} - \frac{D}{J^2} \right)(T_e - T_m) - \frac{c}{J\tau_a} T_e}{-\frac{3}{2J} \frac{k_a}{\tau_a} u I \cos\delta} \\ &\quad + \frac{\tau_a \psi_f}{k_a} \left[\frac{(\omega - \omega_N) \sin\delta}{\cos\delta} - \frac{\dot{I}}{I} \right] \end{aligned} \tag{24}$$

4. **Simulation Results.** The simulation results in the study state were carried out with Matlab/Simulink in order to justify the effectiveness of the considered system using feedback linearization controller as described in the previous sections for the designed MG with VSG. The main analysis is the system frequency change and the active power output of the VSG system for grid-connected and islanded MG. The configuration of the model and adjustable parameters system is shown in Table 1.

TABLE 1. System parameters

Parameter	Value	Parameter	Value
P_N	1300 kW	V_{rms}	510 V
ω_N	314 rad/s	V_{dc}	1100 V
J	0.4 kg·m^2	k_a	0.0005
D	20	τ_a	0.01

In order to verify the proposed controller when it is connected to and disconnected from the power grid under the rated load of 13 kW, the simulation results are shown as follows.

Figure 2 shows the frequency of the system when the system is connected to grid at 0.3 s and then disconnected again to the island state at 0.6 s. With the feedback linearization control strategy, the frequency of the system falls immediately and smoothly during 0.1 s, and then, it is stabilization between 0.1 and 0.3 seconds. However, when without feedback linearization controller, the frequency of the system drops slowly between 0 and 0.3 seconds; meanwhile, it cannot stay steady. So the feedback linearization controller is smoother in the transient process. At 0.6 s, the system is disconnected from the grid, and the frequency is reduced immediately. And, it is shown that during the transition process, the frequency decreases smoothly due to the existence of virtual inertia and damping, and the system frequency changes smoothly.

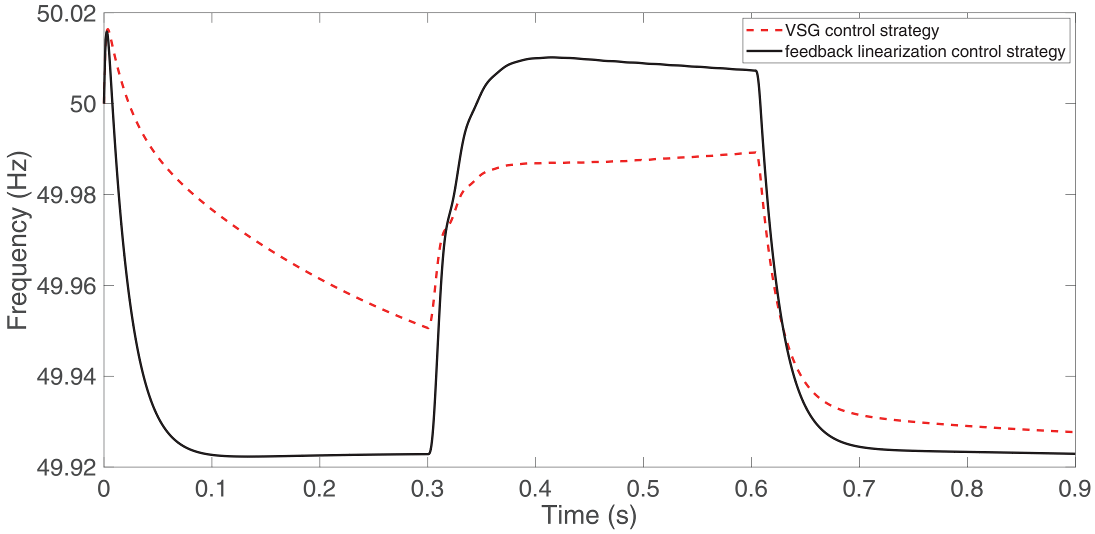

FIGURE 2. Variation of frequencye

Figure 3 exhibits the active power of the system when the system is connected to grid at 0.3 s and then disconnected again to the island state at 0.6 s. According to the simulation results, firstly, the VSG system operates in islanded mode. The VSG system provides 13 kW active power to supply essential local loads. Due to the fact that the frequency cannot stay steady, without feedback linearization controller the active power of the system has to be increasing during 0 to 0.3 s, even the active power provided cannot meet the load demand. However, the active power can quickly reach the desired value under the proposed control strategy. And it is almost in a stable position between 0 and

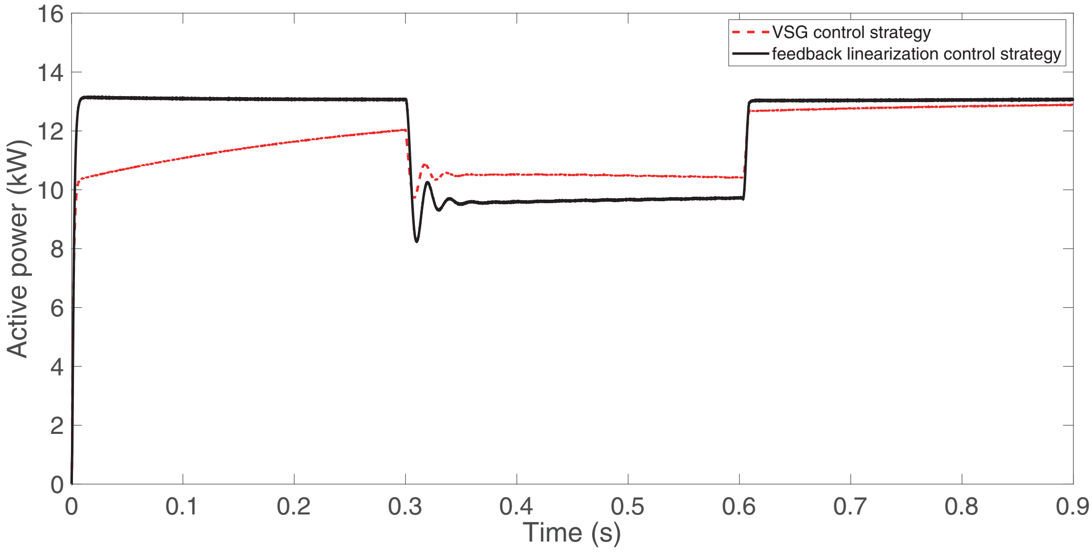

Figure 3. Variation of active power

0.3 seconds. Because the change of frequency will directly lead to the change of active power system. At 0.6 s, the system is disconnected from the grid. The VSG system output power increases immediately. It is obvious that during the transition process, the active power increases with no overshoot.

As can be seen from Figures 4 and 5, using feedback linearization control strategy, the voltage waveform basically remains unchanged, while the current waveform fluctuates slightly when the grid is connected.

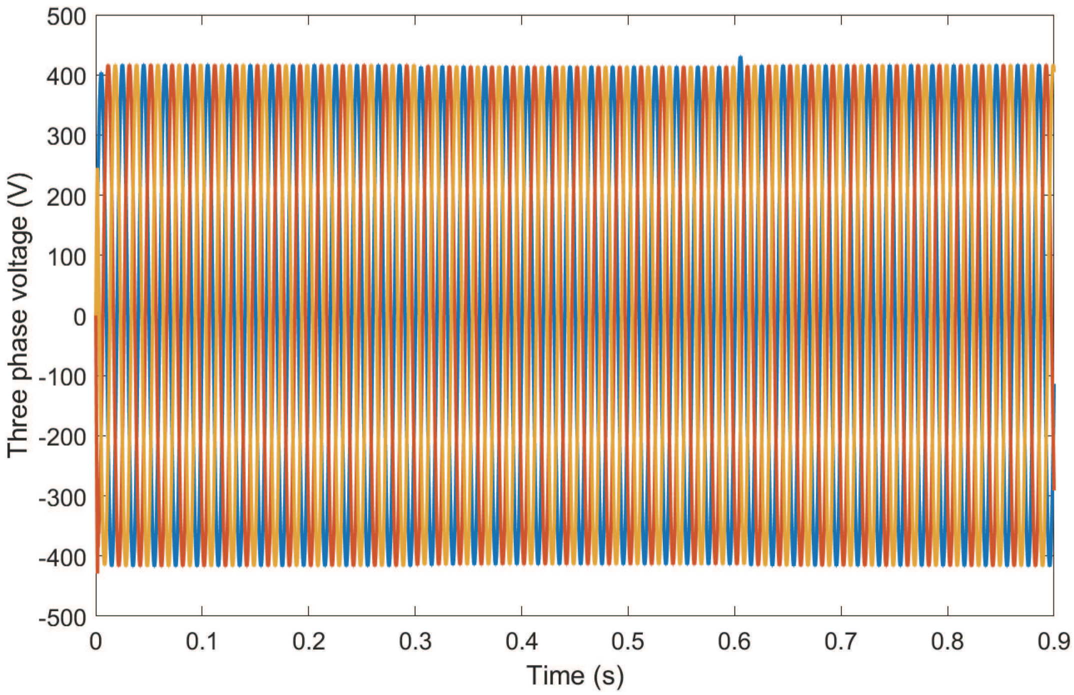

Figure 4. (color online) Variation of voltage under feedback linearization controller

The above analyses mainly prove that the designed controller can achieve smooth switching in the transition process, especially when disconnected to the power system, even without the need for pre-synchronous operation, the system can achieve improved stability.

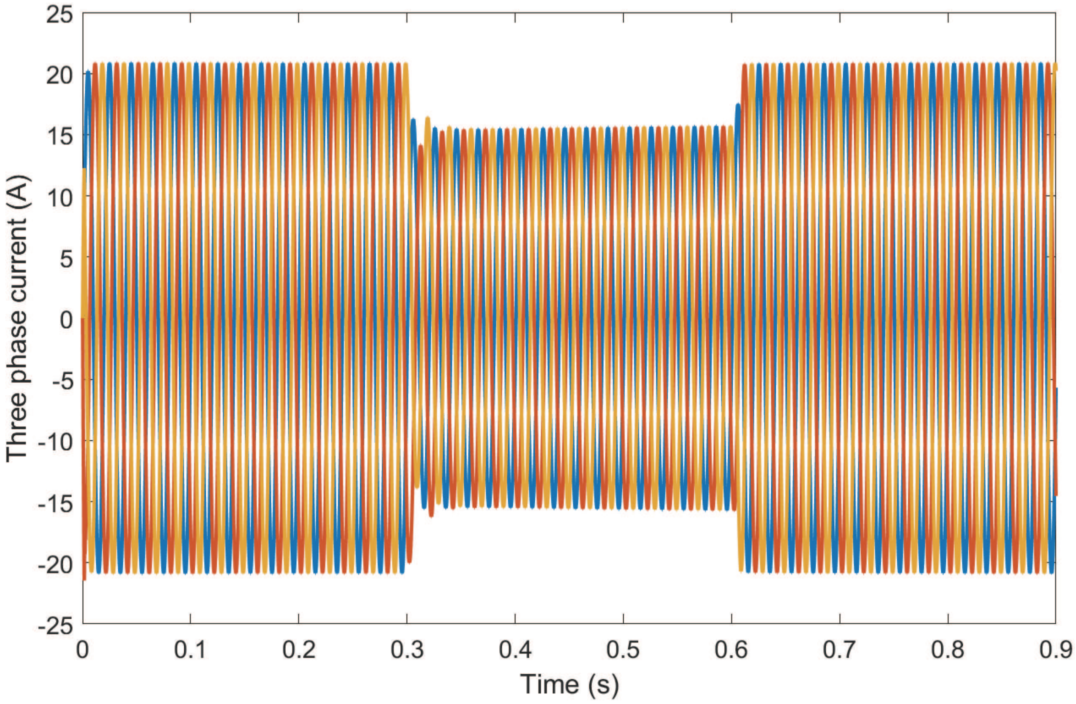

FIGURE 5. (color online) Variation of current under feedback linearization controller

5. Conclusions.

In this paper, a novel method based on VSG is designed with enhanced stability for grid-connected and islanded MG using feedback linearization controller. The linearization controller is designed when the nonlinear power system is exactly linearized. The simulation results show that the strategy improves the frequency response of the transition process by decreasing the frequency response time. Due to the fact that the LQR is applied to getting the linear optimal feedback gain matrix, the robustness against external disturbances in MG is provided. Performance in terms of disturbances and uncertainties in the system parameters is improved by the controller. In view that the power system cannot always be fully linearized, it may be partially linearized. The future work will deal with the design of nonlinear controller for partially linearized power system.

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